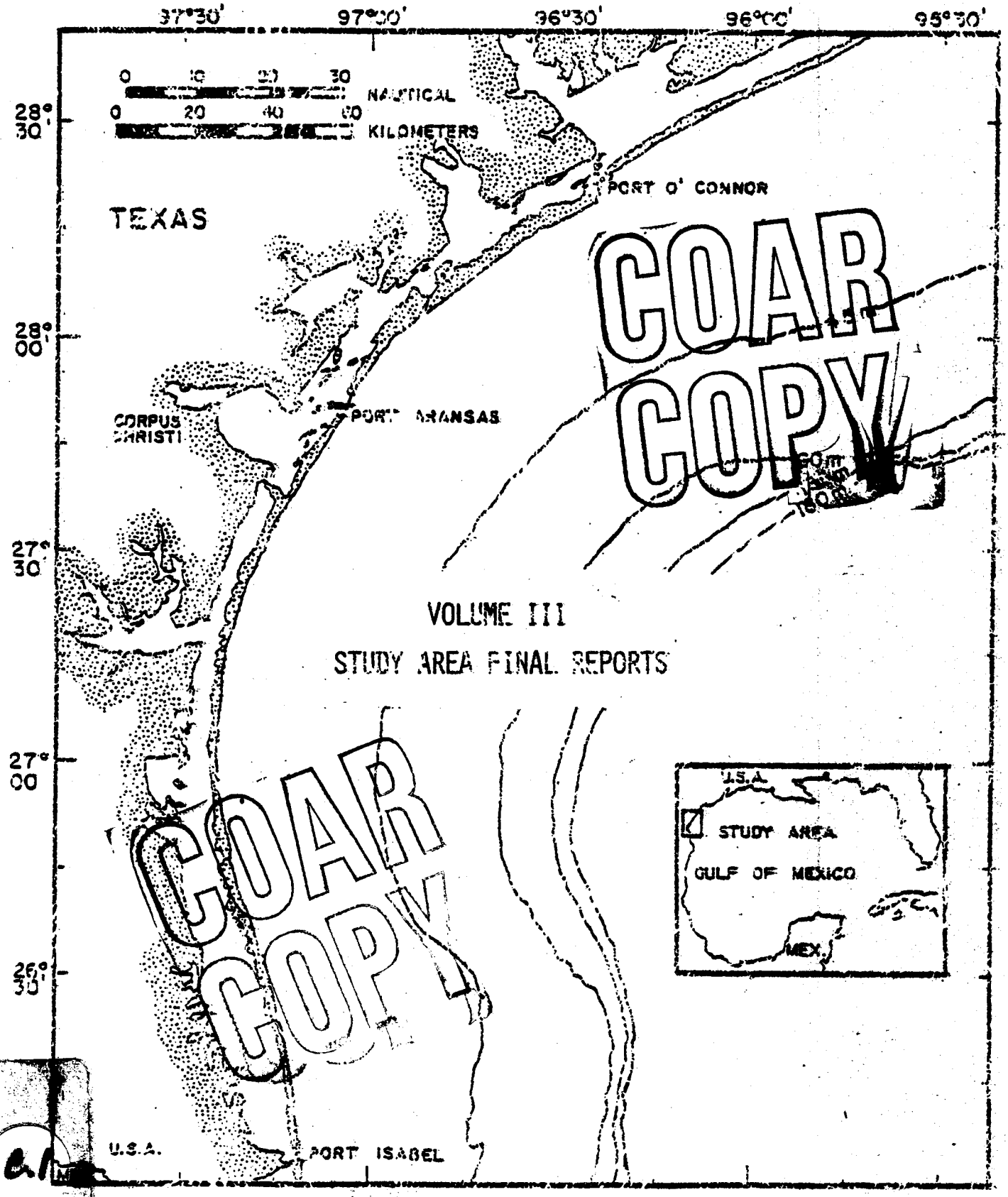
ENVIRONMENTAL STUDIES,
SOUTH TEXAS OUTER CONTINENTAL SHELF,
1975-1977



ENVIRONMENTAL STUDIES,

SOUTH TEXAS OUTER CONTINENTAL SHELF,

1975-1977

VOLUME III

STUDY AREA FINAL REPORTS

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CHAPTER ONE

INTRODUCTION

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Program Manager

INTRODUCTION

The Texas coastal area is biologically and chemically a two-part marine system, the coastal estuaries and the broad continental shelf. These two components are separated by a chain of barrier islands and connected by inlets or passes. The area is rich in finfish and crustaceans, many of which are commercially and recreationally important. The broad continental shelf supports a valuable shrimp fishery which, as a living resource, contributes significantly to the local economy. Although an excellent overview of the zoogeography of the northwestern Gulf of Mexico is provided by Hedgpeth (1953), there are still many unknowns concerning the functioning of this complex marine system.

In 1974, the Bureau of Land Management (BLM), as the administrative agency responsible for leasing submerged federal lands, was authorized to initiate a National Outer Continental Shelf (OCS) Environmental Studies Program. As part of this national program, the BLM developed the Marine Environmental Study Plan for the South Texas Outer Continental Shelf (STOCS) to add to our understanding of this ecosystem. This plan was developed to meet the following four specific study objectives:

1) provide information for predicting the effects of OCS oil and gas development activities upon the components of the ecosystem;
2) provide a description of the physical, chemical, geological, and biological components, and their interactions, against which subsequent changes or impacts could be compared;
3) identify critical parameters that should be incorporated into a monitoring program; and,
4) identify and conduct experimental and problem-oriented studies as required to meet the basic objectives.

BLM contracted the University of Texas at Austin to act for and on behalf of a consortium program of research conducted by Rice University, Texas A&M University, and the University of Texas, to implement the Environmental Study Plan. This plan called for an intensive multidisciplinary three-year study (1975-1977) to characterize the temporal and spatial variation of the shelf marine ecosystem beyond 10 m water depth. The central theme of the STOCS study was to provide an understanding of the living and non-living resources of the shelf. In order to approach the objectives outlined above a broad program was designed which included:

a) water mass characterization;
b) pelagic primary and secondary productivity as described by floral and faunal abundances, standing crop, and nutrient levels;
c) sediment texture characterization;
d) benthic productivity as described by infaunal and epifaunal densities;
e) natural petroleum hydrocarbon levels in biota, water and sediment; and,
f) natural trace metal levels in biota and particulate matter.

This volume represents a compilation and evaluation of selected studies concerning the significant natural environmental characteristics of the northwestern Gulf of Mexico. It has been prepared by a group of qualified scientists collectively conversant with the major environmental aspects of the study region.

The purpose of this volume is to provide an overview of the current status of baseline information and knowledge of an area identified for potential future energy resource exploitation. This information serves as a significant addition to the knowledge required in understanding the

environment and ecology of the STOCS. Selected data have been utilized by the respective authors in their synthesis and integration efforts and there has been no attempt to list or discuss all studies within a study area. It should further be noted that each section of this volume has been compiled and written as a "report within a report" and is meant to stand alone as a distinct scientific document or statement. The integration of the various sections is included in Volume I.

The general area of study corresponds to that portion of the Gulf of Mexico off the Texas coast designated by the Department of the Interior for future oil and gas leasing (Figure 1). The area covers approximately 19,250 km^2 and is bounded by 96°W longitude on the east, the Matagorda Bay complex on the north, the Texas coastline on the west, and the Mexico-United States international border on the south. The Texas continental shelf has an average width of 88.5 km and a relatively gentle seaward gradient that averages 2.3 m/km.

No ecosystem is a completely self-contained unit, and the STOCS system is no exception. It is influenced by adjoining regions such as the open Gulf of Mexico, the Mississippi River to the northeast, the Rio Grande to the south, and the land masses to the west. These adjacent regions have a marked influence on the climate and are the sources of many inputs into the system. Although we look at the region as a somewhat discrete unit, we must continually keep in mind the influence of these contiguous territories.

It is hoped that this brief introduction will enable the reader to comprehend the objectives and scope of the STOCS study. As stated earlier, each section has been developed somewhat independently and should be considered as an independent statement by each author or authors. Acknowledgment is given to all the scientists involved in this muldisciplinary

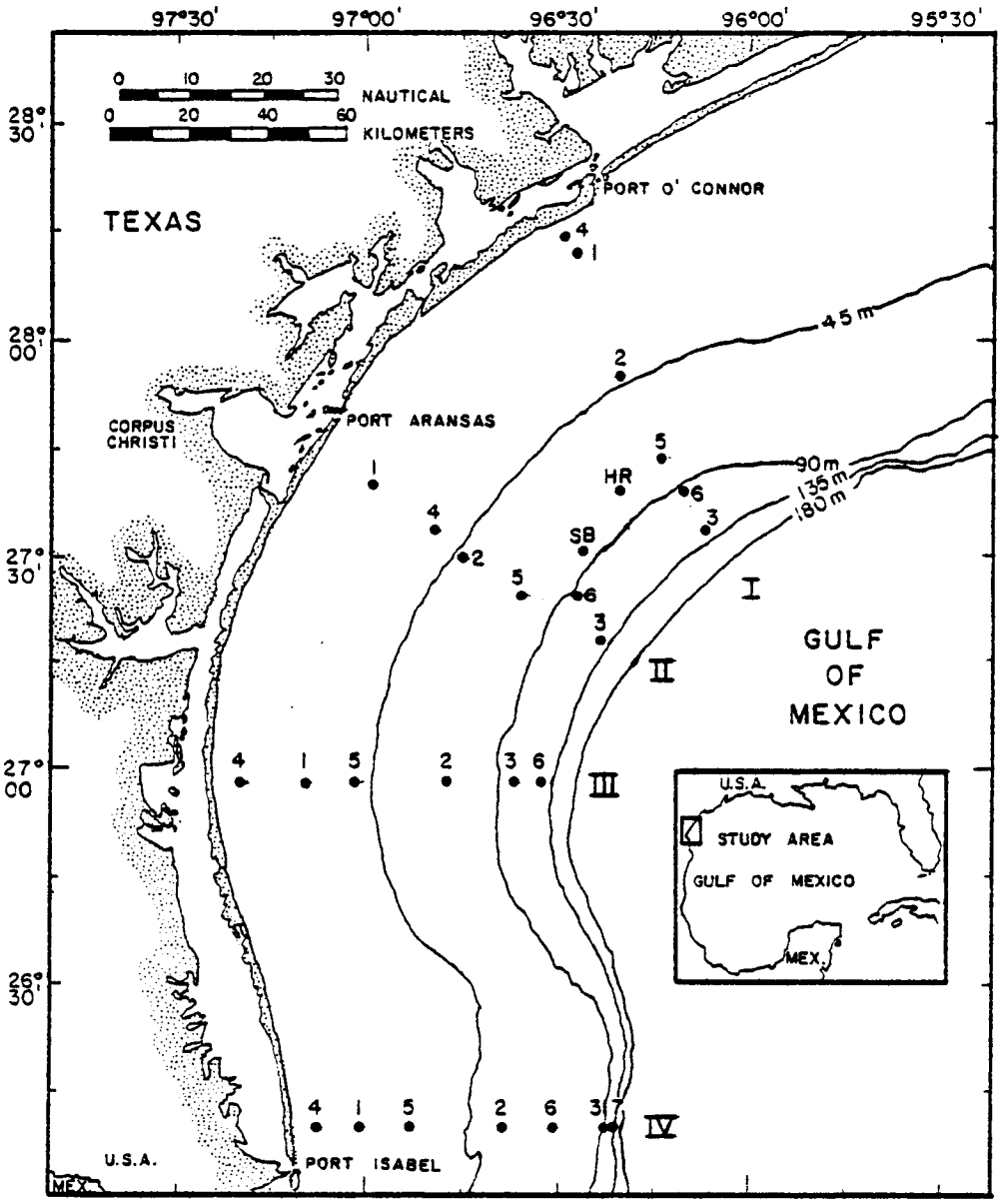

Figure 1. Map showing the south Texas continental shelf bathymetry and location of sampling sites.

program and the contributions they provided. For further reference concerning their specific contributions, see Parker (1976), Berryhill (1977), Groover (1977), Griffin (1979), and Flint and Griffin (1979).

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CHAPTER TWO

HYDROGRAPHIC PROJECT

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ABSTRACT

Temperature and salinity data from 1976 and 1977 are used to describe low-frequency hydrographic variability in Gulf of Mexico shelf waters off the central Texas coast. A total of 23 vertical cross-sections extending across the entire shelf at approximately monthly intervals indicate several recurring features in the annual cycle. Minimum salinities occur in late spring, when values decrease to as low as 18 parts per thousand over the inner shelf; freshwater run-off at other times of the year may decrease salinities to 30-31 ppt. The surface salinity over the outer shelf may be as low as 32-33 ppt in late spring, but deviates little from 36 ppt over the remainder of the year. Highest annual surface temperatures are 28-29°C across the shelf in late summer; lowest temperatures in February range from 12-13°C over the inner shelf to 20-21°C over the outer shelf. Bottom temperatures are dominated by the annual cycle over the inner shelf and vary from approximately 18 to 28°C. Near-bottom temperatures over the outer shelf appear to vary over much shorter time scales which cannot be resolved by monthly sampling. Incorporation of results of circulation studies conducted between 1973 and 1977 suggests that during the late fall through late spring months there is a strong transport of water toward the south-southwest along the central Texas coast. During the summer months, alternating longshore currents decrease the net transport along the Texas coast, but there is some indication of a transient upwelling phenomenon bringing cooler, saltier water onto the inner shelf.

INTRODUCTION

Information on the hydrography of Texas shelf waters has accumulated for years from individual cruises covering varying fractions of the total area. The available data have been summarized as monthly average surface temperatures (Rivas, 1969; Devine, 1976) as the multi-annual mean variation in temperature structure from the surface to a depth of 225 m (Etter and Cochrane, 1975), and as surface and bottom temperatures recorded at an inner and mid-shelf station during cruises extending over a three-year period (Robinson, 1973; Armstrong, 1976). Jones *et al.* (1965) have reported results of hydrographic surveys made over a one-year period along a transect extending out from a point near Port Aransas, Texas. Taken together, these previous studies provide a good overview of the hydrographic climate of Texas shelf waters.

In the surface layer, strong cross-shelf temperature gradients during the mid-winter months disappear with seasonal heating, and surface water becomes horizontally isothermal at approximately 29°C by late summer. Vertical stratification, on the other hand, is nearly absent in shelf waters during the winter months, but it is well developed in summer. Shelf salinities remain relatively high for most of the year. An exception is a short period during the spring and early summer months when a plume of Mississippi River water may cover the entire shelf, lowering salinities through the uppermost 20-30 m.

A better understanding of the processes producing these mean patterns often requires better temporal and spatial resolution than can be obtained by compiling historical data. Thus hydrographic sampling was incorporated into a monitoring program in Texas shelf waters, sponsored by the Bureau of Land Management. Data collection was initiated in 1975 and expanded in

1976 and 1977 to include a total of 26 stations. Cruises were scheduled approximately monthly along one of the transects (Figure 2.1), extending seaward from the central Texas Gulf Coast near Port Aransas to the shelf break, approximately 80 km offshore. Seven stations were occupied along this transect. The other 19 stations were visited only three times each year. Data from the Port Aransas transect during 1976 and 1977 provide both the spatial and temporal resolution required to describe variability in shelf water hydrography occurring over time scales between approximately a month to a year, and to investigate the recurrence of annual cycles.

It is appropriate to begin with a brief overview of the temperature and salinity ranges characteristic of the Gulf of Mexico in general before focusing on shelf waters along the northwestern rim. Background information is available in greater detail in survey papers by Wüst (1964) and Nowlin (1971).

In the open waters of the Gulf of Mexico, water mass distributions are the result of inflow through the Yucatan Channel, outflow through the Straits of Florida, surface conditioning by local air-sea exchange processes, and internal mixing. Together, these produce three well defined water masses in layers below the surface mixed layer. The sill depth of approximately 2000 m between the Yucatan Peninsula of Mexico and the western tip of Cuba exerts a dynamically significant influence on the temperature and salinity (T-S) distribution in open Gulf waters. Below the sill depth, both temperature and salinity are characterized by spatial homogeneity, due to the isolation from the Deep and Bottom Water found in the Atlantic Ocean and the Caribbean Sea. Gulf Basin Water, found below the effective sill depth of approximately 1,500 m, is characterized by potential temperatures between approximately 4.2 and 4.4°C, and salinities

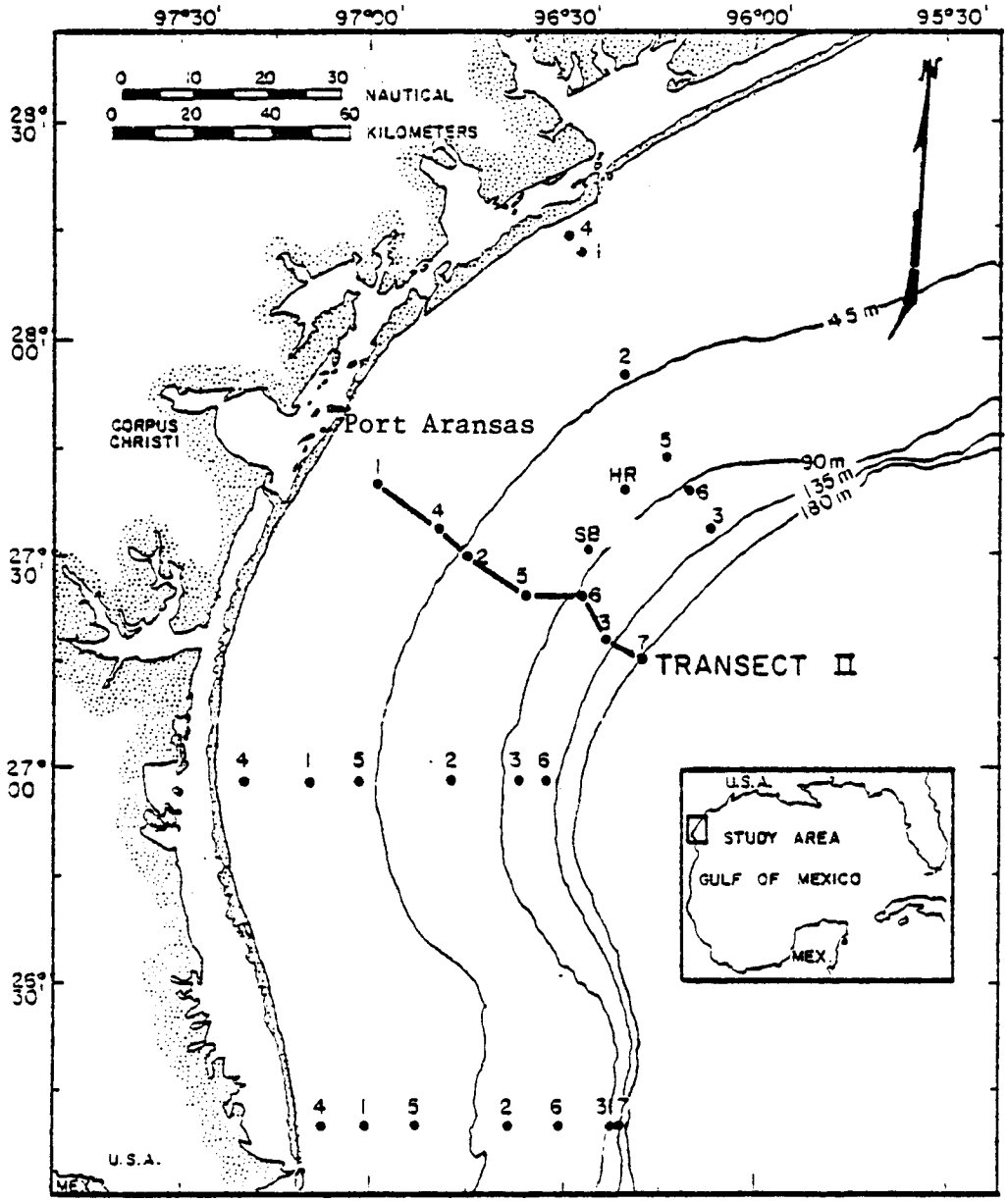

Figure 2.1 Locations of Sampling Stations and Transect II. Insert Shows Study Area in the Northwestern Gulf of Mexico. HR stands for Hospital Rock and SB stands for Southern Bank.

between 34.96 and 34.98 parts per thousand (ppt).

Above the Gulf Basin Water, potential temperatures increase gradually, however salinities decrease to a minimum of approximately 34.86 ppt between depths of 900 and 1,100 m. This salinity minimum reflects the influence of Antarctic Intermediate Water, which can be traced back through the Caribbean Sea, across the tropical Atlantic Ocean and into high southern latitudes to a source at the Antarctic Polar Front at 45-50°S latitude.

Both temperature and salinity increase with decreasing depth above the layer of Antarctic Intermediate Water. A maximum in salinity is characteristically found between approximately 100 and 300 m. This feature can also be traced back through the Caribbean Sea and upstream along the Subtropical Undercurrent to a source under the semi-permanent high pressure center in the Atlantic Ocean east of Bermuda (Wüst, 1964; Nowlin, 1971). In the Caribbean, the Subtropical Underwater has a salinity range of 36.0 ppt to 36.7 ppt. In the Gulf of Mexico, due to vertical mixing from above and below, the range is somewhat narrower, and salinities are generally between 36.2 ppt and 36.7 ppt. Temperatures characteristic of this layer vary between about 18°C and 26°C in open Gulf waters.

The surface mixed layer lies atop the three distinct water masses discussed above. Because of the direct contact between this layer and the overlying atmosphere, it is relatively quickly modified, or conditioned, by conductive, evaporative, and radiative processes. Thus, the shelf waters exhibit not only a well defined annual cycle, but also substantial variability over shorter time scales. The temporal and spatial heterogeneity of the surface layer makes it impossible to describe in more than a general way.

Temperatures characteristic of the mixed layer over the inner Texas shelf range from approximately 11-13°C in late winter to 28-29°C in late

summer. Salinity variations in nearshore waters are also variable, ranging from open Gulf surface values of about 36.4 ppt to 20 ppt or less during the spring run-off or periods of heavy rainfall. Mixed layer T-S variations decrease somewhat with increasing distance from the coast, but even over the outer shelf, annual variations on the order of 10°C and 2-3 ppt are not uncommon for the Texas shelf.

The hydrographic and supplementary current data discussed in this section deal specifically with this uppermost surface layer as it occurs along the Texas coast. The relatively high station density and sampling frequency provide a good data base for a close inspection of the spatial and temporal variability and for postulating the physical processes by which these patterns are formed and evolve in time. The objective here is to discuss observed temporal variability at several locations along a transect extending out from the coast near Port Aransas, Texas (Figure 2.1). The discussion will focus specifically on low-frequency temperature and salinity variations at what are felt to be representative sites over the inner and outer shelf. The two years of available hydrographic data are used to suggest the forcing mechanisms responsible for the recurrence of the annual pattern recorded in 1976 and 1977.

METHODS

Hydrographic profiles were obtained from seven stations along a transect extending seaward to the shelf break from a point approximately midway along the Texas Gulf coast (Figure 2.1). Temperature and salinity (T-S) profiles, extending from surface to near-bottom levels, were provided in analog form by a Plessey Model 9060 Salinity/Temperature/Depth Measuring System (STD), or by direct readout measurements from a Martek

Model TDC Metering System (TDC) in shallow water or when salinities were below 30 ppt.

All hydrographic profiles were calibrated at top and bottom levels with reversing thermometer temperatures and with salinities determined by a laboratory salinometer. Calibrated temperature and salinity values were accurate to approximately 0.1°C and 0.05 ppt, respectively. Hydrographic data were digitized at 3 m intervals.

A total of 11 cruises in 1976 and 12 in 1977 provided the data base for this investigation of the hydrography of Texas shelf waters. Cruises were conducted approximately monthly, and the time interval between successive cruises was well suited for tracing the seasonal progression in temperature and salinity. The more transient events associated with meteorological forcing that may have preceded a cruise could not be resolved by the data.

Environmental Devices Corporation Type 105 recording current meters were used to record sub-surface currents over half-hourly or hourly sampling periods. The accuracy of the speed and direction measurements were ±3% of full scale, and ±5%, respectively, according to the manufacturer's specifications.

Circulation studies have been conducted in Texas continental shelf waters since early 1972. The available current data can be integrated qualitatively with the hydrographic data to explain both the spatial distribution of the temperature and salinity patterns found on any given cruise and the temporal variability of these patterns noted from one cruise to the next. Because the current meter data have received individual attention in the scientific literature (Smith 1975, 1977b, 1978a, 1978c, 1979), the results presented in the following section will deal

exclusively with the hydrographic data. Current data will be combined with temperature and salinity data in the discussion section to present an integrated description of the formation of, and seasonal progression in the observed hydrographic patterns.

RESULTS

The results presented here describe the very low frequency, seasonal and annual variations in temperature and salinity. These hydrographic variables show a well-defined annual progression. Results of circulation studies are incorporated into the next section to explain the patterns observed in any given season, as well as the transition from one season to the next. A good overview of temporal variability at a point is obtained by plotting top and bottom temperature and salinity vs. time. One sees immediately the annual ranges in temperature and salinity in near-surface and near-bottom layers. In addition, this form of presentation provides information on the stratification of the water column over the course of a year.

Figure 2.2 is a composite of surface and near-bottom salinity (top) and temperature (bottom) from Station 3 on Transect II (see Figure 2.1). The noteworthy feature in the data is the relatively stability of these hydrographic variables at the 117 m level. Salinities are all within the range of 36.05 - 36.61 ppt, and values generally vary little from 36.4 ppt; no seasonal variation is apparent. Temperatures indicate a greater degree of variability, but there is not a well-defined seasonal cycle recurring over the two-year study. Temperatures vary from 16.5° to 20.0°C. Highest values in 1976 are seen in the early summer months, however, highest temperatures the following year occur in October.

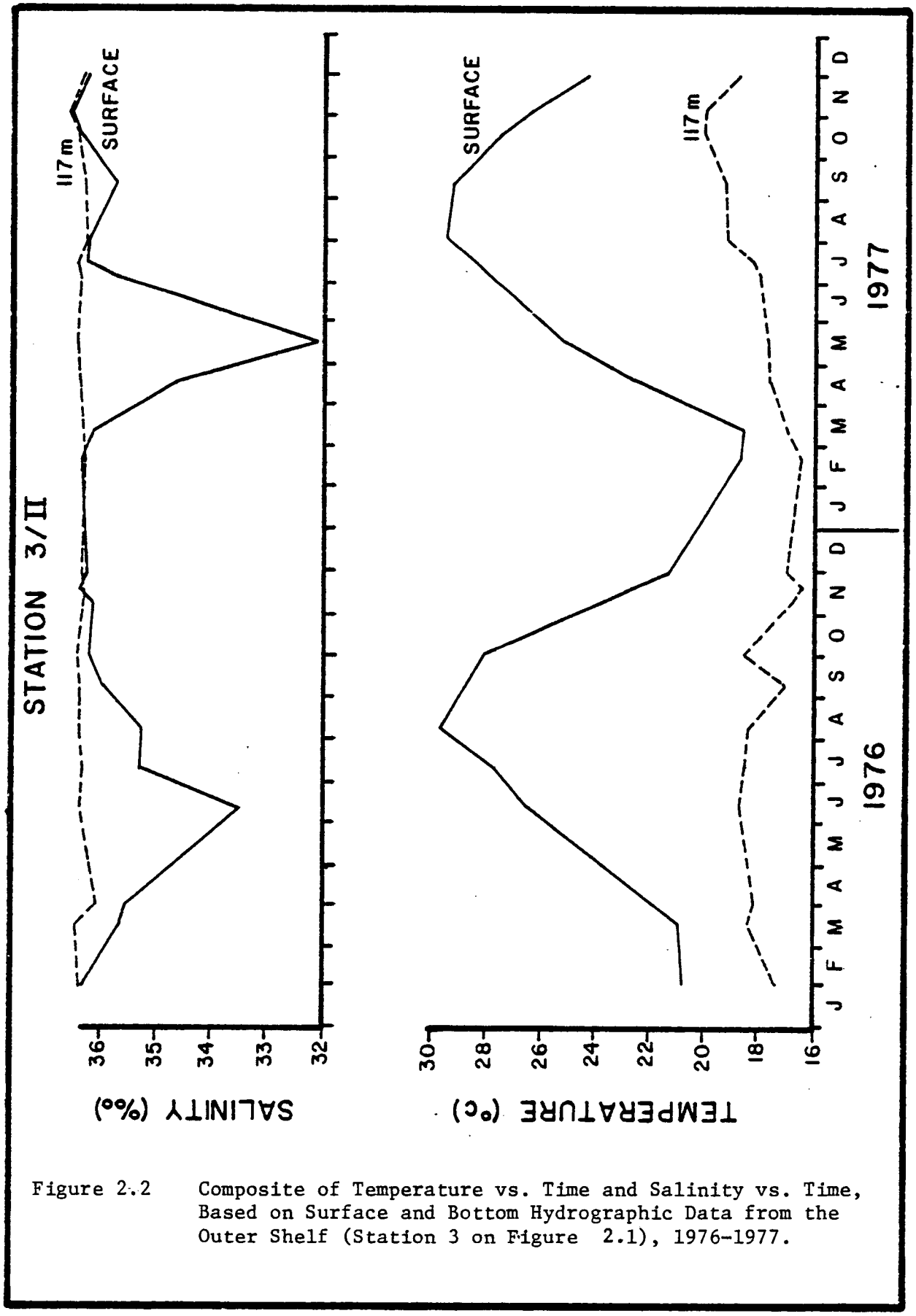

Figure 2.2 Composite of Temperature vs. Time and Salinity vs. Time, Based on Surface and Bottom Hydrographic Data from the Outer Shelf (Station 3 on Figure 2.1), 1976-1977.

In the surface layer at this outer shelf location, a recurring annual cycle is clearly apparent. In both years, a pronounced salinity minimum occurs in the late spring months. Because of the approximately monthly sampling, it is impossible to determine the time of lowest values in more than a general way, and there is undoubtedly some variability from one year to the next. Weather conditions will both affect the discharge of run-off at the mouth of the Mississippi River, and determine the rate at which low salinity water is transported westward along the northern rim of the Gulf of Mexico. The two years of data show that there may be year to year variations in the rate at which surface salinities return to values in excess of 36 ppt. The unavailability of rainfall and current velocity data for this outer shelf location makes it impossible to determine whether the salinity is primarily in response to advection or local precipitation-evaporation processes.

Surface temperatures suggest a sinusoidal annual variation, with highest temperatures occurring in August. Surface waters are heated to just over 29°C both years. Lowest temperatures, recorded in February and March, may be somewhat more variable from one year to the next, depending upon the intensity of the winter season. Minimum temperatures in early 1976, as determined by monthly sampling, were just under 21°C, while lowest recorded temperatures in 1977 were just under 19°C.

Hydrographic data from surface and bottom levels at Station 1 on Transect II are summarized in Figure 2.3. As would be expected, vertical homogeneity is substantially greater in the shallower waters over the inner shelf. Thus, a more clearly defined seasonal variation is apparent at both depths. Surface salinities decrease to an annual low in the spring months, but considerable variability is indicated throughout the

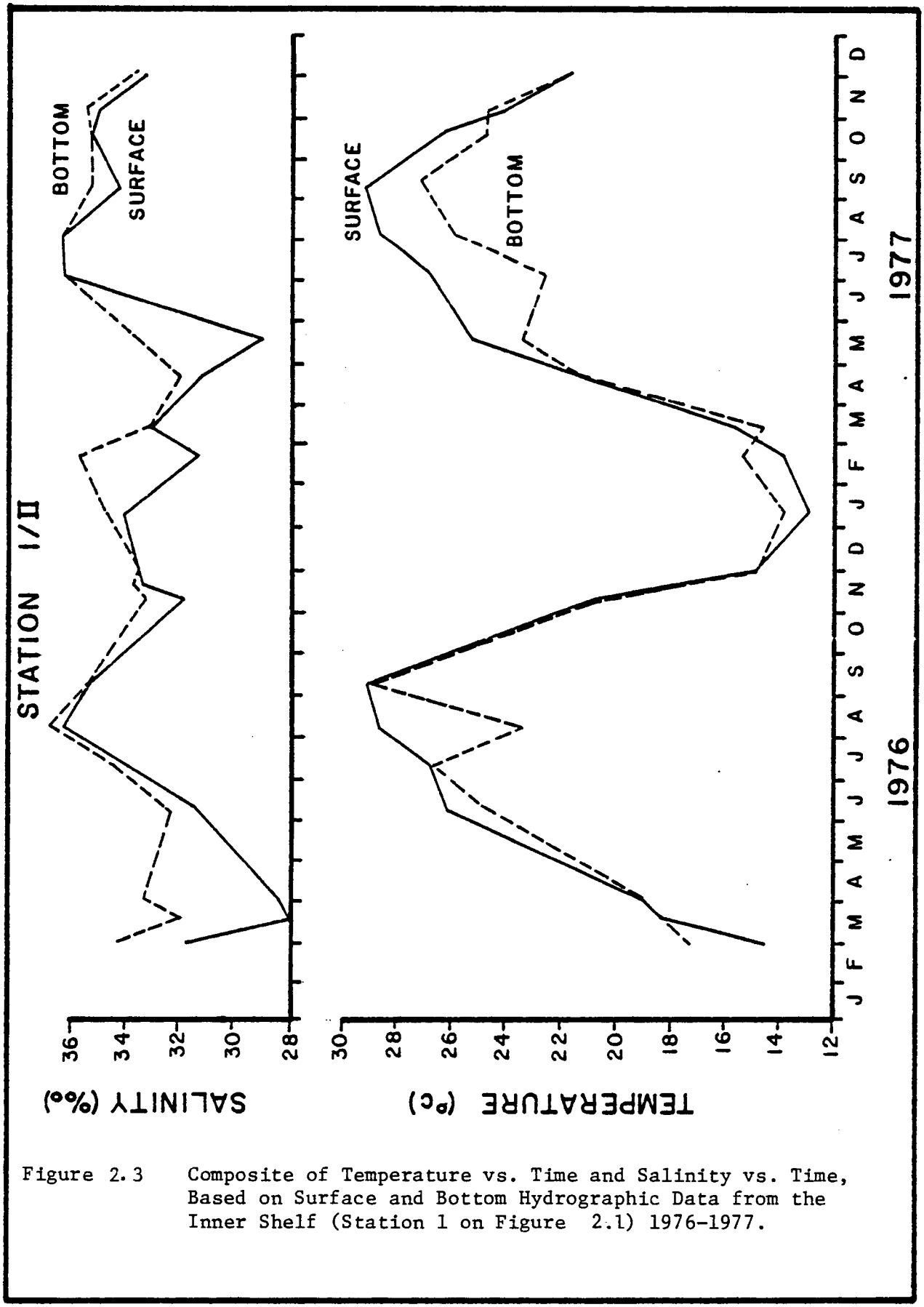

Figure 2.3 Composite of Temperature vs. Time and Salinity vs. Time, Based on Surface and Bottom Hydrographic Data from the Inner Shelf (Station 1 on Figure 2.1) 1976-1977.

rest of the year as well. The proximity of the coast at this location makes the water more responsive to variations in rainfall and the resulting freshwater run-off. Salinities are somewhat more stable at near-bottom levels, and the spring minimum is above 32 ppt both years. The separation of the surface and bottom salinity traces during the spring months suggest that excessive freshwater run-off produces the strongest vertical stratification at this time.

The surface and bottom temperature curves in the lower half of Figure 2.3 trace out nearly the same pattern. The water column over the inner shelf is very nearly isothermal during the fall, winter and spring months. An exception to this is found during the summer months of both 1976 and 1977. The temporary divergence of the two curves suggests that bottom waters may lie below a seasonal thermocline at this time. Bottom temperatures are 2-4°C lower than surface values. The annual temperature range indicated by the curves is about 15°C at both surface and bottom levels. Highest values of approximately 29°C are recorded in late August and early September; lowest values occur in January and February, when cold fronts moving off the Texas coast are most intense.

A comparison of surface temperatures recorded at these two stations (Figures 2.2 and 2.3) provides a crude picture of cross-shelf temperature gradients over the course of the year. During the late summer months, temperatures of slightly over 29°C are found in the surface layers at both stations, and thus cross-shelf gradients appear to be minimal. In contrast to this, lowest temperatures of approximately 14°C over the inner shelf are substantially below the minimum values of 19-21°C found over the outer shelf. This results in strong cross-shelf gradients during the winter months. The nearly isothermal surface water across the

shelf in summer, coupled with significant gradients in winter, results in a lower annual average temperature over the inner shelf.

Several additional features of the hydrography of the surface layer across the shelf are brought out by two elementary statistics--the mean and the standard deviation--computed from the data obtained during the two-year study. Figure 2.4 is a composite of the mean surface temperatures and salinities across the shelf along Transect II, and of the standard deviations about the means at each of the first six stations. Station 2 was not included in this analysis, since data did not extend over the entire two years.

The salinity data shows significantly greater variability in salinities over the inner shelf, and average values increase from 32 ppt near the coast to 35 ppt in mid-shelf waters. Beyond 40 km from the coast, surface waters are relatively isohaline, reaching a value of 36 ppt at a point 80 km offshore. The spatial variations in both the mean and standard deviation support the idea that significant salinity variations in the surface layer are confined to the inner half of the shelf at this point along the coast. The variability in salinity over the inner shelf is produced, in turn, by low salinity plumes moving along the coast, especially in the late spring months. While lowered salinities have been recorded over the entire shelf, freshwater run-off effects do not seem to be pronounced outside the first two stations, beyond about 30 km from the coast.

In sharp contrast to the spatial discontinuity in salinity found over the middle shelf, the cross-shelf variation in both the mean temperature and the standard deviation about the mean is quite uniform. The mean increases gradually from 22°C at the innermost station to just over 25°C

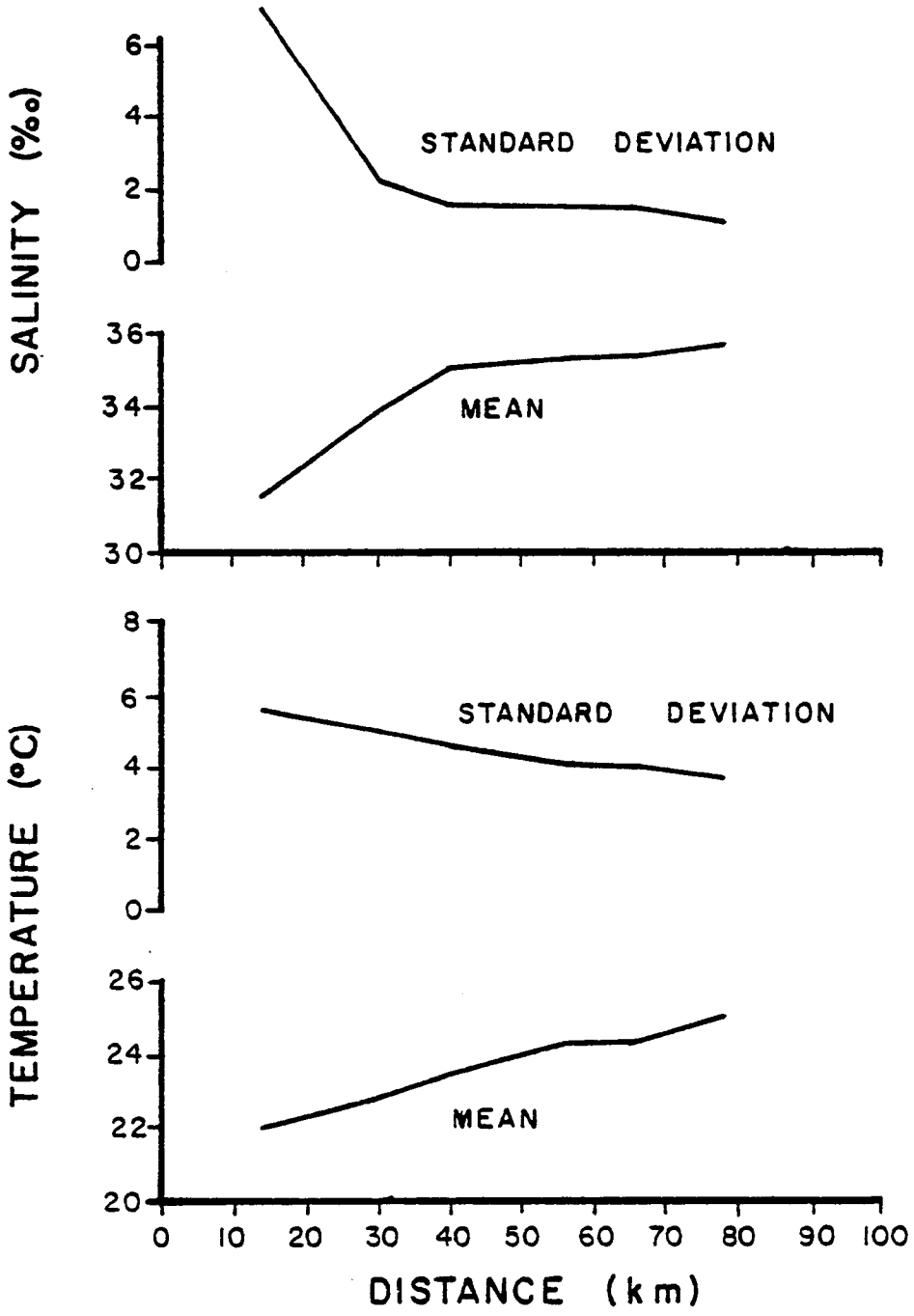

Figure 2-4 Averages and Standard Deviations for Temperature and Salinity Measured at the Surface Along Transect II, January 1976 through December 1977.

at the outer station. The lower mean temperature over the inner shelf, at noted above, is a result of the significantly lower temperatures in late winter. Thus, the annual temperature range appears to be strongly affected by the cross-shelf bathymetry. The water column depth determines the extent to which heat can be stored or given up through local air-sea interactive processes in the summer and winter months, respectively. The hydrographic data therefore suggest an important distinction between variations in temperature and salinity: Salinity variations appear to be most strongly influenced by advective processes, while variations in temperature seem to be controlled primarily by local heat exchange mechanisms.

Figure 2.5 is a composite time-depth plot for both temperature and salinity variations at the outer station during the two-year sampling period. In sharp contrast to the relatively minor variations in salinity at this location, the isotherms show a substantial degree of activity at all depths throughout the year. There is enough repetition in the 1977 data to suggest that there are several recurring features in the annual cycle. At this distance from the coast, significant salinity variations are restricted to the spring and early summer months, and to the upper 15-25 m of the water column. The 36 ppt isotherm is located at a depth of 95 m in early April 1976, but for the rest of the year and all of 1977 reduced salinities are confined to a much shallower surface layer.

The 23 profiles summarized in Figure 2.5 suggest that approximately the upper 90-100 m undergo a significant seasonal variation. In 1976, the 20° isotherm appeared at the surface in early April and descended to the 85-90 m level by late summer. The 18° isotherm rose throughout the winter of 1976-1977 but never intersected the surface. Thus, the 19° or perhaps the 20° isotherm can be used to bound the seasonally heated

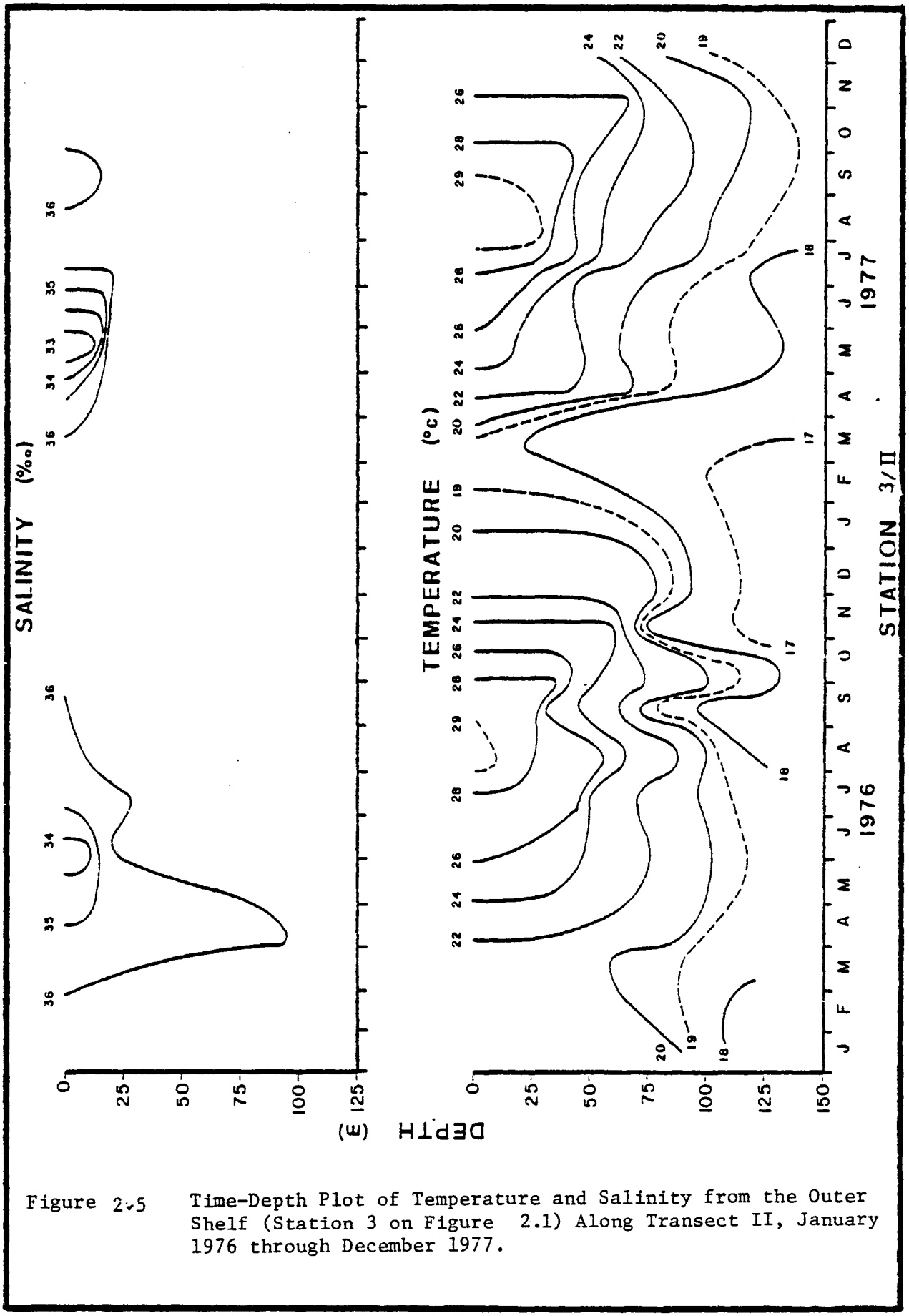

Figure 2.5 Time-Depth Plot of Temperature and Salinity from the Outer Shelf (Station 3 on Figure 2.1) Along Transect II, January 1976 through December 1977.

portion of the water column at this location. Water warmer than this is found only during the late spring, summer and early fall months. On the other hand, cooler water is found through at least a portion of the water column over the entire year. The movement of these isotherms is related more to vertical oscillations in the top of the permanent thermocline than to an annual cycle. The wave-like pattern of the 18°, 19° and 20° isotherms is most likely a result of infrequent sampling through a fairly active thermocline layer. Because of the short time scales associated with these variations, the available data are inadequate to monitor thermal activity in this part of the water column.

Temperature variability in approximately the upper half of the water column is more adequately resolved with the monthly cruise data. Although there is undoubtedly some high frequency contamination resulting from internal wave activity on the seasonal thermocline, the pattern is composed basically of warming in the surface layers from an annual low of about 20° to a late summer high of just over 29°. Fall cooling is rapid from late September through early December, and the associated convective overturning produces an increasingly thick isothermal surface layer, eventually extending to a depth of about 75 m.

The time-depth plots of temperature and salinity data from the inner shelf station (Figure 2.6) show quite different patterns. At this location, the water column is nominally 22 m in depth. With wave-induced mixing extending to the bottom at least occasionally, vertical stratification would be minimal. The more vertical orientation of the isopleths clearly indicates a greater homogeneity in this nearshore water column; temporal variations dominate vertical variations at this location.

The salinity data indicate an annual minimum occurring in April-May of both years. The arrival of low-salinity water shortly after the peak

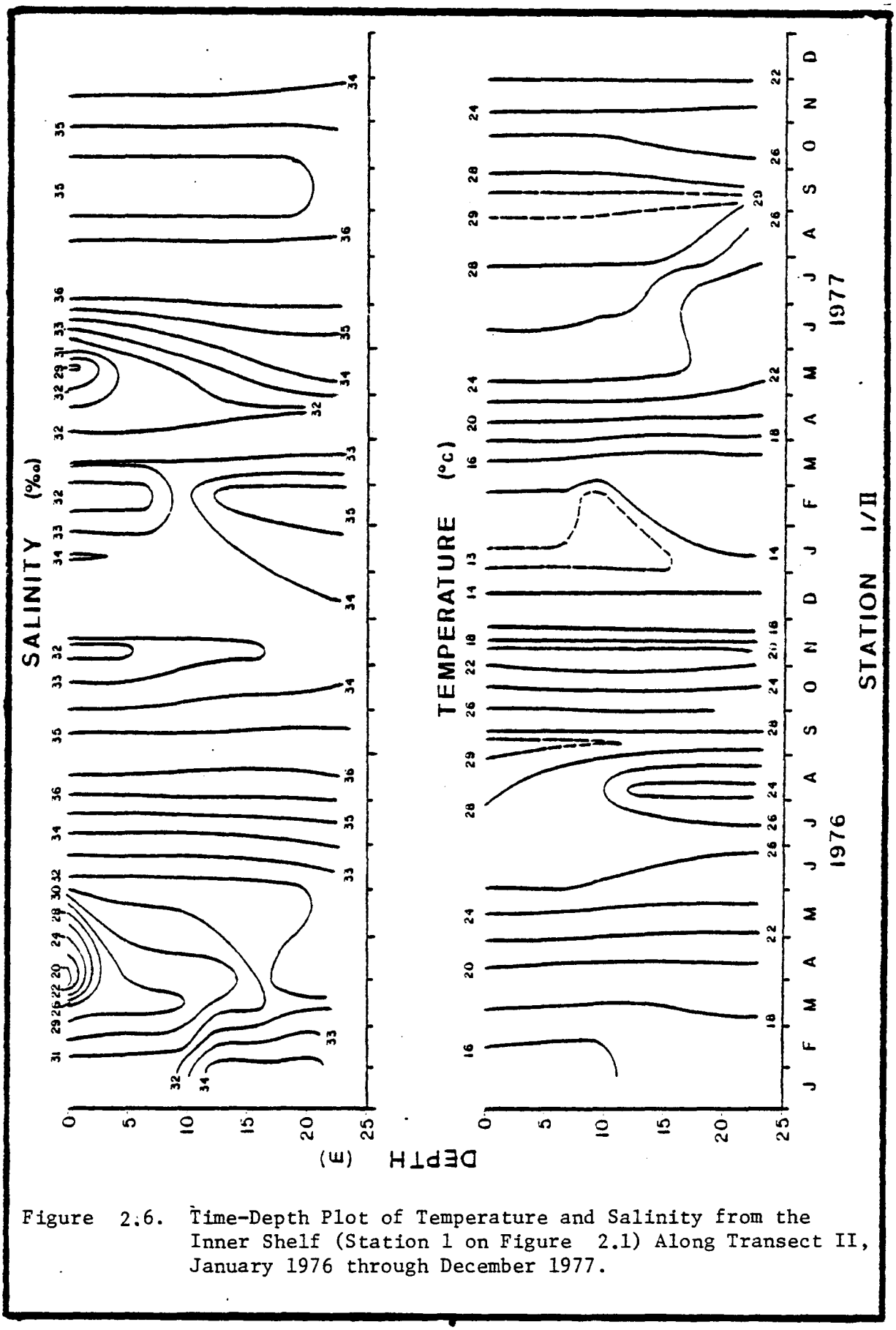

Figure 2.6. Time-Depth Plot of Temperature and Salinity from the Inner Shelf (Station 1 on Figure 2.1) Along Transect II, January 1976 through December 1977.

river discharges produces the only significant salinity stratification during the year. Lowest recorded salinities were 18.3 ppt in 1976 and 29.0 ppt in 1977. The difference may be due as much to the timing of the monthly sampling as to the characteristics of the low-salinity plume moving along the Texas coast. Inner shelf salinities then increase regularly through mid-summer to values of just over 36 ppt.

In both years, a slight decrease in salinity is recorded throughout the water column following the midsummer maximum. The annual precipitation maximum, computed from rainfall records at the International Airport at Corpus Christi, occurs in late summer and early fall. At the same time, with the day length and sun elevation angles decreasing, it is probable that evaporation is reduced somewhat. This postulated increase in the precipitation/evaporation ratio over inner shelf waters is consistent with the observed decrease in salinities at this time of year.

Temperature profile data of Figure 2.6 also suggest a more complete top-to-bottom mixing throughout the year. The nearly vertical orientation of the isotherms indicates that the annual temperature cycle at this location can be characterized as a nearly uniform warming and cooling at all levels. A brief period of thermal stratification occurs in mid-summer, when the seasonal thermocline forms just below mid depth. At these times, the bottom water may be 2-4°C cooler than the surface water. A second period of thermal stratification is noted both years during the mid-winter months. At this time, a reverse thermocline forms, with slightly cooler water lying atop a more saline, near-bottom layer. Maximum temperature differences revealed by the available data are 2-3°C in 1976.

Although the Texas Gulf Coast is not a region normally associated with upwelling, the persistent summer winds out of the southeasterly quadrant, together with the 033-213° orientation of the coastline at the

shoreward end of the Port Aransas transect, appear to produce at least brief periods of upwelling which stand out clearly in the hydrographic cross-sections. Temperature data from 3 June and 9-11 August 1976 show density isopleths curving upwards towards the shore (Smith, 1977b). At other times of the year, the constant density surfaces generally curve upward in an offshore direction or show no appreciable curvature.

Figure 2.7 illustrates the upwelling condition with temperature data collected on 4 August 1977. Warmest water is found in surface layers at some distance from the coast, with the 28° isotherm intersecting the surface over 30 km from the coast. The onshore directed temperature gradient, together with the layer of cool, near-bottom water extending nearly to the coast, comprise a pattern that is consistent with an offshore Ekman transport of surface water and a near-bottom return flow. It is noteworthy that wind data from Port Aransas, recorded during the month of July 1977 indicate that 74% of the wind directions were between southeast and south (Wagner, 1978). Ekman transport to the east-northeast would have a dominant offshore component. Figure 2.8 is a progressive vector diagram constructed from monthly resultant wind vectors, using data recorded at the International Airport in Corpus Christi, Texas. The data suggest that the vector averages are oriented nearly directly onshore during the summer months. Assuming a certain amount of scatter about the mean, there may be periods in excess of a week during which the wind may veer into the southerly quadrant. At such times, an offshore-directed Ekman transport could develop and persist long enough to produce the observed upwelling.

This general pattern of upward-curving isotherms appears to be a regular feature of Texas shelf waters during the summer months. An aperiodic, near-bottom encroachment of water from intermediate depths over the

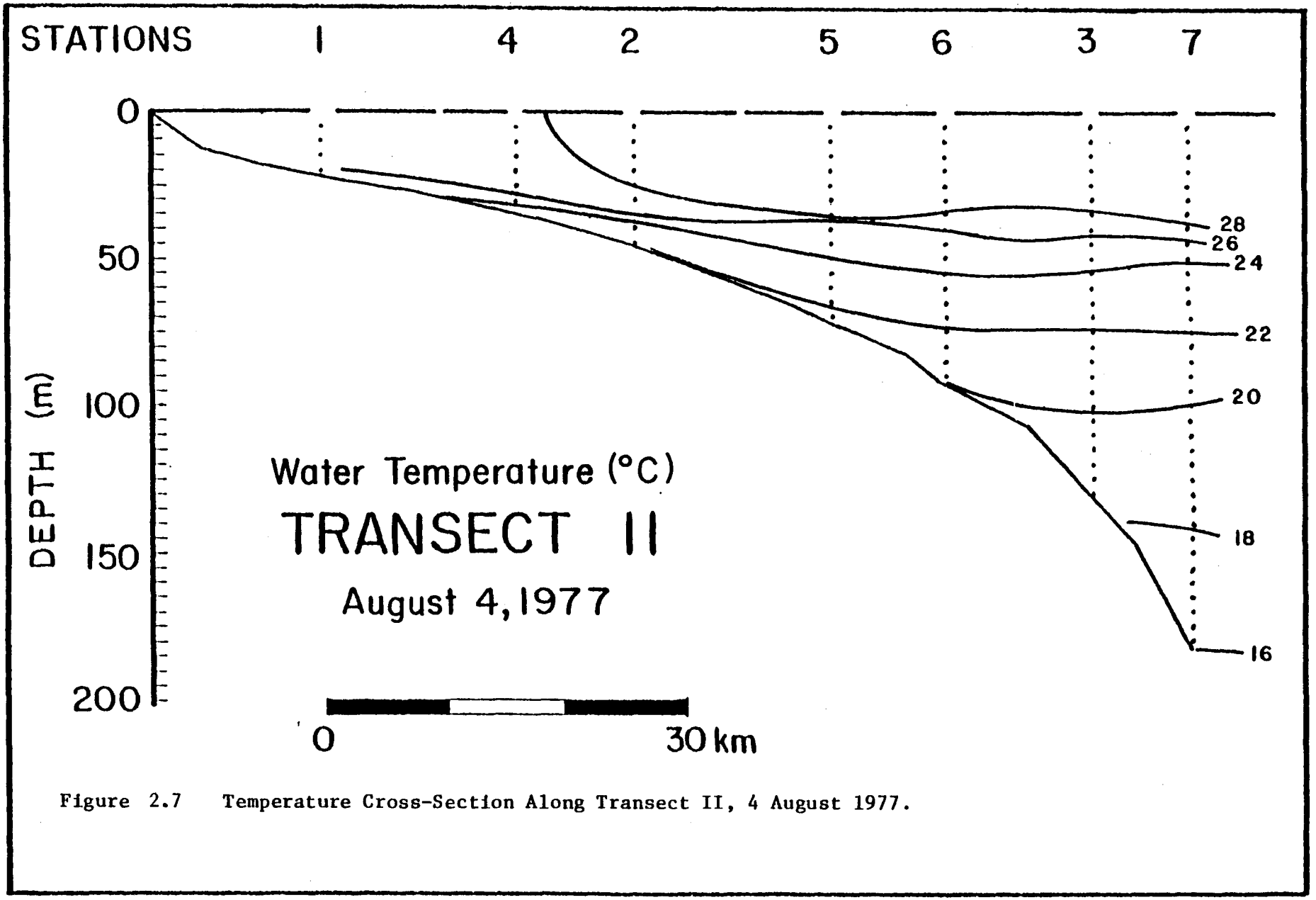

Figure 2.7 Temperature Cross-Section Along Transect II, 4 August 1977.

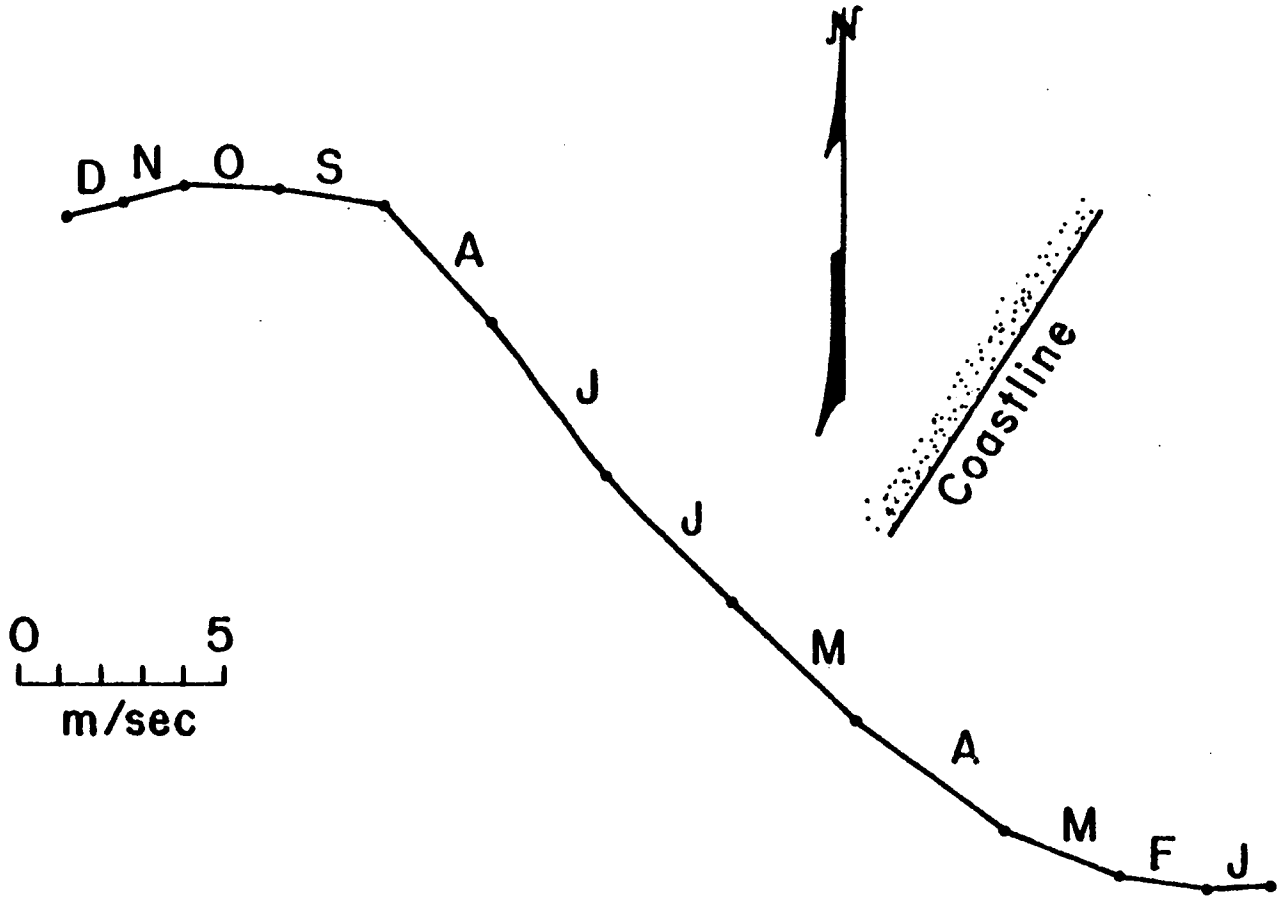

Figure 2.8. Resultant Winds Recorded at the International Airport in Corpus Christi, Texas, 1961-1973.

outer shelf may play an important role in the local hydrography at these times. The importance of cross-shelf motion in transporting salt, heat, suspended solids and/or planktonic life makes this a topic worthy of further study.

DISCUSSION

The graphical summaries of the hydrographic data presented here are useful for quantifying the spatial, as well as the temporal variability in the hydrographic climate in Texas shelf waters. The time scales associated with the dominant local variations in temperature and salinity differ significantly between the inner and outer shelf sites. The annual variation is of major importance over the inner shelf at all depths, and through the surface layer across the shelf.

At greater depths, sufficiently removed from surface conditioning by air-sea exchange processes, the dominant time scales become too short to be properly resolved with the available data. If the temperature variations recorded at near-bottom levels at the outer station are associated with a vertical movement of the top of the permanent thermocline, the associated time scales would be on the order of an hour to several days, depending on whether these reflect internal waves of a meteorologically forced encroachment of water onto the shelf from the open Gulf.

There appear to be several significant events recurring annually and making a well defined impression in the hydrographic data. The plume of Mississippi River water, moving westward and southwestward along the northern rim of the Gulf of Mexico during the winter and spring months, is especially pronounced near the coast, but may at times cover the entire shelf (Smith, 1978b).

The current data obtained between 1973 and 1977 may be combined to

describe an annual cycle in shelf circulation along the Texas coast. When compiled according to season, the current measurements indicate essentially two periods recurring from one year to the next. Between approximately October and March, the currents along the shelf past Port Aransas are toward the south-southwest and at speeds generally between 15 and 45 cm/sec. The quasi-steady motion is halted in early summer, when strong and persistent southeasterly winds affect the study area (Figure 2.8). Between approximately June and September, currents over the Texas shelf are substantially weaker, and the longshore component reverses over time scales on the order of one to two weeks. During this time, current speeds are generally between 5 and 20 cm/sec (Smith, 1975, 1978c).

The explanation for these two periods is suggested by the progressive vector plot of monthly resultant winds (Figure 2.8). While this is not the windstress data one would prefer to have and even though higher frequency events may play an important role in driving the circulation, this provides information which is useful in understanding the local shelf circulation. Between approximately April and August, the orientation of the resultant wind vector is approximately perpendicular to the coastline at Port Aransas (033-213°). Thus, on the average, winds would seem to be relatively ineffective in driving a longshore current. During the winter months, on the other hand, the occurrence of cold fronts acts to reorient the resultant wind vector in such a way as to give it a strong longshore component. This, in turn, is much more effective in driving water south-southwestward along the coast. Time series of current data from the winter months (Smith, 1979, in press) indicate that there can be reversals in the longshore component at any time of year, but there is a dominant net flow to the south-southwest.

This seasonal variation in shelf circulation has a direct and obvious effect on the spatial distribution and temporal variability of hydrographic conditions. The strong and quasi-steady flow to the south-southwest during the winter months, and especially into late spring, is responsible for the advective transport of Mississippi River water along the northwestern rim of the Gulf of Mexico, and along the Texas continental shelf in particular, at a time when the discharge is at its annual maximum. This produces a corresponding annual minimum in shelf salinities, with values as low as 25 ppt over the inner shelf (Smith, 1978b). During the summer months, the shelf waters off the central Texas coast at least become somewhat more isolated, in the sense that the transport associated with an alternating longshore current is relatively minor.

While the longshore component of the current is clearly dominant over the long-term, the cross-shelf component can be of primary importance over shorter time intervals, and these relatively infrequent episodes can have a profound effect on shelf hydrography. Smith (1977b) has documented five periods of predominantly cross-shelf motion during a 43-day period in early winter, 1975. Because of the cross-shelf gradients in both temperature and salinity, cross-shelf motion over even short periods of time can markedly change the hydrography of the mid and inner shelf waters. Progressive vector diagrams suggest that cross-shelf excursions of as much as 30 km may cover a substantial fraction of the shelf width at this location.

The incorporation of current measurements provides a valuable supplement to a purely hydrographic study. The data indicate current directions at various times of the year and thus can be useful for inferring the origin of water comprising the surface mixed layer at any given time. Current data also suggest the time scales over which the patterns recorded

on a particular survey might persist. For example, progressive vectors computed from unpublished nearshore current data obtained in the spring of 1977 suggest that water parcels can move the length of the Texas coastline (approximately 685 km) in less than six weeks. This underlines the need for monthly sampling, during the winter months at least, if an attempt is made to trace seasonally changing hydrographic patterns.

The time-depth plots of temperature and salinity for the outer and inner stations along the Port Aransas transect (Figures 2.5 and 2.6, respectively) show nicely the temporal progression of vertical gradients through the water column. At the same time, they provide useful information relating to the sampling frequency necessary and sufficient to reveal the annual cycle. In general, a more horizontal orientation of the isopleths indicates little temporal variations. At such times, relatively low frequency sampling may suffice. For example, isotherms in the lower part of Figure 2.5 indicate that temperature profiles are more constant in time during late winter and again in late summer. In the first case, the water column is largely unstratified; in the second case, there is a well developed seasonal thermocline before the onset of fall cooling.

On the other hand, more vertically oriented isopleths suggest significant temporal change. Figure 2.6 shows strong spring warming over the inner shelf between late March and early May in both years, and equally strong fall cooling starting in late September. Somewhat more frequent sampling would be required at these times to trace the temperature curve more accurately. Similarly, rapid changes in the salinity of shelf waters during the spring months requires more closely spaced sampling to document the arrival and disappearance of the plume of Mississippi River water.

This study, when combined with hydrographic surveys in Texas shelf waters made over the past 20 years, provides the data base necessary for describing most of the large-scale features and low-frequency changes in temperature and salinity distributions. Annual cycles are well documented, and several events recurring seasonally have been identified. Still, some questions remain unanswered, and they point the way for future studies.

Figures 2.2 and 2.3 show clearly that sampling frequency should be increased during times of rapid transition in the hydrographic properties of shelf waters. For salinity, a relatively sudden drop in late spring, followed by a rapid recovery in early summer is poorly described by monthly sampling. Weekly surveys at this time of year would provide a significantly better picture of how the low salinity plume moves through the study area. For shelf temperatures, the transition from the late summer highs to the late winter lows is generally traced with data from only two or three cruises. Again, more frequent sampling, especially when the first intense cold fronts reach the Texas coast, is needed to better describe fall cooling. Similarly, additional sampling is required during the late winter months to document the annual minimum temperatures.

Two additional questions remain unanswered. The first involves the higher frequency variations in temperature, and perhaps to a lesser extent, salinity. While T-S variations over seasonal and annual time scales have been identified, little is known of the relative importance of variations occurring over time scales ranging from hours to weeks. These would reflect internal wave activity and meteorological forcing. The latter would be particularly important during the winter months. The higher frequency temperature variations could be investigated relatively easily with *in situ* recording instrumentation. The magnitude of these high-

frequency variations provides some indication of the perturbations that may be present in the annual patterns based upon monthly data. High-frequency contamination of temperature records appears to be especially important in near-bottom levels over the outer continental shelf (Figure 2.5).

A second question involves the possibility of the formation of intermediate water layers during periods of intense winter cooling. Over the outer shelf, densities of approximately 1.026 gm/cm^3 are found throughout the year at the 100 m level (Smith, 1977a, 1978b). For comparison, densities in mid-shelf waters in January 1977 were computed to be just over 1.026 gm/cm^3 at the surface. If the Texas shelf is an annually recurring source of water for layers near the top of the permanent thermocline (for example, 100-150 m), the renewal would be most pronounced in mid to late winter, when cold fronts are most intense. The most probable source would be the mid shelf area. There the water column is shallow enough to permit significant cooling, while at the same time salinities are not appreciably lowered by freshwater run-off. The investigation of water mass formation and of higher frequency temporal variability would constitute a logical continuation of previous studies of Texas shelf water hydrography.

ACKNOWLEDGMENTS

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CHAPTER THREE

LOW-MOLECULAR-WEIGHT HYDROCARBONS

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ABSTRACT

As part of a program to establish levels of $C_1 - C_4$ hydrocarbons (LMWH) in south Texas outer continental shelf area waters and sediments, water column LMWH were measured nine times over the 1975-1977 period along four transects. The methane distribution in the water column exhibited both seasonal and spatial variations. Methane was always supersaturated in the surface water with surface concentrations as high as 500 nl/ℓ. Mid-depth maxima (30 to 100 meters) as high as 4000 nl/ℓ observed seasonally were attributed to *in situ* production associated with accumulation of suspended particulates on the pycnocline. The unsaturated LMWH dominated over their saturate analogs except at water depths greater than 100 meters. Propene concentrations were almost always a factor of 4 lower than ethene concentrations. Comparison of water column LMWH, biological and chemical measurements yielded very few good correlations. Ethane was the exception showing correlations with several phytoplankton variables.

Sediment LMWH were only measured during 1977 along all four transects. Methane in the top few meters of STOCS sediments was generally of microbial origin, as evidenced by the existence of anomalously high methane concentrations in the top sediment layers. Two-meter vertical methane profiles in nearshore sediments exhibited near-surface methane maxima ranging from 100 to 500 µl/ℓ pore water. Interstitial concentrations of ethene, ethane, propene, and propane were relatively constant with depth in the upper two meters of shelf, slope, and abyssal sediments, decreasing progressively from 160, 100, 110, and 60 nl/ℓ pore water in nearshore sediments, to fairly uniform levels of 80, 25, 30 and 25 nl/ℓ downslope, respectively. One area of anomalously high methane, ethane and propane concentrations was observed along Transect IV suggesting an input of thermocatalytic gas from the subsurface.

INTRODUCTION

Significance of Work

The purpose of the low-molecular-weight hydrocarbon (LMWH) analysis program was to determine levels of C_1-C_4 hydrocarbons in south Texas outer continental shelf (STOCS) area waters and sediments. In the broadest sense, these dissolved gases can provide information about the STOCS environment that will help the Department of the Interior make management decisions regarding a broad range of OCS activities, including the preparation and review of environmental impact statements, issuance of oil and gas regulations and permits, and implementation of laws. LMWH should be specifically considered for several reasons. These components are very sensitive indicators of spilled petroleum hydrocarbons and natural seepage. Once background LMWH levels have been established in an area, a monitoring program can indicate spilled oil and trace the more highly toxic components of petroleum, without resorting to the expensive and contamination-prone analysis of the liquid-range components. Due to their association with the high-molecular-weight (HMW) components in hydrocarbon reservoirs, correlations of LMWH with HMWH should be observed in sediments and waters which have been exposed to either natural or anthropogenic addition of petroleum. Even without these correlations, detection of seepage of the more mobile gaseous hydrocarbons from the subsurface can be used to evaluate the reservoir potential of an area. High concentrations of interstitial gas can also destabilize sediments and lead to failure of bottom-mounted structures.

Methane in unpolluted areas of the shelf is a good indicator of suspended (organic) matter levels in the water column. Subsurface profiles correlate well with methane. An understanding of suspended matter variations is important because trace metals and petroleum hydrocarbons that

are released during drilling or production operations can be adsorbed onto the surface of particulate material where they may be assimilated by filter and detrital feeders. Similary, C_2 and C_3 levels (ethene, ethane, propene and propane) in the water column are associated with biological productivity, due to production of these gases by plankton. These might be used to trace diurnal and other migrations of significant species.

Sources and Character of LMWH

Hydrocarbon gases have been detected analytically in the Gulf of Mexico for the past 30 years and visually for over a century. Detection of methane, ethane, and propane has been important for environmental monitoring (Brooks and Sackett, 1973; Brooks *et al.*, 1973, 1977; Brooks, 1975) as well as in oil exploration (Sackett, 1977).

Petroleum-related light hydrocarbons are generally thought to be produced by thermal, pressure, and catalytic influences on complex organic matter and/or higher molecular-weight hydrocarbons at depth in the sediment. These thermogenic gases typically consist of methane and carbon dioxide with several percent ethane and higher alkanes. The carbon isotopic composition ($\Delta^{13}C$ values) of the methane is also characteristically heavy, ranging from -35 to -55‰ vs. the PDB standard. The detection of thermogenic gas in marine waters is considered indicative of petroleum-related hydrocarbons either from a natural source such as reservoired gas or from some anthropogenic sources (see Water Column LMWH section).

Microbially produced gases, on the other hand, are produced by a diverse suite of anaerobic bacteria, and consist almost exlusively of methane and carbon dioxide. Although a general belief among microbiologists is that alkane gases other than methane are not produced by anaerobes, Bernard *et al.* (1977) have shown small amounts of biogenic ethane production along with ethane. Microbial (or biogenic) gases are characterized by methane-to-higher-hydrocarbon ratios that typically exceed 10^4, and carbon isotope ratios in methane ranging from -50‰

-100‰ vs. PDB. Thus, sources of light hydrocarbon gases found in marine waters and sediments can often be delineated by molecular and isotopic compositions, although there are problems with fractionation during gas migration which must be considered (Bernard *et al.*, 1977).

Microbial LMWH Production

Microorganisms produce methane in a variety of environments such as dung heaps and anaerobic sewage digestors (Smith, 1966), digestive tracts of animals (Beijer, 1952; Bryant, 1965), landfills (Games and Hayes, 1974), glacial drift (Meents, 1960; Wasserberg *et al.*, 1963; Coleman, 1976), marshes (Teal and Kanwisher, 1966; Whelan, 1974a), paddy fields (Koyama, 1955, 1963, 1964a; Takai, 1970), freshwater lakes (Kayama, 1953, 1964b; Oana and Deevey, 1960; Cappenburg, 1972, 1974a,b; Koyama *et al.*, 1973) anoxic marine waters (Atkinson and Richards, 1967; Deuser *et al.*, 1973; Lomantagne *et al.*, 1973; Hunt, 1974; Reeburgh, 1976), and marine sediments (Emery and Hoggan, 1958; Reeburgh, 1969; Nissenbaum *et al.*, 1972; Claypool and Kaplan, 1974; Hammond, 1974; Lyon, 1974; Martens and Berner, 1974; Reeburgh and Heggie, 1974; Whelan, 1974b; Oremland, 1975; Barnes and Goldberg, 1976; Bernard *et al.*, 1977; Martens and Berner, 1977). Physiological and ecological constraints limit the extent of biogenic methane production, however, so these environments of methane production have distinct similarities. Methane-producing bacteria are strict anaerobes (Brock, 1974) and apparently will not proliferate even in the presence of dissolved sulfate (Claypool and Kaplan, 1974; Martens and Berner, 1977).

In contrast, Barnes and Goldberg (1976) suggested that methane generation and sulfate reduction are not mutually exclusive processes. Rather, low concentrations of methane in the sulfate-reducing zone of

sediments represent a balance between production by methanogenic bacteria and consumption by sulfate reducers. Alternatively, methane may be produced to a limited extent, but at a much smaller rate than when sulfate is present. As an example, Martens and Berner (1974) suggested that methane could be produced in the presence of interstitial sulfate within organic-rich microenvironments free of sulfate such as the interior portions of decaying organisms. Similarly, Brooks *et al.* (1979) and Bernard *et al.* (1977) have observed apparent enhanced microbial methane production within organic-rich microenvironments.

Cappenberg (1974a, b) demonstrated an ecological succession with a slight overlap in distributions whereby the sulfate reducers are found above the methanogens in lake sediments. This succession was attributed to the toxic effect of sulfide on the methanogenic bacteria. Oremland and Taylor (1978) found that the sulfate reducers and methanogens compete for available hydrogen produced from the degradation of organic matter by fermentative bacteria. However, methanogens are not nearly so efficient in competing for hydrogen when sulfide is abundant, and sulfate reducers effectively consume the available hydrogen produced in the sediment. When sulfate is reduced to insufficient concentrations to support cell growth of sulfate reducers, hydrogen becomes available to the methane producers. In fact, the authors pointed out that in the absence of sulfate, sulfate-reducing bacteria <u>generate</u> hydrogen by degradation of organic matter. Hydrogen for the reduction of carbon dioxide by methanogenic bacteria would then be provided in part by the sulfate reducers. These observations suggest that neither sulfate nor hydrogen sulfide is inhibitory to methanogenesis, rather than a limited amount of incomplete hydrogen utilization by the sulfide reducers, even without so-called sulfate-free microenvironments.

Thermocatalytic LMWH Production

In depositional environments conducive to the preservation of organic material, low-molecular-weight hydrocarbons can be generated abiotically at higher temperatures and pressures in the subsurface. Natural inputs of these oil-related gases are significant in the Gulf of Mexico system due to their upward migration and seepage from hydrocarbon reservoirs into surficial sediments and Gulf waters. Mechanisms of production of thermocatalytic gases have been postulated by several investigators, including Silverman (1964), Colombo *et al.* (1965, 1966), Sackett (1968), Frank and Sackett (1969), Colombo *et al.* (1969), Galimov (1969) Sackett *et al.* (1970), Alekseyev *et al.* (1972), Frank *et al.* (1974), Fuex (1977), Bernard (1978), and Sackett (1978). Exhaustive examinations of carbon isotope effects have played a significant role in presently accepted theories regarding production and migration mechanisms, but it is sufficient for these purposes to restate that thermocatalytically-produced gases typically consist of 0.5% to 10% non-methane hydrocarbons, with $\Delta^{13}C$ values of methane ranging from -35‰ to -55‰ vs. PDB. Laboratory pyrolysis experiments indicate that the primary initial alkane products of thermal degradation of organic matter at 400-500°C are ethane and propane (Sackett, 1978). Thermal cracking for longer periods results in a decrease in the non-methane hydrocarbons and a predominance of methane. Wet natural gases (containing more hydrocarbons than just methane) are considered to be relatively immature, and thermally-produced dry gases (primarily methane) are considered to have been "overcooked" by extremes in temperatures and pressure. Immature dry gases are considered to be of a microbial origin. In theory then, microbial and thermocatalytic gases in the Gulf of Mexico system can be distinguished by molecular and

isotopic analysis. Measuring carbon isotope ratios on nannoliter or microliter quantities of gas present in most samples is extremely difficult, however, so initial investigations of the STOCS area have involved only the measurement of quantities of each of the LMWH along with ancillary parameters. These measurements have proved sufficient for elucidating relatively large scale oil-related LMWH inputs to the relatively "clean" STOCS area, both from anthropogenic and natural sources.

Water Column LMWH

Although methane is no doubt the most studied reduced gas in the ocean, considerable uncertainty exists concerning its geochemistry. Scientists at the Naval Research Laboratories (Lamontagne *et al.*, 1971, 1973, 1974, 1975; Swinnerton and Lamontagne, 1974) and Texas A&M University (Brooks and Sackett, 1973; Brooks *et al.*, 1973; Sackett and Brooks, 1975; and Brooks and Sackett, 1977) among others have established the open ocean as a source of methane to the atmosphere. Several recent publications (Scranton and Brewer, 1977; and Scranton and Farrington, 1977) have shown that shallow methane maxima are common in at least the Atlantic Ocean and Gulf of Mexico. The maxima that have been reported are found near or in the major pycnocline (50 to 200 m) and have about twice the atmospheric equilibrium concentrations (35 to 50 nl/ℓ for subtropical zones). Shallow maxima have been attributed to advection off the shelf and/or *in situ* production. Although *in situ* production of methane has been postulated by a number of investigators, all known methane-producing bacteria are obligate anaerobes (see Introduction Section). Thus, the existence of methane-producing bacteria in the high oxygen-containing waters of the ocean is only speculative at present, although recent work has fairly well demonstrated that advection off shelf regions

cannot supply the shallow maxima observed in parts of the open ocean.

In coastal regions, natural processes and man-related activities contributing excess LMWH to the water column can sometimes be differentiated. On the upper Texas-Louisiana shelf, ports and estuaries with their associated commercial and petrochemical activities, offshore petroleum operations, and shipping activity are the major man-derived sources of LMWH. Of these, the underwater venting of waste gases and brine discharges, both associated with offshore production platforms, are the major sources of non-methane LMWH. These sources can elevate LMWH levels in surrounding waters by 3 to 4 orders of magnitude. The STOCS area is not at present influenced by major man-related activities as is the Louisiana shelf.

Natural sources of LMWH to coastal waters include runoff, *in situ* production within the water column and sediment seepage of gas. Brooks (1975) has shown that LMWH in the Mississippi River are several orders of magnitude above "normal" marine levels and are principally man-derived. Similar measurements in the Brazos River indicate few of the non-methane LMWH and a principally biogenic origin. Although several rivers empty into south Texas coastal waters, the large intracoastal bays and estuaries mask most direct freshwater inputs into STOCS waters. The Rio Grande inflow to the south may be the possible exception. The significance of *in situ* production in coastal waters has not been studied.

Gas seepage is a relatively common occurrence in the northwestern Gulf of Mexico. Early work indicated that bubbles rising from gas seeps can be readily detected at sea by standard sonar equipment (Ohle, 1959; McCartney and Bary, 1965; Albright, 1973; Geyer and Sweet, 1973; and Sackett, 1977). Over the past few years sevearl thousand small bubbling seeps have been located along the continental shelf of the northern Gulf

of Mexico by this method (Sweet, 1973; and Tinkle *et al.*, 1973). Recently Watkins and Worzel (1978) reported that over 19,000 seeps probably exist in a small area about 6,000 sq km on the south Texas shelf (designated Serendipity Gas Seep Area). Gas seepage has also been observed at Southern Bank in the STOCS area using a submersible (Bright, personal communications). Cline and Holmes (1977, 1978) have identified what appears to be petrogenic seepage in Norton Sound, Alaska by anomalous concentrations of LMWH alkanes in the water column. Brooks *et al.* (1974) and Bernard *et al.* (1976) have reported that of 21 seep gases collected in the Gulf of Mexico only a relatively small percentage contain thermogenic components. LMWH anomalies in marine waters and sediments are sued in geochemical prospecting for natural gas and petroleum.

Little attention has been given in the literature to unsaturated LMWH in the marine environment. Although several papers have reported concentrations of unsaturates (Swinnerton and Lamontagne, 1974; Brooks, 1975; and Brooks and Sackett, 1977), little is known about the processes controlling their concentrations.

Sediment LMWH

Sediment methane distributions in highly-reducing sediments have been the subject of considerable investigation in recent years. Significant contributions include the work of Emery and Hoggan (1958), Koyama (1963), Atkinson and Richards (1967), Reeburgh (1969), Claypool and Kaplan (1974), Martens and Berner (1974, 1977) and Barnes and Goldberg (1976). All of these authors investigated methane concentrations in estuarine or freshwater sedimentary environments, with no consideration of other LMWH. Through 1978, the only reliable data to be published concerning methane in open marine sediments, or other LMWH in any type

of surficial sediments, is that which has culminated from the BLM support of sediment LMWH measurements during 1977 (Bernard *et al.*, 1977).

Scope of Work

Figure 3.1 shows stations sampled in the STOCS survey. Water column LMWH were measured nine times seasonally over the 1975-1977 period along the four transects (denoted I-IV). In addition, during 1976 and 1977 water column measurements were made during 12 additional monthly cruises along Transect II. Stations were occupied at Southern Bank and Hospital Rock during 1976. A minimum of three depths (near-surface, one-half the depth of the photic zone, and near-bottom) were sampled except during 1976 when sampling at one-half the depth of the photic zone was not required. During most every sampling, however, several additional mid-depth samples were obtained. All stations shown in Figure 3.1 were sampled for sediment LMWH during 1977.

METHODS

Water Column

Water samples, obtained using standard Niskin or Nansen bottles equipped with reversing thermometers, were transferred by gravity flow into either one-liter ground-glass stoppered bottles or 125-ml narrow mouth bottles, poisoned with sodium azide, and capped. The bottles were capped in such a way as to avoid trapping gas bubbles. Samples were analyzed using a stripping technique (Brooks, 1975).

Concentrations were calculated from peak heights, which were linear over the typical concentration ranges encountered. Calibrations were made using a C_1-C_3 standard gas (Air Products and Chemical, Inc.). The relative error of three replicate analyses of 20 samples ranging in

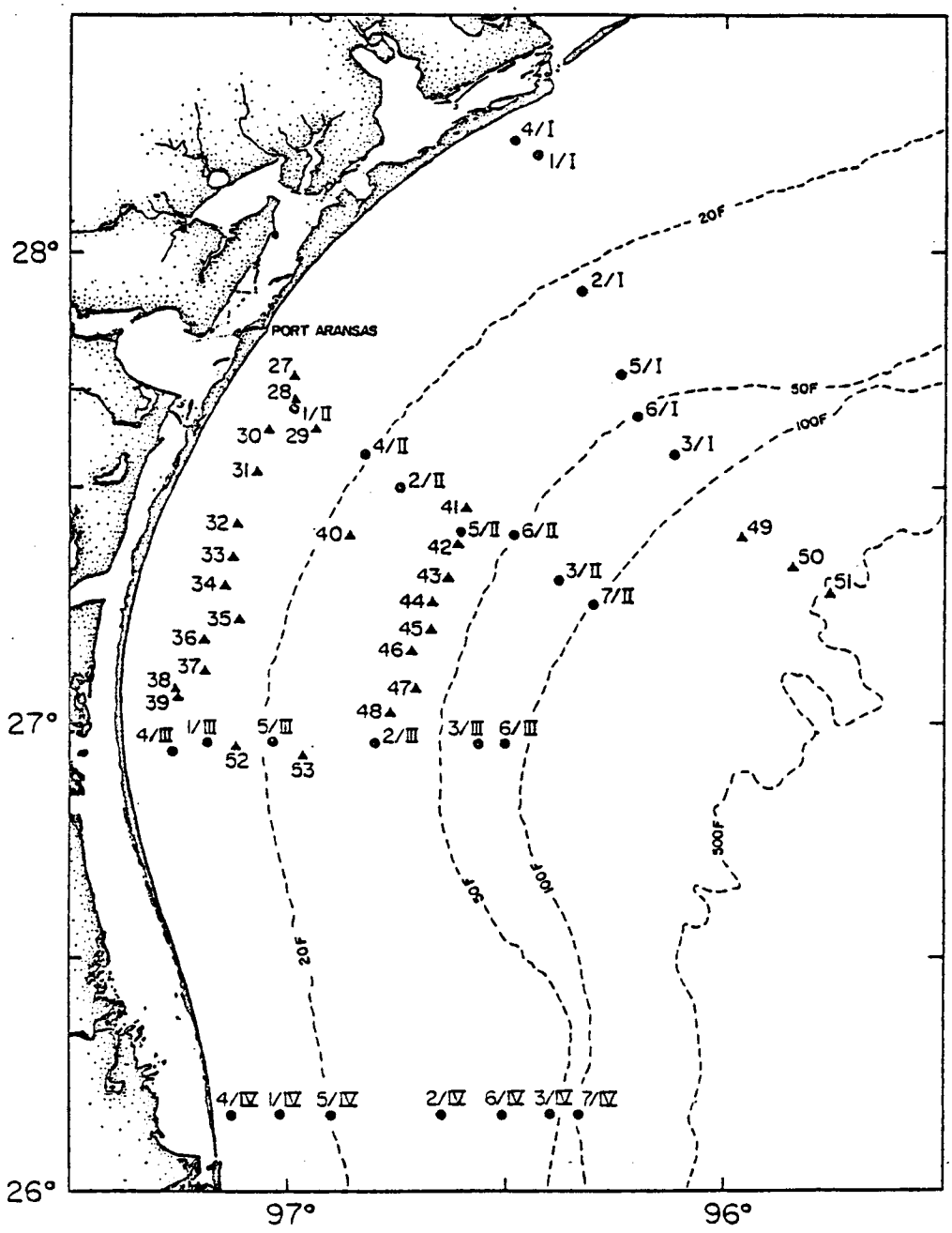

Figure 3.1 Sediment Low-Molecular-Weight Hydrocarbon Sampling Locations on the South Texas Shelf.

methane concentration from 77 to 450 nl/ℓ averaged 6% for methane and ranged from 6% to 9% for the C_2 and C_3 hydrocarbons (Table 3.1). Precision increases as concentration increase above background levels. The limit of detection is 0.02 nl/ℓ.

LMWH were determined on most mid-depth samples by McAullife's (1971) method of multiple phase equilibrium. This involves equilibrating 25 ml of purified helium with 25 ml of sample water in a 50 ml syringe equipped with a Luer-Lock stopcock. Over 96% of the light aliphatic hydrocarbons partition into the gas phase, and are analyzed by injecting a sample of the equilibrated helium into the chromatographic stream by means of a sample loop. The precision of this method at the lower limit of sensitivity [10 x 10^{-9} liters of gas_{NTP}/liter of seawater (10 nl/ℓ)] is ±10%, but precision and accuracy increase rapidly with increasing concentration.

Sediments

Sampling consisted of coring sediments with a two-meter, plastic-lined gravity core, removing the liner upon retrieval, and sectioning the core sample. Core sections (typically 5 cm long for LMWH) were immediately placed in processing containers and sealed under nitrogen atmosphere. The LMWH, partitioned into the headspace of the container during vigorous shaking, was then flushed from the headspace into a trap, and were subsequently desorbed for injection into a gas chromatograph. The detailed procedure has evolved from several years of experimentation, achievements which included quantitative removal of LMWH for GC analysis as well as for carbon isotopic analysis of methane. Discussion of the procedure in Bernard (1978) include the results of this testing and experimentation, as well as a comparison to other commonly used methods for sediment gas analysis. Advantages basically included the assurance

TABLE 3.1

REPLICATE ANALYSES OF TWENTY SAMPLES FOR LOW-MOLECULAR-WEIGHT HYDROCARBONS.
THE MEAN ($\bar{X}$) AND STANDARD DEVIATION (S.D.) ARE BASED ON THREE REPLICATE ANALYSES AT EACH STATION.
RELATIVE ERROR (R.E.) IS THE QUOTIENT OF THE STANDARD DEVIATION AND THE MEAN GIVEN IN PERCENT*.
ALL CONCENTRATIONS ARE GIVEN IN NANNOLITERS/LITER (nl/ℓ)

SEASON	STATION	DEPTH	METHANE (nl/l)			ETHENE (nl/l)			ETHANE (nl/l)			PROPENE (nl/l)			PROPANE (nl/l)		
			$\bar{X}$	S.D.	R.E.	$\bar{X}$	S.D.	R.E.	$\bar{X}$	S.D.	R.E.	$\bar{X}$	S.D.	R.D.	$\bar{X}$	S.D.	R.E.
Nov. 76	II/1	0 m	91.33	2.309	2.53	4.697	0.196	4.18	0.633	0.015	2.41	1.497	0.040	2.70	0.550	0	0
		18 m	77.33	12.423	16.06	3.137	0.241	7.68	0.543	0.035	6.46	1.180	0.291	24.66	0.540	0.062	11.56
	II/2	0 m	83.67	6.028	7.20	2.677	0.093	3.47	0.433	0.021	4.70	0.817	0.045	5.52	0.500	0.046	9.17
		40 m	104.33	10.970	10.51	3.757	1.106	29.43	0.500	0.017	3.46	0.983	0.015	1.55	0.483	0.021	4.31
	II/3	0 m	83.33	10.693	12.83	4.127	0.523	12.68	0.363	0.038	10.42	0.920	0.070	7.61	0.430	0.079	18.46
		120 m	161.33	11.719	7.26	0.590	0.121	20.55	0.423	0.015	3.61	0.193	0.025	13.02	0.503	0.057	11.30
	SB/4	0 m	83.67	4.619	5.52	5.167	1.218	23.58	0.440	0.010	2.27	0.943	0.029	3.06	0.440	0.010	2.27
		70 m	449.67	11.590	2.58	2.227	0.156	6.99	0.473	0.029	6.10	0.313	0.029	9.21	0.490	0.030	6.12
	HB/2	0 m	77.67	11.846	15.25	4.12	0.127	3.09	0.387	0.049	12.76	0.933	0.025	2.70	0.470	0.046	9.75
		70 m	415.33	19.348	4.66	3.597	0.075	2.09	0.557	0.021	3.74	0.497	0.025	5.07	0.500	0.017	3.46
Dec. 76	II/1	0 m	107.33	7.23	6.74	2.32	0.20	8.80	0.58	0.04	6.22	0.44	0	0	0.51	0.02	4.56
		18 m	106.00	6.56	6.19	2.09	0.21	10.22	0.62	0.05	7.41	0.45	0.02	3.85	0.49	0.01	2.37
	II/2	0 m	97.67	4.73	4.84	2.65	0.10	3.73	0.63	0.01	1.84	0.66	0.02	2.33	0.59	0	0
		40 m	88.33	0.58	0.65	2.28	0.22	9.49	0.55	0.03	4.60	0.60	0.01	0.97	0.51	0.02	4.11
	II/3	0 m	106.67	6.11	5.73	2.41	0.12	4.77	0.45	0.02	5.09	0.46	0.02	3.77	0.38	0.03	8.11
		125 m	102.00	8.00	7.84	0.63	0.09	14.33	0.36	0.03	8.85	0.15	0.05	32.22	0.54	0.10	18.29
	SB/1	0 m	106.00	3.00	2.83	2.27	0.03	1.27	0.80	0.05	6.14	0.53	0.02	4.38	0.59	0.05	8.80
		70 m	122.67	2.52	2.05	2.37	0.06	2.64	0.45	0.02	5.09	0.53	0.01	2.17	0.55	0.06	11.27
	HB/1	0 m	132.67	5.86	4.42	2.43	0.09	3.73	0.52	0.03	5.77	0.57	0.06	9.77	0.48	0.07	15.18
		70 m	133.33	2.31	1.73	2.39	0.08	3.39	0.49	0.03	6.12	0.54	0.01	1.08	0.43	0.02	3.58
	AVERAGE				6.37			8.81			5.65			6.78			7.63

* Also called coefficient of variation.

of quantitative removal of gases in relatively large samples with a minimum of gas loss and contamination. Sample size was not restricted by the method, so relatively large volumes of gas can be collected (this is especially important for LMWH other than methane and for isotope work). The sampling method is extremely rapid, allowing possibly hundreds of samples to be processed in a day at sea, and on-board analysis of LMWH is not required. Samples can be frozen and stored almost indefinitely before and during transmittal to the laboratory, so sea-time can be devoted to sampling. Processing is not limited by analysis time, as is the case with some "harpoon" or "*in situ*" samplers. This is particularly advantageous in gas chromatographic work, due to the typically poorer performance and higher probability of failure of the analytical instrument at sea.

Possible improvements of the method should initially be directed to the sampling procedure (as opposed to the processing and/or analysis procedures). A method of quicker, less tedious, and more uniform sectioning of core samples based on hydraulic extrusion of the core should be devised. Since sampling speed is presently limited by the time spent sectioning the sample, a semi-automated method could prove cost-effective in view of shiptime expense. This consideration is particularly important when sampling sediments beneath shallow waters such as the STOCS area. In deeper waters, sampling speed becomes limited by wire-time rather than sample sectioning time.

RESULTS AND DISCUSSION

Water Column

Methane

Methane in STOCS waters exhibited considerable vertical, seasonal,

and spatial variability (Table 3.2). The predominant processes controlling concentrations (*e.g.* air-sea exchange and biological processes) appeared to be similar to those occurring in the open ocean waters of the Gulf of Mexico except that biological and physical variations (*e.g.* salinity and temperature) are more pronounced in the coastal waters resulting in greater variability. If there were no man-derived or natural inputs of methane, surface concentrations would be controlled by Bunsen solubilities (Yamamoto *et al.*, 1976) according to Henry's Law. The fact that R values (ratio between measured and equilibrium solubilities at existing temperatures and salinity) were almost always above 1 (ranging from 0.91 to 124) indicates that air-sea exchange acts to lower concentrations in the coastal zone. The spring and fall concentrations in Figure 3.2 were typical of STOCS waters. Although higher values are usually observed at near-shore stations, no doubt due to the close proximity of the sediment-water interface and coastal contributions (*e.g.* runoff) no spatial or seasonal patterns were observed in these surface samples. Higher surface methane values were associated with Stations 1/I and 1/II than with Stations 1/III and 1/IV probably due to more river and estuarine runoff into the more northerly nearshore areas.

Also noted in Figure 3.2 are high concentrations of methane in the surface water at the outer stations during the winter sampling. These high levels existed throughout the water column in most of the STOCS area. The highest levels were found at Stations 2 and 3 along all transects implying a non-coastal source. The winter methane contour of Transect II (Figure 3.3) illustrates a wedge of higher than normal methane levels along the middle of this transect. The other transects also show this wedge of high methane. The source is unknown although one possibility

TABLE 3.2

NUMBER OF OBSERVATIONS, MEAN, MINIMUM, AND MAXIMUM LOW-MOLECULAR-WEIGHT HYDROCARBON CONCENTRATIONS (nl/ℓ) AT STOCS WATER COLUMN STATIONS DURING 1976 and 1977

Parameter	1976			1977		
	Obs.	Mean	[Min. - Max.]	Obs.	Mean	[Min. - Max.]
Methane	299	97	[41 - 500]	328	239	[41 - 4000]
surface methane (water)	54	73	[41 - 157]	54	112	[44 - 578]
Ethene	219	4.5	[0.1 - 25]	304	4.5	[0.1 - 21]
surface ethene (water)	54	6.7	[0.2 - 25]	54	4.2	[1.9 - 10]
Ethane	108	0.4	[0.1 - 1.3]	273	0.7	[0.1 - 4.6]
surface ethane (water)	53	0.4	[0.1 - 0.9]	53	0.5	[0.1 - 1.6]
Propene	107	1.0	[0.1 - 2.5]	172	1.0	[0.3 - 2.6]
surface propene (water)	54	1.3	[0.4 - 2.5]	54	1.2	[0.4 - 2.6]
Propane	107	0.5	[0.2 - 0.8]	170	0.5	[0.2 - 1.5]
surface propane (water)	54	0.4	[0.2 - 0.8]	53	0.4	[0.2 - 1.3]

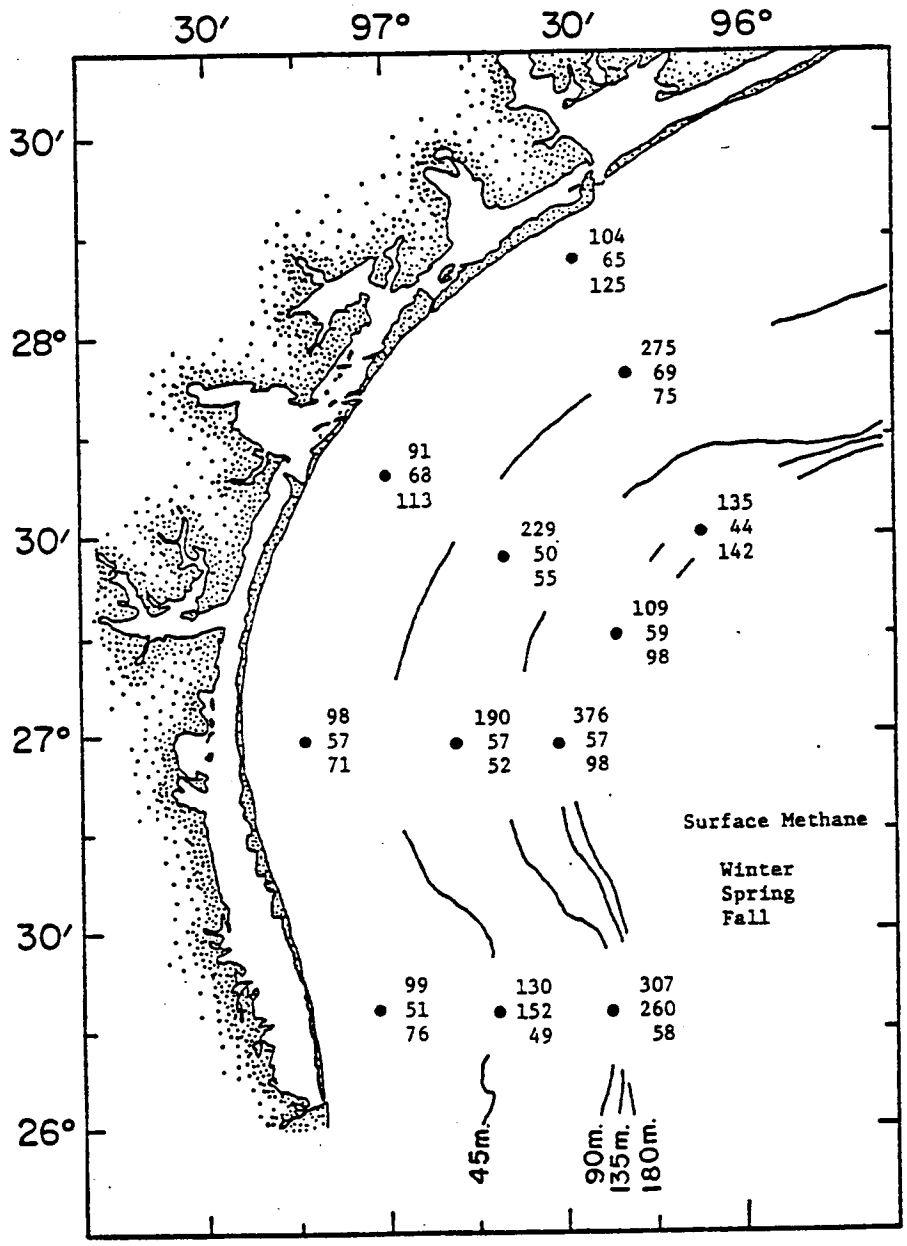

Figure 3.2 Water Column Surface Methane Concentrations (nl/ℓ) in the STOCS Area During the Seasonal Cruises in 1977.

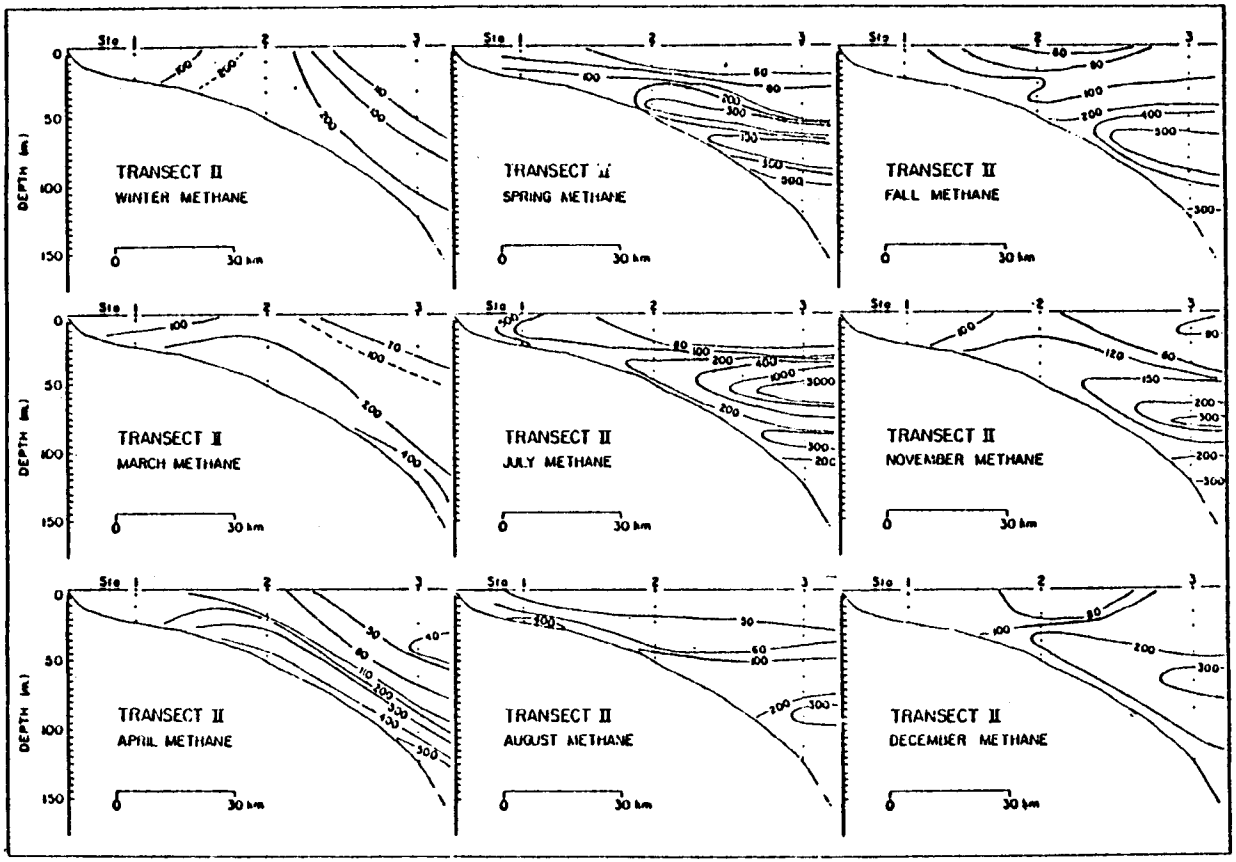

Figure 3.3 Methane Sections Along Transect II During 1977.

is the intrusion of high methane from a major well blowout that occurred about 100 miles south of Galveston during late November and December 1976 (Brooks *et al.*, 1978). The high levels produced by this blowout could have been advected by currents into the STOCS.

The methane distribution in the water column exhibited both seasonal and spatial variations. Figure 3.3 shows typical methane sections along Transect II for the nine sampling periods in 1977. Methane exhibited large seasonal variations at intermediate depths (30 to 100 m). In 1975, the water column was fairly uniformly mixed with respect to methane in the winter, in spring a large maximum (up to 4000 nl/ℓ) was observed at several stations, and a much smaller maximum was observed in the fall. In 1976, a similar but not identical pattern developed with no concentrations observed in the thousands of nl/ℓ. The maximum was present along Transect II during March, August, fall, and November, and was absent during April, spring, July, and December. In 1977, large mid-depth maxima were again observed with concentrations over 1000 nl/ℓ. In 1977, the maximum appeared to develop with the formation of the thermocline in April. The maximum became pronounced at 60-70 meters during spring, July and fall with concentrations as in 1975 reaching 4000 nl/ℓ. The maximum was deeper (80-100 m) and therefore only present at Station 3 during August and November.

Of the 12 stations sampled, Station 3/IV is unique in that the near-bottom samples from this station always showed very high methane concentrations. Concentrations have been measured as high as 400 nl/ℓ, with no seasonal influence. Methane concentrations typically remained above 100 nl/ℓ at 20-40 meters above the bottom. These high concentrations measured continuously over a three year period are the result of natural gas seepage across the sea-sediment interface. Figure 3.4 shows three typical

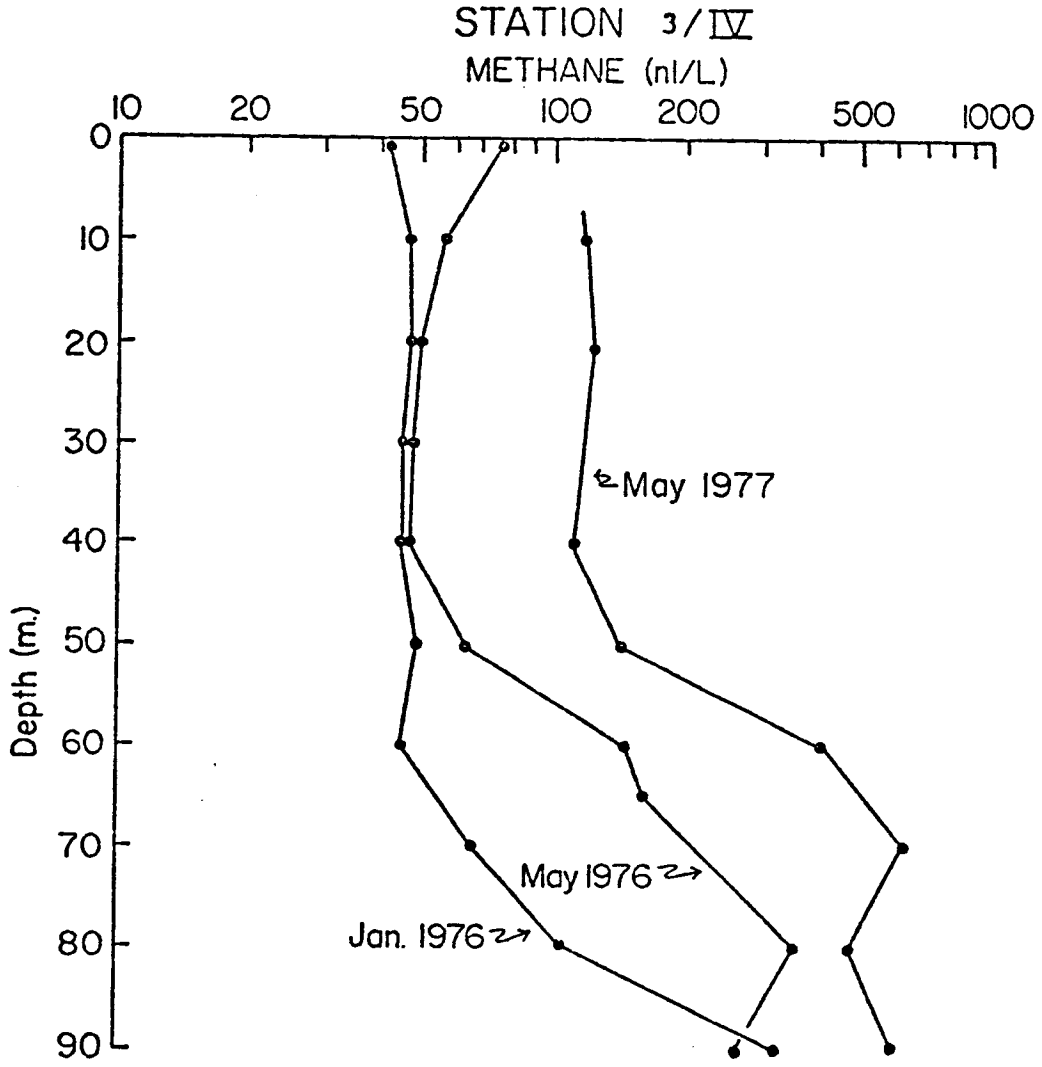

Figure 3.4 Three Water Column Methane Profiles Illustrating Bottom Seepage at Station 3, Transect IV.

methane profiles from this station.

C_2-C_4 LMWH

Table 3.1 shows concentrations of ethene, ethane, propene and propane during the 1976 and 1977 samplings. The unsaturates dominate over their saturated analogs in most areas of STOCS, with exceptions generally occurring at water depths greater than 100 meters. Propene concentrations were almost always a factor of 4 lower than ethene concentrations. There was good agreement in 1976 and 1977 between average olefin concentrations. Figure 3.5 shows surface concentrations of ethene during the seasonal cruises in 1977. The highest concentrations of olefins occurred at inshore stations during the winter sampling. The opposite trend was observed during the spring and fall samplings; highest surface concentrations were observed at offshore stations. There did not appear to be any overall north-south trend in olefin levels in the STOCS area. The trends observed probably reflect biological productivity patterns, since olefins are known to be metabolic intermediates. As shown in Figure 3.5 there is a general olefin trend of low concentrations in the winter months with higher concentrations in the spring and fall. These trends emulate seasonal productivity measurements. Olefin concentrations decrease rapidly with depth and are found only in trace amounts below a few hundred meters. In the water column there is generally a subsurface maximum in ethane concentrations. The maximum is generally shallower than the methane maximum. Concentrations of ethane (Figure 3.6) and propane are generally higher at inshore stations and decrease seaward. Butane levels were almost always below detection limits in the STOCS area.

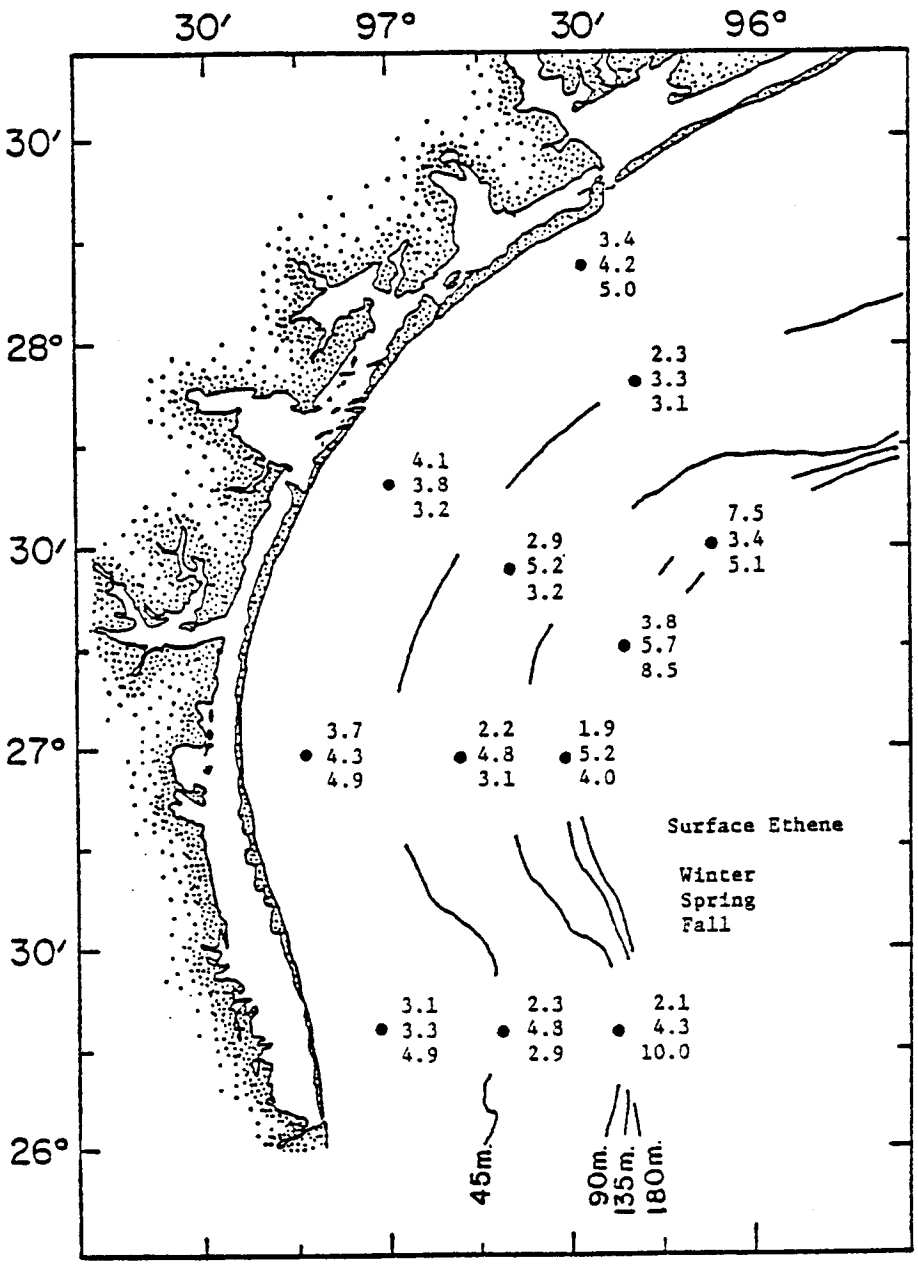

Figure 3.5 Water Column Surface Ethene Concentrations (nl/ℓ) in the STOCS Area During the Seasonal Cruise in 1977.

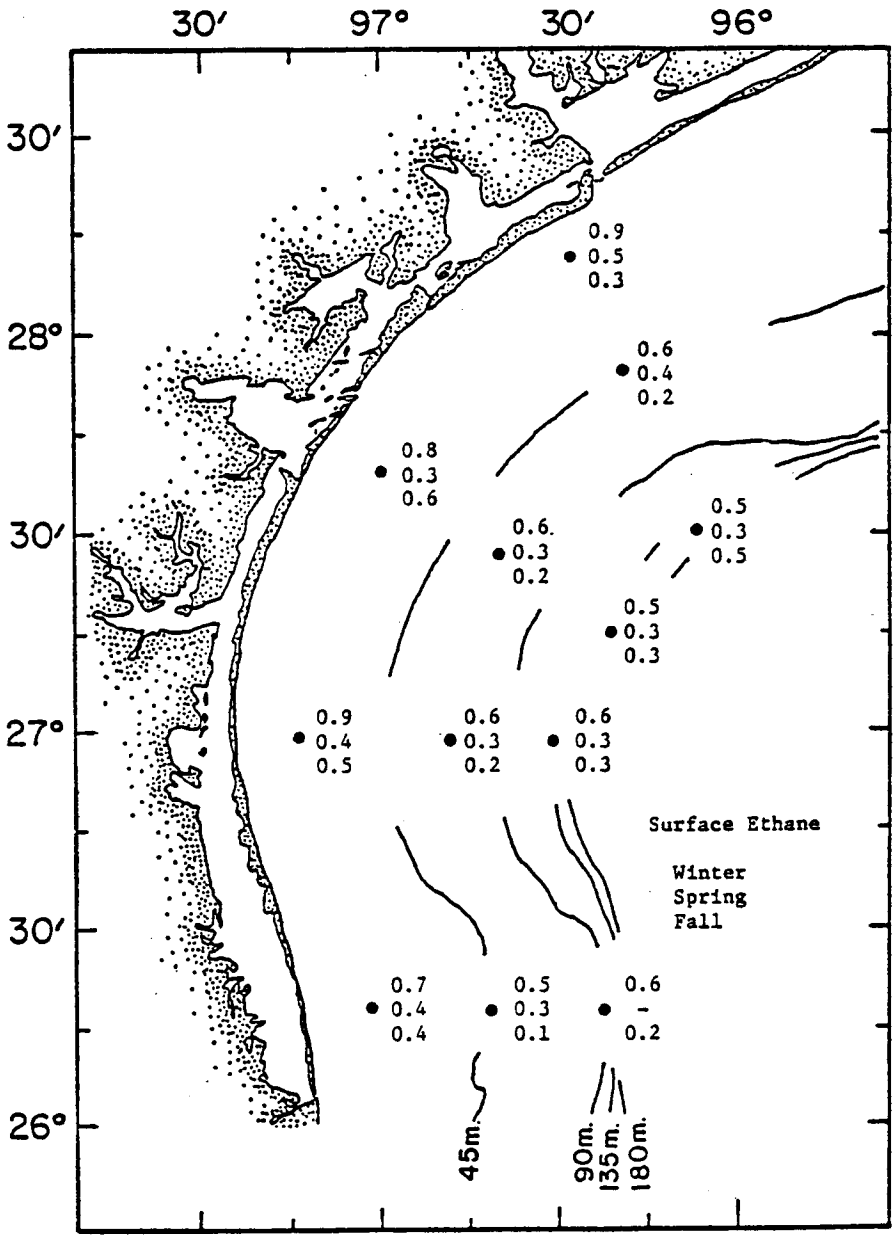

Figure 3.6 Water Column Surface Ethane Concentrations (nl/ℓ) in the STOCS Area During the Seasonal Cruises in 1977.

Mid-Depth Methane Maxima

The origin of the mid-depth methane maximum is only partially understood. The tongue-like methane maxima shown in Figure 3.3 extending inward from outer-shelf waters do not originate from man-derived sources since they contain few C_2-C_4 hydrocarbons. Advection of methane contributed by dissolution of rising gas bubbles from seepage or diffusion across the sea-sediment interface are possible sources to the subsurface maxima. Bernard *et al.* (1976, 1977) have shown that both these inputs, in most instances, are composed principally of methane. The region of widespread seepage near Station 3/IV never had methane concentrations in near-bottom waters during the three year period above several hundred nl/ℓ although the methane tongues shown in Figure 3.3 contained up to 4000 nl/ℓ. In several profiles reported by Brooks and Sackett (1977) taken directly over bubbling gas seeps, the highest dissolved methane concentrations observed were only a few hundred nl/ℓ. These observations suggest that seepage is not capable of producing waters containing thousands of nannoliters of methane such as found in the near surface layer. Also, it is doubtful that seepage could affect a relatively uniform maximum at 50 to 60 meters commonly observed throughout the northwestern Gulf of Mexico.

A possibility exists that the maxima could be derived from advection of near-bottom waters containing large quantities of methane contributed by diffusion across the sediment-water interface. Most shelf sediments contain, in sequence, a narrow aerobic sediment layer of only a few centimeters; an underlying sulfate zone varying from a few centimeters in areas such as the Mississippi Delta to tens of meters along the outer shelf and slope; and a sulfate-free zone in which sulfate has been

bacterially depleted and CO_2 is the preferred electron acceptor in bacterial mediated reactions. Although interstitial waters in shelf sediments contain μl/l quantities of methane at the sediment-water interface and ml/l quantities just a few meters further below, the flux out of these sediments is relatively small. This is because oxidizing bacteria in the sulfate zone apparently utilize the upward diffusing methane produced by methanogens in the sulfate-free zone (see Sediment LMWH Section). A high flux of methane from sediments may be obtained in regions where the sulfate-free zone is at the sediment-water interface and therefore in direct contact with the overlying water column. In such regions the methane concentrations often reach supersaturation at shallow depths and the flux is controlled by bubble formation. Several investigators (Reeburgh, 1969; Hammond *et al.*, 1975; and Martens, 1976) have found evidence for bubble stripping of gases in bay and estuarine sediments. In the Gulf, areas such as these exist in the Mississippi Delta region and in very near-shore and estuarine sediments. In the STOCS, the flux of methane across the sea-sediment interface does not appear to support the mid-depth water column maxima.

Various biological theories have been suggested to explain the super-saturation of methane in the upper layer of the ocean, including production in the gut of zooplankters, bacterial production in reducing microenvironments, inside fecal pellets, dead cells, etc., and metabolic byproducts of algae. Since zooplankters are very migratory organisms it is unlikely they would produce a well defined maximum. Although Scranton and Brewer (1977) reported, without supporting data, that preliminary results show that trace amounts of methane can be produced in axenic cultures of marine algae, the association of methane with phytoplankton

is highly suspect. Lamontagne *et al.* (1975) did not observe any correlation between chlorophyll a and methane. Although methane may be produced in phytoplankton as a metabolic by-product such as CH_3I and other methylated compounds (Lovelock *et al.*, 1973), it is unlikely that any trace by-product could account for the large anomalies observed in the upper water column.

Methane in the STOCS study did not exhibit a significant correlation with chlorophyll or any phytoplankton parameter. This would seem to negate the probability of methane's being derived from phytoplankton. Brooks *et al.* (1979) have indicated that methane and ATP profiles often exhibit similar covariances. Figure 3.7 shows one of the few profiles in the STOCS area where simultaneous ATP, methane and transmissometry measurements were obtained. This profile shows an excellent correlation between ATP and methane. Since the chlorophyll maximum is not associated with the ATP-methane maxima, the most likely source of the ATP is bacterial activity and/or possibly zooplankton. The ATP-methane maxima are also associated closely with a decrease in light transmittance (as measured by transmissometry), indicating the presence of increased suspended matter. The STOCS data suggests that the methane supersaturation in the Gulf of Mexico originates from *in situ* production in the water column. Although *in situ* production possibly occurs throughout the water column, a production maximum appears to be associated with the upper thermocline/pycnocline. The sequence of events thought to produce the observed mid-depth distributions are as follows: suspended particulate material produced or deposited in the mixed layer sink at a relatively uniform rate until reaching the top of the thermocline where the sharp increase in density produces a corresponding increase in the bouyant forces acting

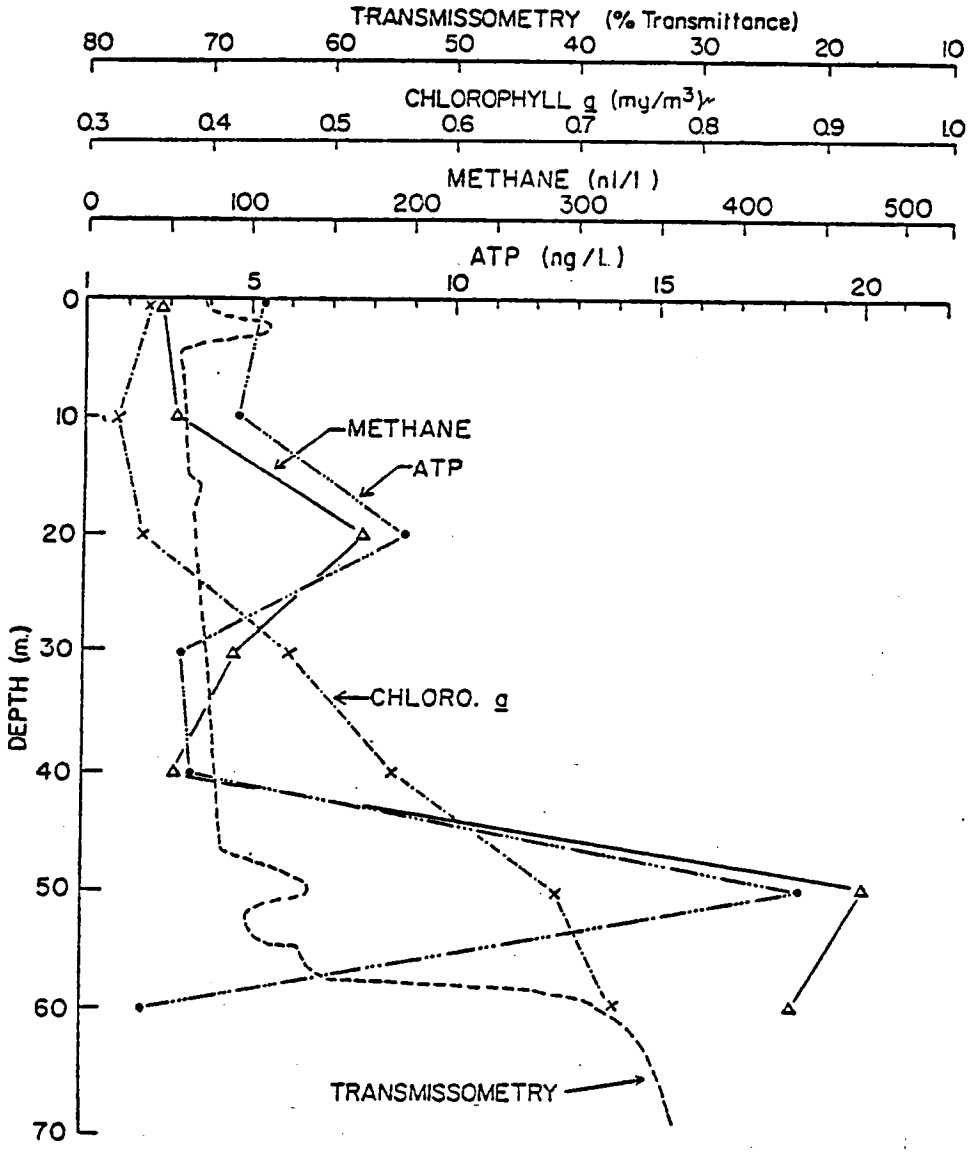

Figure 3.7 Depth Profile of Methane, ATP, Chlorophyll a, and Transmissometry (nl/ℓ) in the STOCS Area During the Seasonal Cruises in 1977.

on the material, resulting in a decrease in the rate of sinking and a relative buildup of suspensoids at that depth; bacterial action in organic reducing microenvironments produces a relative methane maximum; these processes continue even in the winter, but at a slower rate, which, combined with increased vertical mixing and exchange with the atmosphere produce a decrease in the gas concentration of the maximum layer.

The above sequence of events is supported by the physical data which show that methane maxima are associated with the upper part of the thermocline where TSM maxima have been shown to exist in the Gulf of Mexico. A bacterial source of methane is also favored since other biological sources (*e.g.* phytoplankton and zooplankton) probably would not produce a well-defined maximum, since they are migratory organisms. These hypotheses are also supported by profiles such as Figure 3.7 which shows a close covariance between methane, ATP, and transmissometry.

Near-Bottom LMWH Maxima

Near-bottom LMWH levels higher than observed at overlying sampling depths were common in the STOCS study. The near-bottom maxima are most pronounced for methane, but often observed for other LMWH. In areas such as Station 3/IV where there is obvious gas seepage, the increase extended several tens of meters off the bottom with methane levels elevated up to 500 nl/ℓ. Ethane and propane were rarely elevated by more than a factor of two at Station 3/IV. A similar near-bottom LMWH maxima was occasionally observed at Station 3/I. Near-bottom LMWH maxima were also associated with the bottom nepheloid layer. Figure 3.7 shows that the nepheloid layer at this station was accompanied by a methane maxima. Although simultaneous measurements of transmissometry and LMWH were only obtained at a few stations, it appears that nepheloid layers are common especially at

Stations 1 and 2 (and bank stations). Also common at these stations was a bottom methane maxima. Most methane maxima were accompanied by small increases in ethane levels. It is uncertain whether high LMWH levels in nepheloid layers resulted from resuspension of bottom sediments containing higher LMWH levels and/or from *in situ* production associated with the layer. Higher nutrient and productivity levels associated with these layers may result in high *in situ* production rates.

C_2-C_4 LMWH

Unlike methane, the exchange of C_2-C_4 LMWH across the air-sea interface in the STOCS region is speculative. This is because there are no well-established atmospheric partial pressures, and solubility data at oceanic temperatures and salinities do not exist in the literature. However, since oxidation of the olefins occurs within hours in the atmosphere, all the olefins found in the surface waters of the Gulf must be biologically derived and/or introduced through losses from refined products during transportation or manufacturing operations. It is therefore assumed that the direction of olefin exchange across the air-sea interface is from the ocean to the atmosphere. The saturated C_2- C_4 hydrocarbons have man-derived and *in situ* sources similar to methane. It is also resaonable to assume that some of the long-lived anthropogenic hydrocarbons (*e.g.* ethane and propane) found in marine atmospheres are deposited into the ocean either by rainout or by air-sea exchange.

Correlations between water column LMWH, biological and chemical measurements yielded very few good coefficients. Table 3.3 contains some significant correlations obtained using the 1976 and 1977 data sets. Using the entire data set, ethane and propane were the only LMWH that gave significant correlations with other parameters measured in the STOCS study.

TABLE 3.3

SIGNIFICANT CORRELATIONS USING 1976 AND 1977 DATA SETS

	Observations	Correlation Coefficient (R)
Surface ethane vs. chlorophyll	106	0.76
Surface ethane vs. phyto-plankton abundance	106	0.58
HPZ* ethane vs. chlorophyll	56	0.65
HPZ ethane vs. phytoplankton abundance	56	0.56
Surface propane vs. chlorophyll	107	0.44

*Half the depth of the photic zone

Although ethane correlated with several phytoplankton variables, the best correlation was with chlorophyll. The correlation coefficient was best in surface waters and below 0.40 in near-bottom waters probably due to inputs from sediment. The good correlation between ethane and chlorophyll probably indicates that ethane is derived at least in surface waters as some type of intermediate or by-product of phytoplankton growth or metabolism.

Sediments

Methane in the top few meters of STOCS sediments is generally of microbial origin, as evidenced by the existence of anomalously high methane concentrations in the top sediment layers. Apparently, bacterial production of methane is not restricted to the sulfate-free zone, but also occurs within microenvironments in sediments having near-seawater interstitial sulfate concentrations. In Texas shelf sediments, sulfate is not depleted until several meters depth and methane existing in the upper few meters of sediment cannot be explained by upward diffusive processes or inputs from overlying water. Two-meter vertical methane profiles in near-shore sediments exhibited maxima ranging from 100 to 500 microliters per liter pore water. Figure 3.8 is a schematic representation of interstitial methane in the upper four meters of sediment based on samples taken in the STOCS area as compared to slope and abyssal sediments examined independently. The diagram illustrates the disappearance of the maxima as well as the trend of decreasing interstitial methane in an offshore direction. These trends were associated with variations in temperature and microbial activity and will be discussed later.

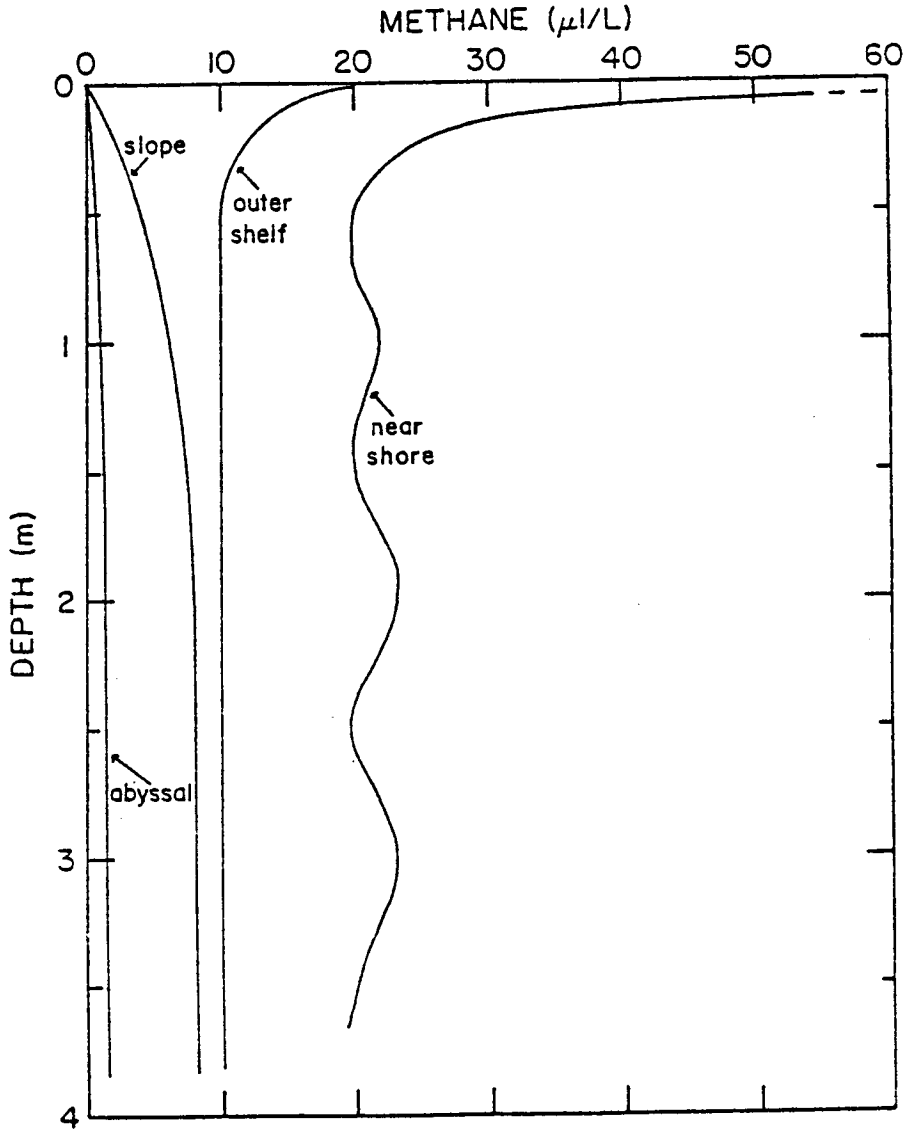

Figure 3.8 Schematic Diagram of Methane Variations in the Upper Four Meters of Sediment.

Interstitial concentrations of ethene, ethane, propene, and propane, decreased progressively from 160, 100, 110 and 60 nl/ℓ pore water in nearshore sediments, to fairly uniform levels of 80, 25, 30 and 25 nl/ℓ downslope, respectively. These trends are illustrated in Figure 3.9, which shows average concentrations of the four hydrocarbons throughout the cores of Transect I stations. Transect I is sued because Stations 49, 50 and 51 are located on the slope and represent an extrapolation of the transect to deeper water.

The trends of the C_2 and C_3 hydrocarbons with distance from shore are similar to the behavior of methane. These patterns suggest that the concentrations of C_2 and C_3 in the top few meters of shelf and slope sediments were microbially supported. Like methane, concentrations of the C_2 and C_3 hydrocarbons are probably controlled by biological oxidation and diffusion into the overlying water.

The concentrations illustrated in Figure 3.9 generally represent "baseline values" of the light hydrocarbons on the Texas shelf. One area of anomalously high ethane and propane was found, however, suggesting an input of thermocatalytic gas from the subsurface. Figures 3.10 and 3.11 show ethane and propane concentrations with depth at the Transect IV stations as compared to Transect III stations. Corresponding to the seepage observed in the water column at Transect IV, sediment LMWH showed anomalously high concentrations at Stations 4, 6, 3, and 7 along this transect. The stations along Transect III are typical of the normal distribution of light hydrocarbons from biogenic sources in the shelf sediments. Interstitial ethane and propane concentrations varied between 20 and 40 nl/ℓ in this area. As shown in Figures 3.10 and 3.11, ethane and propane concentrations along Transect III tended to decrease in an offshore direction

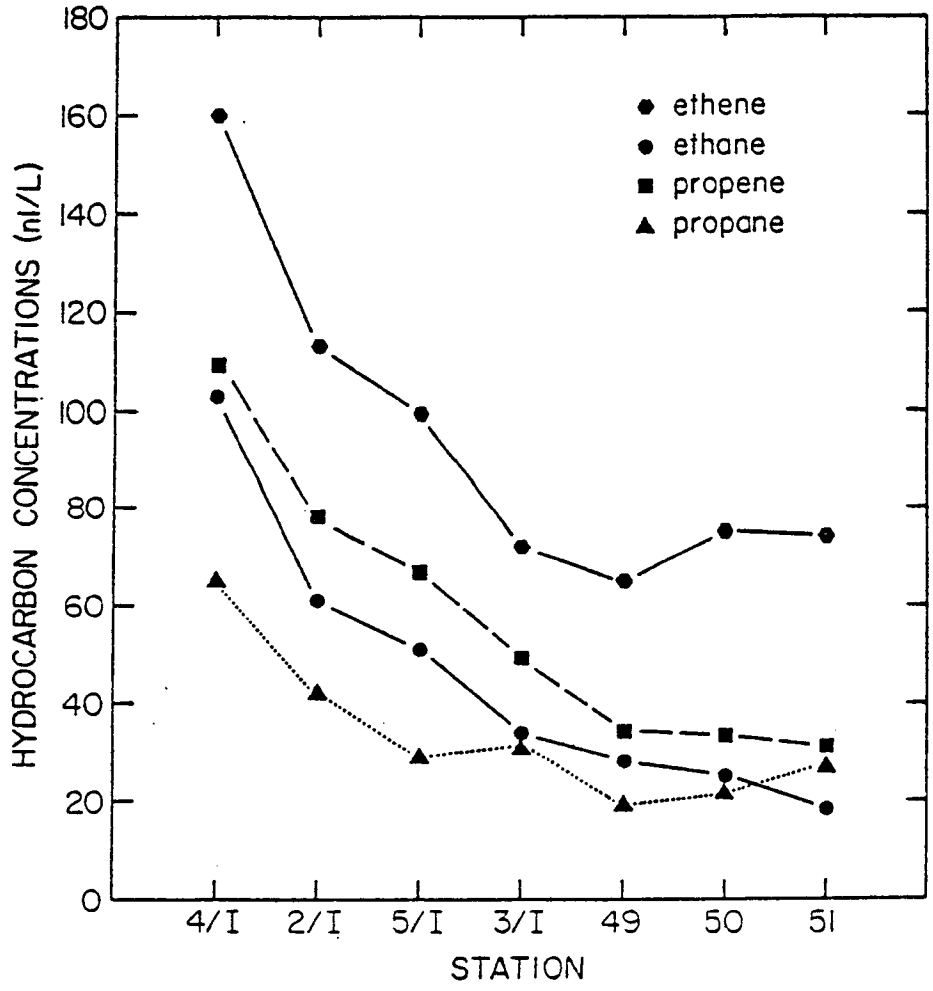

Figure 3.9 Average Concentrations of the C_2 and C_3 Hydrocarbons at Transect I Stations (see Figure 3.1 for Station Locations).

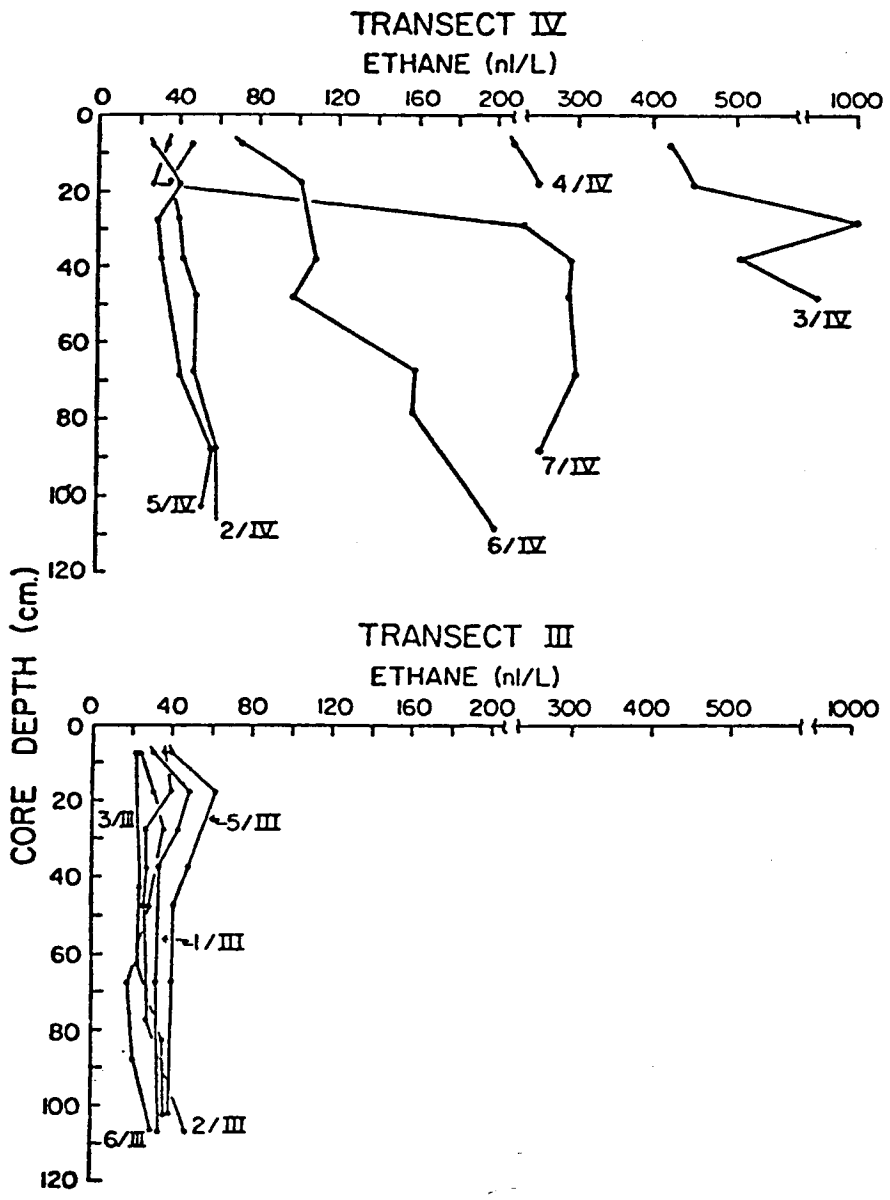

Figure 3.10 Interstitial Ethane Concentrations (Nannoliter per Liter Pore Water) at Stations Along Transects III and IV.

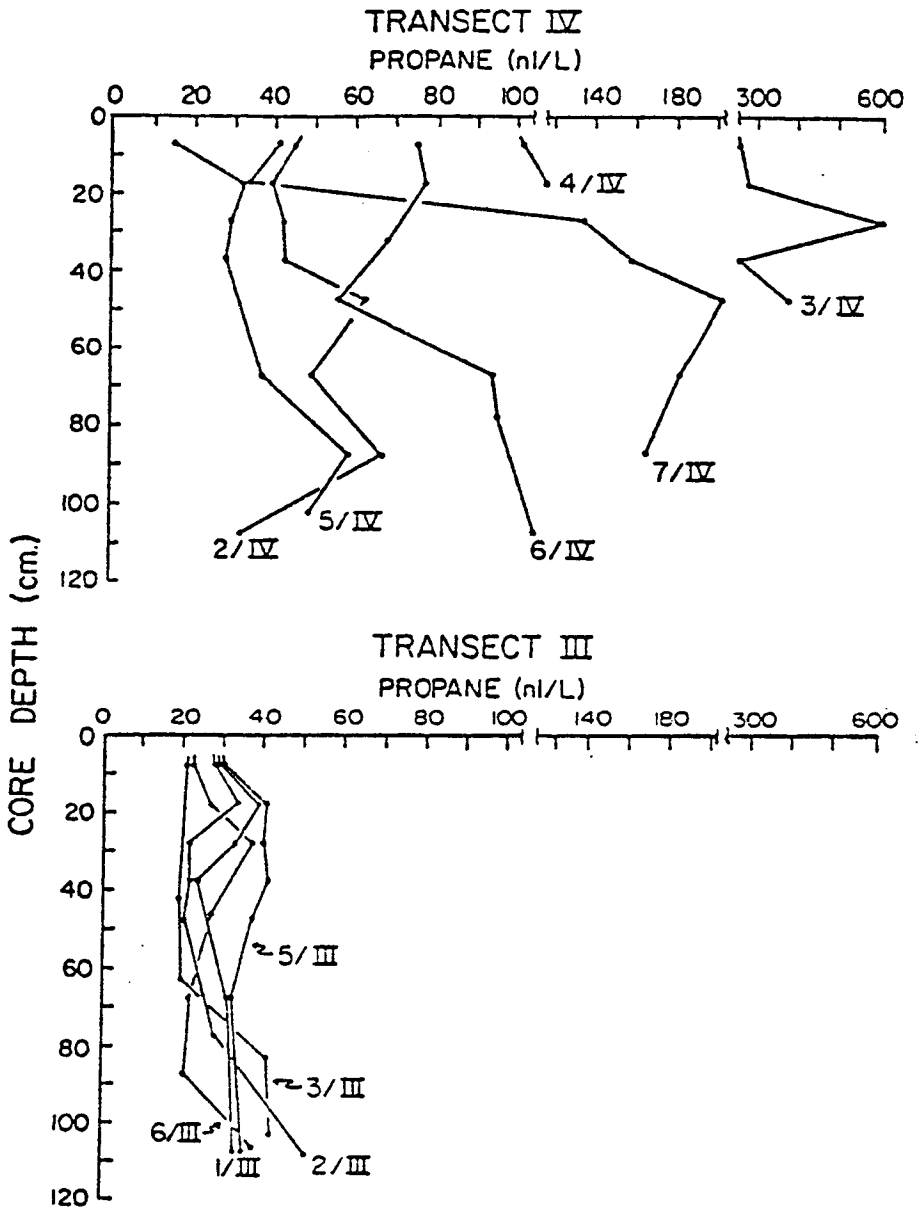

Figure 3.11 Interstitial propane concentrations (nannoliter per liter pore water) at stations along Transects III and IV.

with ethane levels generally slightly higher than propane, in a manner very similar to Transect I.

Figures 3.10 and 3.11 indicate that the largest anomalies on Transect IV occurred at Station 3, corresponding to observed seepage identified by near-bottom water sampling, as discussed in the water column LMWH section. The interstitial ethane and propane concentrations were at least two orders of magnitude above normal levels in the outer three stations. Figure 3.12 shows methane, ethane, and propane concentrations and $C_1/(C_2+C_3)$ ratios in sediments at Stations 3/IV and 3/III. Whereas interstitial methane increased five-fold between the two stations, ethane and propane changed by almost two orders of magnitude. This is illustrated by $C_1/(C_2+C_3)$ ratios of several hundred at Station 3/III, decreasing to as low as 14 at Station 3/IV. The increase in $C_1/(C_2+C_3)$ ratios near the surface at Station 3/IV can be attributed to biogenic production in the upper few tens of centimeters diluting the more thermogenic ratios observed below 30 or 40 cm.

Eight cores were also taken in the western part of the Serendipity Gas Seep region of south Texas. Watkins and Worzel (1978) reported widespread occurrences of smear zones and wipeouts within the uppermost sedimentary section and acoustically detected seeps in this region. None of the cores taken showed anomalous LMWH levels.

Integration of LMWH with Other Parameters

In order to systematically examine correlations, scatterplots of all possible permutations of the LMWH with other sediment parameters were generated. The parameters considered are listed in Table 3.4. It should be noted that in order for data correlations to be valid, samples for each parameter should be taken from the same location at the same time. These

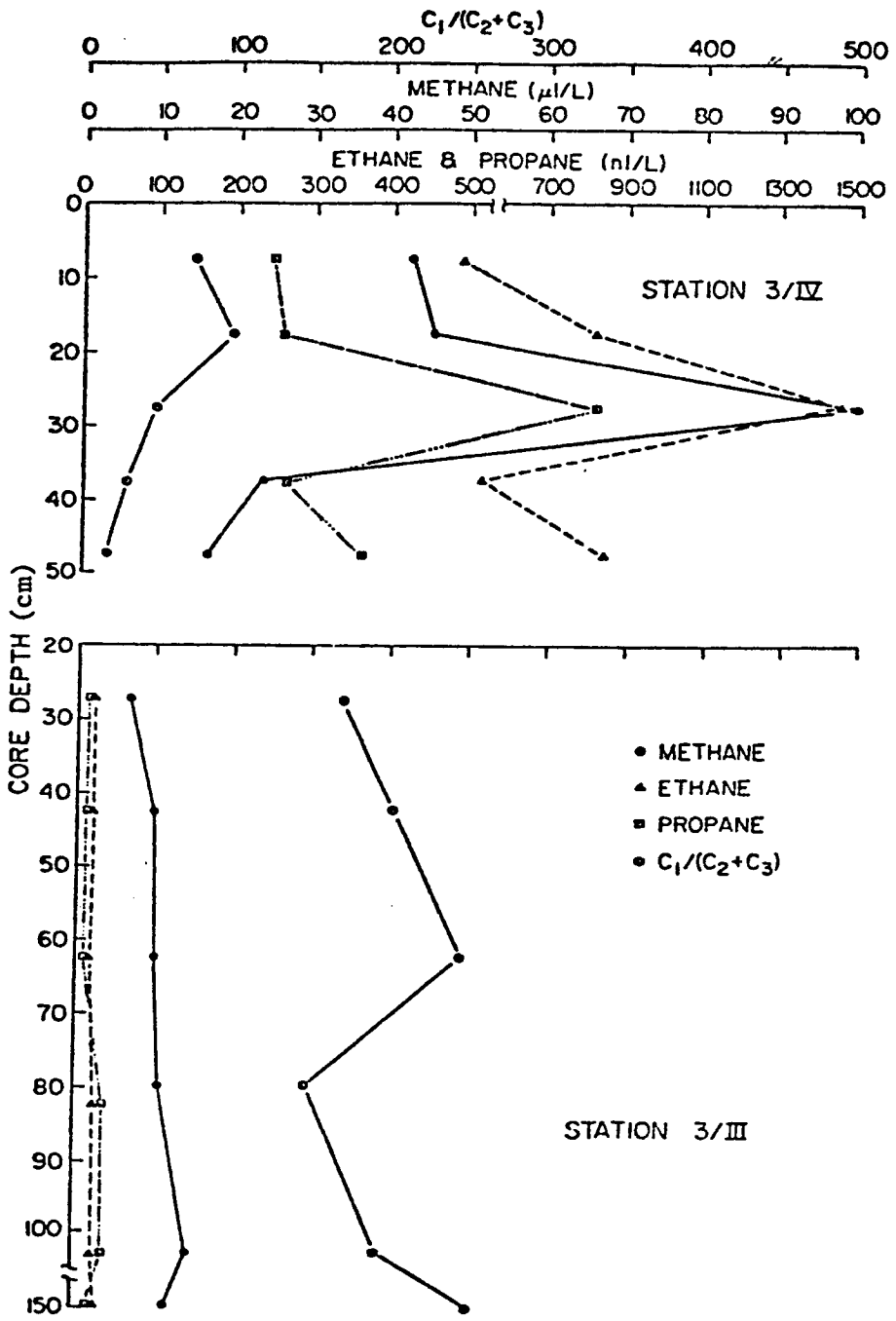

Figure 3.12 Interstitial Hydrocarbons Concentrations (Nannoliters Per Liter Pore Water) at Shelf Break Stations on Transects III and IV.

TABLE 3.4

Sediment LMWH Parameters:

- Methane
- Ethene
- Propene
- Propane

HMWH Parameters:

- Total hydrocarbons (TOTHC)
- Pristane/Phytane Ratio (R_1)
- Pristane/C_{17} Ratio (R_2)
- Phytane-C_{18} Ratio (R_3)
- Pristane + Phytane/n-alkane Ratio (R_4)
- Odd to Even Carbon Preference in the C_{14}-C_{20} Range (OEP1)
- Odd to Even Carbon Preference in the C_{20}-C_{32} Range (OEP2)

Other Organic Parameters:

- Total Organic Carbon (TOC)
- Delta $\Delta^{13}C$ of Organic Carbon (DEL)

Bacteriological Parameters:

- Total Oil Degrading Bacteria (OIL)
- Total Heterotrophic Aerobes (BAC)

Physical Sediment Parameters:

- Mean Sediment Grain Size (MGS)
- Grain Size Standard Deviation (GSSD)
- Grain Size Skewness (SKEW)
- Grain Size Kurtosis (KURT)
- Percent Sand (SAND)
- Percent Silt (SILT)
- Percetn Clay (CLAY)
- Percent Phi Grain Size > 10.6 (PHI)
- Sand-Mud Ratio (R_5)
- Silt-Clay Ratio (R_6)

two criteria were not satisfied for the STOCS study due to logistics problems inherent in this type of multidisciplinary investigation. Sediment and benthic bacteriological parameters were generally sampled on different cruises than the LMWH, so observed correlations must be qualified by this uncertainty. Furthermore, the bulk of data for LMWH was generated from samples at several depths in the sediments, whereas all other parameters listed above were measured on surface grab samples. Computer comparisons have, then only treated sediment surface data, greatly reducing the amount of comparable data and perhaps the significance of correlation. Comparable data has been further reduced by the fact that sampling for sediment LMWH took place only during 1977, whereas other parameters were measured for as long as three years, and that LMWH were sampled only once at each station, whereas other parameters were sampled at least seasonally. It should be mentioned in this regard that comparisons were made only with data taken during the same season, *e.g.* LMWH sampled in the fall of 1977 are compared to other data sampled during the fall seasonal sampling period.

Relation of LMWH to Water Temperatures and Benthic Bacteriology

As shown in the schematic diagram of Figure 3.8, methane concentrations show distinct trends with distance from shore. Not only did the sediment-surface methane anomaly disappear, but overall methane concentrations throughout the top two meters decreased seaward. The trends are best illustrated by Figure 3.13, which is a plot of four Transect I stations and three continental slope stations. These stations were sampled in March of 1977.

Concentration profiles are positioned on the figure relative to the sea floor depth where the cores were taken (dashed lines represent sea floor contours). Water depths and distances from shore to the stations

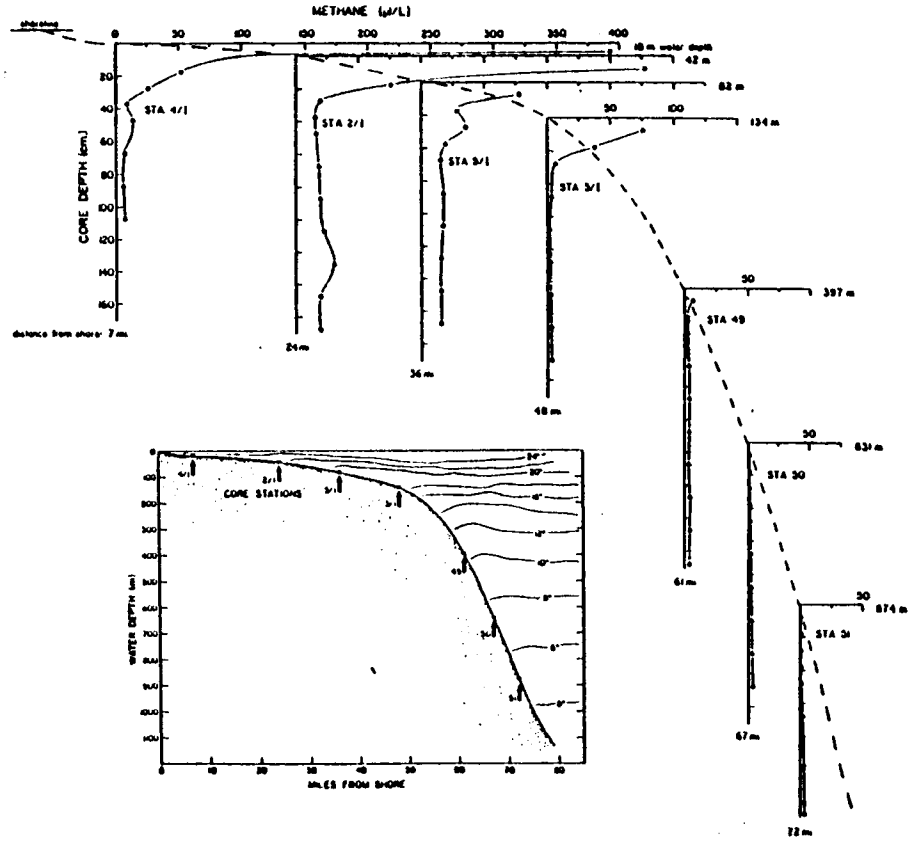

Figure 3.13 Interstitial Methane Along Transect I, Positioned on the Sea Floor Contour. Inset Shows the General Temperature Structure of the Area in Spring.

are written along the axes of the profiles. The profiles are plotted in this manner to illustrate the changes in methane concentration profiles with increasing water depth. Methane levels were generally higher at nearshore stations, and showed very discernible maxima within the top 30 to 40 cm of sediment.

Interstitial sulfate in the top few meters of these shelf sediments has not been significantly depleted, and in this area of the south Texas shelf sulfate persists several meters below the sediment surface, so methane should not be produced so extensively in the surface sulfate-rich sediments.

Water column methane concentrations were measured monthly over a three-year period in the STOCS area. Methane maxima in near-bottom waters were consistently observed in some areas, but few concentrations above 0.4 microliters per liter were observed. Therefore, methane concentrations in surface sediments as high as several hundred microliters per liter cannot be a result of diffusion downward from the water column, but must result rather from *in situ* production.

The fact that microbial populations are most extensive and physiologically versatile in the top layers of sediment has been known for some time (Certes, 1884; Russell, 1892; Drew, 1912; Lloyd, 1931; Reuszer, 1933; Zobell and Anderson, 1936; Kaplan and Ribbenburg, 1963). Wherever vertical profiles of bacterial populations have been examined in marine sediments, a progressive decrease in the bacterial populations with increasing sediment depth has been observed (Zobell, 1946). The decrease is most rapid in the top few centimeters of sediment, and generally slows, becoming erratic with increasing depth, as illustrated by Table 3.5 taken from Zobell (1942).

TABLE 3.5

BACTERIA PER GRAM SEDIMENT AT THREE CORE SITES OFF THE CALIFORNIA COAST (FROM ZOBELL, 1942)

Core Depth (cm)	Bacteria per gram	Bacteria per gram	Bacteria per gram
0-2	840,000	38,000,000	7,500,000
3-5	102,000	940,000	250,000
10-12	63,000	88,000	160,000
23-25	19,000	36,000	23,000
36-38	1,500	2,400	8,700
48-50	2,200	400	2,100
74-76	370	180	600
99-101	190	330	200
150-152	210	250	300
201-203	140	130	100
252-254	140	290	150
Water depth	430m	950m	1090m

The vertical distribution of bacteria in sediments could be directly correlated with available organic matter and nutrient material. Much of the organic matter of marine sediments consists of material which is fairly refractory to bacterial decomposition, so changes in total organic matter with sediment depth due solely to microbial activity are seldom observable. The surface sediment is subject to a constant rain of organic detritus, however, including the more labile material which is rapidly consumed by bacteria before burial. As available organic matter and nutrients disappear with depth in the sediment, bacterial populations decrease.

There are obvious similarities between vertical bacterial distributions and the vertical methane profiles of nearshore stations illustrated in Figure 3.13. The figure suggests that the methanogenic bacteria exist in large numbers near the sediment surface, and are possibly active inside small, sulfate-free microenvironments in the sediment after reduction of ambient sulfate has occurred. These micro-niches could take the form of fecal pellets, decaying organic matter, shell fragments, or flocculent clay particles. Methane produced in the microenvironments apparently diffuses into the surrounding sediment where it is bacterially oxidized, and moved upward into the overlying bottom water where it is removed by advection.

Figure 3.13 also illustrates the disappearnce of the surface methane maximum in cores taken progressively further offshore. The methane maximum decreases significantly at Station 3/I, is barely visible at Station 49, and disappears at Stations 50 and 51. The decrease of the near-surface methane with increasing distance from shore can be explained by changes in microbial populations and/or activity. Benthic bacteriology measurements indicated that total heterotrophic bacterial numbers decreased outward on the Texas continental shelf. Aerobic heterotrophic bacteria in surficial

sediments decreased as the water depth above them increased. Correlation coefficients between bacteria with water depth were -0.72, -0.87 and -0.55 for winter, spring, and fall, respectively. Sediment LMWH on Transect I were sampled between the winter and spring bacteriological samplings and seaward trends are very similar to those of heterotrophic aerobe populations. The correlation coefficient of methane and total aerobes at the 12 primary stations is 0.40. The actual correlation of the two parameters may have been much better if samples had been taken simultaneously.

General water temperature contours of the STOCS area are shown in the insert of Figure 3.13. These temperatures are representative of late spring but do not change significantly below 200 meters throughout the year. Stations are marked on the insert and surface methane concentrations correlate well with the temperature contours. Temperatures below ∿15°C and decreased labile organic inputs beyond the shelf break, apparently inhibit microbial activity and methane production to an extent that methane diffuses out of the sediment before it can accumulate as it does nearer shore. The increase in hydrostatic pressure may also suppress production of methane in these slope sediments. For example, Jannasch *et al.* (1971) found that rates of microbial activity were 10 to 100 times slower in the deep-sea than in controls at comparable temperatures.

Changes in production with temperature imply that surface methane concentrations in Texas shelf sediments are seasonally influenced. Schwarz (1979) states that significant seasonal fluctuations in total heterotrophic aerobes occurred at all stations except 2/I, 2/II, and 3/II. Although methanogenic bacteria were not cultured, the evidence suggested that methanogens surviving in microenvironments were similarly influenced by temperature changes. Low temperatures nearshore in winter (∿12°C) should

inhibit microbial activity and slow methane production. Warming of the sediments in the spring, enhanced by increased detrital input from phytoplankton blooms and runoff, might accelerate methane production in the microenvironments. Increased nearshore water temperatures in the summer, coupled with a depletion of nutrients and labile organic carbon, could again suppress bacterial activities in surficial sediments.

Indeed, samples taken in July of 1977 from Transect II stations are different from those taken in March (Figure 3.14). The profiles along Transect I in March show methane increasing upward to the 50-10 cm interval, whereas the summer profiles of Transect II indicate a methane maximum at the 25-30 cm interval caused by an apparent suppression of production at the sediment surface. The absence of high surface methane concentrations along Transect II could be attributed to seasonal influences. Nearshore water temperatures approaching 30°C in the summer months may be above the temperature range for optimum growth of the methanogens, effectively inhibiting methane production. Other possible seasonal effects include changes in fluxes of organic detritus and nutrients to the surface sediments. Since no significant correlation of methane, or any of the other sediment LMWH with any of the other physical sediment measurements, existed surficial methane variations appear to be controlled by seasonal and temperature influences rather than by sediment type.

Transects III and IV stations were sampled in September and November of 1977, and few surface methane anomalies were observed. Apparently, suppression of bacterial activities continues through the year. If we assume that low water temperatures in winter continue to inhibit microbial activity and slow methane production, then rewarming of the sediments in spring, enhanced by regeneration of nutrients and detrital input from

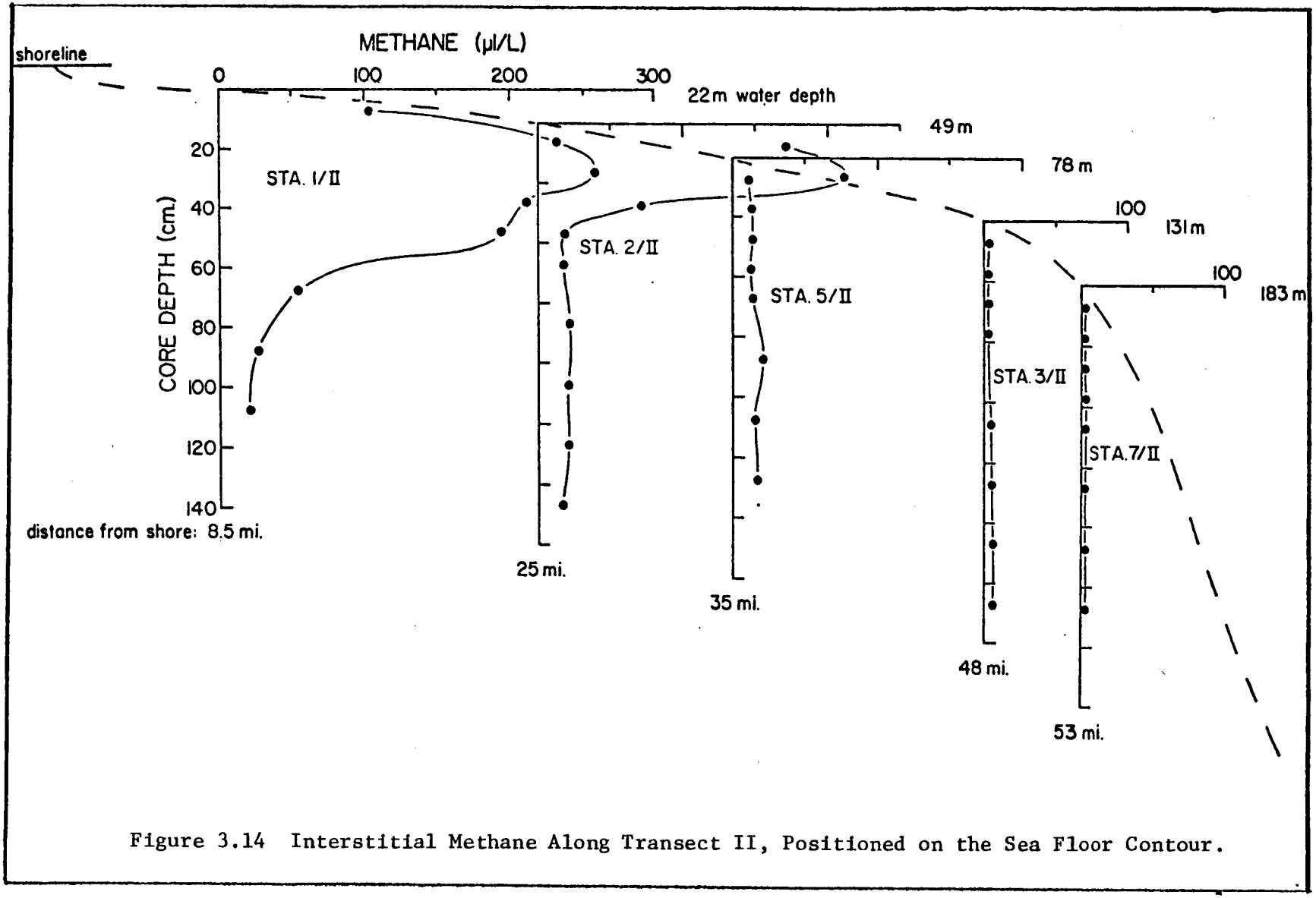

Figure 3.14 Interstitial Methane Along Transect II, Positioned on the Sea Floor Contour.

continental runoff, could complete the cycle, causing annual oscillations of methane in near-shore surficial sediments. Methane produced extensively in the spring must slowly diffuse out of the surficial sediments during the rest of the year. These oscillations could provide an excellent means of evaluating the magnitude of the effective diffusion coefficient of methane in porous sediments.

The other LMWH did not show drastic variations with time or location due to temperature or other seasonal influences. If the background ethane and propane levels are indeed microbially controlled as suggested earlier, they should probably be considered "waste" products of some secondary metabolic process involved in the breakdown of fatty acids or other organic matter in sediments. As illustrated previously, the high ethane and propane levels at Station 3/IV were too high to be explained by microbial processes. The $C_2/(C_2+C_3)$ ratios throughout the core strongly suggested a contribution from thermocatalytic gas sources. This conclusion implies the seepage of hydrocarbons from a subsurface reservoir into the surficial sediments and bottom waters. Water column analyses which confirmed this conclusion have been discussed earlier in the chapter. Correlation of sediment LMWH data with other parameters measured in this region also prove interesting.

Relation of LMWH to HMWH and Bacteriology

As the benthic bacteriological data reported by Schwarz (1979) was examined for seasonal effects, it was observed that two stations in Transect IV were anomalously high in both number percent and total hydrocarbon degraders during the fall of 1977 (Figure 3.15). This seasonal sampling effort was almost coincidental with the sampling for sediment LMWH on

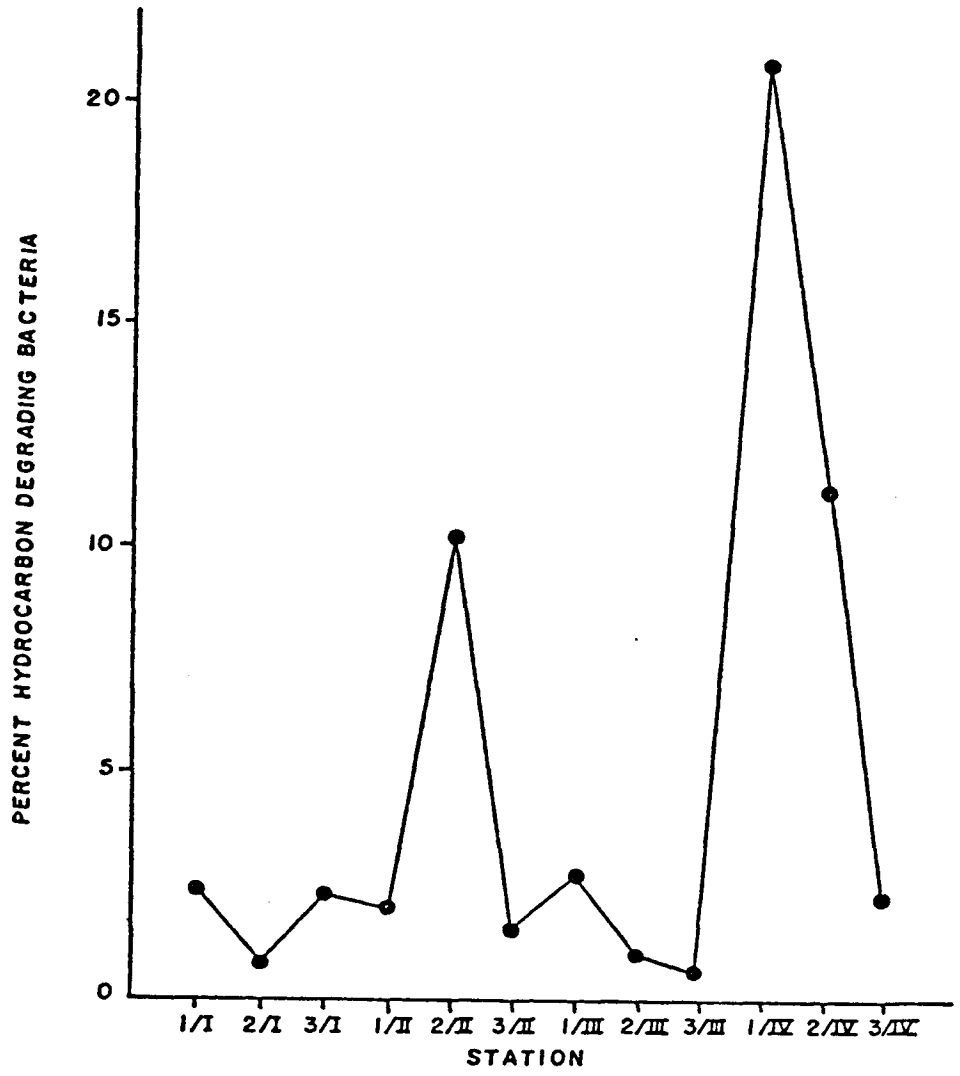

Figure 3.15 Percent Hydrocarbon Degrading Bacteria During Fall 1977 Surficial Sediment Sampling.

Transect IV from which the anomalous ethane and propane levels were observed. The correlation of ethane or propane with hydrocarbon degraders is not good, since the maximum for the bacteriological parameters was observed at Station 1, whereas the maximum for the LMWH anomaly was observed at Station 3. However, analysis of variance calculations showed that the percent hydrocarbon-degrading bacteria determined for Transect IV stations on both a seasonal and yearly basis were 2.5 times higher than the next highest transect (II), with a maximum of 10 times the average on other transects. Also, the mean crude oil degradation rate was significantly higher for natural sediment bacterial populations from Transect IV stations each season over the entire year. Both these parameters are indicators of the exposure of a particular sediment to hydrocarbons. In comparison, ethane and propane levels on Transect IV average almost 5 times, with some values over 10 times, the average of the other transects. The presence of high concentrations of hydrocarbon-degrading bacteria suggest the seepage input of LMWH to the Transect IV area.

Correlation coefficients of sediment LMWH vs. HMWH and bacteriological sediment parameters are shown in Table 3.6. Methane correlates with most of the HMWH parameters, whereas the other LMWH tend to correlate with oil degrading bacteria and total organic carbon. All of the HMWH parameters are designed to reflect the extent of oil-related hydrocarbon contamination in a sediment sample. For example, the odd to even preference ratio in the C_{20} to C_{32} hydrocarbon range (OEP2) reflects an increasing component of petroleum contamination in an alkane extract as the preference ratio approaches unity from pristane values of five or greater. Methane vs. OEP2 shows the best correlation (-0.83). The correlation is due to high methane concentrations and low ($\sim$2) OEP2 ratios at Stations 1/I, 3/I,

TABLE 3.6

CORRELATION COEFFICIENTS OF SEDIMENT LMWH VS. HMWH AND BACTERIOLOGICAL SEDIMENT PARAMETERS

	Correlation Coefficient (R)
Methane vs.	
Total Hydrocarbons	-0.40
Pristane-C_{17} Ratio	-0.45
Pristane + Phytane/n-alkanes	0.63
Odd to Even C_{14}-C_{20} Preference	-0.43
Odd to Even C_{20}-C_{32} Preference	-0.83
Total Aerobic Heterotrophs	0.40
Total Organic Carbon vs.	
Ethene	-0.42
Ethane	-0.54
Propene	-0.32
Propane	-0.52
Total Oil-Degrading Bacteria vs.	
Ethene	0.54
Ethane	0.47
Propene	0.51
Propane	0.46

1/II and 2/II. Comparable data were not available for the secondary stations (4, 5 and 6) because the HMWH were not sampled there. Methane values are high at Stations 4/I, 5/I, and 6/I and HMWH analysis of these locations should reveal low ratios of OEP2 (Parker, personal communication). These trends are best explained by an enhanced terrestrial influence of both nearshore and northernmost stations, due to increased river runoff and industrial activity adjacent to these areas. Methane is high due to inputs of nutrients and organic substrates; OEP2 ratios are low due to an increased component of anthropogenic hydrocarbons. It seems then, that the established "background" levels of these parameters have themselves been influenced by man's activity.

The other LMWH hydrocarbons did not correlate well with any of the HMWH parameters, but rather with oil-degrading bacteria and total organic carbon. It is interesting that all of the $C_2 - C_3$ hydrocarbons correlated similarly, with no distinction between olefins and alkanes. Of the two observed LMWH relationships, the correlation with oil-degraders is probably the most significant. It would be unrealistic to postulate an influence of LMWH production on the total sediment organic carbon. In fact, it is extremely difficult to attribute any changes in TOC to bacterial activities, simply because the organic material available for bacterial metabolism is only a small fraction of the total. The relation of the C_2-C_3 hydrocarbons is more interesting because the observed positive correlation suggests that hydrocarbon degraders are producing "waste" LMWH during catabolism of the heavier hydrocarbons. This gas production need not be a discrete step in the biochemical reaction sequence, but could be viewed as a secondary metabolic process. Therefore, an increase in activity of the hydrocarbon degraders might cause an increase in LMWH levels in

sediments. This postulation should be investigated, since microbial production of ethane and propane has not been demonstrated conclusively in the laboratory.

The initial objective of examining correlation coefficients was to establish a relation between LMWH and HMWH due to seepage of hydrocarbons on Transect IV. However, except for methane, the LMWH bear no relation to the HMWH. The oil-related input of gas to the Transect IV surficial sediments appears to be the only good chemical evidence for seepage in that area.

CONCLUSIONS

The lower Texas shelf is relatively "clean" with respect to hydrocarbons, as LMWH in the south Texas OCS area are chiefly derived from natural sources. The major sources of methane appears to be *in situ* production in the water column or seepage across the sediment-sea interface. There appears to be a seasonal pattern to the vertical distribution of methane in the water column. In the winter, due to turbulent mixing, the water column was fairly uniform with respect to saturated LMWH. During the summer and fall, as stratification of the water column develops, a maximum in methane associated with the thermocline developed. This concentration maximum was almost an order of magnitude higher than levels above and below. The maximum probably resulted from accumulation of suspended matter on the stratification boundary due to restriction of settling velocities across the density gradient, with subsequent production of methane in small micro-reducing environments of suspended particles. High methane values during the winter 1977 could have resulted from anthropogenic additions.

The unsaturated hydrocarbons (*e.g.* ethene and propene) generally followed productivity patterns, being low in winter with higher values in the spring, and fall. Ethene and propene are known to be produced by biological processes, thus their strong correlations with phytoplankton productivity parameters are to be expected. Ethene also showed a shallow subsurface maxima associated with a productivity maximum. The unsaturates dominated over their saturated analogs in the STOCS area. Ethane showed a good correlation to phytoplankton standing crop.

An indirect correlation existed between sediment methane and aerobic bacteria since methane is produced by anaerobic bacteria. Controlling factors for both parameters included seasonal and spatial temperature changes and availability of nutrients and organic material. In addition, sediment methane was related to sediment HMWH parameters due apparently to an influx of terrestrial or man-derived organic matter at nearshore and northernmost stations.

The other sediment LMWH were related to total oil-degrading bacteria in the surface sediments. This correlation was possibly due to the production of these gases as "waste" or secondary metabolic by-products during the catabolism of high-molecular-weight hydrocarbons in the sediments.

RECOMMENDATIONS

The measurement of LMWH in STOCS waters and sediments have provided invaluable baseline data for monitoring the affects of offshore development. Water column LMWH are very sensitive indicators of offshore petroleum pollution. Much of the Louisiana offshore waters are contaminated with LMWH from offshore production. Unfortunately, in the Louisiana area it is impossible to totally differentiate natural and anthropogenic inputs.

This distinction should be much easier on the south Texas shelf with three years of baseline values. Based on experiences on the Louisiana shelf, one would expect LMWH and associated higher hydrocarbons to increase as production operations expand. LMWH should be measured as oil fields are developed in the STOCS.

Although, sediment LMWH were measured for only one year on the STOCS. they provided considerable information relating to biological activity and seepage in the STOCS. An effort should be made to study seasonal variability in LMWH. Also, LMWH are very useful in identifying areas of seepage in shelf sediments. Only a very minimal effort was made to identify seep areas in the STOCS. The one large area of seepage identified around Station 3/IV needs a considerable amount of study to identify its source and extent. Carbon isotope measurements of interstitial methane, seep gas, etc., would be useful in this study.

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CHAPTER FOUR

HIGH-MOLECULAR-WEIGHT HYDROCARBONS IN WATER, ZOOPLANKTON AND SEDIMENT

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ABSTRACT

Analyses of high-molecular-weight hydrocarbons in seawater, zooplankton and sediments were carried out on samples collected over a three year period from the south Texas outer continental shelf (STOCS). Results indicate seawater and sediment samples from the study area are relatively pristine with respect to petroleum hydrocarbons. Zooplankton samples obtained by oblique tows were shown to contain increased quantities of petroleum hydrocarbons during this study. Petroleum hydrocarbons were probably present in zooplankton samples as micro tarballs. The source of petroleum pollution is thought to be tanker traffic rather than exploration or production in the area.

INTRODUCTION

The analyses of high molecular weight hydrocarbons in seawater, zooplankton and sediments from the STOCS region were performed to provide BLM with a data base obtained prior to extensive oil and gas exploration and production in lease areas. Similar measurements subsequent to oil and gas related activities could document the addition, if any, of anthropogenic petroleum hydrocarbons.

For the data base to be useful it should contain sufficient information about the natural variation of the various parameters within the study area to allow interpretation of extreme values with confidence. In addition to concerns for long term seasonal and inter-station variability equal attention must be given to short term temporal and spatial variations which have been described as "patchiness" of the material to be measured.

Superimposed upon the previously mentioned variations are those which occur due to sample handling through contamination or alteration and those which are related to analytical procedures. The sampling and analytical procedures described in the following sections were carefully designed and executed to minimize procedure-associated variations which could easily be of the same magnitude as natural variations.

The concentration of high molecular weight hydrocarbons in the water column is quite low with the exception of tar balls and hydrocarbons associated with the surface microlayer. Literature data (Brown *et al.*, 1973; Gordon *et al.*, 1974) report a decrease in hydrocarbon concentration from the surface to a depth of about 10 meters below which values are generally less than 1 μg/ℓ. This decrease with depth suggests that the hydrocarbons are present as particulate matter rather than in true solution even though concentrations are below known solubility. Adsorption on

mineral and organic particles and aggregation into micelles are all probable mechanisms by which hydrocarbons could become associated with particles. The validity of division of hydrocarbons into "dissolved" and particulate fractions even if only in terms of an operational definition may be questioned by some investigators.

The available literature on the hydrocarbon composition of marine zooplankton represents a few isolated analyses. The data suggests the hydrocarbon content of zooplankton results from assimilation and modification of dietary components. Blumer proposed that pristane and phytadienes present in zooplankton were derived from metabolism of phytol (Blumer *et al.*, 1963; Blumer and Thomas, 1965). Phytoplankton hydrocarbons may be incorporated into zooplankton with little if any modification. Marine phytoplankton generally produce a simple mixture of hydrocarbons containing from 15 to 21 carbon atoms with a strong odd carbon preference (Han and Calvin, 1969; Winters *et al.*, 1969; Blumer *et al.*, 1968).

The C_{19} and C_{21} hydrocarbons of phytoplankton often contain one to six double bonds. Synthesis of olefins with more than 21 carbon atoms by algae has been reported (Gelpi *et al.*, 1970).

A greater body of knowledge exists concerning the organic components of sediments than any other carbon reservoir in the marine environment. A material balance of organics in a typical Gulf of Mexico sediment has been constructed from data of many analyses and presented in Table 4.1. STOCS sediments generally contain 0.2 to 2 ppm saturated hydrocarbon which is lower than concentrations reported for most recent sediments from the U.S. continental shelf. Most recent sediments contain concentrations which fall between 3 - 12 ppm values for the eastern Gulf (Gearing *et al.*, 1976) and 100-200 ppm values for basins off California (Emery, 1960; Hoer-

TABLE 4.1

MATERIAL BALANCE IN AN IDEALIZED GULF OF MEXICO SURFACE SEDIMENT[1]

Dry Weight	16 g
Total Organic Carbon	100 mg
Non-Lipid Carbon	95 mg
Total Lipid Carbon	5 mg
Total Non-Saponifiables	3 mg
Total Fatty Acids	0.4 mg
Total Sterols	0.1 mg
Total Fatty Alcohols	0.1 mg
Total Saturated Hydrocarbons	0.03 mg

[1]from Parker (1967), Parker (1969), and Sever and Parker (1969)

ing, 1968). The concentration of hydrocarbons in sediments even in the STOCS region however, is orders of magnitude greater than the concentration of hydrocarbons in the water column above the sediment.

In recent sediments odd carbon number n-alkanes are much more abundant than even number homologs, particularly in the C_{25} to C_{35} range. The similarity in distribution of hydrocarbons between recent sediments and most higher plants has prompted numerous investigators to propose a terrigenous source for a large portion of sedimentary hydrocarbons.

Bimodal distributions of n-alkanes in recent sediments have been reported by several groups to be indicative of two different sources of hydrocarbons (Blumer *et al.*, 1972; Gearing *et al.*, 1976). A maximum at or near C_{17} has been suggested as representative of marine production while a second maximum at $C_{27} - C_{31}$ was thought to result from terrigenous input.

Numerous investigators have reported $^{13}C/^{12}C$ ratios for Gulf of Mexico sediments (Sackett and Thompson, 1963; Hedges and Parker, 1976; Gearing *et al.*, 1977). The values for $^{13}C/^{12}C$ expressed as Delta ^{13}C range from about -26.0 ‰ to -20.0 ‰. Inshore sediments which receive substantial input of terrigenous organic matter have more negative values, -26 ‰ to -24 ‰ while offshore sediments have rather uniform values near -20 ‰. Seagrasses which have Delta ^{13}C values ranging from -3 ‰ to -13 ‰ (Calder, 1969; Parker and Calder, 1970; Fry, 1977) have been shown to contribute sufficient carbon to sediments to cause bay and nearshore sediments to have Delta ^{13}C values more positive than -20 ‰. Gearing *et al.* (1977) and Fry *et al.* (1977) have reported this "reverse" Delta ^{13}C gradient for transects into the Gulf of Mexico off south Texas.

Crude oils exhibit a wide range of Delta ^{13}C values but the majority fall between -25 ‰ and -30 ‰ with an average value about -26.6 ‰ (Degens, 1969). If a crude oil with a Delta ^{13}C value near -30 ‰ were

incorporated into a typical STOCS sediment (-20 ‰) the Delta ^{13}C of the sediment would shift in proportion to the amount of oil added.

MATERIALS AND METHODS

Sample Collection

The sampling frequency, stations sampled, and number of samples collected varied between the three year project depending upon the specific aims of the sampling efforts. In 1975, the sampling was primarily directed toward establishing sampling techniques and baseline sampling over 12 stations and three periods. In 1976, the number of stations was expanded to 25 to better determine spatial differences. Also in 1976, replicates were used extensively to determine variance within a station, and monthly sampling used to follow seasonal trends. Sampling in 1977 again emphasized baseline data and attempted to improve sensitivities and identifications.

Zooplankton samples were collected with a 1-m net (250 μm NITEX mesh) which was towed obliquely from near-bottom to near-surface for 15 minutes. The samples were placed in precleaned glass jars with teflon lid liners.

Seawater samples were collected from 10 m below the surface using a collection device consisting of a glass carboy which could be opened and closed (from the ship's deck) by means of a plug attached to a nylon line. A minimum of 38 ℓ (two, 5-gallon carboys) was taken. The samples were filtered through glass fiber filters which had been precleaned by reflux with chloroform. The nominal pore size of the filters was 1.2 μm. The pads containing the particulate organic matter (POC) were placed in small glass jars with teflon lids and frozen. The filtrate was poisoned with 50 ml of chloroform and processed as soon as possible on returning to the laboratory.

Sediment samples were obtained as subsamples of repeated Smith-McIntyre grabs and were taken from the top 5 cm of the grab. The samples were placed in precleaned glass jars with teflon lid liners, taking care not to fill each jar more than one-half full. The samples were frozen on board ship and kept frozen until analysis.

Total organic carbon and Delta ^{13}C sediment samples were obtained by the same technique and frozen in plastic sampling bags.

Laboratory Analysis

Throughout the study, purified solvents, inorganic chemicals and double distilled water were used. Control samples and blanks were used to insure that no gross contamination was present. At no time was severe contamination encountered.

Zooplankton

Zooplankton hydrocarbons were isolated and purified by the same technique over the three years of the STOCS program. A Soxhlet extraction apparatus was employed to reflux about 25 g (wet weight) of sample using a solvent charge of 125 ml of methanol-toluene (7:3) azeotrope. After 13 hours the solvent was replaced with fresh mixture and the refluxing repeated. The two extracts were combined and reduced to near dryness using a roto-vap apparatus.

The lipids recovered by Soxhlet extraction were saponified by refluxing (six hours) with a 0.5 KOH-methanol solution. Non-saponifiable lipids, which included hydrocarbons, were extracted into three 15 ml portions of n-hexane. The saponifiable fraction was discarded, and the nonsaponifiable extracts combined and set aside for purification by column chromatography.

Column chromatography was carried out to purify the total hydrocarbon extract and to separate it into two chemical fractions; saturated hydro-

carbons and unsaturated hydrocarbons. The unsaturated hydrocarbons include both olefins and aromatic compounds.

Water-Particulate HMWH

The frozen filters containing particulate hydrocarbons were thawed, placed in a 50 ml flask and extracted with 15 ml hexane on a hot plate at 50°C for at least three hours. The hexane was decanted, replaced with an equal volume of chloroform and the extraction was repeated for an additional three hours at 50°C. The extracts were combined and reduced to near dryness under a nitrogen stream. A small amount of hexane was added continuously to replace the chloroform phase. The hexane was evaporated to about 0.1 ml and transferred to a micro silica-gel-alumina column (0.4 cm x 8 cm). Another 0.4 ml portion of hexane was used to rinse the vial in which the sample was evaporated and this hexane was added to the column. Hexane was used to elute a 0.2 ml initial fraction which was discarded, following which a 2-ml hexane fraction was collected. The non-saturates were eluted with 2 ml of benzene. Hexane and benzene eluates were tightly sealed in a vial with Teflon-lined caps and further concentrated to a volume of about 25 µℓ (exact volume was measured with a 50 µℓ syringe) just prior to gas chromatographic analysis.

Water-Dissolved HMWH

Samples were extracted with chloroform in a continuous flow extractor as shown in Figure 4.1. The 38-ℓ sample was passed through the apparatus at a flow rate of about 25 ml/minute (38 ℓ in 24 hours). After the water had been extracted, chloroform from the extraction chambers was transferred through glass tubing to a flask in which the pressure had been reduced by means of a small diaphragm pump. Chloroform from the carboys was poured

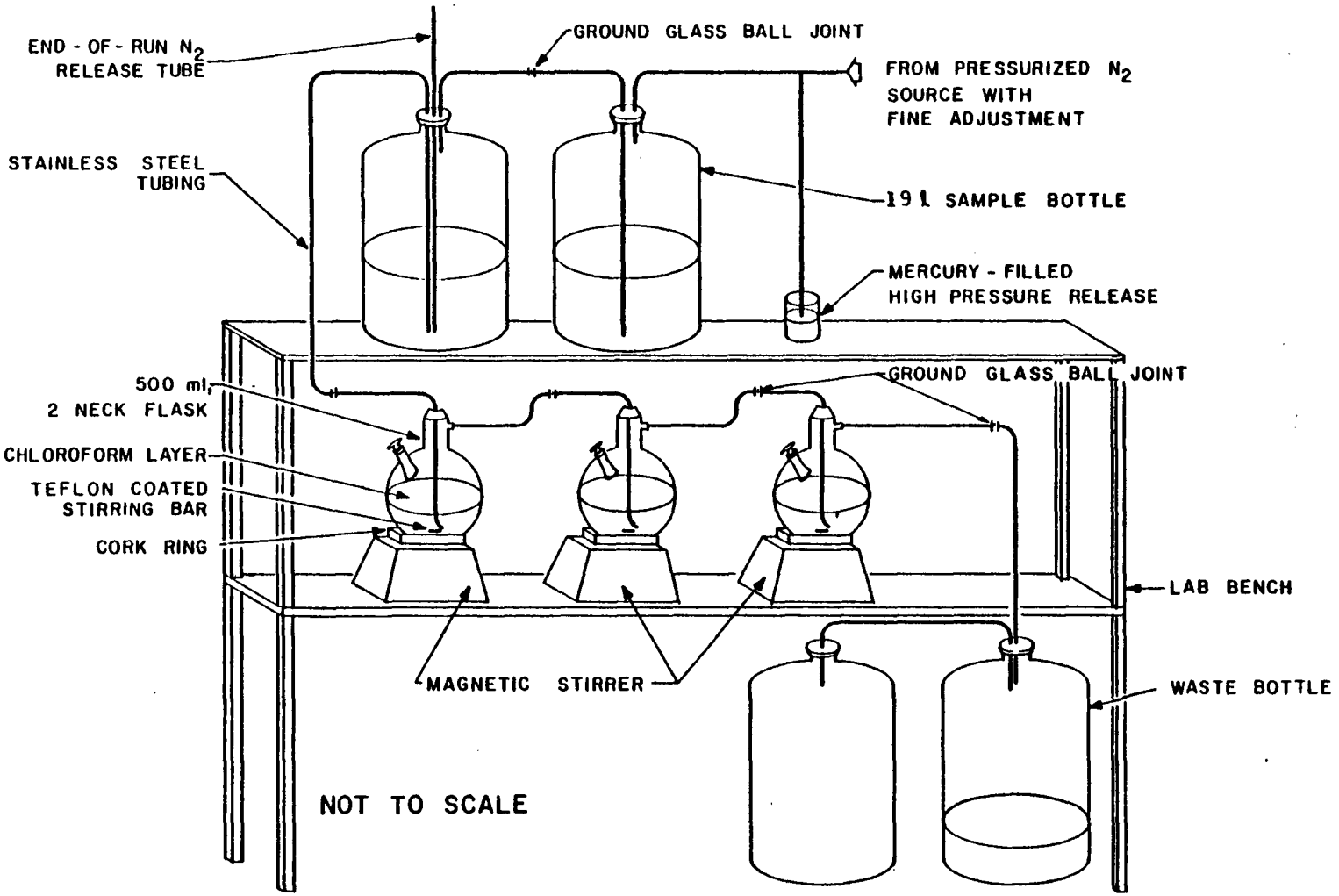

Figure 4.1 Apparatus for the Extraction of Seawater With Chloroform.

into the same flask. The sides of the extraction chambers and the collection carboys were rinsed with fresh chloroform. The chloroform extracts were then combined and reduced to a volume of 5 ml by distilling off the chloroform at reduced pressure through a Kuderna-Danish column. The sample was then further concentrated under nitrogen and transferred to a micro silica-gel-alumina column as described for the particulate hydrocarbon samples. The final hexane and benzene eluates were held for GLC and GC/MS analysis.

Sediment

The water was removed from the thawed sediment sample by freeze-drying in 1976 and 1977 and by methanol rinses in 1975. The sample was then refluxed with extraction solvent [toluene-methanol azeotrope (3:7) used in 1976-1977 and benzene in 1975], and the process repeated using fresh solvent. The sediment was filtered onto a Buchner funnel, and all extracts combined.

The combined extracts were taken to near dryness on a roto-vap and taken up in hot KOH-methanol (0.5 N) for saponification. The non-saponifiable lipids were submitted to silica-gel-alumina column chromatography. The two hydrocarbon fractions recovered from the column chromatography, saturated and non-saturated, were taken up in a small volume of hexane (0.5 to .5 ml) for GLC and GC/MS analyses.

Total Organic Carbon and Delta ^{13}C

The percent total organic carbon was measured using a high temperature combustion technique which has been used for several years in this laboratory (Hedges and Parker, 1976). From the sample, 100-200 mg of dried sediment which had been treated to remove carbonate carbon was weighed into a LECO clay combustion cup. Iron powder and CuO were added and the

sample burned in a LECO RF furnace for two minute intervals.

The evolved CO_2 was collected by freezing with nitrogen, the excess O_2 was pumped away and the CO_2 measured manometrically (Calder, 1969).

The samples for Delta ^{13}C analysis were treated according to the same procedure. In this case, it was necessary to burn a large enough sediment sample to yield 3 milliliters of CO_2 for mass-spectrometric (MS) analysis. The MS analysis was done on a 15.24 cm, 60° sector field mass spectrometer (Model 6-60-RMS-26) made by Nuclide Corp., State College, Pa.

Instrumentation

Gas Chromatographic Analyses

The primary tool for component identification and quantification used in this project was the gas chromatograph (GLC). Identification by GLC is accomplished by comparison of the relative retention times of the unknown compounds with those of selected known standard compounds. Such identification techniques are reasonably valid if the mixture is not complex and expected components are encountered.

GLC peak data consists of a listing of peak retention indices and concentrations in the sample for each of the two analyzed fractions: hexane eluate and benzene eluate from liquid column chromatography. The retention index used was normalized to the relative retention times of the n-alkanes. Thus, for example, the hydrocarbon n-hexadecane had a relative retention index equal to 1600, n-heptadecane equal to 1700, etc. Hydrocarbons having intermediate retention times between n-alkanes were assigned interpolated retention indices; for example, pristane (19 carbon atoms) had a retention index of 1670 and phytane (20 carbon atoms) a retention index of 1780 in as much as their peaks were eluted prior to elution of n-heptadecane and n-octadecane, respectively, on the columns in this study.

Gas Chromatography-Mass Spectrometer-Computer Analyses

Where complex component mixtures were to be analyzed it was necessary to augment the chromatographic technique with other organic compound identification methods. One of the more powerful methods was mass spectrometry. Gas chromatography combined with mass spectrometry (GC/MS) was applied to many of the samples also characterized by gas chromatography. A computerized data system was used to assist with data acquisition and data analysis.

Samples for GC/MS analysis were not selected randomly, but rather were selected to provide information about peaks which consistently were found prominent in many samples. The retention index and concentration data for all analyses were manipulated by a computer program to sort out those chromatographic peaks of "importance" and to flag those samples which could be used to characterize the peak by GC/MS analyses. Such lists of "important" peaks were prepared for each sample type (zooplankton, sediment, water) and each fraction type (saturated, non-saturated). Peak identifications were made from analysis of the mass spectrum of the component. Various "libraries" of mass spectral data were used to assist in interpretation of spectra (McLafferty, 1973; Stenhagen *et al.*, 1974).

The GC/MS "software" was used to search the mass spectra for mass fragment ions of "significance". By constructing a mass chromatogram for a given ion (m/e), certain compounds can be emphasized in the total chromatogram thus aiding detection of those compounds. For example, a mass chromatogram of m/e = 156 pinpoints a major peak at scan number 139 as shown in Figure 4.2A. This peak is attributed to dimethylnaphthalene added as a "spike" in the sample. The mass spectrum for this compound (Figure 4.2B) confirms the identification.

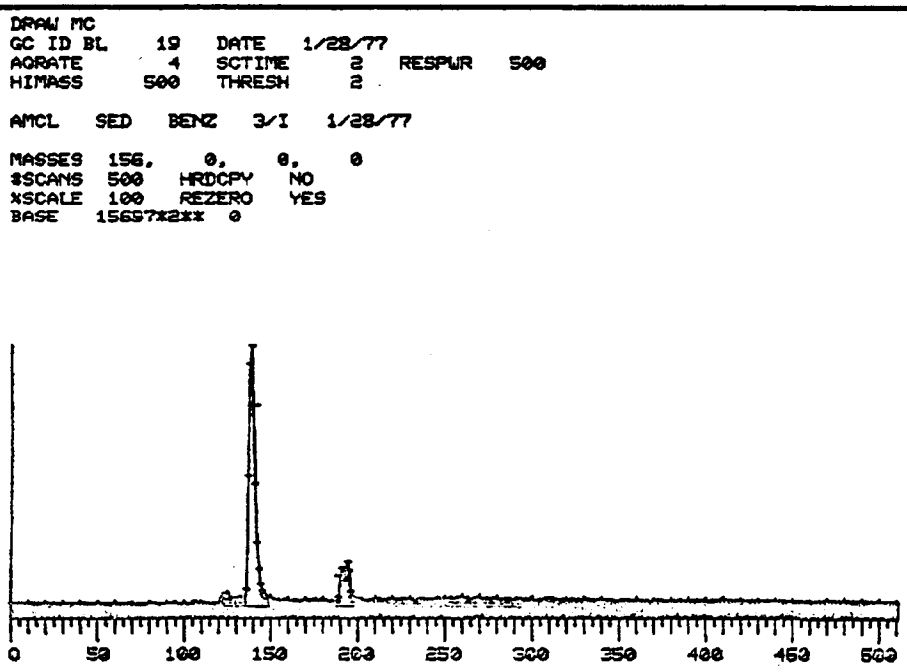

Figure 4.2A Mass Chromatogram at m/e = 156 for Sample AMCL Benzene Eluate.

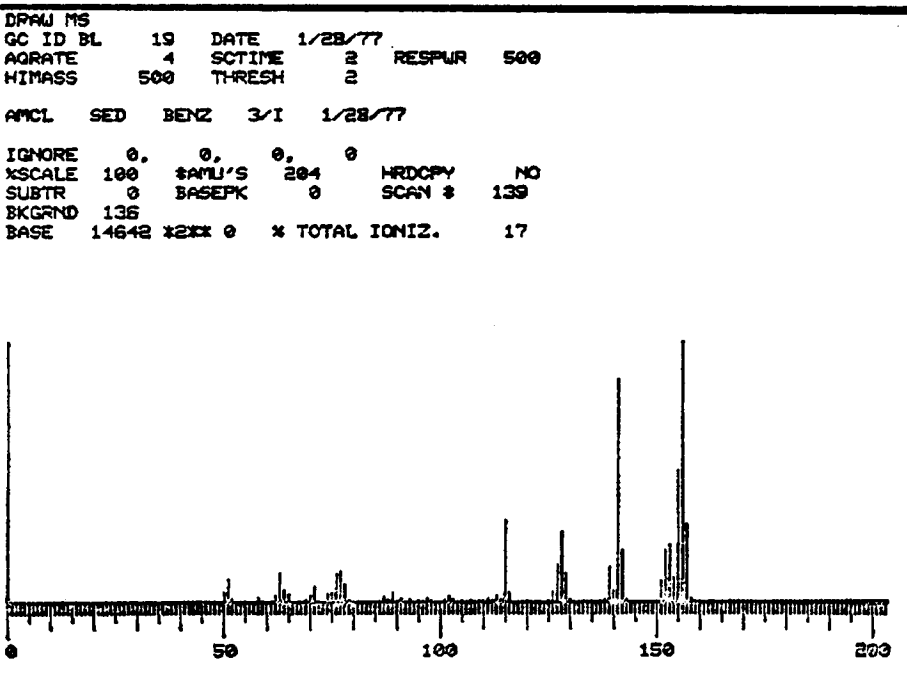

Figure 4.2B Mass Spectrum of Scan #139 for Sample AMCL Benzene Eluate.

In this manner the GC/MS can be used to identify prominent peaks and scan for selected compounds which may be important as indicators of pollution.

RESULTS AND DISCUSSION

The results of three years of data synthesis will largely focus on parameters in the data base which could provide information concerning the presence and quantity of petroleum hydrocarbons in a rather pristine offshore marine ecosystem. Petroleum components include saturated hydrocarbons with straight, branched, isoprenoid and cyclic carbon chains composed of from one to more than fifty carbon atoms and aromatic hydrocarbons containing from one to four or more rings. Experimental procedures employed in this study were able to detect saturates containing 15 to 32 carbon atoms and aromatics with 2 to 4 rings. Parameters which have been suggested (Farrington *et al.*, 1976) for the characterization of petroleum hydrocarbons in this molecular weight range include:

1) Ratios of pristane/phytane, pristane/C_{17} and phytane/C_{18}.

Pristane, a C_{19} isoprenoid hydrocarbon, has been shown to be a significant component of many types of marine samples by numerous investigators. A mechanism for the formation of pristane from the phytol group of chlorophyll has been proposed (Avigan and Blumer, 1968). Phytane, the C_{20} homolog of pristane does not appear to be a natural constituent of marine organisms with the possible exception of microorganisms (Han *et al.*, 1969). Pristane, phytane and other isoprenoid homologs do, however, occur in significant concentrations in most crude oils.

For any given sample type the ratios of pristane/phytane (Pr/Ph), pristane/C_{17} (Pr/C_{17}), and phytane/C_{18} (Ph/C_{18}) should fall within a given range. Incorporation of crude oil into the sample should shift

these ratios due to an increased phytane concentration.

2) Odd-Even Predominance (OEP) and carbon preference index (CPI).

Analyses of a wide variety of terrestrial and marine organisms indicate that organisms generally biosynthesize a rather limited suite of n-alkanes in which odd carbon number compounds are present in significantly higher concentrations than even carbon number homologs. The n-alkanes of crude oils, in contrast, cover a broad molecular weight range and the concentration of any n-alkane, n-Cx, is similar to that of homologs which differ by a single carbon atom, $n\text{-}C_{x-1}$ and $n\text{-}C_{x+1}$.

The ratio of odd to even carbon number n-alkanes have been expressed as carbon preference index (CPI) over specified carbon numbers as described by Bray and Evans (1965) and Clark and Blumer (1967).

Scalan and Smith (1970) developed an expression of odd/even ratio as a function of carbon number herein described as odd-even predominance (OEP). This technique can be used to generate a plot (OEP curve) in addition to calculation of average OEP over a specified range similar to CPI values. A set of OEP curves and average OEP values has been prepared for each sample type. The presence of a significant amount of petroleum derived n-alkanes in a sample would be expected to shift the OEP curve and average OEP value due to the increased concentration of even carbon number n-alkanes.

3) Presence of an unresolved complex mixture of hydrocarbons.

Due to the tremendous molecular diversity found in petroleum it has been impossible to separate each component by gas chromatography even on glass capillary columns hundreds of meters in length. The coelution of unresolved components causes a shift in the apparent baseline which results in a very broad "peak" in the chromatogram. The occurrence and magnitude of the unresolved complex mixture in a hexane eluate suggests

the presence and magnitude of petroleum hydrocarbons in that sample.

4) Presence of aromatic hydrocarbons.

A criterion considered important to establish the presence and quantity of petroleum hydrocarbons in STOCS samples has been detection and quantitation of aromatic hydrocarbons in the benzene eluate. Although production of aromatic hydrocarbons by plants has been reported (Hancock *et al.*, 1970) the quantity and diversity of these compounds is insignificant when compared to that of petroleum. The biosynthesis of polynuclear aromatic hydrocarbons (PAH) by microorganisms has been reported (Zobell, 1959) but questioned by recent work (Hase and Hites, 1976). Production of PAH by combustion of fossil fuels followed by transportation to the STOCS via airborne particulates or river runoff would have to be considered a potential source. Pyrolytic PAH, however, have a homolog distribution which differs considerably from that of petroleum (Youngblood and Blumer, 1975).

Unfortunately, in addition to any aromatic compounds which could be present in trace quantities in the benzene eluate most marine samples contain significant quantities of a multitude of unsaturated hydrocarbons of recent biological origin (Blumer and Thomas 1965a & b). These unsaturates which contain from one to six or more double bonds elute over a wide span of retention times and effectively make small amounts of aromatics which could be present in a gas chromatogram. Analysis by computer assisted gas chromatography-mass spectrometry was used to overcome this problem. Computer generated mass chromatograms (described in Materials and Methods, *e.g.* Figure 4.2) allowed detection of aromatic compounds even though they coeluted with much larger quantities of native biogenic compounds.

A list of the variables in the data base which were subjected to

statistical analyses for all HMWH samples has been given in Table 4.2.

Total n-alkanes (C_{14}-C_{32}) in Seawater

The change in concentration of total (dissolved + particulate) n-alkanes, C_{14}-C_{32}, with season has been shown in Figure 4.3A. The data indicate that although total n-alkane (C_{14}-C_{32}) concentration did oscillate with time it did not do so in a regular annual cycle.

Total n-alkane (C_{14}-C_{32}) averaged by station number on an annual basis have been presented in Table 4.3. Station 1 concentrations were consistently higher than Stations 2 and 3. Stations 2 and 3 were similar with a slightly higher average for Station 2 values. These higher total n-alkane (C_{14}-C_{32}) concentrations at inshore stations were largely a result of increased particulate hydrocarbon as indicated below.

Particulate Hydrocarbons, Hexane Eluate

Particulate n-alkanes (C_{14}-C_{32}) have been averaged on a seasonal basis and presented in Figure 4.3B. No clear seasonal trends were indicated. The average seasonal values (Table 4.4) suggest highest values in winter with lower values in spring and fall.

Calder (1977) also reported highest concentrations of particulate aliphatic hydrocarbons present in winter (0.49 µg/ℓ) with lower concentrations in summer (0.14) and lowest in fall (0.06) for the northeastern Gulf of Mexico (MAFLA). These concentrations were similar to STOCS values and the yearly averages were almost identical (STOCS, 0.21; MAFLA 0.23 µg/ℓ).

Concentrations of particulate n-alkanes (C_{14}-C_{32}) averaged by station number are given in Table 4.3. The data indicate a higher average

TABLE 4.2

VARIABLES USED IN STATISTICAL ANALYSES

Variable	Definition or Abbreviation	Units
1. Sum of n-alkanes, C_{14}-C_{32}	N-alkanes (C_{14}-C_{32})	µg/g (µg/ℓ)
2. Pristane/phytane	Pr/Ph	-
3. Pristane/n-C_{17}	Pr/n-C_{17}	-
4. Phytane/n-C_{18}	Ph/n-C_{18}	-
5. (Pristane + Phytane)/sum of n-alkanes		-
6. Sum of n-alkanes,C_{14} to C_{18}	SUM LOW	% of Total n-alkanes
7. Sum of n-alkanes,C_{19} to C_{24}	SUM MID	% of Total n-alkanes
8. Sum of n-alkanes,C_{25} to C_{32}	SUM HI	% of Total n-alkanes
9. Average OEP of n-alkanes, C_{14} to C_{18}	OEP LOW	-
10. Average OEP of n-alkanes, C_{19} to C_{24}	OEP MID	-
11. Average OEP of n-alkanes, C_{25} to C_{32}	OEP HI	-
12. Average OEP of n-alkanes, C_{14} to C_{32}	AV. OEP	-
13. Average OEP of n-alkanes, C_{14} to C_{20}	OEP1	-
14. Average OEP of n-alkanes, C_{20} to C_{32}	OEP2	-
15. CPI of n-alkanes, $C_{14}$to C_{20}	CPI1,(see Giam*)	-
16. CPI of n-alkanes, $C_{20}$to C_{32}	CPI2,(see Giam)	-

*For definition of CPI see Giam et al. in this report.

TABLE 4.3

N-ALKANES (C_{14}-C_{32}) IN SEAWATER AVERAGED BY STATION NUMBER (DEPTH)

Total n-alkanes (C_{14}-C_{32}), dissolved + particulate µg/ℓ

	Station 1 All Transects	Station 2 All Transects	Station 3 All Transects
1975	0.43	0.31	0.20
1976	0.34	0.25	0.21
1977	0.46	0.31	0.33
Avg.	0.41	0.29	0.25

Particulate n-alkanes (C_{14}-C_{32}), µg/ℓ

	Station 1 All Transects	Station 2 All Transects	Station 3 All Transects
1975*	0.11	0.10	0.05
1976	0.13	0.06	0.05
1977	0.35	0.11	0.12
Avg.	0.20	0.09	0.07

Dissolved n-alkanes (C_{14}-C_{32}), µg/ℓ

	Station 1 All Transects	Station 2 All Transects	Station 3 All Transects
1975*	0.16	0.11	0.15
1976	0.20	0.19	0.16
1977	0.11	0.20	0.21
Avg.	0.16	0.17	0.17

*Fall season only

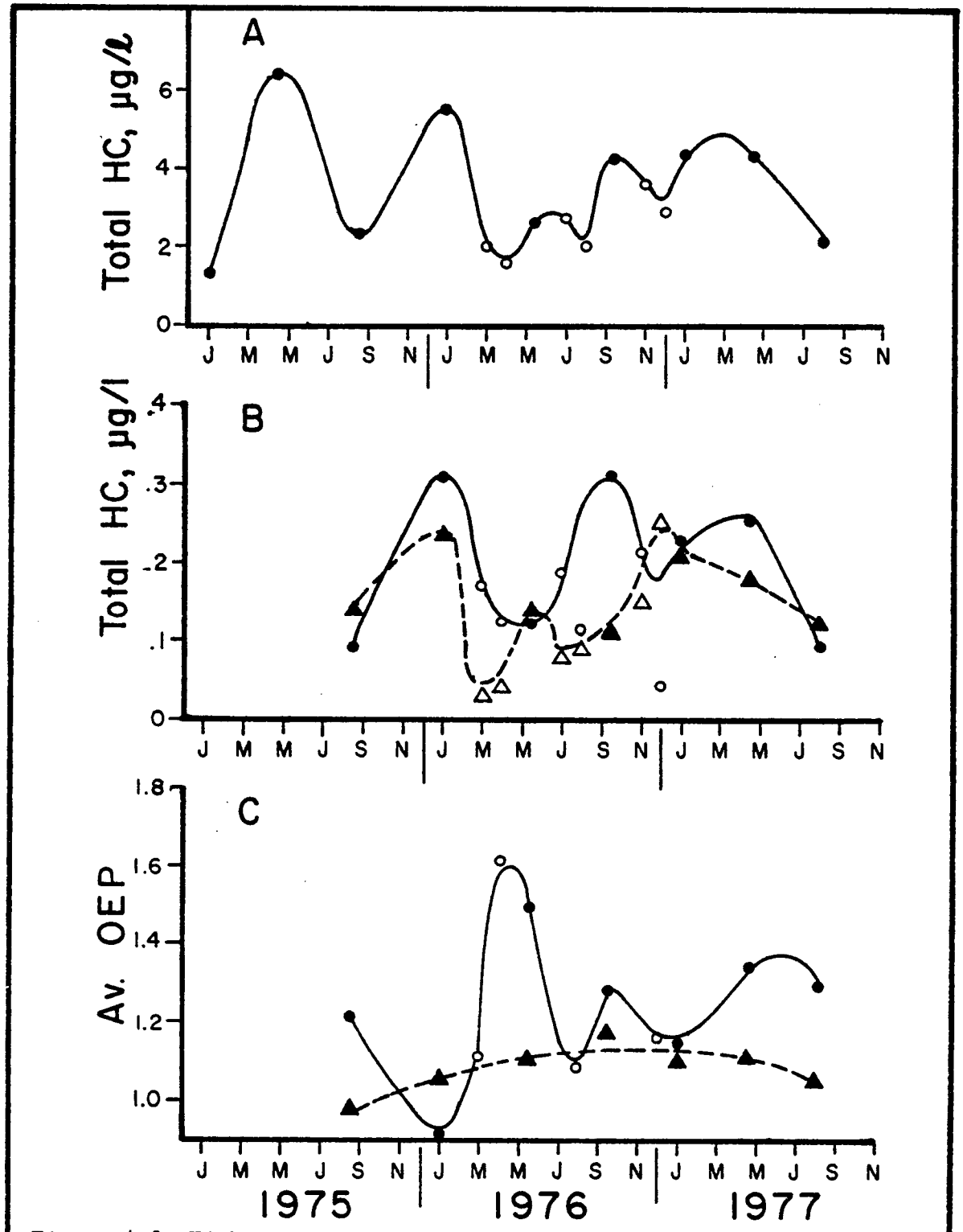

Figure 4.3 High-molecular-weight hydrocarbons in seawater: A) total n-alkanes (dissolved and particulate); B) dissolved (▲), and particulate (●), n-alkanes; C) average OEP (C_{14}-C_{32}) of dissolved (▲), and particulate (●), hydrocarbons. Solid symbols indicate seasonal samples taken from all four transects; open symbols signify monthly samples from Transect II.

TABLE 4.4

N-ALKANES (C_{14}-C_{32}) IN SEAWATER AVERAGED BY SEASON

Total n-alkanes (C_{14}-C_{32}), dissolved + particulate, µg/ℓ

	Winter	Spring	Fall
1975	0.13	0.64	0.23
1976	0.55	0.26	0.42
1977	0.43	0.43	0.21
AVG.	0.37	0.44	0.29

Particulate n-alkanes (C_{14}-C_{32}), µg/ℓ

	Winter	Spring	Fall
1975	N.A.	N.A.	0.09
1976	0.31	0.12	0.31
1977	0.22	0.25	0.09
AVG.	0.27	0.19	0.16

Dissolved n-alkanes (C_{14}-C_{32}), µg/ℓ

	Winter	Spring	Fall
1975	N.A.	N.A.	0.14
1976	0.24	0.14	0.11
1977	0.21	0.18	0.12
AVG.	0.23	0.16	0.12

N.A. - not available

concentration at Station 1 with little or no difference between Stations 2 and 3.

Higher concentrations of particulate hydrocarbons at inshore stations appear to result from terrigenous input through direct addition of particles and increased *in situ* productivity. A similar trend of increased particulate hydrocarbons at inshore stations was reported by Calder (1977) in the MAFLA area.

The average values and usual ranges of the isoprenoid parameters of HMWH samples have been given in Table 4.5. The values of these parameters for particulate, dissolved and sediment hydrocarbons were similar. Analysis of the particulate phytane/C_{18} data indicate a trend of increasing values in 1976 and 1977 (Table 4.6, $p = .001$). The increased phytane/n-C_{18} values suggest an increased contribution of petroleum hydrocarbons. No other spatial or temporal trends were noted.

Average odd-even preference (OEP_{14-32}) for all stations at each season was plotted in Figure 4.3C. The average OEP_{14-32} of particulate matter varied from 0.9 to 1.6 with some suggested regularity. High values were recorded in spring (April-May) of 1976 and 1977 with lower values in the winter of each year. Secondary maxima occurred in the fall of all three years. Higher OEP values probably resulted from increased productivity and/or terrestrial input due to runoff. Examination of spring and fall data indicated the higher OEP values were not restricted to inshore stations. Station 3 averages were equal to or greater than Station 1 values which suggests *in situ* production.

The higher OEP values for particulate hydrocarbon are, however, considerably lower than values found for zooplankton in this study. Zooplankton average OEP values for nine seasonal sampling periods ranged from 2.0 to 15.4 with an average of 5.79. The comparatively low values of OEP for

TABLE 4.5

AVERAGE VALUES AND USUAL RANGE OF ISOPRENOID HYDROCARBON VARIABLES

Sample Type		Pristane/Phytane	Pristane/n-C_{17}	Phytane/n-C_{18}
Water-particulate	avg. value	2.2	0.5	0.3
	usual range	0.5-4.0	0.3 - 2.0	0.1 - 0.6
Water-dissolved	avg. value	2.0	0.6	0.7
	usual range	0.5-4.0	0.3 - 2.0	0.2 - 1.1
Zooplankton	avg. value	388	7.0	0.3
	usual range	60-1600	1.0 - 20.0	0.1 - 10.0
Sediment	avg. value	3.1	0.6	0.3
	usual range	0.5-6.0	0.3 - 1.0	0.1 - 0.6

TABLE 4.6

SIGNIFICANT YEARLY EFFECTS FOR WATER OR ZOOPLANKTON

Study Area Variable Grand Mean	Year	Depth by Year	Transect by Year	Year by Season
		p = .001	p = .001	p = .001
Water-particulate	1975	-.42*	-.36	-.34
Ph/n-C_{18}	1976	-.27	-.28	-.35
Grand Mean: .46	1977	.37	.36	.44
		p = .001	p = .001	p = .001
Zooplankton	1975	-13.85	-14.01	-13.91
Sum Hi (C_{25}-C_{32})	1976	5.61	5.69	5.64
Grand Mean: 16.59%	1977	7.47	7.54	7.50
		p = .024	p = .008	p = .008
Zooplankton	1975	2.00	1.96	1.69
Avg. OEP (C_{14}-C_{32})	1976	2.06	2.23	2.34
Grand Mean: 5.60%	1977	-3.62	-3.73	-3.60

*Values indicate adjusted deviation from Grand Mean.

particulate hydrocarbon suggest that the majority of these hydrocarbons were not synthesized by zooplankton or higher plants. Microbial synthesis could explain the low OEP values.

Particulate n-alkanes also had a larger percentage of components in the C_{25}-C_{32} (Sum Hi) region than was found in zooplankton. Sum Hi ranged from 0.0% to 38.2% with an average value of 16.3% for zooplankton sampled during the nine seasonal periods, while particulate Sum Hi ranged from 45.8% to 89.9% with an average of 71.6%. Again microbial production could account for a large portion of the increased C_{14}-C_{32} n-alkanes observed in particulate matter. The presence of weathered crude oil residues as micro tar balls in samples would also contribute to a higher Sum Hi value.

Particulate Hydrocarbons, Benzene Eluate

Total benzene eluate concentrations has a usual range of from 0.01 to 10.0 µg/ℓ with more than 60% having a concentration less than 1.0 µg/ℓ. There was a trend of higher concentrations at inshore stations in 1976 and a higher seasonal average was observed in spring 1977, however, overall averages did not strongly support either.

Major components in all particulate benzene samples examined by gas chromatography/mass spectrometry were tentatively identified as either polyunsaturated hydrocarbons or phthalates. The most abundant compound of each class was squalene and diethylhexylphthalate, respectively. No aromatic hydrocarbons were detected.

Dissolved Hydrocarbons, Hexane Eluate

The average seasonal concentrations of dissolved n-alkanes (C_{14}-C_{32}) have been presented in Table 4.4 and plotted in Figure 4.3B. The data of Table 4.4 indicate similar seasonal averages between years with winter

values higher than spring or fall. A higher concentration of dissolved aliphatics in winter was also reported by Calder (1977). Unlike particulate hydrocarbons no trend of higher concentrations of dissolved hydrocarbons was seen at inshore stations (Table 4.3).

Ratios of Pr/Ph and Pr/C_{17} were quite similar to those of particulate hydrocarbons. The Ph/C_{18} ratio of dissolved hydrocarbons averaged higher than that of particulates apparently due to decreased C_{18} concentration.

The average OEP (14-32) of dissolved hydrocarbons was remarkably constant over the study period (Figure 4.3C). Average OEP of dissolved hydrocarbons was only slightly greater than unity which suggests microbial production as discussed for particulate hydrocarbons. The Sum Hi (C_{25}-C_{32}) average value for dissolved hydrocarbons ranged from 32.3% to 76.3% for the nine seasonal periods. The overall average of Sum Hi for dissolved hydrocarbons was 54.7% as compared to 71.6% for particulates. The higher value of Sum Hi for particulates may reflect a greater input of petroleum hydrocarbons as micro tar balls or may result from an increased adsorbtion of larger alkanes on detrital organic matter.

Dissolved Hydrocarbons, Benzene Eluate

The dissolved organics which eluted with benzene varied over a wide concentration range, from less than 0.1 µg/ℓ to more than 100 µg/ℓ. More than half of the samples, however, were less than 2 µg/ℓ. No statistically significant spatial or temporal variations were noted. The samples were characterized by a few large components which were identified by gas chromatography-mass spectrometry as biogenic olefins or phthalates. A large portion of the phthalates were probably introduced during sample handling. No aromatic compounds were detected.

Zooplankton, Hexane Eluate

The usual range of n-alkane (C_{14}-C_{32}) concentrations was 50 to 500 µg/g. N-alkanes (C_{14}-C_{32}) did not show either temporal of spatial correlations.

None of the isoprenoid parameters were shown to vary in a statistically significant manner.

In a zooplankton sample the presence of a suite of n-alkanes in the C_{25}-C_{32} range which has an OEP near unity strongly suggested the presence of petroleum pollution. The percent composition of n-alkanes in this range (Sum Hi, C_{25}-C_{32}) could give a semi-quantitative estimate of petroleum hydrocarbons present in the sample. The seasonal average of Sum Hi C_{25}-C_{32} could provide a semi-quantitative estimate of petroleum hydrocarbons present in the water column of the STOCS at that time. Seasonal averages of zooplankton Sum Hi, C_{25}-C_{32} have been plotted in Figure 4.4A.

Another parameter which appeared to be a useful semi-quantitative indicator of petroleum hydrocarbons present in zooplankton samples was average OEP. As the percent of petroleum hydrocarbons increase the average OEP (C_{14}-C_{32}) of a zooplankton sample should decrease. Seasonal averages of average OEP should also indicate the extent of petroleum pollution of the STOCS. These seasonal averages have also been plotted in Figure 4.4A. Since both parameters plotted in Figure 4.4A were estimates of the quantity of petroleum hydrocarbons they were considered as a single data set and a curve was constructed. The large standard deviation associated with both parameters result from the "patchiness" of zooplankton and petroleum hydrocarbons likely present as micro tar balls. In view of the difficulty in obtaining representative samples composed of two components each having its own unequal distribution the fit of points to the curve is rather good. The data of Figure 4.4A suggest a

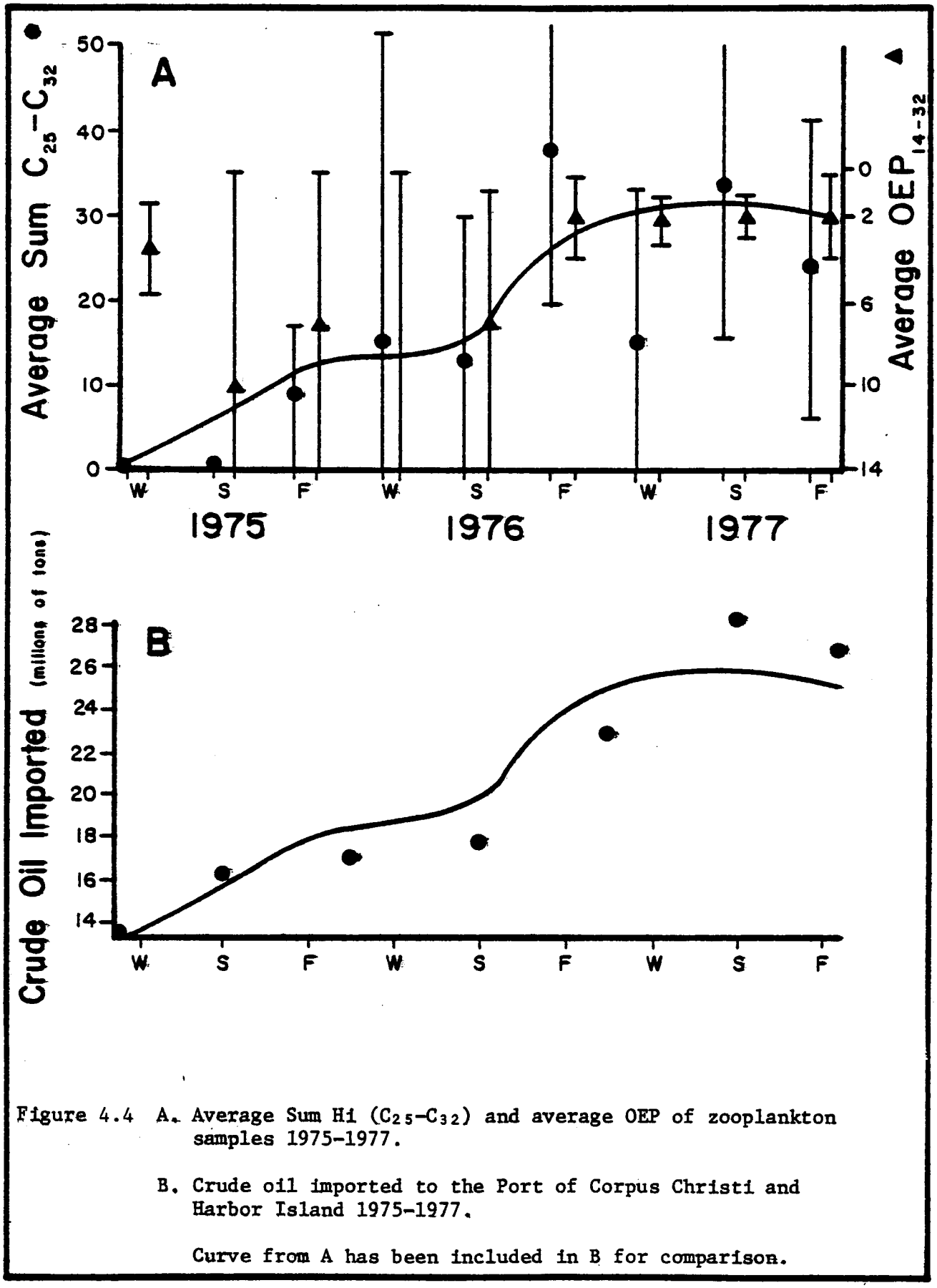

Figure 4.4 A. Average Sum Hi (C_{25}-C_{32}) and average OEP of zooplankton samples 1975-1977.

B. Crude oil imported to the Port of Corpus Christi and Harbor Island 1975-1977.

Curve from A has been included in B for comparison.

significant increase in the contribution of petroleum hydrocarbons to zooplankton samples during the three year study period.

Exploration and drilling activities in the study area probably were not a major source of petroleum residues found in the zooplankton samples. A much more likely source would be the oil tankers which delivered increased quantities of crude oil to Texas ports during the study period. The quantity of crude oil imported to the Port of Corpus Christi and Harbor Island from 1974 through 1978 has been given in Table 4.7 and plotted in Figure 4.4B. The curve generated by the data of Figure 4.4A has been included in Figure 4.4B for comparison.

Zooplankton, Benzene Eluate

Confirmation of the presence of petroleum in zooplankton required the detection of a broad suite of aromatic hydrocarbons in the benzene eluate. Aromatic hydrocarbons were positively identified or strongly suggested by mass spectral data in at least five of seven 1977 zooplankton samples suspected from n-alkane patterns to contain petroleum hydrocarbons. The low and sometimes undetectable quantities of aromatics present in suspect samples may be due to the preferential removal of aromatics during weathering. The greater solubility and volatility of aromatic compounds probably result in lower aromatics from small crude oil residues which produce micro tar balls found in zooplankton samples. Weathering processes which remove aromatics also result in increased density of the oil residues. Oil particles which approach neutral bouyancy would become suspended in the water column where they could be caught in subsurface oblique plankton tows such as was used in the STOCS study.

TABLE 4.7

CRUDE OIL IMPORTED TO THE PORT OF CORPUS CHRISTI AND HARBOR ISLAND FROM 1974 THROUGH 1978

Year	Crude Oil, Tons	2-Year Average
1974	10,343,599	
		13,279,849
1975	16,216,099	
		17,027,061
1976	17,838,023	
		23,054,449
1977	28,270,874	
		26,727,193
1978	25,183,512	

Source: Navigation district report by Perry McGee communicated by Thomasina Saladino

Sediment, Hexane Eluate

Statistical analyses provided only weak evidence for temporal and spatial variations of sediment n-alkanes (C_{14}-C_{32}). The data presented in Table 4.6 suggested sediments contained slightly higher n-alkanes (C_{14}-C_{32}) in fall, intermediate values in winter and lower values in spring. Transect III stations had highest concentrations, Transect II had mid to high values, I and IV had the lowest values.

Statistically significant seasonal effects were noted for Sum Low (C_{14}-C_{18}) in 1975 and 1976 data. These effects have been expressed as seasonal deviations from the grand mean of the variables and presented in Table 4.8. Seasonal changes in Sum Low may reflect biological activity and molecular dynamics which take place within the sediment. The high spring and fall values for Sum Low could result from increased production of these compounds in the water column or at the sediment-water interface. Microorganisms within the sediment consume the added organic matter including lower molecular weight hydrocarbons and produce their own characteristic hydrocarbon distribution which contains a larger percentage of higher carbon number alkanes. Sediment Sum Low therefore decreases as primary production of lower molecular weight hydrocarbons decrease.

Long term temporal changes in sediment were also observed for Sum Mid and Sum Hi hydrocarbons. The data presented in Table 4.8 and Figure 4.5 indicate a significant increase in Sum Hi ($P = .001$) and a concommitant decrease in Sum Mid ($P = .001$) over the three year study.

No significant change in OEP HI (C_{25}-C_{32}) was observed over the study period despite the tremendous increase in Sum Hi (C_{25}-C_{32}). OEP Mid (C_{19}-C_{24}) did however show a significant change ($P = .001$) as a result of the decrease in Sum Mid (C_{19}-C_{24}). The lack of change in OEP HI and

TABLE 4.8

SIGNIFICANT[1] EFFECTS FOR SEDIMENTS BASED ON 1975 AND 1976 DATA

Yearly Effects Variable Grand Mean	Year	Depth by Year	Transect by Year	Year by Season
Sum Mid (C_{19}-C_{24})	1975	10.84[2]	10.34	10.26
Grand Mean: 25.11%	1976	-5.05	-4.82	-4.78
Sum Hi (C_{25}-C_{32})	1975	-9.90	-9.53	-9.67
Grand Mean: 64.89%	1976	4.61	4.44	4.51
OEP Mid (C_{19}-C_{25})	1975	-.32	-.32	-.31
Grand Mean: 1.19	1976	.15	.15	.15

Seasonal Effects	Season	Depth by Season	Transect by Season	Year by Season
	Winter	-5.27	-5.20	-5.23
Sum Lo (C_{14}-C_{18})	Spring	1.91	1.83	1.82
Grand Mean: 10.01%	Fall	3.18	3.19	3.22

[1]Effects were significant at a probability of 0.001.

[2]The value of Sum Mid for 1975 was 10.84% greater than the Grand Mean value (25.11%) or 35.95%. Similar values for the three comparisons; Depth by year, Transect by year, and Season by year indicate depth, transect and season were not responsible for a significant amount of the observed yearly variation.

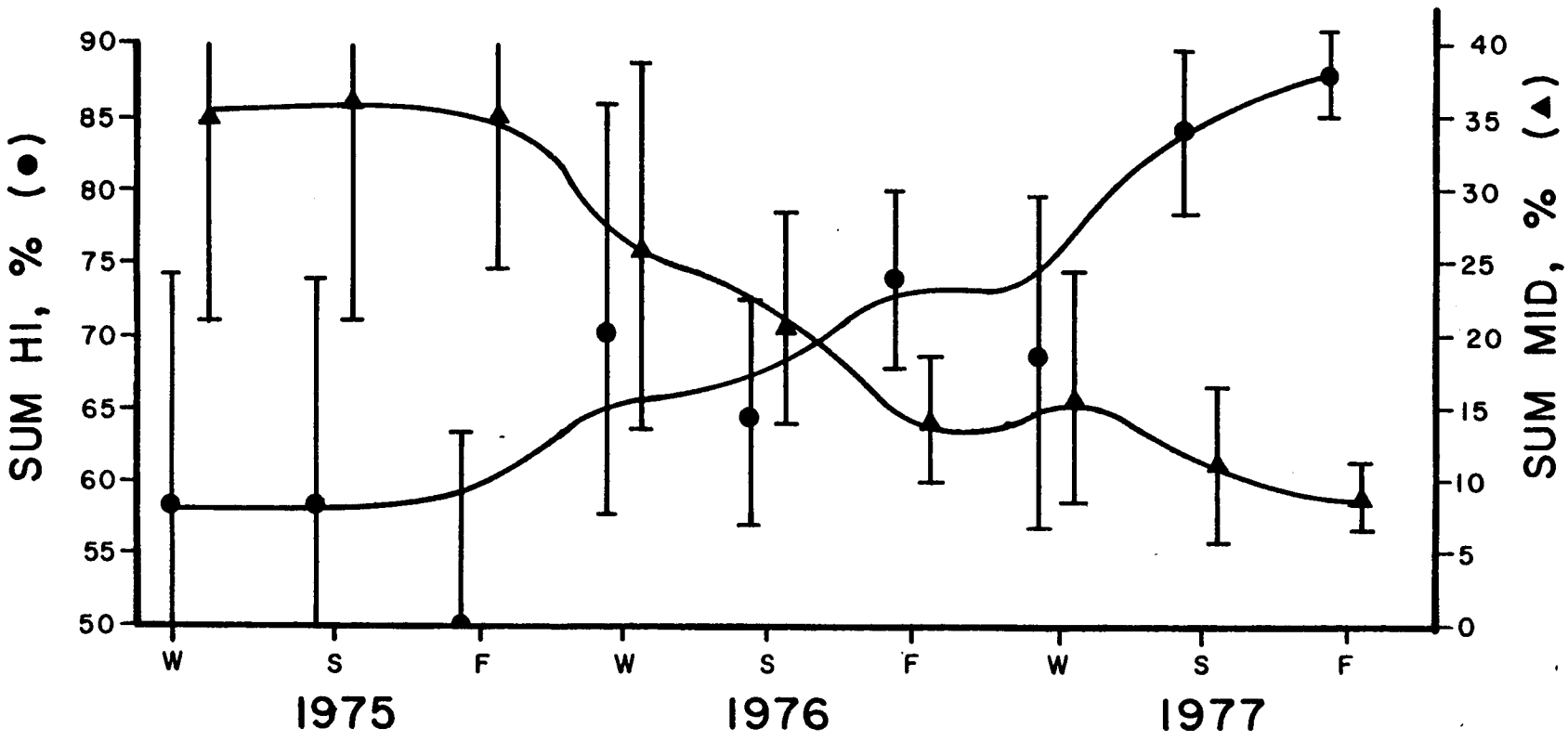

Figure 4.5 Percentage of sediment n-alkanes in the Sum Mid (C_{19}-C_{24}) and Sum Hi (C_{25}-C_{32}) ranges.

the changes which did occur in Sum Mid and OEP Mid suggest that the increase in Sum Hi during the study period was due to natural processes rather than the direct addition of petroleum hydrocarbons.

Sediment, Benzene Eluate

The lack of evidence for the presence of aromatic hydrocarbons in sediments suggested minimal petroleum pollution of STOCS sediments. Petroleum pollution in the form of micro tar balls observed in the water column (zooplankton samples) apparently did not contribute a sufficient quantity of petroleum hydrocarbons to sediments to significantly change sediment OEP Hi or permit detection of aromatics.

Delta ^{13}C and Total Organic Carbon

The results of the Delta ^{13}C and total organic carbon analyses are summarized in Table 4.9. There was a very clear trend of increasing total organic carbon with distance from shore ($P = .001$). This trend correlated with the percent clay in the samples (correlation coefficient = .76). There was also a significant change ($P = .001$) in Delta ^{13}C with more positive (^{13}C enriched) values nearer shore. Seagrasses are more ^{13}C enriched than plankton (Fry, 1977; Calder, 1969) and this trend may represent the export of seagrasses from the estuary to the shelf especially along Transects I and II. The bank stations were very uniform.

The rather uniform pattern of Delta ^{13}C and the low values of total organic carbon suggest that petroleum pollution at a fairly gross level could be detected by Delta ^{13}C shifts. If oil of Delta ^{13}C equal to -30 is added to sediment at a level to shift the total organic carbon level from 0.5 to 1.0, then the Delta ^{13}C will shift from -20 to -25. Such a total organic carbon shift could go undetectedbut such a Delta ^{13}C shift would be easily noted. Even if the oil lost its chemical identity as a

TABLE 4.9

SUMMARY OF SEDIMENT DELTA ^{13}C AND PERCENT TOTAL ORGANIC CARBON DATA

Line I	Nearshore	Mid Shelf	Offshore	Line Average
Winter	-19.92(.72)	-20.40(.88)	-20.24(1.02)	-20.18(.87)
Spring	-19.58(.47)	-20.50(1.06)	-20.46(1.04)	-20.18(.86)
Fall	-19.24(.58)	-19.68(.94)	-19.89(.56)	-19.60(.69)
Yearly	-19.58(.58)	-20.20(.96)	-20.20(.88)	-19.99(.81)
Line II				
Winter	-20.35(.70)	-20.35(.88)	-20.50(1.12)	-20.40(.90)
Spring	-20.17(.93)	-20.38(.89)	-20.36(1.13)	-20.30(.98)
Fall	-19.43(.82)	-19.65(1.02)	-20.24(1.28)	-19.77(1.04)
Yearly	-19.98(.82)	-20.12(.93)	-20.36(1.18)	-20.17(.97)
Line III				
Winter	-19.75(.94)	-19.90(1.02)	-20.10(.84)	-19.92(.94)
Spring	-19.54(.44)	-19.95(.97)	-20.32(1.12)	-19.94(.84)
Fall	-18.94(.42)	-19.98(1.01)	-19.88(1.30)	-19.60(.91)
Yearly	-19.40(.60)	-19.94(1.00)	-20.10(1.08)	-19.82(.90)
Line IV				
Winter	-19.40(.73)	-20.10(.77)	-20.30(1.10)	-19.99(.90)
Spring	-19.18(.28)	-19.75(.79)	-19.91(.79)	-19.61(.62)
Fall	-19.32(.21)	-19.99(1.75)	-20.26(.86)	-19.86(.94)
Yearly	-19.30(.50)	-19.94(.82)	-20.16(.52)	-19.82(.82)

	Bank 8	Bank 9	Bank Average
Winter	-20.35(1.01)	-20.30(.70)	-20.32(.86)
Spring	-20.26(1.04)	-20.38(1.12)	-20.32(1.08)
Fall	-20.32(1.03)	-20.19(1.22)	-20.26(1.12)
Yearly	-20.31(1.03)	-20.29(1.04)	-20.30(1.04)

	Line I	Line II	Line III	Line IV
Nearshore	4,1	1,4	4,1	4,1
Mid Shelf	2,5	2,5	5,2	5,2
Offshore	6,3	6,3	3,6	6,3,7

hydrocarbon, due to partial oxidation and incorporation into cells, the Delta ^{13}C shift would persist.

CONCLUSIONS

The STOCS area is relatively pristine with respect to petroleum hydrocarbons. Petroleum-derived aromatic hydrocarbons were found in significant quantities only in zooplankton samples. The quantity and frequency of petroleum hydrocarbons present in zooplankton samples increased during the study period. Tanker traffic appears to be the most likely source of these pollutant hydrocarbons. These results suggest future hydrocarbon studies to monitor the impact of exploration/production of petroleum within the STOCS will require differentiation between transportation and production-related pollution.

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CHAPTER FIVE

HIGH-MOLECULAR-WEIGHT HYDROCARBONS IN BENTHIC MACROEPIFAUNA AND MACRONEKTON

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ABSTRACT

Inspection and statistical analyses of the data from the analyses of 442 macroepifauna samples and 149 macronekton samples performed during the past three years yielded no indication of significant petroleum contamination of the study area. No spatial relationships were noted and there were few statistically significant seasonal changes in hydrocarbon content and distribution. Of the macroepifauna, shrimp (*Penaeus aztecus*) may be a promising species for future monitoring. The low levels of hydrocarbons normally present and the consistency of seasonal changes in hydrocarbon distribution should facilitate the detection of petroleum contamination in shrimp. Fish were found to have generally more complex and variable hydrocarbon distributions. Seasonal changes in zinc levels in *P. aztecus* and in sediment hydrocarbons occurred, but their relationship to the seasonal changes in *P. aztecus* hydrocarbons is difficult to evaluate. The utility of the data would be increased if laboratory studies on the effects of petroleum exposure on the hydrocarbons of the species studied were performed and if more uniform sampling practices were used.

INTRODUCTION

The determination of the impact of petroleum in the marine environment is an active area of investigation (American Institute of Biological Sciences, 1976, 1978; American Petroleum Institute, 1977, 1979; National Academy of Sciences, 1975; National Bureau of Standards, 1974). The majority of the studies regarding petroleum pollution have centered on the immediate and long term effects of catastrophic events such as oil spills. This emphasis is partly due to the identifiable apparent impact of large amounts of oil in an area and partly due to the relative ease of identifying and quantifying some petroleum compounds in spill situations. The effects of low level and chronic inputs of petroleum on environmental hydrocarbons have been less intensively studied and information on background levels of hydrocarbons in unpolluted environments is scarce. Although the difficulty of identifying and quantifying trace quantities of petroleum hydrocarbons has been the major deterrent to low level studies, methods are rapidly being developed for hydrocarbon trace analyses.

Among the analytical techniques which have been used for the detection of oil, gas chromatography is probably the most widely used for environmental analyses since it yields a great deal of information from a single sample (National Academy of Science, 1975). Often, the appearance of the chromatogram alone can be suggestive of petroleum as the hydrocarbon composition of organisms is generally simple relative to that of petroleum (Ehrhardt and Blumer, 1972). However, a number of problems arise when characteristic petroleum patterns are not evident. In fact, one of the major problems associated with quantifying trace levels of petroleum in the environment is differentiating petrolic compounds from biogenic hydrocarbons. This differentiation is complicated by the effects of weathering or

environmental degradation on the hydrocarbon composition of petroleums. Unlike the case of an oil spill, where a single source of petroleum generally provides a very characteristic hydrocarbon pattern, trace levels of petroleum may be from a number of sources, such as petroleum production, shipping and waste disposal, which further complicates hydrocarbon patterns and thus detection and quantitation.

The use of a number of parameters has been suggested to aid the analyst in distinguishing sources of hydrocarbons in environmental samples. One of these is the measurement of ratios of concentrations of individual hydrocarbons, such as the ratios of n-heptadecane (C_{17})/pristane and of pristane/phytane (Ehrhardt and Blumer, 1972). These ratios have been suggested as aids in the detection of a single source of petroleum contamination as they are generally characteristic of an oil. Microbial degradation, which generally occurs most rapidly with n-alkanes, can affect these ratios (Ehrhardt and Blumer, 1972) as can biogenic hydrocarbons. Farrington and Medeiros (1975) have shown that the heptadecane/pristane, octadecane/phytane, pristane/phytane and heptadecane/octadecane ratios of a fuel oil added to clam tissues were different from those of the oil due to interference from hydrocarbons present in the tissues. Variations from oil sample ratios were noted in the ratios calculated from water samples in the vicinity of an oil platform, indicating that interference from biogenic hydrocarbons was also present in these samples (Middleditch and Basile, 1978).

Petroleum hydrocarbons generally have fairly uniform distributions of n-alkanes within homologous series, while biogenic hydrocarbons tend to have a predominance of odd-chain hydrocarbons. Several methods have been proposed to measure the presence or absence of odd-carbon dominance as a means of detecting petroleum hydrocarbons. One of these, the Carbon Preference

Index (CPI) (Cooper and Bray, 1963) can be used to calculate the odd-carbon dominance of hydrocarbons from tetradecane to eicosane (C_{14}-C_{20}) and from eicosane to dotriacontane (C_{20}-C_{32})(Clark and Finley, 1973). Using this method, petroleums have values close to one in both ranges, while hydrocarbons of biogenic origins tend to produce high values in the lower range (Giam and Chan, 1979). Biogenic hydrocarboms tend to have values close to one in the higher range, making the C_{20}-C_{32} CPI ratio of little value in determining petroleum contamination in organisms. Another measure of odd-carbon dominance is the Odd-Even Preference (OEP) ratio (Scalan and Smith, 1970). This ratio is greater than one if odd-carbon n-alkanes predominate and will approximate one if no odd-carbon dominance is present, as is usually the case with petroleums. It can be used for homologous series of five or more carbons. The CPI and OEP ratios may be altered by high concentrations of biogenic hydrocarbons. Sediment samples with other indicators of petroleum contamination were found to have high CPI's, probably due to the presence of plant hydrocarbons (Bieri *et al.*, 1978) and OEP ratios were not found to be good indicators of petroleum contamination in organisms from an oil field (Middleditch and Basile, 1978).

An unresolved complex mixture (UCM) appears in the gas chromatogram of most petroleums as a hump below the resolved peaks. Its presence has been proposed as a means of initial screening of samples for petroleum contamination (Farrington *et al.*, 1973). However, the sensitivity of this technique is variable as the size of the UCM is a function of the resolution of the column, being smaller with higher resolution (National Academy of Sciences, 1975).

The presence of phytane has also been suggested as an indicator of petroleum contamination (Farrington *et al.*, 1972). Phytane appears to arise

from geochemical sources (Blumer and Snyder, 1965) and thus should not be present in uncontaminated samples.

Clark and Finley (1973, 1974) have outlined a series of steps for establishing levels of petroleum contamination in organisms. In addition to the initial interpretation of the gas chromatogram and the calculation of ratios, they suggest that chromatograms of unexposed organisms be subtracted from those of organisms suspected of petroleum contamination. If petroleum is present in the sample, the residual pattern should resemble that of petroleum.

Another problem in determining trace levels of petroleum in organisms is the relative lack of knowledge of the fate of hydrocarbons in animals. Organisms adsorb, metabolize and excrete hydrocarbons at different rates. This, along with the fact that relatively little is known about the natural distribution of hydrocarbons in marine biota, often makes it very difficult to determine whether an observed n-alkane pattern is biogenic or is partly due to petroleum exposure. A number of studies have been conducted on the fate of petroleum hydrocarbons in marine organisms and they further underscore the complexity of the problem. Some species, including crabs (Lee *et al.*, 1976), fish and shrimp (Neff *et al.*, 1976) adsorb and release petroleum hydrocarbon relatively rapidly while others, including eels (Ogata *et al.*, 1977), mussels (Lee *et al.*, 1972), oysters and clams (Neff *et al.*, 1976) adsorb and release these compounds more slowly. Due to their slow release of petroleum hydrocarbons, bivalves, particularly mussels, have been proposed as indicator organisms for detecting petroleum contamination (DiSalvo *et al.*, 1975). However, even analyses of bivalves can be complicated by intra- and inter-species differences. For example, lipid levels in oysters have been shown to affect the long term accumulation of

hydrocarbons by oysters (Stegeman and Teal, 1973). Boehm and Quinn (1977) have shown that the duration of exposure to petroleum affects the rate of depuration in clams.

Selective retention of hydrocarbons has been demonstrated in a number of fish species. Salmon fry exposed to C_{12} to C_{30} n-alkanes from oil showed this distribution in gills during the first 10 hours of exposure. During the remaining 86 hours of exposure, only C_{15}-C_{19} alkanes were found in gills; these compounds were also the only ones found at any time in viscera and muscle (Rice *et al.*, 1977). Flounder exposed to 100 ppb fuel oil for 75 days had 1.6 µg/g of hydrocarbons in the liver, but n-alkanes were mainly of chain lengths greater than 19 carbons, while the oil was composed mainly of n-alkanes of fewer carbons (Kühnhold *et al.*, 1978). Codfish similarly accumulated C_{24}-C_{28} hydrocarbons in liver on exposure to a crude oil with an abundance of lower hydrocarbons (Hardy *et al.*, 1974). Thus, research on the uptake, metabolism and retention of hydrocarbons by the species to be monitored is needed before monitoring results can be of maximum utility (Clark, 1974).

The form or physical state of petroleum in the environment may affect its availability to organisms. Neff *et al* (1976) have shown that molluscs exposed to dispersions of oil accumulate higher quantities of n-alkanes than when exposed to water soluble fractions of oil, probably due to the ingestion of oil droplets in the former case. Petroleum hydrocarbons appear to be readily adsorbed from water (Neff *et al.*, 1976; Lee *et al.*, 1976; DiSalvo *et al.*, 1975; Anderson *et al.*, 1974; Stegeman and Teal, 1973) and from food (Lee *et al.*, 1976). Uptake from sediment appears to be quite variable and dependent on the concentration of oil and the species being studied. Flatfish exposed to highly contaminated sediments (700 µg/g

decreasing to 400 µg/g during the study) showed a high initial uptake of petroleum hydrocarbons, followed by rapid depuration during the exposure period (McCain *et al.*, 1978). Clams exposed to highly contaminated sediments (887 µg/g decreasing to 420 µg/g) showed concentrations of hydrocarbons less than sediments. Concentration factors from water, however, were calculated at 10 to 1349 (Roesijadi *et al.*, 1978). Concentrations of hydrocarbons in clams collected from various areas did not correlate with those in sediment; the clams were found to have 8.5 to 11 µg/g of hydrocarbons in sediments that ranged from 9 to 228 µg/g (Gilfillan *et al.*, 1977). Benthic organisms collected from unpolluted deep sea areas had hydrocarbon distributions quite different from those hydrocarbon concentrations found in sediment (Teal, 1976). These reports indicate that the effect of sediment-adsorbed hydrocarbons on the hydrocarbons of benthic epifauna is quite difficult to predict. It is probable that hydrocarbons in water, including those from sediment desorption in interstitial water, have a greater effect on the hydrocarbon content of benthic organisms than those adsorbed directly from sediment. Uptake from food is also probably a more important source of hydrocarbons than sediment.

Information on mechanisms of hydrocarbon transport in the marine environment, such as food chain transfer and uptake from water and sediment is important for assessing the probable effects of petroleum hydrocarbons. However, few studies of hydrocarbon distributions and transport, particularly in benthic organisms and the benthic environment, have been reported. Although laboratory studies are useful in determining many aspects of these mechanisms, environmental monitoring is necessary to assess the effects of many parameters, for example, seasonal fluctiation in biogenic hydrocarbon patterns and movements of organisms within an

environment. Because of the uncertainties involved in determining whether observed hydrocarbon patterns in environmental samples are due to biogenic or to petroleum hydrocarbons, obtaining baseline data on hydrocarbon concentrations and distribution from unpolluted areas is an important aspect of environmental monitoring. During the past three years, we have performed heavy molecular weight hydrocarbon analyses of 442 macrobenthic and 149 macronekton samples from the STOCS as part of a study to characterize this area prior to oil and gas exploration and production. The purpose of this report is to assess seasonal and temporal variations of hydrocarbons in the organisms studied, to determine the effects of petroleum derived hydrocarbons on the observed hydrocarbon patterns and to integrate the findings from these studies with those of related studies, particularly those of hydrocarbons in other media and of trace metals.

METHODS

Sampling

Macroepifauna were obtained from each of the three stations on the four transects shown in Figure 5.1 three times per year. The sampling periods corresponded to winter (January-February), spring (May-June) and fall (September-October). During the 1975 sampling periods, four samples were taken at each station. During the remaining two years, three samples were collected at each for heavy-molecular-weight hydrocarbon analyses. Each sample consisted of a sufficient number of individuals, usually five, to provide approximately 100 g of tissue for analysis. Attempts were made to obtain representatives of each of three phyla, *i.e.* molluscs, crustaceans and fish, at each station, but this was not always possible; fish were collected most often. A total of 377 samples were obtained from seasonal sampling over the three years of the study. An additional 65

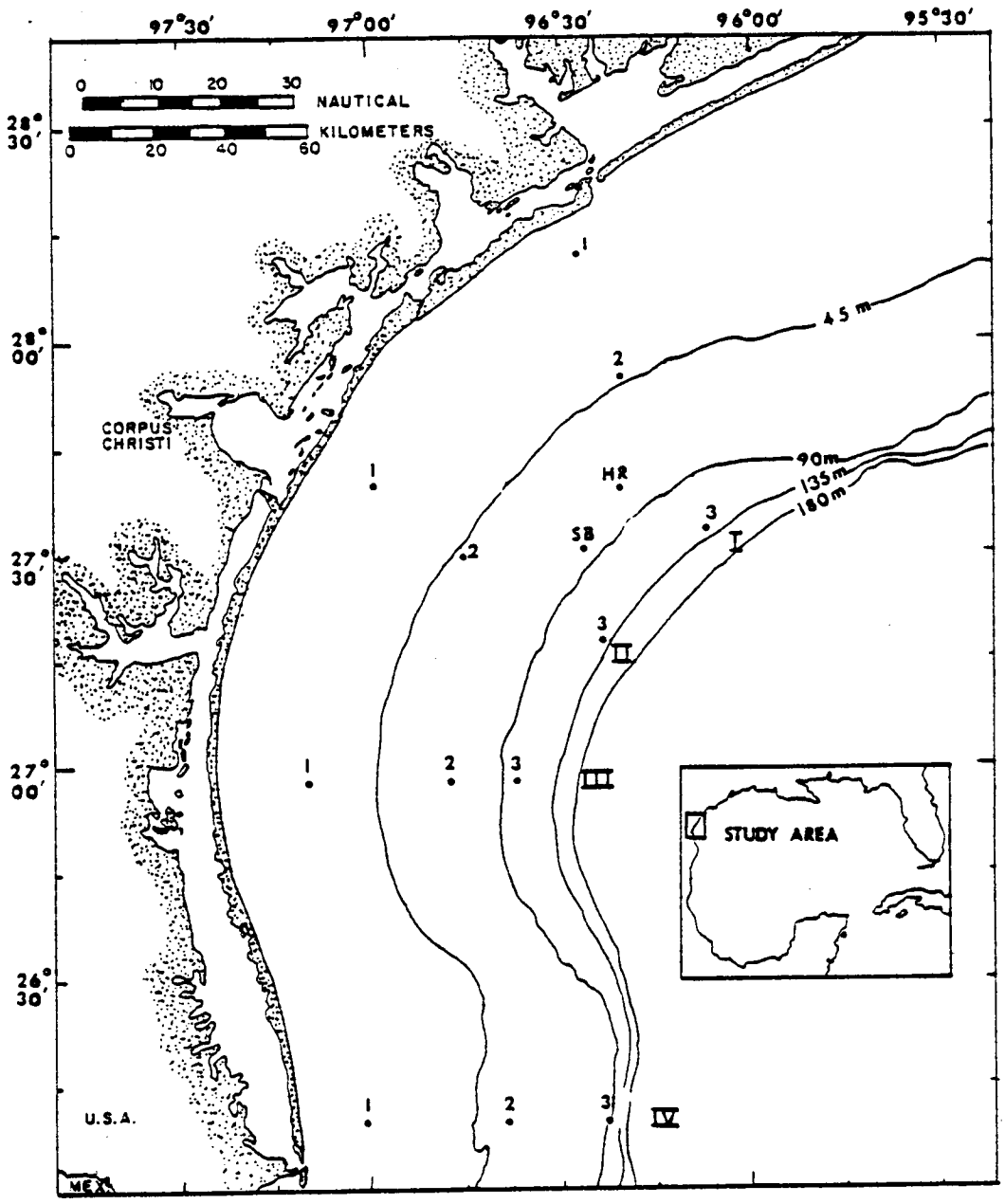

Figure 5.1 Location of Sampling Sites for Macroepifauna and Macronekton.

samples were obtained opportunistically for replicate and large sample analyses.

Macronekton were obtained at the two fishing stations, Hospital Rock and Southern Bank, shown in Figure 5.1. They were collected both seasonally and monthly in 1976 and 1977. A total of 149 samples were obtained for analyses. The seasonal samples consisted of five individuals which were pooled for analysis, while the monthly samples usually contained only one individual per sample. The samples were mainly red and vermilion snappers and were dissected into muscle, liver and gill (1976) or gonad (1977) for analysis.

Analytical Techniques

During the three years of this study, the basic techniques of extraction, saponification, column chromatography and gas chromatography (GC) were used to isolate and quantitate the hydrocarbons present in the samples (Giam and Chan, 1976, 1977a,b, 1979). Alkanes and arenes were identified by comparison of retention times with authentic standards and by GC-mass spectrometry on at least 10% of the samples. A number of modifications in technique were introduced, but these changes did not alter the quantitation of hydrocarbons which was performed by comparison of GC peak areas from the samples and from external standards by programmable integrators. For example, the initial use of Soxhlet extraction of the sample followed by saponification was replaced by digestion of the tissues in methanolic potassium hydroxide (Farrington and Medeiros, 1975). This combined extraction-saponification procedure reduced sample work-up time without altering recovery. Also, the gas chromatographic columns were changed from packed columns of 1% SE30 or 5% FFAP during the first two years of the study to SCOT capillary columns of SE-30 or OV-101 dur-

ing the final year. This change produced an increased resolution of peaks which aided identification and quantitation, but did not affect the level of aliphatic hydrocarbons detected in the samples.

Procedure blanks were performed frequently and averaged less than 5% of the hydrocarbons measured in the samples. The limit of detection for aliphatic hydrocarbons was 0.001 µg/g, while for aromatic hydrocarbons, it was 0.005 µg/g. Recovery studies were performed by subjecting known amounts of hydrocarbons to all steps in the analytical procedure. As shown in Table 5.1, recoveries varied for individual hydrocarbons. For aliphatic hydrocarbons, the recoveries averaged 80 ± 13% which is in good agreement with other workers (Farrington *et al.*, 1973). The recovery of aromatics averaged 74 ± 22%.

Data Presentation

The samples were analyzed by gas chromatography and the percent distribution of n-alkanes from tetradecane (C_{14}) to dotriacontane (C_{32}) was calculated from peak areas by electronic integration. The concentrations of n-alkanes, pristane, phytane and of total alkanes were also calculated from the chromatograms. The pristane/heptadecane, phytane/octadecane and pristane/phytane ratios were calculated from the concentrations.

Carbon preference indices (CPI's) were calculated according to the following formula (Clark and Finley, 1973; Cooper and Bray, 1963; Bray and Evans, 1961):

$$CPI_{14-20} = 1/2 \left[\frac{\sum_{n=15}^{n=19} \text{HC odd}}{\sum_{n=16}^{n=20} \text{HC even}} + \frac{\sum_{n=15}^{n=19} \text{HC odd}}{\sum_{n=14}^{n=18} \text{HC even}} \right]$$

TABLE 5.1

PROCEDURAL RECOVERY OF ALIPHATICS AND AROMATICS

Compound	Mean Recovery (%)[1] (± 1 Standard Deviation)
n-Pentadecane (C_{15})	78±17
n-Hexadecane (C_{16})	84±12
n-Heptadecane (C_{17})	79±11
Pristane (Pr)	80±11
1-Octadecane ($C_{18:1}$)	69±16
n-Octadecane (C_{18})	79±10
Phytane (Py)	80±12
n-Nonadecane (C_{19})	78±11
1-Eicosene ($C_{20:1}$)	72±13
n-Eicosane (C_{20})	82±11
n-Uncosane (C_{21})	80±11
n-Docosane (C_{22})	81±10
n-Hexacosane (C_{26})	79±20
n-Octacosane (C_{28})	80±13
n-Triacontane (C_{30})	80±17
n-Dotriacontane (C_{32})	92± 7
Naphthalene	51±39
1-Methylnaphthalene	64±33
1,3-Dimethylnaphthalene	80±27
Biphenyl	78±21
Acenaphthene	85±18
Fluorene	81±22
9,10-Dihydrophenanthrene	91±12
Phenanthrene	84±18
3,6-Dimethylphenanthrene	70±13
Pyrene	47±24
Nonadecylbenzene	79±17

[1]Recovery of hydrocarbons subjected to all steps in the analytical procedure in the absence of biota; 20 analyses were performed.

$$CPI_{20-32} = 1/2 \left[\frac{\sum_{n=21}^{n=31} \text{HC odd}}{\sum_{n=22}^{n=32} \text{HC even}} + \frac{\sum_{n=21}^{n=31} \text{HC odd}}{\sum_{n=20}^{n=30} \text{HC even}} \right]$$

Where Σ HC is the sum of n-alkane concentrations. Odd-even preference (OEP) ratios were also calculated for the ranges C_{14}-C_{20}, C_{20}-C_{32}, C_{14}-C_{18}, C_{19}-C_{24} and C_{25}-C_{32} according to the method of Scalan and Smith (1970), *i.e.*:

$$OEP = \left[\frac{C_i + 6C_{i+2} + C_{i+4}}{4C_{i+1} + 4C_{i+3}} \right]^{(-1)^{i+1}}$$

Where C_i = weight percent of hydrocarbon of i length. An OEP value was calculated only if the concentrations C_i through C_{i+4} were all nonzero.

Data Analysis

Due to the vast amount of data from this study and the difficulty of assessing trends over so many species, the six most frequently occurring macroepifauna species (Table 5.2) were selected for further data analysis. The data from the two major macronekton species, *Lutjanus campechanus* and *Rhomboplites aurorubens* was also subjected to data analysis. The data analyses involved calculations of distribution statistics for the variables listed in Table 5.3.

Statistical analyses for linear and higher order correlations between all pairs of these variables within species were also calculated, as were linear correlations for each variable between pairs of species. In addition, temporal and spatial interactions with the parameters listed in Table 5.3 were evaluated for each species.

TABLE 5.2

MACROEPIFAUNA SPECIES USED FOR
HEAVY MOLECULAR WEIGHT HYDROCARBON CORRELATIONS

Loligo pealei (squid)

Penaeus aztecus (brown shrimp)

Pristipomoides aquilonaris (wenchman)

Serranus atrobranchus (blackeared sea bass)

Stenotomus caprinus (longspine porgy)

Trachurus lathami (rough scad)

TABLE 5.3

VARIABLES SUBJECTED TO STATISTICAL ANALYSIS

1. Total hydrocarbons (μg/g)
2. Pristane/phytane
3. Pristane/n-heptadecane (C_{17})
4. Phytane/n-octadecane (C_{18})
5. (Pristane + phytane)/sum of n-alkanes
6. Sum of low n-alkanes (n-C_{14} to n-C_{18}) (relative percent)
7. Sum of mid n-alkanes (n-C_{19} to n-C_{24}) (relative percent)
8. Sum of high n-alkanes (n-C_{25} to n-C_{32}) (relative percent)
9. OEP low (n-C_{14} to n-C_{18})
10. OEP mid (n-C_{19} to n-C_{24})
11. OEP high (n-C_{25} to n-C_{32})
12. Average OEP (n-C_{14} to n-C_{32})
13. OEP 1 (n-C_{14} to n-C_{20})
14. OEP 2 (n-C_{20} to n-C_{32})
15. CPI 1 (n-C_{14} to n-C_{20})
16. CPI 2 (n-C_{20} to n-C_{32})

For the analysis of temporal and spatial relationships, three sets of variables were considered. These were season (winter, spring, fall), transect (I through IV) and station (1 through 3). Data cases were scattered over the possible collection sites and times and parameters were frequently not calculable (*e.g.* pristane/phytane or phytane/octadecane were not calculated if phytane was not detected). Thus, all analyses involved unbalanced data and standard analysis of variance was not useful. Instead, multiple linear regression analysis was used to assess the effect of one factor while other factors were covaried (Kerlinger and Pedhazur, 1973; Rao, 1965; Searle, 1971). All regression analyses were calculated using the "Regression Option" of subprogram "ANOVA" from the Statistical Package for the Social Sciences (Nie *et al.*, 1975). There were insufficient data to allow 3-way analyses incorporating season, transect and station. Instead three separate 2-way analyses were performed (*i.e.* season and transect, season and station, and station and transect).

RESULTS

Macroepifauna

Some 400 samples of benthic macroepifauna representing 48 species were analyzed for heavy hydrocarbons. The means and standard deviations of selected parameters from the analyses of the six most frequently occurring species are given in Table 5.4. Overall, total hydrocarbon concentrations ranged from less than 0.01 µg/g (ppm) to 54.47 µg/g dry weight with the majority of samples containing less than 1 µg/g. Pentadecane (C_{15}) and heptadecane (C_{17}) were the dominant n-alkanes, frequently constituting 70% or more of the alkanes. Pristane was found in almost all samples at relatively high levels. Phytane was found in approximately 20% of the samples, generally at less than 0.05 µg/g. The pristane/phytane, pristane/heptadecane and

TABLE 5.4

MEANS AND STANDARD DEVIATIONS FOR SELECTED PARAMETERS FROM HEAVY MOLECULAR WEIGHT HYDROCARBON ANALYSES OF MACROEPIFAUNA

Species (Number Analyzed)	Total Alkanes (µg/g)	Sum of Alkanes (%)			Pristane / Phytane	Pristane / C_{17}	Phytane / C_{18}	CPI_{14-20}	CPI_{20-32}
		C_{14}-C_{18}	C_{19}-C_{24}	C_{25}-C_{32}					
Loligo pealei (45)	1.89±3.32 (45)	60.9±34.0 (42)	16.5±18.6 (42)	22.7±28.5 (42)	166.5±172.9 (2)	9.3±13.4 (34)	2.7±3.2 (2)	18.6±10.4 (23)	3.7±4.2 (27)
Penaeus aztecus (48)	0.14±0.28 (48)	39.7±7.2 (34)	9.1±12.7 (34)	51.1±39.1 (34)	44.0±58.0 (2)	2.0±1.7 (17)	0.2±0.1 (2)	1.6±0.6 (5)	6.8±10.1 (22)
Pristipomoides aquilonaris (38)	2.98±4.28 (38)	82.7±26.3 (38)	7.1±10.3 (38)	10.2±3.2 (38)	46.7±20.5 (5)	2.6±2.4 (34)	0.6±0.1 (5)	16.0±7.2 (28)	6.7±18.3 (18)
Serranus atrobranchus (27)	0.19±0.20 (27)	69.4±32.7 (21)	9.7±11.8 (21)	20.9±28.8 (21)	13.0±5.6 (2)	3.6±6.0 (18)	1.0±0.7 (2)	6.2±3.5 (8)	1.4±0.8 (8)
Stenotomus caprinus (27)	1.02±1.83 (27)	55.2±31.4 (26)	13.3±18.1 (26)	31.5±26.3 (26)	32.8±25.3 (6)	5.9±3.9 (25)	0.9±0.2 (5)	5.6±3.3 (16)	10.1±21.8 (17)
Trachurus lathami (25)	8.58±12.00 (25)	69.0±36.3 (25)	13.5±17.7 (25)	17.5±23.7 (25)	132.0±65.9 (10)	33.4±37.0 (18)	2.1±0.8 (10)	19.3±6.9 (15)	6.2±8.6 (17)

phytane/octadecane ratios had a wide range of values and did not appear to be indicative of a common source of petroleum in the study area. The CPI_{14-20} and CPI_{20-32} ratios also were not indicative of petroleum contamination. Squalene was frequently the only compound detected in the aromatic fraction. Aromatic compounds were rarely detected and were usually at 0.005 µg/g or lower concentrations. The distribution of aromatics was not suggestive of petroleum origins. Unresolved complex mixture (UCM) humps were also rarely detected and were very low when present. The distribution of phytane in the samples appeared to yield a spatial trend. Phytane was found most frequently at Stations 1 and 2, Transects III and IV (7-8 samples each); Stations 1 and 2, Transects I and II also had a higher frequency of phytane occurrence (3-5 samples each), than Stations 3 (0-3 samples each), all Transects. (See Figure 5.1).

The bivariate analyses of the interaction of the parameters did not yield any significant or consistent interrelationships except between OEP and CPI ratios for the same range of hydrocarbons. These parameters are both measures of odd-even preference and correlated well in most cases, as shown in Table 5.5. For *P. aquilonaris*, the OEP for the range C_{25}-C_{32} had an R^2 of 0.70 ($p=0.01$) when compared to CPI_2.

Of the 288 possible two-way analyses (3 analyses x 16 variables x 6 species), only 159 had sufficient data for calculation. Of these, only 16 produced significant ($p < 0.05$) results. When these significant two-way analyses (*i.e.* variable for a species by station or transect or season) were inspected further, it was found that only four variables were significant when subjected to both two-way analyses possible for the seasonal or temporal effect being considered. (Yearly effects were not calculable.) The other variations, although statistically significant, are not meaningful

TABLE 5.5

CORRELATIONS OF OEP AND CPI RATIONS
IN MACROEPIFAUNA

Species	Coefficient of Determination (R^2)[a]	
	$\frac{OEP_1}{CPI_1}$[b]	$\frac{OEP_2}{CPI_2}$
Loligo pealei (Squid)	0.80 (0.00)[c]	0.77 (0.00)
Penaeus aztecus (Brown shrimp)	I.D[d]	0.95 (0.00)
Pristipomoides aquilonaris (Wenchman)	0.44 (0.01)	0.39 (0.21)
Serranus atrobranchus (Blackeared sea bass)	0.78 (0.22)	0.92 (0.05)
Stenotomus caprinus (Longspine porgy)	0.64 (0.03)	0.96 (0.00)
Trachurus lathami (Rough scad)	0.71 (0.02)	0.89 (0.00)

[a]The coefficient of determination is the correlation coefficient (R) squared and is a measure of the variance in one variable accounted for by another.

[b]Subscript 1 is for the range C_{14} to C_{20}; subscript 2 is for C_{20} to C_{32}.

[c]Numbers in parentheses are p values or level of significance.

[d]I.D. = Insufficient data for calculation.

as they did not allow the differentiation of true seasonal or spatial effects from seasonal effects confounded with station or transect effects or from station and transect effects confounded with season. When the data from these non-definitive results were inspected, it was found that the species involved generally had highly variable hydrocarbon patterns or sampling frequencies.

Of the four meaningful significant effects found (see Table 5.6) the three correlations found for the shrimp appear to be the best indicators of seasonal changes in hydrocarbon distribution. As can be seen in Figure 5.2, the hydrocarbon distribution changed with season, causing significant changes in the low and high sums of hydrocarbons ($p=0.02$) and the CPI_2 ($p=0.01$). In the case of *Trachurus*, the variation in the sum of the C_{25}-C_{32} relative percent concentrations is due mainly to a tendency for the C_{25}, C_{27} and C_{31} hydrocarbons to occur with greater frequency in winter than in the fall and spring samples. The hydrocarbon distributions found for *Trachurus* varied widely within seasons, so that seasonal patterns were not as clearly defined as they were for shrimp.

Macronekton

Of the approximately 140 macronekton analyses performed, 120 were for two species, the red and vermilion snappers (*Lutjanus campechanus* and *Rhomboplites aurorubens*). Approximately 20 samples were obtained for each species over the two years of this study. Each sample yielded three analyses, as muscle, liver and gill (1976) or gonad (1977) tissues were analyzed separately. The ranges and means of total hydrocarbon concentrations found for the macronekton are summarized in Table 5.7. The means of several of the parameters measured in muscle and liver are shown in Table 5.8. The alkanes, n-pentadecane (C_{15}) and n-heptadecane (C_{17}), and pristane were the

TABLE 5.6

MEANINGFUL SIGNIFICANT MAIN EFFECTS

		Adjusted Deviation from Grand Mean		
		Season by Transect Analysis		Season by Station Analysis
Species:	Season		Grand Mean	
Trachurus lathami				
Parameter: $\Sigma C_{25}-C_{32}$	Winter	22.22	17.46 %	20.68
	Spring	-13.38		-12.01
	Fall	-10.54		-10.80
Species:				
Penaeus aztecus				
Parameter: $\Sigma C_{14}-C_{18}$	Winter	-1.41	37.88 %	-0.36
	Spring	-29.28		-28.02
	Fall	31.78		30.13
Parameter: $\Sigma C_{25}-C_{32}$	Winter	-0.34	52.71 %	-1.00
	Spring	24.14		21.78
	Fall	-25.76		-23.05
Parameter: CPI_{20-32}	Winter	-5.99	6.84	-4.98
	Spring	-2.99		-3.12
	Fall	11.37		11.35

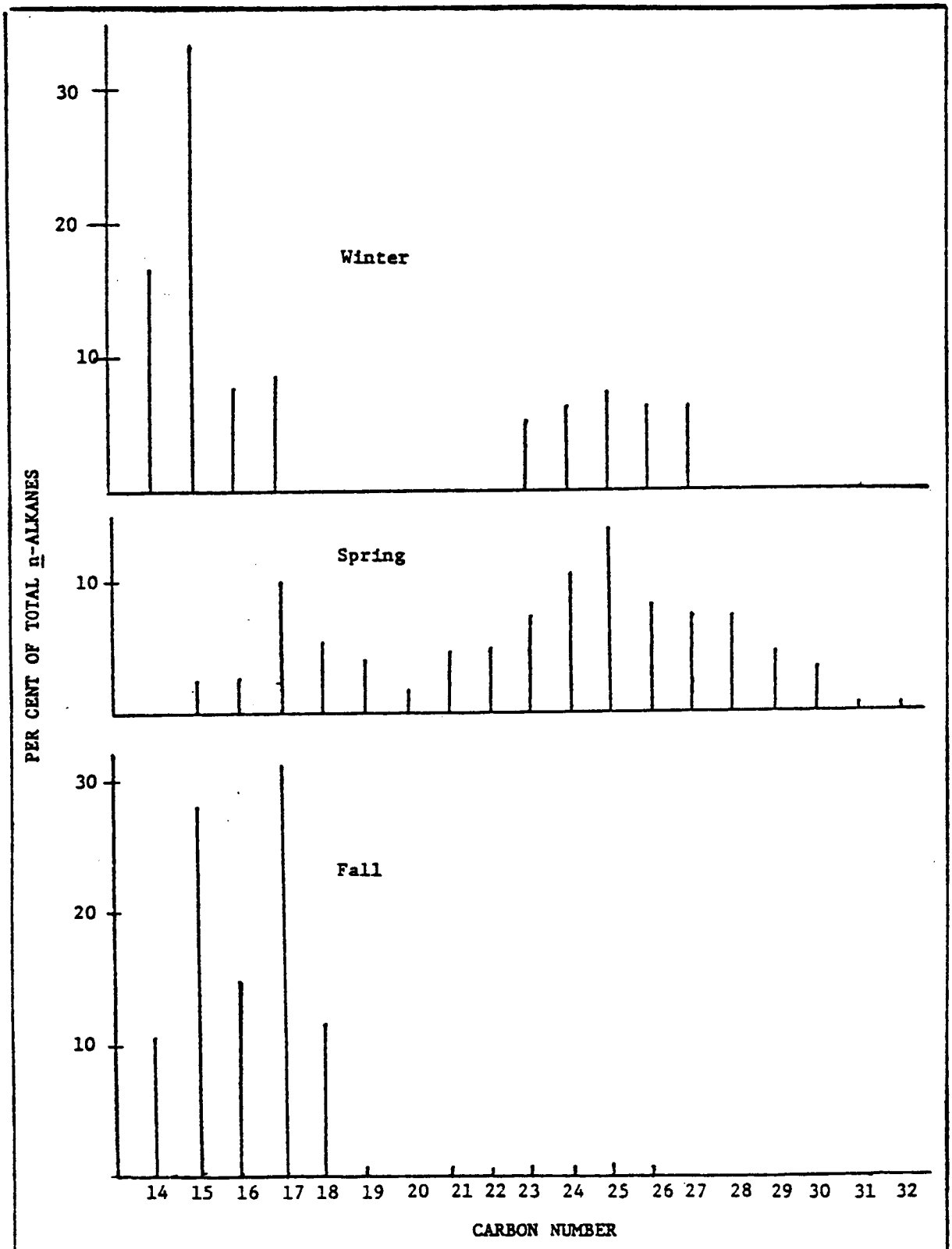

Figure 5.2 Percent Distribution of n-Alkanes in *Penaeus aztecus* (shrimp) Samples.

TABLE 5.7

RANGES OF TOTAL HYDROCARBON CONCENTRATIONS
FOR MACRONEKTON

Species	Concentration (µg/g, dry weight)			
	Muscle	Liver	Gill	Gonad
Red Snapper (*Lutjanus campechanus*)				
Range	0.03-7.4	1.1-43.8	0.1-20.0	1.7-55.1
Mean ± 1 S.D.	0.7±1.6	8.7±9.6	4.7±6.1	36.8±31.8
Vermilion snapper (*Rhomboplites aurorubens*)				
Range	0.02-4.3	0.6-35.8	0.0-30.6	2.3-25.3
Mean ± 1 S.D.	1.4±1.3	13.6±9.8	7.0±9.4	6.8±7.2

TABLE 5.8

MEANS AND STANDARD DEVIATIONS FOR SELECTED PARAMETERS FROM HEAVY MOLECULAR WEIGHT HYDROCARBON ANALYSES OF MACRONEKTON

	Species and Organ			
	Lutjanus campechanus		*Rhomboplites aurorubens*	
	Muscle	Liver	Muscle	Liver
ΣC_{14-18}	87.9±25.6	83.4±19.5	91.2±12.5	80.3±22.9
ΣC_{19-24}	4.5±10.2	6.6±7.8	5.0±8.3	8.6±11.4
ΣC_{25-32}	7.6±19.6	10.0±15.1	3.8±8.9	11.0±13.2
$\frac{\text{Pristane}}{\text{Phytane}}$	13.5±4.8	30.0±24.1	87.7±38.5	81.4±59.1
$\frac{\text{Pristane}}{C_{17}}$	1.9±1.5	2.5±1.5	16.3±29.0	10.7±9.9
$\frac{\text{Phytane}}{C_{18}}$	0.6±0.2	0.9±0.9	1.3±0.8	0.7±0.5
CPI_{14-20}	16.7±9.7	12.7±10.5	22.6±14.3	25.4±35.7
CPI_{20-32}	1.0±0.1	2.0±2.2	1.5±0.4	2.9±4.1

major aliphatic hydrocarbons in all samples. In red snapper muscle, the C_{15} plus the C_{17} n-alkanes totaled 23 to 100% of the n-alkanes; the total was less than 75% in only 3 of the 20 samples. One of these samples had the C_{27} n-alkane as the major n-alkane while the other two had a wide range of hydrocarbons. In vermilion snapper muscle, C_{15} plus C_{17} ranged from 42 to 100% of the n-alkanes. The C_{19} or C_{23} alkanes had relatively high concentrations in the two samples with the lowest C_{15} plus C_{17} concentrations. A wider range of hydrocarbons, as well as higher concentrations of the C_{18}-C_{30} n-alkanes, appeared to be present in the spring samples relative to the fall and winter samples, but the differences were not statistically significant at the $p=0.05$ level. The liver, gill and gonad samples also had pentadecane, heptadecane and pristane as the major hydrocarbons with non-significant seasonal changes similar to those found in muscle. Phytane was found in 10% of the muscle samples, in more than 50% of the liver samples and in all of the gonad samples, generally at low concentrations. Small, generally unquantifiable, unresolved complex mixture humps were detected in many of the chromatograms. Aromatic compounds were rarely detected and, when found, were generally at the limits of detection (0.005 μg/g).

Computer calculated distribution statistics for the 16 parameters measured for the two species were calculated, as were bivariate correlational analyses between the parameters for each tissue-species combination. The distribution statistics showed wide variations about the mean and skewed distributions. The correlations found for some of the parameters are listed in Table 5.9.

Two-way analyses of the macronekton data were performed using month, year, and topographic bank as the independent variables. No spatial effects were noted in these analyses. Of the meaningful significant main effects

TABLE 5.9

CORRELATIONS IN MACRONEKTON PARAMETERS

	Coefficient of Determination[a]			
	Lutjanus campechanus		Rhomboplites aurorubens	
Parameter	Muscle	Liver	Muscle	Liver
$\frac{\Sigma \text{ low}}{\Sigma \text{ mid}}$[b]	0.56 (0.02)[c]	0.60 (0.01)	0.61 (0.00)	0.89 (0.00)
$\frac{\Sigma \text{ low}}{\Sigma \text{ high}}$	1.00 (0.00)	0.91 (0.00)	0.67 (0.00)	0.90 (0.00)
$\frac{OEP_1}{CPI_1}$	0.83 (0.08)	0.93 (0.00)	0.96 (0.00)	0.98 (0.00)
$\frac{OEP_2}{CPI_2}$	I.D.[d]	0.41 (0.46)	I.D.	0.98 (0.00)

[a]The coefficient of determination is the correlation coefficient (R) squared.

[b]Low indicates C_{14} to C_{18}, mid is C_{19} to C_{24} and high is C_{25} to C_{32}; subscript 1 is for C_{14} to C_{20}, subscript 2 is for C_{20-32}.

[c]Numbers in parentheses are p values.

[d]I.D. means insufficient data for calculation.

found, the variation in the pristane/C_{17} ratio with time in *R. aurorubens* liver was the only one which yielded a seasonal trend (See Table 5.10). The other meaningful significant main effects were decreases between 1976 and 1977 for the Σ mid, OEP low, OEP average, OEP_1, and CPI_1 for *L. campechanus* liver.

DISCUSSION

Analytical Techniques

The analytical techniques used in this study provided adequate sensitivity for detecting and quantifying the low levels of hydrocarbons present in the benthic organisms analyzed. Throughout the study period, excellent blanks were routinely obtained and no evidence of contamination from ship board activities were noted indicating that the precautions taken to avoid contamination were effective (Giam *et al.*, 1976, 1975; Giam and Wong, 1972). Recovery studies, calibration curves for quantitation and retention times for identification were obtained from certified external standards, which provided consistency in results over the three-year period. GC/MS was also used on 10% of the samples to confirm the identification of hydrocarbons. The analyses of larger samples did not provide additional information, indicating that the methods used were sufficiently sensitive and that the sample size (*ca* 100g) was adequate (Giam and Chan, 1979).

Macroepifauna

An overview of the data obtained in this study indicated several trends in the data. The dominant hydrocarbons were pristane, pentadecane and heptadecane (Giam *et al.*, 1976). These hydrocarbons probably reflect dietary sources as pristane is the major hydrocarbon in zooplankton (Blumer *et al.*, 1964) and pentadecane and heptadecane are the major hydrocarbons in unpolluted algae (Clark and Blumer, 1967). The overall concentration of hydro-

TABLE 5.10

MEANINGFUL SIGNIFICANT MAIN EFFECT

Rhomboplites aurorubens Pristane/$\underline{n}$-C_{17} Ratio in Liver

	Adjusted Deviation from Grand Mean Grand Mean: 10.67	
Month	Year by Month Analysis	Transect by Month Analysis
Winter	-3.27	.94
March	-4.91	-6.02
April	25.70	23.67
Spring	9.99	10.35
July	-5.13	-4.47
August	-5.47	-7.04
Fall	-2.30	- .75
November	-8.12	-10.15
December	-8.46	-10.49

carbons in the samples was generally quite low (less than 1 µg/g dry weight in many samples) and the hydrocarbon distributions found were not suggestive of petroleum. The CPI ratios showed the high odd-carbon dominance characteristic of biogenic hydrocarbons (Clark, 1974; Clark and Finley, 1973; Cooper and Bay, 1963) although shrimp (*Penaeus aztecus*) tended to have CPI_{14-20} values close to 1. The pristane/phytane, pristane/heptadecane and phytane/octadecane ratios did not yield any trends indicative of petroleum contamination. These ratios and odd-even preferences have not been found to be useful in assessing low levels of petroleum contamination in organisms due to interference from biogenic hydrocarbons (Middleditch and Basile, 1978; Farrington and Medeiros, 1975), although they may be useful in detecting high levels of petroleum contamination (Whittle *et al.*, 1978; Ehrhardt, 1972). Phytane was the only potential indicator of petroleum (Farrington *et al.*, 1972; Blumer and Snyder, 1965) found with any frequency in the samples. It was found most often in samples from Stations 1 and 2 (Figure 5.1). This may indicate some petroleum contamination from onshore or shipping activities or may reflect species variation and mobility, as the species collected at Stations 1 and 2 were generally different from those at Stations 3. No conclusions can be drawn in the absence of other indicators of petroleum.

Several investigators have suggested that the presence of an unresolved complex mixture (UCM) is a good indicator of petroleum contamination in organisms (Rossi *et al.*, 1979; Milan and Whelan, 1978; Farrington *et al.*, 1973). When detected in this study, the UCM's were generally too small for quantitation. Aromatic compounds were detected infrequently by GC/MS at levels too low for quantitation (< 5 ng/g). The compounds detected most frequently were acenaphthene, 3,3'-dimethylbiphenyl, 9,10-dihydrophenanthrene, and pyrene. The distribution of aromatics, when present, was not suggestive

of petroleum sources. Thus, petroleum contamination of the benthic organisms of the study area was not significant during the study period and the data obtained should provide an excellent data bank for future studies of petroleum pollution. The data synthesis efforts have concentrated on maximizing the utility of the data for characterization purposes.

The wide variance about the means of the parameters due to distributions determined in the data analyses were not unexpected due to natural variation in organisms, the relatively small number of samples available and the fact that the samples involved specimens of varying sex and maturity. Of the many bivariate relationships investigated between the parameters from this study, only the OEP and CPI ratios for a given hydrocarbon range showed relatively consistent correlations. As they are both measures of odd-even preference, such correlations might be expected. The species which showed the poorest correlation in both ranges was *Pristipomoides aquilonaris* (the wenchman). The difference in the ratios may be due to significant levels of hydrocarbons in the C_{18} to C_{22} range which would affect the OEP ratios more than the CPI ratios.

The two-way analyses for seasonal and spatial effects on the parameters gave disappointingly few significant results. This is probably due to the scattered nature of the data cases over time and space, *i.e.* not all samples were obtained at all stations or at all seasons. The significant findings for *Trachurus lathami* are not particularly useful as the hydrocarbon distribution for that species is relatively random. The increase in the sum of the C_{25}-C_{32} relative percent concentration in winter relative to spring and fall is usually due to an increase in one or more of the odd-chain n-alkanes in that region rather than to an overall change in hydrocarbon patterns as in the shrimp.

The significant results for shrimp (*Penaeus aztecus*) are indicative of a change in hydrocarbon distribution that occurs in shrimp in spring, possibly due to spawning activities or to dietary effects (Figure 5.2). The hydrocarbon distribution during fall and winter is relatively simple, with the highest concentrations of hydrocarbons occurring from the C_{14} through the C_{19} n-alkanes and an occasional sample containing the C_{21} to C_{27} hydrocarbons. In the spring samples, the hydrocarbons are broadly distributed from C_{14} to C_{32}. The hydrocarbon levels in shrimp were also lower in winter and fall (0.04 and 0.06 µg/g, respectively) than in spring (0.33 µg/g), although the differences were not significantly different at the p=0.05 level.

From the results of this study, the shrimp appears to be an excellent organism for monitoring of the presence of petroleum hydrocarbons. It does demonstrate significant changes in hydrocarbon distribution with season, but these changes are relatively consistent and quantifiable. The low levels of hydrocarbons present in shrimp may also simplify the detection of pollutant hydrocarbons. A post-drilling sample obtained in winter had 0.6 µg/g total hydrocarbons (Giam and Chan, 1977b) compared to 0.4 µg/g found for the winter samples in this study. This sample also had very low CPI's (CPI_{14-20}=1.1, CPI_{20-32}=0.06) and a distribution of hydrocarbons suggestive of petroleum, especially when compared to the patterns found for shrimp in this study, as shown in Figure 5.3. Shrimp from an oil producing area of the Gulf had higher hydrocarbon levels (0.53 to 2.45 µg/g) than found in this study, although the author did not find evidence for petroleum contamination in several of the samples (Middleditch and Basile, 1978). Seasonal patterns also were not distinct in that study, probably because of the small number of samples, obtained only in August and October, or

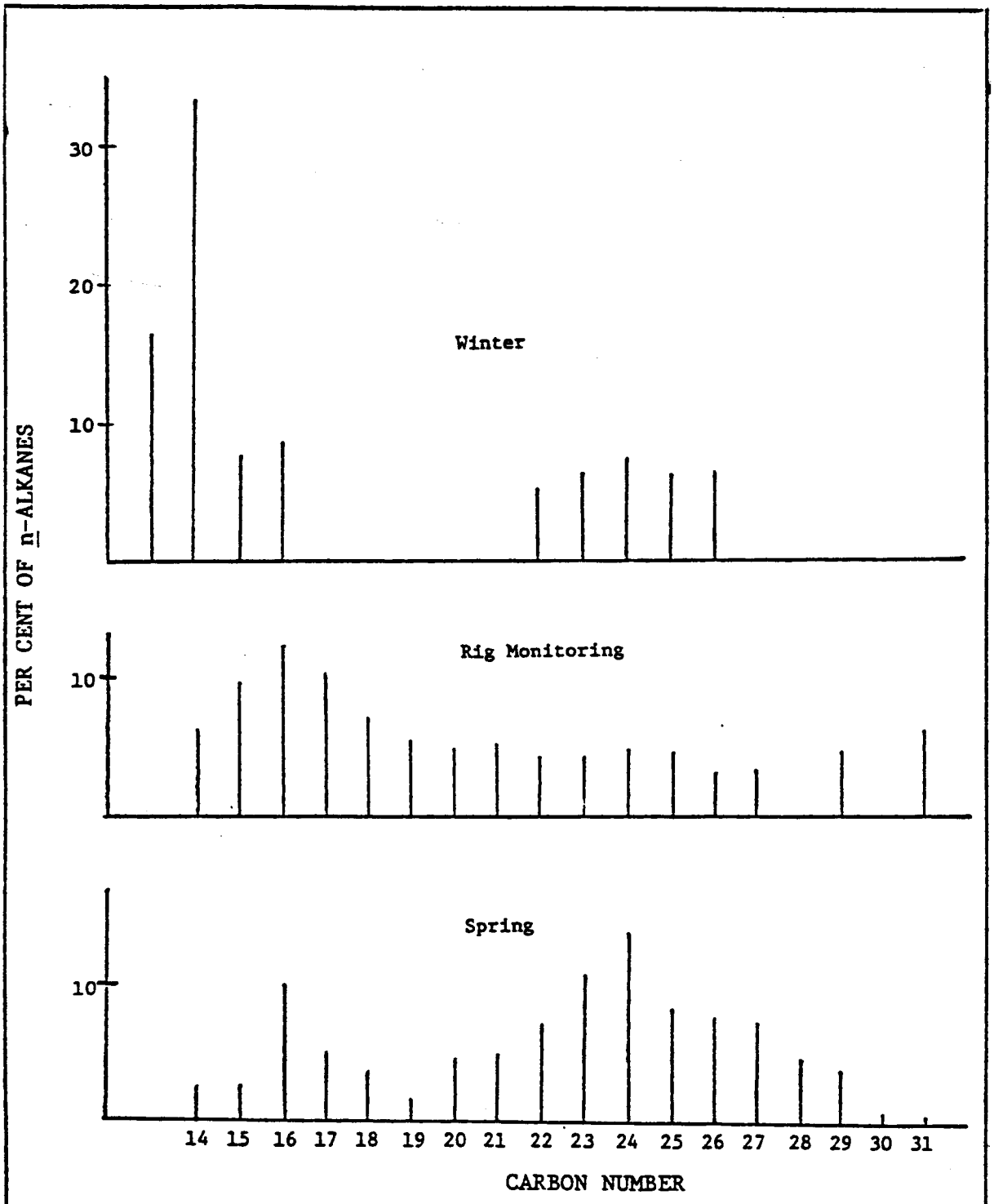

Figure 5.3 Comparison of Rig Monitoring and Seasonal Hydrocarbon Distribution in *Penaeus aztecus* (Shrimp).

possibly because of masking by petroleum hydrocarbons. The good baseline data obtained for shrimp in this study should reduce ambiguities and aid interpretation of petroleum effects in future studies (Clark and Finley, 1973).

Macronekton

As in the case of macroepifauna, the parameters examined did not indicate the presence of significant levels of petroleum pollution in the study area. Phytane and unresolved complex mixtures were found in a number of samples but other indicators of petroleum, such as hydrocarbon distributions with no odd-even preference and aromatics, were absent. Also, the detection of phytane mainly in the lipid pools of the liver and gonads probably reflects uptake and storage from very low water concentrations rather than active uptake from petroleum contamination. This probability is reinforced by the absence of phytane in gill samples. The pristane/phytane, pristane/heptadecane, phytane/octadecane and CPI_{14-20} ratios were quite variable and not indicative of petroleum contamination of the samples.

Seasonal trends in hydrocarbon content and distribution appeared to be present upon inspection of the macronekton data, but the only meaningful significant main effect noted in the two-way analyses of the data for seasonal effects was the pristane/C_{17} ratio in *R. aurorubens* liver. This ratio was highest in spring and lowest in November and December and may reflect dietary changes or spawning activities. The absence of other meaningful significant main effects due to seasonal or monthly changes may be partially due to the small number of samples and the scatter in the data. Also, the use of single specimens for the monthly samples appeared to produce wider fluctuations in the data than were present in pooled seasonal samples. Differences in hydrocarbon content due to the sex and size of

fish have been noted in another study (Milan and Whelan, 1978). In the samples obtained for this study, wide variations were noted in the sexes and sizes of the specimens analyzed which contributed to the wide variations noted in the analysis of individual samples. In pooled samples, the ratios of male, female and juvenile individuals also appeared to have an effect on the hydrocarbon content of the sample, but sufficient samples were not available to quantify this effect.

The meaning of the significant annual differences in some of the parameters for *L. campechanus* liver analyses is difficult to assess in the absence of data from other years. As the changes noted indicate a decrease in the odd-even preference indices, the changes could be due to petroleum input; highly variable biological processes or sample composition may also be responsible.

Comparison with Other Study Areas

The data from the two studies most directly related to this study, trace metals in benthic macroepifauna and heavy molecular weight hydrocarbons in zooplankton, water and sediment, were inspected for possible correlations. One correlation was the absence of significant spatial effects in all three studies.

In the trace metal studies, significant seasonal trends were found for several metals in *Trachurus lathami* and for zinc in *Penaeus aztecus*. As these were the two species for which significant seasonal changes in hydrocarbon distribution were detected, the data suggests more pronounced cyclical changes in these species than in the other species studied. Whether these changes are purely physiological or are environmentally dependent is not clear from the data.

The results of the heavy molecular weight hydrocarbon studies indicated that no significant seasonal variations in concentration or distribution were present in water or zooplankton samples. The distribution of hydrocarbons in sediment samples, however, varied significantly with season as shown by changes in the sum of low and mid range hydrocarbons and in the OEP and CPI ratios. The changes in the relative distribution of hydrocarbons in sediment and shrimp did not have similar patterns, but the CPI_2 ratios for both types of samples were highest in the fall samples and lowest in winter samples. The seasonal patterns of total hydrocarbon concentrations, although not statistically significant, showed a one-season difference. Shrimp hydrocarbons were highest in the spring, decreasing over fall and winter, while sediment hydrocarbons were highest in the fall, decreasing over winter and spring. This data implies that significant uptake of hydrocarbons from sediment by *P. aztecus* does not occur, as might be expected from the results of other studies (McCain *et al.*, 1978; Roesijadi *et al.*, 1978; Gillifan *et al.*, 1978; Teal, 1976). Instead the one-season lag in hydrocarbon levels may be due to the deposition of biogenic hydrocarbons in the sediment during the summer. In the absence of significant changes in the hydrocarbon levels in water, no definite conclusions are possible.

CONCLUSIONS

The heavy hydrocarbon analysis of macroepifauna and macronekton samples from the STOCS indicated little, if any, petroleum contamination of the study area. No significant spatial trends and few seasonal trends were present in the data, suggesting relative stability in the hydrocarbon pools of the organisms studied. Of the species studied, the brown shrimp, *Penaeus aztecus*, appears to be the best indicator organism for monitoring purposes.

The data from this study should be useful as inventory data for future studies of petroleum contamination of the study area. However, the variability in the hydrocarbon profiles and the wide and skewed distributions about the means of the parameters indicate that caution should be exercised in interpreting the hydrocarbon data. Laboratory studies of petroleum uptake and storage to determine the effects of petroleum hydrocarbons on the natural hydrocarbons would aid interpretation (Clark, 1974; Hardy *et al.*, 1974; Neff *et al.*, 1976; Rice *et al.*, 1977). Possibly, in the future the variability in the data could be reduced by more uniform sampling practices.

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CHAPTER SIX

TRACE METALS IN ZOOPLANKTON, SHRIMP AND FISH

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ABSTRACT

The concentrations of Al, Ca, Cd, Cr, Cu, Fe, Ni, Pb, V and Zn were determined in zooplankton, fish (muscle, gill, liver) and shrimp (muscle, hepatopancreas) from the South Texas Outer Continental Shelf (STOCS) during 1975-77. This report is a synthesis of these organismal trace element data. Emphasis in this report was placed on those species sampled most frequently and consistently during the study. These organisms included zooplankton, four species of demersal fish (*Pristipomoides aquilonaris, Serranus atrobranchus, Stenotomus caprinus, Trachurus lathami*), two species of shrimp (*Penaeus aztecus, P. setiferus*) and two species of submarine bank-associated fish (*Lutjanus campechanus, Rhomboplites aurorubens*). No significant trace metal pollution was observed in the STOCS area. Levels of Cd, Cr, Ni and Pb were lower than most literature values. Trace metal concentrations in each species were generally uniform over the entire study area. This was most likely a reflection of organism mobility and the lack of significant point (riverine) sources of trace metal input to the STOCS. A consistent increase in zooplankton Cd concentrations offshore was the only clear cut geographical trend observed. Significant seasonal fluctuations in trace element levels were only observed in those organisms inhabiting the changeable nearshore environment. Incorporation of aluminosilicate detritus was significant for several of these species. There was a general lack of strong correlations between trace element concentrations in sediments and those in organisms collected concurrently. Data from this study will be useful in detecting any future anthropogenic perturbations involving rather large areas of the STOCS.

INTRODUCTION

As part of the Bureau of Land Management (BLM) sponsored South Texas Outer Continental Shelf (STOCS) Benchmark Study, the concentrations of selected trace elements were determined in organisms collected from this area over a three year period (1975-1977). The primary purpose of this project was to establish an inventory of data for trace element levels in STOCS biota prior to large-scale oil and gas exploration and production in this region. These data would then be used to evaluate the impact which future petroleum-related activities might have on organismal trace element body burdens. This report synthesizes the three years of data concerning trace element levels in marine organisms. The goal of this synthesis effort was to identify those specific trace element/organism variables which most consistently characterized the STOCS study area and thus would be useful parameters for future monitoring and research. A secondary goal was to gain some understanding of the factors and processes which appear to strongly influence trace element levels in marine organisms within the STOCS ecosystem.

This report is not intended to be a comprehensive discussion of all organismal trace element data. A complete compilation of results is found in the annual final reports for this project (Boothe and Presley 1977, 1979; Presley and Horowitz, 1976). In this synthesis effort, emphasis was placed on those species which were sampled most frequently and consistently during the three year study. These organisms included zooplankton, six species of fish and two species of shrimp.

Considerable variability exists within the organismal trace element data set. An effort was made to identify those parameters which consistently account for significant portions of this variability in trace element levels within each selected species or sample type. This approach

is important because it permits more precise estimates of observed trace element body burdens with less unexplained variability. The amount of variability attributable to the time and place of sample collection was investigated most completely. Assuming a good correlation between trace element concentrations in organisms and levels in the surrounding environment, these spatial and temporal factors should be significant sources of the variability observed. Also, an understanding of such geographical and seasonal trends in the data is essential for any future monitoring effort. An effort was also made to identify other abiotic and biotic factors which accounted for significant amounts of variability within certain of the selected species studied.

Ten trace elements were analyzed in this study including cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), vanadium (V), zinc (Zn), aluminum (Al) and calcium (Ca). Nickel and V were selected because they are present in large concentrations in some oil and tars. Cadmium and Pb, two very toxic metals, are frequently observed to be above natural levels near industrial centers. Copper and Zn are essential trace metals which can reach toxic levels as a result of man's activities. Iron is also an essential trace element in biological systems (Dulka and Risby, 1976; Brooks, 1977). Iron and Al, because of their abundance in the environment, are important in making geochemical comparisons among trace elements (Trefry and Presley, 1976a). Finally, Ca is important in identifying potentially severe matrix interferences in our analytical procedures.

Background

The northwest Gulf of Mexico (GOM), including the STOCS study area, appears to be free of any significant trace element contamination. Metal pollution has been observed in sediments from Corpus Christi Bay (Neff *et al.*, 1978; Holmes *et al.*, 1974), the Houston Ship-Channel-Galveston Bay area (Hann and Slowey, 1972), the Mississippi River delta (Trefry and Presley, 1976a) and a few inland waterways (Slowey *et al.*, 1973). There is no evidence of large scale offshore transport of these contaminants to the outer continental shelf, however, and little contamination in shelf sediments (Trefry and Presley, 1976a). This situation is not unexpected especially for the STOCS area, which is not highly industrialized.

Anthropogenic trace elements, along with other materials are transported to the ocean from continents by freshwater discharges (e.g. sewage outfalls, storm run off, river discharge, etc.) and atmospheric processes (Trefry and Presley, 1976b). Direct freshwater discharge into the STOCS region is minimal. The Mississippi and Atchafalaya rivers account for >95% of the freshwater entering the northwest GOM (Berryhill, 1977). The discharge points of these rivers are located >700 and >500 km respectively from the study area. In addition, all rivers on the south Texas coast (except the Rio Grande) discharge into bays and estuaries which are separated from the GOM by barrier islands. Along the nearly 300 km of coastline adjacent to the STOCS study area, there are only five narrow passes linking these inland waters with the GOM.

The magnitude of atmospheric inputs of trace elements to the STOCS area has not been documented. Recent work in other areas suggests that airborne inputs may comprise sizable fractions of total inputs to conti-

nental shelf waters. This situation is especially true for coastal waters adjacent to industrialized areas (Leland *et al.*, 1977). However, most of the coastal lands adjacent to the study area are used for agriculture or recreation and most of the industrialized coastal areas are northwest of the study area. Only Transect II is adjacent to an industrialized coastal area (i.e. Corpus Christi). The highly industrialized and densely populated Houston-Galveston-Port Arthur region is about 250 km northwest of this area. Significant atmospheric input of trace elements from these industrialized regions to the STOCS waters, if it occurs, should be most apparent in the northern part of the study area.

Considerable offshore oil and gas exploration and development is carried out within the STOCS study area. The extent to which trace elements are released into the shelf environment from these drilling and production platforms is not well known. In a 1975 study of two oil rigs in the Santa Barbara channel, the V levels in liver tissue of fish from near the platforms were significantly higher than values for control specimens. These values for V in livers of fish from the two platforms were also significantly different from each other (McDermott-Ehrlich and Alexander, 1976). In a "before-during-and-after" study of a temporary oil drilling rig off Mustang Island, Texas, the concentration of Fe was higher in muscle tissue of local shrimp collected during rig operations than in those sampled before or after this period (Presley and Boothe, 1976). Elevated Ba concentrations in surficial sediments around drilling rigs have been observed (Presley, 1976). These observations suggest that significant amounts of certain trace elements can be released during petroleum drilling.

METHODS

Sampling, preparation and analytical procedures used in this study are described fully in Presley and Horowitz (1976) and Boothe and Presley (1977; 1979). However, a brief discussion of these procedures and significant changes among the years of this study are given below. Similar field procedures, designed to minimize the incidence of sample contamination during collection, handling and transportation, were used throughout the study. Sample dissections, digestions and dilutions were done in a clean room. By 1976, elaborate procedures had been developed to minimize and monitor possible contamination during this sample preparation phase. Procedural blanks during the last two years were quite low and averaged 1% of the amount of trace elements in the samples analyzed (cf. Table 6.1).

In 1975 seven trace elements (Cd, Cr, Cu, Fe, Ni, Pb, Zn) were determined exclusively by flame atomic absorption spectroscopy (AAS). Vanadium, aluminum and calcium were measured in zooplankton samples by neutron activation analysis (NAA). Due to the low levels of several trace metals (Cd, Cr, Ni, Pb) present in muscle tissue, these metals were measured in all samples in 1976 and 1977 by flameless AAS. This change in analytical procedures revealed that for all sample types (except zooplankton), the concentration of Cr, Ni, Pb and to a lesser extent Cd, were below the detection limits of flame AAS. This situation meant that the true concentrations of these elements in most 1975 samples had been systematically overestimated. Thus except for zooplankton, only Cu, Fe and Zn data from 1975 were used in this synthesis.

The accuracy and precision of our AAS procedures was excellent. Trace element concentrations in National Bureau of Standards (NBS) Bovine Liver

TABLE 6.1

ACCURACY, PRECISION AND CHARACTERISTICS OF ATOMIC ABSORPTION ANALYSES

Element	Standard Reference Material Bovine liver (NBS No. 1577) This Study (n=15)	NBS Values	Precision[1] This Study	NBS Values	Minimum Detectable Concentration[2] (ppb)	Sensitivity[4] (pg or ppm)	Average Total Procedural Blank (ng)
	Concentration (ppm dry wt. 1 S. D.)						
Cd	0.28 ± 0.03	0.27 ± 0.04	11	15	0.025	9	4
Cr	0.08 ± 0.02	<0.2[5]	25	NA	1	25	25
Cu	190 ± 15	193 ± 10	8	5	--[3]	0.05	< 75
Fe	244 ± 42	270 ± 20	17	7	--[3]	0.07	<100
Ni	0.08 ± 0.03	<0.2[5]	38	NA	4	100	< 95
Pb	0.38 ± 0.08	0.34 ± 0.08	21	24	0.3	25	28
Zn	130 ± 11	130 ± 10	8	8	--[3]	0.02	< 75

[1] Precision expressed as percent coefficient of variation i.e. [Standard deviation (S.D.)/mean] x 100

[2] At 10x scale expansion and approximately 1 chart unit; except Ni at 3x and 2 chart units.

[3] Minimum detectable concentration was generally about one half of the sensitivity.

[4] For Cd, Cr, Ni, Pb: average amount of metal injected giving a signal of .0044 absorbance units. For Cu, Fe, Zn: average concentration giving a signal of .0044 absorbance units.

[5] Not certified values.

Reference Material were determined continually during the study. The results and other parameters of our AAS analyses are summarized in Table 6.1. Our determinations averaged 100% of the NBS certified values. The precision of the analyses, measured as mean percent coefficient of variation (CV) was 18%. The accuracy of NAA for Al, Cr, and V was generally $\geq$ 85% of values for the same samples determined by AAS. The precision of Al, Cr, and V analyses, again measured as percent CV, averaged 5%, 20%, and 50%, respectively. The greater variability in V determinations was largely a result of the very low levels of this metal in many of the samples analyzed.

Table 6.2 summarizes the number of samples of each species and sample type analyzed during this three year study. Organisms were collected at three stations on four transects during three different seasons each year (Figure 6.1). In addition, two species of snapper were collected seasonally and monthly (1976) from two fishing banks [Hospital Rock (HR) and Southern Bank (SB)](Figure 6.1) located between Transects I and II. Consistently sampling the same species from all 12 stations was not possible. This fact is illustrated by the large number of species analyzed in 1975 (28) and 1976 (27). This difficulty with consistent sampling is not surprising when one considers that the 12 stations encompass an area of > 19,000 km^2 and a range of water depths from 18-134 m. Table 6.2 also shows that, excluding zooplankton, muscle (flesh) was the predominant tissue analyzed during these two years (*i.e.* 100% in 1975, 80% in 1976). The concentrations of Cd, Cr, Ni, Pb and V in flesh were frequently below the detection limits even for flameless AAS. As a result the levels of these elements in many samples could only be expressed as "less-than" values.

To ameliorate these two problems, only a few selected species were analyzed in 1977. The species selected were ones that had been sampled

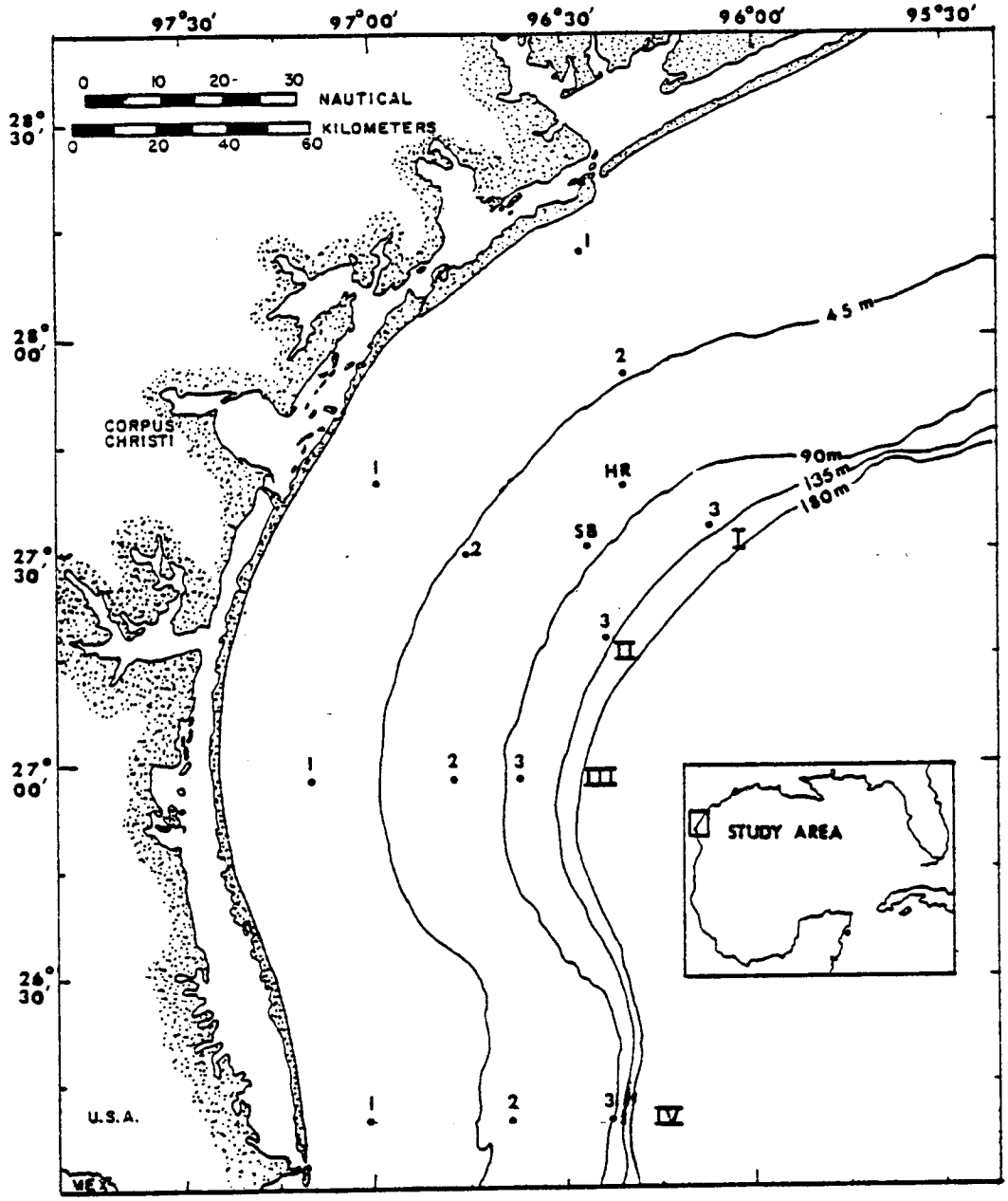

Figure 6.1 Location of STOCS Study Area and Sampling Stations for Trace Metals Project.

TABLE 6.2

ANALYSES BY SAMPLE TYPE, SPECIES AND COLLECTION DATA FOR THREE YEAR STUDY

Sample Type and Species	Number of Samples Analyzed 1975	1976	1977	Number of Different Season/ Year Sampled[1]	Number of Transect/ Seasons Sampled[2]	Number of Station/ Seasons Sampled[2]	Number of Bank Stations/ Seasons Sampled[4]
Zooplankton	72	62	60	9	36	108	-
Macroepifauna							
A. Shrimp (Flesh)							
1. *Penaeus aztecus*	27	9	15	9	30	51	-
2. *Penaeus setiferus*	3	5	3	6	10	10	-
3. *Solenocera vioscai*	2	4	-	3	4	4	-
4. *Sicyonia dorsalis*	4	-	-	2	3	4	-
5. *Penaeus duorarum*	2	-	-	2	2	2	-
6. *Parpandalus longicauda*	-	1	-	1	1	1	-
7. *Sicyonia brevirostris*	1	-	-	1	1	1	-
8. *Sicyonia* sp.	1	-	-	1	1	1	-
B. Shrimp (Hepatopancreas)							
1. *Penaeus aztecus*	-	-	67	3	11	15	-
2. *Penaeus setiferus*	-	-	19	2	4	4	-
C. Squid (Flesh)							
1. *Loligo* spp.	24	12	-	6	20	36	-
2. *Lolliguncula brevis*	-	2	-	2	2	2	-
D. Miscellaneous Invertebrates							
1. *Callinectes similis* (crab, whole)	1	1	-	2	2	2	-
2. *Squilla empusa* (stomatopod, flesh)	-	1	-	1	1	1	-

TABLE 6.2 CONT.'D

Sample Type and Species	Number of Samples Analyzed 1975	1976	1977	Number of Different Season/ Year Sampled[1]	Number of Transect/ Seasons Sampled[2]	Number of Station/ Seasons Sampled[2]	Number of Bank Stations/ Seasons Sampled[4]
Demersal Fish							
A. Flesh							
1. *Pristipomoides aquilonaris*	9	28	12	9	31	33	-
2. *Stenotomus caprinus*	13	9	11	9	24	30	-
3. *Trachurus lathami*	8	12	8	7	19	27	-
4. *Serranus atrobranchus*	4	11	11	7	18	23	-
5. *Syacium gunteri*	11	8	-	4	10	15	-
6. *Synodus foetens*	4	10	-	4	10	12	-
7. *Upeneus parvus*	4	5	-	4	7	9	-
8. *Micropogon undulatus*	6	2	-	3	8	8	-
9. *Cynoscion arenarius*	2	5	-	4	5	5	-
10. *Chloroscombrus chrysurus*	-	5	-	2	2	3	-
11. *Prionotus paralatus*	3	2	-	3	5	5	-
12. *Peprilus burti*	-	4	-	2	2	2	-
13. *Leiostomus xanthurus*	-	3	-	1	1	1	-
14. *Syacium* sp.	3	-	-	1	2	3	-
15. *Centropristis philadelphica*	2	-	-	1	2	2	-
16. *Cynoscion nothus*	2	-	-	2	2	2	-
17. *Polydactylus octonemus*	-	2	-	2	2	2	-
18. *Gonioplectrus hispanus*	-	1	-	1	1	1	-
19. *Lagodon rhomboides*	1	-	-	1	1	1	-
20. *Larimus fasciatus*	-	1	-	1	1	1	-
21. *Prionotus* sp.	1	-	-	1	1	1	-
22. *Syacium papillosum*	1	-	-	1	1	1	-
23. *Trichopsetta ventralis*	-	1	-	1	1	1	-
B. Liver							
1. *Pristipomoides aquilonaris*			39	3	11	12	-
2. *Stenotomus caprinus*			27	3	9	11	-
3. *Serranus atrobranchus*			3	1	1	1	-

TABLE 6.2 CONT.'D

Sample Type and Species	Number of Samples Analyzed 1975	1976	1977	Number of Different Season/ Year Sampled[1]	Number of Transect/ Seasons Sampled[2]	Number of Station/ Seasons Sampled[3]	Number of Bank Stations/ Seasons Sampled[4]
Submarine Bank							
Associated Fish							
A. Flesh							
1. *Lutjanus campechanus*	2	13	4	3	2	3	15
2. *Rhomboplites aurorubens*	-	10	4	-	-	-	14
3. *Holocentrus rufus*	-	1	-	-	-	-	1
B. Liver							
1. *Lutjanus campechanus*	-	12	22	-	-	-	15
2. *Rhomboplites aurorubens*	-	8	24	-	-	-	12
3. *Holocentrus rufus*	-	1	-	-	-	-	1
C. Gill							
1. *Lutjanus campechanus*	-	12	4	-	-	-	15
2. *Rhomboplites aurorubens*	-	10	4	-	-	-	14
3. *Holocentrus rufus*	-	1	-	-	-	-	1
TOTAL SAMPLES ANALYZED	213	274	337				

[1] Three seasonal samplings (Winter = Jan.-Feb.; Spring = May-June; Fall = Sept.-Oct.) conducted each year. Total of 9 seasonal samplings made during the 3 year study.

[2] Four transects sampled 3 seasons each year. Total of 36 transect/season samplings made during the 3 year study.

[3] Three stations on each of 4 transects sampled 3 seasons each year. Total of 108 station/season samplings made during the 3 year study.

[4] Two bank stations (Hospital Rock and Southern Bank) sampled 3 seasons each year. Same banks sampled each non-seasonal month during 1976. Total of 30 bank station/season (+ monthly 1976) samplings made during the 3 year study.

most consistently during the first two years of the study and that had some economic or possible ecological importance within the STOCS area. Four species of demersal fish (*i.e. Pristipomoides aquilonaris, Stenotomus caprinus, Serranus atrobranchus, Trachurus lathami*), two species of shrimp (*Penaeus aztecus, Penaeus setiferus*) and two species of submarine bank-associated fish (*Lutjanus campechanus, Rhomboplites aurorubens*) were chosen. Every time these species were collected during 1977, they were sampled for trace element analysis. The analysis of muscle tissue from these species was continued in 1977 for comparison purposes. However, emphasis was placed on the analysis of liver (fish) and hepatopancreas (shrimp) tissue from each individual of the selected species collected. Both tissues contain detectable concentrations of almost all the trace metals of interest.

Table 6.2 gives further details concerning how consistently species were sampled over space and time. The number of season/years, transect/seasons and station/seasons for which samples of each species were collected are listed. These values are to be compared with the maximum number of samples possible for each classification as described in the table footnotes. Only zooplankton was collected from all possible stations and seasona during the three year study. *Penaeus aztecus* was collected from 51 of a possible 108 station/season combinations. The remaining species exhibit an even more scattered spatial and temporal coverage of the study area. For several species the number of transect/seasons and station/seasons sampled were very similar. This situation indicates that samples of these species were collected from only one or occasionally two stations on a transect during any given season.

Sufficient data to permit multivariate statistical analysis were obtained for zooplankton and eight selected species. The species include *P. aquilonaris* (flesh and liver), *S. caprinus* (flesh and liver),

S. atrobranchus (flesh), *T. lathami* (flesh), *P. aztecus* (flesh and hepatopancreas), *P. setiferus* (flesh), *L. campechanus* (flesh, liver and gill) and *R. aurorubens* (flesh, liver and gill. However, certain irregularities within each data set had to be corrected before the data could be analyzed. Replicate samples (*i.e.* > 1 sample taken at the same place and time) were taken infrequently for these species and were scattered irregularly among different collection sites and seasons. As a result, data from these replicate samples were averaged to arrive at a single data case per collection site and period. As discussed above, data cases for most species were concentrated at one or two of the three stations on each transect. Except for zooplankton and *P. aztecus* (flesh) it was not possible to include data from all three stations in the statistical analyses. Hopefully, the consequence of this action gives more reliable conclusions concerning a more limited geographical area. Data were also scattered with regard to transect and season, but the scattering was much less severe than in the case of stations. No effort was made to discard transects or seasons from analyses because of low frequency of occurrence. Finally, the concentrations of several metals in the flesh of these selected species were frequently below the detection limits of our analytical procedures. These "less-than" values could not be logically assigned a meaningful value and thus were treated as missing data.

In these analyses, concentrations of the 10 trace elements served as dependent variables for each species-tissue category. The primary analysis questions involved the effect of three independent variables (season, transect, station) on each of the 10 dependent variables. A straightforward, three-factor (three-way) analysis for each dependent

variable was not possible because of low cell frequencies ($\leq$ 4) for all sample types. Three two-way analyses were attempted for each dependent variable. These three analyses were season by transect (12 cells), season by station (9 cells) and transect by station (12 cells). All analyses involved unbalanced data (i.e. unequal cell frequencies). Standard analysis of variance (ANOVA) calculation techniques are not useful with unbalanced data. All effects, both main effects and interactions are confounded. ANOVA using a multiple linear regression approach is the technique suggested for use with unbalanced data (Searle, 1971). For the present data, this approach was used to assess the effect of a factor with all other factors in the design covaried (statistically controlled). All such analyses were calculated using the "Regression Option" of subprogram "ANOVA" from the *Statistical Package for the Social Sciences* (SPSS; Nie *et al.*, 1975).

The degree of association between trace element concentrations and potentially relevant abiotic and biotic factors was determined using correlation analysis. For zooplankton over 140 variables were used in this analysis. These variables included hydrographic parameters (e.g. temperature, salinity, dissolved nutrients and hydrocarbons), zooplankton high molecular weight hydrocarbons body burdens and numerous parameters describing zooplankton and phytoplankton communities in the STOCS area (e.g. species diversity, biomass, species density and composition, etc.). For shrimp and demersal fish, 278 variables were employed which related to sediment characteristics, epifauna and infauna communities and hydrocarbon body burdens and bottom water chemistry. Pearson correlation coefficients were calculated using SPSS. To avoid accepting chance-produced significant coefficients as valid, correlation results for each sample type/metal combination were initially screened. The correlation

analysis data for a combination were ignored unless the percentage of significant ($p < .05$) coefficients was greater than the 5% expected by chance.

RESULTS

Two-way ANOVA tests were performed on trace element data from selected species to identify significant effects attributable to spatial (transect or station) or temporal (season) variability in the STOCS study area. These analyses are summarized in Table 6.3. Of the 206 analyses performed, 35 (17%) produced significant ($p. < .05$) overall F-ratios. These overall F-ratios provide a single test of all effects (main effects and interactions) pooled together. To lessen the probability of erroneously accepting chance-produced significant results, a significant main effect or interaction was accepted as valid only if the corresponding overall F-ratio was also valid. Using this criterion, 48 significant main effects and interactions were accepted as valid. Finally, a main effect was accepted as a truly meaningful result if it was significant in both two-way analyses involving that main effect. Only one significant station effect and seven significant season effects were found to be clearly meaningful. No significant transect effect was clearly meaningful. The meaningful results were limited to zooplankton, *T. lathami* (flesh) and *P. aztecus* (flesh). They will be discussed in appropriate sections below.

Zooplankton

Table 6.4 summarizes the three years of zooplankton trace element data in terms of station/transect sampled. The only truly meaningful spatial effect observed in zooplankton was an increase in Cd concentrations offshore (Table 6.5). The reason for this trend is not clear. The trend does

TABLE 6.3

GENERAL SUMMARY OF ANOVA RESULTS FOR TEMPORAL SPATIAL-EFFECTS

Species	Organ[1]	No. of Analyses Attempted	No. of Analyses with Sufficient Data	No. of Inter-Action Tests	Range of No. of Data Cases	No. of Significant Overall F-Ratios	No. of Significant Main Effects or Inter-Actions
				Station by Season			
Zooplankton	-	10	10	10	62-144	5	10
Penaeus aztecus	F	10	10	3	9-51	1	3
Penaeus aztecus	H	10	10	0	12-14	5	6
Trachurus lathami	F	10	9	3	7-27	4	7
				Transect by Season			
Zooplankton	-	10	10	10	62-144	4	7
Pristipomoides aquilonaris	F	10	9	9	7-33	0	0
Serranus atrobranchus	F	10	8	2	6-22	1	2
Stenotomus caprinus	F	10	8	3	6-30	1	1
Trachurus lathami	F	10	8	0	7-27	3	5
Lutjanus campechanus	F	10	6	0	9-15	1	1
Rhomboplites aurorubens	F	10	5	0	7-14	1	2
Pristipomoides aquilonaris	L	10	9	0	5-11	0	1
Stenotomus caprinus	L	10	9	0	7-9	0	1
Lutjanus campechanus	L	10	8	0	7-15	1	2
Rhomboplites aurorubens	L	10	8	0	5-12	1	1
Lutjanus campechanus	G	10	9	0	9-15	0	0
Rhomboplites aurorubens	G	10	9	0	10-14	1	1
Penaeus aztecus	F	10	10	7	9-51	2	2
Penaeus setiferus	F	10	4	4	5-9	0	1
Penaeus aztecus	H	10	10	10	12-14	1	5
				Transect by Station			
Zooplankton	-	10	10	10	62-144	1	4
Penaeus aztecus	F	10	10	3	9-51	0	0
Penaeus aztecus	H	10	10	9	12-44	1	5
Trachurus lathami	F	10	7	0	11-27	0	0
TOTAL		240	206	83	-	35	68

[1] F = Flesh, L = Liver, G = Gill, H = Hepatopancreas

TABLE 6.4

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN ZOOPLANKTON FROM THE STOCS STUDY

Transect	Station	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
			Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
I	1	18	1.4 (0.65-3.0)	6.0 (0.10-22)	14 (5.0-23)	4500 (400-13000)	8.5 (0.60-20)	22 (1.8-160)	21 (4.0-45)	120 (9.0- 500)	7000 (1900-19000)	35000 (14000-40000)
	2	20	3.0 (1.6 -6.0)	4.5 (0.35-14)	21 (6.0-90)	1900 (100- 5000)	6.0 (2.0 -11)	13 (1.4- 75)	9.5 (1.2-20)	125 (6.0- 210)	2500 (140- 6500)	30000 (4500-60000)
	3	12	5.0 (3.0 -7.0)	2.5 (0.40-6.0)	24 (9.5-70)	1200 (130- 3900)	8.0 (3.0 -15)	7.0 (1.3- 13)	7.0 (1.4-25)	130 (95- 160)	2200 (100-10000)	35000 (22000-65000)
II	1	16	2.4 (0.95-5.5)	4.0 (0.70-14)	20 (2.5-75)	3000 (35-13000)	5.0 (2.2 -16)	11 (1.3- 70)	16 (0.4-70)	130 (25- 250)	5500 (12-25000)	30000 (16000-45000)
	2	20	3.5 (1.8 -5.5)	3.5 (0.50-9.0)	190 (5 -2500)	2100 (20- 8500)	7.0 (1.9 -30)	11 (1.0- 70)	16 (2.2-65)	180 (22- 500)	4000 (75-14000)	65000 (8000-140000)
	3	12	5.0 (3.5 -7.0)	2.5 (0.10-7.5)	21 (7.0- 90)	1600 (40- 8000)	6.5 (2.0 -18)	12 (0.6- 65)	14 (2.0-25)	110 (40- 190)	2500 (95-12000)	30000 (16000-50000)
III	1	18	2.0 (0.65-4.0)	4.5 (0.60-13)	16 (5.5- 60)	3000 (240-17000)	5.5 (0.95-30)	15 (0.60-45)	25 (4.0-60)	130 (30- 270)	7000 (850-30000)	60000 (18000-100000)
	2	20	3.5 (1.5 -5.5)	4.5 (0.30-10)	14 (8.0- 20)	3000 (550- 6600)	7.0 (3.0 -18)	10 (0.80-40)	15 (3.0-70)	140 (35- 500)	6000 (1300-30000)	50000 (25000-80000)
	3	12	4.5 (1.8 -6.0)	3.5 (0.75-8.0)	13 (6.0- 30)	2500 (350-11000)	7.0 (2.0 -17)	8.5 (0.80-30)	10 (3.5-35)	220 (75-1300)	4500 (300-17000)	30000 (25000-35000)
IV	1	16	3.0 (0.80-4.5)	3.0 (0.45-8.5)	13 (6.0- 35)	3000 (200-12000)	6.0 (2.0 -16)	7.0 (0.80-40)	13 (4.5-50)	170 (75- 500)	4500 (550-20000)	25000 (9500-35000)
	2	18	3.0 (0.60-4.5)	5.5 (0.11-16)	50 (8.0- 300)	5000 (24-15000)	10 (2.0 -40)	23 (0.55-140)	24 (2.3-85)	350 (9.0-2000)	9000 (80-25000)	40000 (10000-70000)
	3	12	4.0 (2.5 -6.0)	4.0 (0.10-11)	17 (7.5- 55)	550 (70- 1600)	5.5 (3.0 -8.0)	12 (0.60- 40)	13 (5.0-25)	180 (80-1000)	1500 (200- 3000)	4000 (35000-50000)
	Transect [1]		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Station [1]		.001	NS	NS	.005	NS	NS	NS	NS	.008	NS

[1] ANOVA results: metals for which the main effect indicated was significant at level shown. NS means not significant ($p > .05$)

TABLE 6.5

MEANINGFUL SIGNIFICANT SPATIAL AND TEMPORAL MAIN EFFECTS FROM TWO-WAY ANOVA OF STOCS ZOOPLANKTON TRACE METALS DATA[1]

Element	Grand Mean (ppm dry weight)	Station or Season[2]	STATION (SPATIAL) MAIN EFFECT Adjusted Mean Concentrations[3] (ppm dry weight)		SEASON (TEMPORAL) MAIN EFFECT Adjusted Mean Concentrations[4] (ppm dry weight)	
			From Station by Season 2-way ANOVA	From Station by Transect 2-way ANOVA	From Season by Station 2-way ANOVA	From Season by Transect 2-way ANOVA
		1	2.0	2.0		
Cd	3.3	2	3.4	3.4		
		3	4.6	4.6		
		Winter			4300	4100
Al[5]	5300	Spring			1000	1100
		Fall			11000	11000
		Winter			2200	2200
Fe	2800	Spring			800	800
		Fall			5300	5300
		Winter			5.5	5.5
Ni	7.0	Spring			6.2	6.2
		Fall			9.4	9.4

[1] Each main effect shown was significant ($p = .001$) in both 2-way ANOVA tests made which included that effect.

[2] For station designations see FIGURE 1. Seasons: Winter = Jan.-Feb.; Spring = May-June; Fall = Sept.-Oct.

[3] Station means have the confounding influence of season or transect adjusted (partialled) out.

[4] Season means have the confounding influence of station or transect adjusted (partialled) out.

[5] Season by transect interaction was significant ($p = .012$).

not suggest any significant anthropogenic input of Cd to the nearshore environment. Zooplankton Cd levels were significantly ($p < .05$) correlated with over 55% of the pelagic variables for which pairwise coefficients were determined. Secchi depth was strongly correlated with Cd levels ($r^2 = .30$) indicating as secchi depth increased offshore Cd also increased. This parameter is a measure of turbidity and suggests that zooplankton Cd levels are influenced in some way by a change in the amount of suspended particulate matter in the water column.

However, most of the correlated variables accounted for < 10% (*i.e.* $r^2 < .10$) of the observed variability in the zooplankton Cd body burden data. Cd levels did not appear to be influenced by the density of the zooplankton populations sampled. Cadmium was not strongly correlated with either copepod or total zooplankton density ($r^2 < .08$). There was a similar weak relationship with total phytoplankton biomass as measured by total chlorophyll ($r^2 < .14$). In 1977 zooplankton trace metal samples were split. Half of the sample was analyzed for trace element content and the other half used to determine taxonomic composition. No significant correlations were observed between Cd and the density or percent abundance of any taxonomic group.

Table 6.6 summarizes the average seasonal concentrations of trace metals in zooplankton observed during this three year study. Aluminum, Fe, and Ni exhibited significant seasonal trends (Table 6.5). None of the metals were strongly correlated (*i.e.* $r^2 > .25$) with any pelagic variable tested. Elevated levels of Al and Fe in zooplankton samples are generally interpreted as incorporation of abioseston (*e.g.* clay particles) by the zooplankters (Martin and Knauer, 1973). Considerable evidence suggests that this process is responsible for the seasonal trends observed here. The concentrations of Al and Fe in suspended matter from the GOM are

TABLE 6.6

AVERAGE SEASONAL CONCENTRATIONS OF TRACE ELEMENTS IN ZOOPLANKTON FROM THE STOCS STUDY

Season[1]	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
		Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
Winter	56	3.0 (0.85-5.0)	4.0 (0.60-8.5)	15 (4.5-45)	2300 (120-6000)	5.5 (2.0-9.5)	15 (1.5 -45)	13 (4.0-40)	160 (25- 500)	4500 (250-13000)	30000 (9500-50000)
Spring	70	3.5 (1.1 -6.0)	3.5 (0.10-10)	16 (6.0-38)	950 (23-3500)	6.0 (1.9-18)	7.5 (0.60-45)	13 (1.3-65)	130 (40- 200)	1300 (75- 5000)	45000 (16000-90000)
Fall	68	3.0 (0.65-6.0)	5.5 (0.15-14)	70 (5.5-210)	5500 (30-15000)	9.5 (1.6-25)	14 (0.65-80)	25 (4.0-45)	220 (9.0-1000)	11000 (100-25000)	50000 (16000-95000)
Season[2]		.022	NS	NS	.001*	.001*	NS	NS	NS	.001*	.005

[1] Seasons: Winter = Jan.-Feb.; Spring = May-June; Fall = Sept.-Oct.

[2] ANOVA Results: metals for which season main effect was significant at the level shown. NS means not significant ($p > .05$). Asterisk (*) indicates season main effect was significant in both 2-way ANOVA tests made which included that effect.

approximately 9% and 5%, respectively (Trefry and Presley, 1976b). The Fe/Al ratio in such particulates is 0.56. Aluminum and Fe levels in zooplankton samples from this study are strongly correlated (r^2 = .81) and the average Fe/Al ratio is 0.52. In addition, the trend in zooplankton Al and Fe concentrations (Table 6.6) corresponds well with the observed seasonal fluctuations in suspended matter concentrations in STOCS surface waters. Suspended particulate concentrations are generally highest in the fall and lowest in the spring (Berryhill, 1978). Also Al and Fe levels in zooplankton decrease with increasing distance from shore. These geographical trends for zooplankton were significant in only one of the two ANOVA tests conducted involving station effect. As a result they cannot be considered completely clear cut. Still they were consistent and followed suspended matter concentrations which also decreased offshore (Berryhill, 1978). Zooplankton Ni levels are strongly correlated with Al and Fe concentrations (*i.e.* r^2 = .55 and .66, respectively). This fact suggests that the seasonal trend in Ni is also the result of variable incorporation of abioseston.

Demersal Fish

Table 6.7 summarizes trace element data for the four selected species of demersal fish in terms of transect sampled. The levels of several trace metals (*i.e.* Cd, Cr, Ni, Pb, V) in fish muscle were at or below the detection limits of our analytical procedures. For these metals it was obviously not possible to distinguish any spatial or temporal trends. Still, even for elements present in detectable amounts, none of the species exhibited any significant geographical patterns in muscle tissue trace element levels. *Trachurus lathami* was the only species to show any significant seasonal trends in trace metal concentrations.

TABLE 6.7

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN MUSCLE OF DEMERSAL FISH FROM THE STOCS STUDY

Transect	Species	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
			Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
I	*Pristipomoides aquilonaris*	7	<0.05	<0.05	1.3 (0.70-3.0)	4.5 (2.0-6.0)	<0.07	<0.04	<0.10	13 (11-16)	25 (19-30)	700 (400- 950)
	Serranus atrobranchus	4	<0.02	<0.05	0.95 (0.50-1.6)	3.5 (2.0-5.0)	<0.09	<0.03	<0.10	10 (6.0-12)	30 (24-32)	1100 (900-1300)
	Stenotomus caprinus	7	<0.06	<0.05	1.0 (0.70-1.3)	5.5 (4.0-6.0)	<0.10	<0.08	<0.20	14 (11-17)	20 (15-25)	700 (400-1200)
	Trachurus lathami	2	<0.04	<0.03	2.4	9.5	<0.08	<0.05	<0.15	24	19	800
II	*Pristipomoides aquilonaris*	23	<0.03	<0.04	1.4 (0.70-1.9)	4.0 (1.0-7.0)	<0.08	<0.04	<0.30	8.5 (1.0-17)	30 (16-45)	700 (350- 850)
	Serranus atrobranchus	8	<0.03	<0.05	0.90 (0.60-2.0)	3.0 (1.0-5.0)	<0.08	<0.05	<0.40	10 (6.0-14)	30 (25-40)	1900 (700-4500)
	Stenotomus caprinus	11	<0.05	<0.05	1.1 (0.70-1.7)	5.0 (2.0-8.0)	<0.08	<0.06	<0.10	13 (6.0-25)	25 (12-55)	700 (400-1400)
	Trachurus lathami	8	0.10 (0.01-0.25)	<0.05	2.3 (1.7 -3.0)	15 (8.0-20)	<0.10	<0.06	<0.10	24 (12-35)	30 (15-40)	750 (550-1000)
III	*Pristipomoides aquilonaris*	7	<0.03	<0.04	1.0 (0.60-1.6)	4.0 (2.0-7.0)	<0.07	<0.05	<0.10	10 (2.0-16)	22 (16-30)	500 (300- 600)
	Serranus atrobranchus	9	<0.02	<0.04	1.3 (0.50-3.5)	3.0 (2.0-4.0)	<0.09	<0.05	<0.10	10 (2.0-17)	20 (14-30)	1300 (750-2000)
	Stenotomus caprinus	8	<0.06	<0.05	0.90 (0.60-1.1)	4.5 (4.0-5.0)	<0.08	<0.06	<0.10	13 (10-18)	13 (10-20)	600 (350- 850)
	Trachurus lathami	9	0.12 (0.01-0.30)	<0.10	2.5 (1.7 -3.5)	15 (7.0-25)	<0.10	<0.10	<0.15	24 (15-40)	25 (10-50)	1000 (300-2500)
IV	*Pristipomoides aquilonaris*	12	<0.05	<0.07	1.1 (0.60-2.0)	4.0 (1.8-6.0)	<0.08	<0.07	<0.10	14 (10-20)	18 (15-25)	600 (300-1100)
	Serranus atrobranchus	5	<0.02	<0.07	0.80 (0.50-1.6)	5.5 (4.0-6.0)	<0.10	<0.05	<0.15	12 (11-16)	17 (14-30)	1800 (750-3500)
	Stenotomus caprinus	7	<0.05	<0.05	1.1 (0.60-1.5)	4.0 (3.0-6.0)	<0.08	<0.04	<0.10	12 (6.0-15)	23 (20-25)	1200 (750-1600)
	Trachurus lathami	9	0.04 (0.01-0.09)	<0.07	2.2 (0.50-3.0)	15 (6.0-25)	<0.09	<0.09	<0.10	19 (13-25)	17 (12-30)	800 (550-1200)

Table 6.8 summarizes these significant temporal relationships and Table 6.9 gives the average seasonal trace element concentrations in *Trachurus* flesh for the entire study. Aluminum levels exhibited the same seasonal pattern as did zooplankton. Aluminum and Fe in *Trachurus* muscle were strongly correlated (r^2 =.41). Also *Trachurus* was the only demersal fish species collected predominantly at nearshore stations. Almost 90% of the samples came from Stations 1 or 2. These facts suggest that the temporal trend in Al levels was a reflection of the more changeable nearshore environment which is characterized by sizable seasonal fluctuations in the amount of suspended aluminosilicate particulate matter. The other three species of fish had generally similar concentrations of Al (Table 6.7), but no seasonal trends were observed. These species were collected predominantly from offshore stations (*i.e.* 80% of the samples from Station 3, cf. Figure 6.1) which are characterized by lower concentrations of organic-rich suspended matter.

The reasons for the seasonal fluctuations in Cd and Zn levels are not known. The trends for these metals were opposite to that of Al. No relationship was observed between size (age) and the concentrations of Cd and Zn. Also no strong correlations (r^2 > .20) were found with environmental variables such as temperature, salinity, dissolved oxygen or nutrients. Potential environmental sources of trace metals did not appear to influence directly the observed levels of these metals. For example, no strong correlations were observed with variables related to the density or diversity of epifaunal of infaunal prey organisms. Also no significant correlations were observed between Cd and An levels in the sediments and concentrations of the metals in *Trachurus* collected at the same stations. This absence of significant correlations between corresponding sediment and muscle tissue trace element levels was quite general for all demersal fish species.

TABLE 6.8

MEANINGFUL SIGNIFICANT SPATIAL AND TEMPORAL MAIN EFFECTS FROM TWO WAY ANOVA OF STOCS EPIFAUNA AND DEMERSAL FISH TRACE METAL DATA[1]

Organism (tissue)	Element	Grand Mean (ppm dry weight)	Level of Significance	Season[2]	SEASON (TEMPORAL) MAIN EFFECT Adjusted Mean Concentrations[3] (ppm dry weight)	
					From Season by Station 2-way ANOVA	From Season by Transect 2-way ANOVA
	Al	23	p = .001	Winter	28	27
				Spring	15	15
				Fall	39	40
Trachurus lathami (flesh)	Cd	0.09	p = .009	Winter	0.16	0.16
				Spring	0.05	0.05
				Fall	0.01	0.01
	Zn	22	p = .001	Winter	28	28
				Spring	20	21
				Fall	17	15
Penaeus aztecus (flesh)	Zn	53	p = .001	Winter	49	49
				Spring	49	49
				Fall	59	59

1 Each main effect shown was significant in both 2-way ANOVA tests made which included that effect.

2 Seasons: Winter = Jan.-Feb.; Spring = May-June; Fall = Sept.-Oct.

3 Season means have the confounding influence of station or transect adjusted (partialled) out.

TABLE 6.9

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN MUSCLE OF *Trachurus lathami*

Season[1]	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
		Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
Winter	9	0.16 (0.07-0.30)	<0.05	2.7 (2.1 -3.5)	20 (17-25)	<0.10	<0.10	<0.20	28 (18-40)	30 (23-32)	950 (750-1000)
Spring	15	0.05 (0.01-0.17)	<0.05	2.2 (0.50-3.0)	13 (6.0-25)	<0.10	<0.10	<0.10	20 (16-26)	15 (12-20)	650 (300-1200)
Fall	4	<0.03	<0.10	2.0 (1.4 -2.4)	14 (8.0-24)	<0.10	<0.05	<0.20	16 (12-26)	40 (25-50)	1500 (950-2500)
Season[2]		.008*	NS	.001	NS	NS	NS	NS	.002*	.001*	NS

[1] Seasons: Winter = Jan.-Feb.; Spring = May-June; Fall = Sept.-Oct.

[2] ANOVA Results: metals for which season main effect was significant at the level shown. NS means not significant ($p > .05$). Asterisk (*) indicates season main effect was significant in both 2-way ANOVA tests made which included that effect.

Of the 32 possible pairwise correlations (*i.e.* 4 species x 8 metals common to both organismal and sediment samples) only two were significant ($p < .05$) and each accounted for 21% of the observed variability.

Trace metal levels were measured in liver tissue from individuals of *P. aquilonaris* and *S. caprinus* in 1977 (Table 6.10). No significant spatial or seasonal trends in trace element concentrations were observed. It is likely that this situation was due in part to the limited number of metals (Cd, Cr, Fe, Ni, Pb, Zn) were significantly greater ($p < .05$) in *S. caprinus* livers. These differences were evaluated using a paired t statistic which compared samples of the two species collected at the same time and place. Correlation analyses also revealed significant differences between these species. Levels of Cd, Cr, Fe, and Zn in *Stenotomus* livers all showed strong correlations ($r^2 > .30$) with corresponding sediment trace metal concentrations and sediment texture parameters from the same collection sites. Similarly, several metals (Cd, Fe, Pb, Zn, Al) were strongly correlated ($r^2 > .50$) with one or more parameters describing infaunal communities at the sampling stations. Comparable correlations for *Pristipomoides* liver trace metal data were weak ($r^2 < .10$) or not significant ($p > .05$). These results suggest that trace metal levels in *Stenotomus* liver tissue are a better reflection of ambient trace element concentrations than are those of *Pristipomoides*.

Shrimp

Trace element data for penaeid shrimp muscle are summarized in Table 6.11 in terms of station/transect sampled. No significant spatial trends in the data were detected for either species. *Penaeus setiferus* was collected only from the inshore stations (#1) on each transect. *P. aztecus*, however, was consistently collected from 10 of the 12 stations sampled during this three year study. Flesh trace element concentrations were not

TABLE 6.10

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN LIVERS OF DEMERSAL FISH FROM THE 1977 STOCS STUDY

Transect	Species	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
			Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
I	*Pristipomoides aquilonaris*	12	4.5 (1.9-15)	<0.20	21 (8.0-50)	600 (200-1400)	<0.40	0.22 (0.08-0.70)	0.60 (0.20-1.6)	110 (80-160)	45 (20-120)	< 600
	Stenotomus caprinus	4	8.5 (5.0-12)	0.25 (0.20-0.30)	75 (30-100)	1200 (900-1600)	1.8 (1.0-3.0)	3.5 (0.30-5.0)	6.5 (5.0 -8.0)	250 (170-300)	55 (8.5- 80)	<1000
II	*Pristipomoides aquilonaris*	13	4.0 (1.2-15)	<0.20	30 (11- 80)	500 (60-1100)	<0.30	0.25 (0.10-0.60)	1.1 (0.25-3.5)	130 (90-210)	40 (18- 90)	< 650
	Stenotomus caprinus	10	9.0 (3.0-14)	0.16 (0.08-0.20)	40 (11- 90)	1300 (400-2300)	2.1 (0.70-5.0)	9.0 (2.5 -20)	2.5 (1.2 -6.0)	200 (95-500)	55 (25- 85)	<1000
III	*Pristipomoides aquilonaris*	4	1.8 (1.3-2.0)	<0.20	15 (7.0- 30)	400 (220- 500)	<0.30	0.18 (0.10-0.20)	0.35 (0.30-0.45)	100 (90-150)	40 (25- 55)	< 600
	Stenotomus caprinus	8	7.5 (2.1-25)	0.25 (0.10-0.40)	45 (17-110)	1000 (400-2400)	1.4 (0.70-2.0)	5.5 (2.2 -13)	1.8 (0.35-4.5)	190 (130-250)	55 (40-100)	<1000
IV	*Pristipomoides aquilonaris*	10	3.5 (1.5-6.0)	<0.20	30 (11- 80)	650 (400-1200)	<0.30	0.24 (0.10-0.40)	0.85 (0.40-1.7)	130 (90-230)	40 (17-110)	< 750
	Stenotomus caprinus	5	2.4 (1.1-4.0)	0.18 (0.10-0.20)	25 (12- 40)	450 (260- 600)	<0.40	2.0 (1.4 -3.0)	1.9 (1.2 -3.5)	140 (130-180)	65 (35-160)	<1000

TABLE 6.11

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN FLESH OF PENAEID SHRIMP FROM THE STOCS STUDY

Transect	Station	Species	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
				Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
I	1	*Penaeus aztecus*	3	0.13 (0.10-0.20)	<0.05	25 (20-30)	3.0	<0.10	<0.05	<0.07	45 (20-60)	18	1200
		Penaeus setiferus	3	0.05 (0.01-0.10)	<0.05	21 (19-22)	3.5 (2.0-5.0)	<0.10	<0.10	<0.05	50 (45-60)	20 (17-25)	950 (750-1100)
	2	*Penaeus aztecus*	7	0.08 (0.01-0.20)	<0.05	25 (20-35)	4.5 (1.0-10)	<0.10	<0.07	<0.20	50 (40-55)	20 (8.0-30)	1100 (750-1900)
	3	*Penaeus aztecus*	2	0.15 (0.13-0.17)	--	25 (20-30)	--	--	--	--	50 (40-65)	--	--
II	1	*Penaeus aztecus*	5	0.08 (0.02-0.12)	<0.05	24 (19-30)	3.5 (3.0-4.0)	<0.15	<0.15	0.30	55 (50-65)	36	2500
		Penaeus setiferus	8	0.05 (0.01-0.12)	<0.05	24 (19-30)	2.5 (0.50-5.0)	<0.10	<0.10	<0.05	60 (50-70)	25 (15-35)	1500 (450-2500
	2	*Penaeus aztecus*	6	0.11 (0.02-0.25)	<0.05	25 (20-30)	6.5 (4.0-12)	<0.10	<0.10	<0.10	50 (40-60)	24 (14-34)	950 (800-1100)
III	1	*Penaeus aztecus*	4	0.07 (0.01-0.11)	<0.05	25 (25-30)	4.5 (3.0-6.0)	<0.10	<0.05	<0.06	60 (55-65)	13	1100
	2	*Penaeus aztecus*	5	0.10 (0.01-0.25)	<0.05	25 (18-35)	2.5 (2.0-3.0)	<0.08	<0.10	<0.10	60 (50-70)	20 (17-25)	1100 (850-1500)
	3	*Penaeus aztecus*	4	0.18 (0.04-0.35)	<0.05	24 (18-35)	2.0	0.10	0.08	0.12	50 (40-55)	20	1400
IV	1	*Penaeus aztecus*	4	0.06 (0.01-0.16)	<0.05	24 (20-28)	2.0 (1.0-3.0)	<0.08	<0.03	<0.10	55 (45-70)	22 (16-25)	700 (550- 900)
		Penaeus setiferus	1	0.01	<0.05	17	1.0	<0.10	<0.10	<0.05	30	60	400
	2	*Penaeus aztecus*	6	0.08 (0.01-0.13)	<0.10	24 (18-30)	13 (3.0-30)	<0.30	<0.15	<0.40	50 (45-60)	45 (13-90)	2000 (450-3500)
	3	*Penaeus aztecus*	5	0.18 (0.11-0.25)	<0.10	25 (20-30)	4.0	<0.30	<0.06	<0.20	50 (45-60)	24 (18-30)	1000

significantly different between the two species (*i.e.* paired *t* statistic, $p < .05$). No strong correlations were observed between these data and corresponding sediment trace metal or potential prey organism variables. Aluminum and Fe levels in *P. aztecus* muscle were strongly correlated ($r^2 > .72$) and both metals exhibited significant correlations ($r^2 \geq .36$) with certain sediment texture parameters. These results suggest that shrimp were assimilating sediment-derived Al and Fe into their muscle tissue.

Zinc levels in *P. aztecus* did exhibit a significant seasonal effect with a fall maximum (Table 6.8). The reason for this relationship is not clear. The trend was not related to differences in the size (age) of shrimp analyzed among seasons. The seasonal fluctuations could have been a result of environmental changes which reflected physiological changes in the shrimp. Although no strong correlations ($r^2 > .20$) were observed between Zn levels and corresponding temperature, salinity or dissolved oxygen conditions at the sampling sites, these parameters were strongly correlated ($r^2 > .32$) with Zn concentrations in the hepatopancreas of the same shrimp.

In 1977 hepatopancreatic tissue from both species of shrimp was analyzed (Table 6.12). Trace metal levels between the two species were generally similar. There were sufficient data only for *P. aztecus* to conduct spatial-temporal analyses. No significant geographical trends were found in the data. Significant seasonal effects were observed for six metals (Table 6.13). Aluminum, Cd and Cu exhibited Winter maxima and Cr, Fe and Pb levels were highest in the Spring. However, these trends were only significant in one of the two ANOVA tests made involving season. Thus these results cannot be considered as truly meaningful. This situation is a result of the small and unbalanced number of data cases. It

TABLE 6.12

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN HEPATOPANCREAS OF PENAEID SHRIMP FROM THE 1977 STOCS STUDY

Transect	Station	Species	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
				Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
I	1	*Penaeus aztecus*	4	6.0 (3.0-9.0)	0.25 (0.10-0.40)	180 (19- 400)	200 (50-400)	2.5 (2.0-3.0)	<0.10	9.5 (0.60-25)	80 (60-100)	45	<1500
		Penaeus setiferus	8	5.0 (2.7-7.0)	0.45 (0.20-2.0)	160 (40- 500)	160 (50-600)	4.0 (2.0-6.0)	<0.10	9.9 (1.3-3.0)	100 (80-150)	65 (60- 80)	<1200
	2	*Penaeus aztecus*	11	7.5 (2.5-15)	0.50 (0.20-1.0)	500 (40-1100)	300 (70-700)	11 (3.0-30)	0.35 (0.20-0.60)	4.5 (0.30-13)	120 (70-160)	1300 (25-9500)	3000 (750-6500)
II	1	*Penaeus aztecus*	10	8.0 (5.0-15)	0.75 (0.20-2.0)	300 (30-1000)	400 (70-800)	11 (2.0-14)	0.55 (0.20-1.0)	1.8 (0.50-3.5)	110 (70-190)	550 (100-1400)	3500 (1400-6000)
		Penaeus setiferus	8	4.6 (2.5-8.0)	0.50 (0.20-1.0)	400 (30-1000)	300 (110-600)	10 (4.0-18)	0.25 (0.04-0.50)	2.5 (1.3 -5.5)	130 (100-180)	450 (140-1200)	4000 (600-6000)
	2	*Penaeus aztecus*	3	9.5 (6.0-12)	0.40 (0.30-0.50)	1000 (600-1200)	220 (200-260)	14 (11-15)	0.35 (0.20-0.40)	13 (9.5 -17)	120 (110-120)	500 (250- 950)	6000 (3500-7500)
III	1	*Penaeus aztecus*	13	5.5 (1.3-9.0)	0.35 (0.20-0.80)	400 (160- 800)	170 (60-400)	2.5 (1.0-5.0)	0.19 (0.04-0.40)	2.5 (0.50-16)	85 (60-190)	300 (55- 950)	4000 (950-12000)
	2	*Penaeus aztecus*	8	12 (7.0-16)	0.50 (0.09-0.80)	800 (250-1000)	300 (60-600)	13 (6.0-25)	0.30 (0.10-0.70)	11 (2.5 -30)	130 (110-190)	250 (30- 700)	4500 (1200-11000)
	3	*Penaeus aztecus*	2	22 (20-25)	0.25 (0.10-0.40)	600 (400- 800)	130 (80-180)	7.0 (6.0-8.0)	0.10	11 (7.5-14)	140 (110-170)	110 (25- 190)	4000 (3000-4500)
IV	1	*Penaeus aztecus*	8	8.0 (4.0-12)	0.50 (0.30-1.0)	300 (50- 900)	300 (150-500)	4.5 (2.0-11)	0.25 (0.08-0.50)	3.0 (1.2-5.0)	140 (80-200)	300 (110- 600)	<2000
		Penaeus setiferus	3	8.5 (7.0-10)	0.30	450 (400- 500)	180 (120-300)	14 (11-17)	0.35 (0.20-0.50)	2.5 (2.0-3.0)	150 (140-160)	110 (75- 170)	1800 (1100-2500)
	2	*Penaeus aztecus*	8	9.0 (4.0-16)	0.25 (0.07-0.40)	400 (30- 800)	110 (40-180)	6.5 (1.0-10)	0.22 (0.06-0.40)	4.0 (1.0-8.0)	120 (80-190)	150 (40- 450)	3000 (1800-5000)

TABLE 6.13

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN HEPATOPANCREAS OF *Penaeus aztecus*

Season[1]	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
		Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
Winter	18	11 (4.0–25)	0.30 (0.07–0.80)	750 (300–1200)	170 (60–600)	10 (3.0–27)	0.30 (0.10–0.70)	8.5 (2.5 –20)	120 (80–190)	750 (25– 950)	4000 (1200–7500)
Spring	9	4.5 (1.3–10)	0.85 (0.30–2.0)	270 (140– 400)	480 (160–800)	6.5 (2.0–11)	0.60 (0.30–1.0)	4.5 (0.95–16)	100 (60–140)	600 (25–1400)	6000 (2000–12000)
Fall	40	8.0 (3.0–15)	0.40 (0.10–1.0)	350 (19–1000)	240 (40–500)	7.0 (1.0–20)	0.22 (0.06–0.50)	3.5 (0.30–25)	110 (60–190)	300 (30–1100)	2500 (750–4500)
Season[2]		.029	.016	.014	.028	NS	.006	NS	NS	.011	NS

[1] Seasons: Winter = Jan.-Feb.; Spring = May-June; Fall = Sept.-Oct.

[2] ANOVA Results: metals for which season main effect was significant at the level shown. NS means not significant ($p > .05$). For no metal was the season effect significant in both 2-way ANOVA tests made which included that effect.

appears likely that there are meaningful seasonal trends in hepatopancreas trace element levels. However, without a larger, more balanced data set, this conclusion must be considered speculative.

The levels of most trace elements in hepatopancreatic tissue exhibited strong correlations ($r^2 > .25$) with variables related to infaunal and epifaunal organisms. However, no significant correlations were observed with ambient sediment trace metal concentrations. Aluminum, Fe and Cr were strongly correlated in this tissue ($r^2 > .70$). This situation is probably a result of hepatopancreas "contamination" by ingested but unassimilated sediment.

Submarine Bank-Associated Fish

Two species of snapper (*L. campechanus* and *R. aurorubens*) were collected from two fishing banks during this three year study. The two banks, Hospital Rock and Southern Bank, are located 18 km apart between Transects I and II (Figure 6.1). Trace metal levels were determined in muscle, liver and gill tissue. Two-way ANOVA tests revealed no truly meaningful spatial or temporal trends in trace element concentrations for any of these tissues or species. However, the number of data cases was quite small for all species-tissue categories. Trace element concentrations in liver tissue from the two snapper species are summarized in Table 6.14. Interspecific comparisons using a paired *t* statistic showed that Cd and Zn concentrations were significantly ($p < .05$) higher in *R. aurorubens* liver than in liver tissue from *L. campechanus*. These differences may be a result of different food habits for the two species. Lipids from *R. aurorubens* and *L. campechanus* exhibit different $d^{13}c$ values (Fry and Parker, 1979). Also Al and Fe are strongly correlated in liver tissue from *R. aurorubens* (i.e. $r = 0.98$) but not in similar tissue from *L. campechanus*. Both these facts suggest that the dietary habits of these

TABLE 6.14

AVERAGE CONCENTRATIONS OF TRACE ELEMENTS IN LIVERS OF SUBMARINE-BANK ASSOCIATED FISH FROM THE STOCS STUDY

Species	Number of Samples	Concentration in ppm dry weight (95% confidence interval observed around mean)									
		Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Al	Ca
Lutjanus campechanus	34	1.6 (0.60-3.0)	<0.07	17 (4.5-40)	550 (100-1000)	<0.20	0.19 (0.04-0.45)	0.40 (0.09-1.2)	120 (60-180)	40 (16-160)	1000 (400-1900)
Rhomboplites aurorubens	32	11.0 (2.1 -22)	0.09 (0.02-0.20)	30 (8.0-70)	1300 (300-2500)	<0.35	0.40 (0.06-0.80)	2.00 (0.45-5.0)	350 (100-850)	55 (16- 80)	950 (350-1400)

two species are different.

DISCUSSION

One of the most striking aspects of this organismal trace element data set is the general lack of any significant spatial trends. This situation may in part be a result of the generally small number of data cases for many species which made the detection of actual effects difficult. However, this absence of geographical trends could be the result of at least two other factors. First, all of the species discussed here, with the possible exception of zooplankton, are quite mobile. Although the extent of their movements is generally not well documented, it certainly could be significant. This mobility would tend to integrate trace metal exposures at many sites and damp out any differences between them. Second, geographical trends in trace metal levels within the STOCS resulting from man's activities are probably minimal. As discussed earlier, any significant input of trace metals into the STOCS area is most likely to be from diffuse (atmospheric) sources. Due to the relatively small amount of industrialization in the adjacent coastal areas, this atmospheric input is probably quite low and generally similar for all parts of the STOCS region.

Organism mobility may also be an important reason for the general absence of relationships between trace metal levels in benthic organisms and environmental sources of these elements. Variables related to infaunal and epifaunal communities (e.g. density, diversity, etc.) were generally not strongly correlated ($r^2 > .25$) with trace element concentrations in organisms collected at the same time and place. Limited time and resources precluded conducting correlation analyses using population data for each dominant species in these benthic communities. It is difficult to know

if this approach would have revealed any significant relationships. Organismal trace metal levels were also poorly correlated with sediment trace metal concentrations. This situation is not surprising. In addition to organism mobility damping out differences, the manner in which sediment-sorbed trace elements and benthic organisms interact is poorly understood. Sediments can act as either a source or sink for trace metals in organisms (Neff *et al.*, 1978). The extent to which STOCS area sediments serve as sources or sinks of various trace metals for benthic macroepifauna is not known.

The increase in zooplankton Cd levels offshore was the only consistent and significant spatial effect observed in the entire organismal trace element data set. This trend does suggest a difference in the bioavailability of Cd in nearshore and offshore waters. This difference could be related to marked differences in the concentration and nature of suspended matter in these two water masses as described by Berryhill (1978). Inshore waters are characterized by high (compared to offshore) concentrations of suspended particulates which are predominantly terrigenous aluminosilicate clays. The Cd concentration in these particulates is comparatively low. These clays could "scavenge" dissolved Cd from the water column and thus reduce the amount of Cd available for uptake by zooplankters. Offshore waters contain a much lower concentration of suspended matter. Thus in offshore waters, there is less particulate matter "competing" with zooplankters for available dissolved Cd. Also incorporation of these offshore particulates by zooplankters could represent a significant additional source of Cd.

It is also worth noting that all of the significant seasonal trends observed (Tables 6.5, 6.8) appeared to be linked to the more changeable nearshore environment. Only species which were collected consistently (> 50% of the samples) at nearshore stations (1, cf Figure 6.1) exhibited any significant seasonality in trace metal levels. Species collected only at offshore stations (2, 3) showed no seasonal trends. This observation suggests that in any future monitoring effort, it should be easier to detect changes in the levels of bioavailable trace elements at offshore stations than at nearshore ones.

There are little comparative data on trace element concentrations in STOCS biota. Sims (1975) measured trace metal levels in zooplankton from Corpus Christi Bay and the northwest GOM. His values agree closely with data from this study including the increasing levels of Cd in zooplankton offshore. Sims and Presley (1976) analyzed shrimp and fish from San Antonio Bay. Again agreement with our data was generally good except that Pb levels in bay fish were higher than those observed in this study. Data on trace element levels in shrimp from the Mississippi River area (Presley *et al.*, 1972) were also similar to data obtained here.

Considerable comparative data exists in the recent literature concerning trace element levels in similar organisms from other areas of the world's oceans. Trace metal concentrations have been measured in zooplankton and copepods from the New York Bight (Greig *et al.*, 1977), the Canadian Arctic (Bohn and McElroy, 1976), Greece (Zafiropoulos and Grimanis, 1977) and the northeast Pacific (Martin and Broenkow, 1976; Martin and Knauer, 1973). These data are generally quite similar to those observed here. Iron levels in arctic zooplankton were much lower (< 100 ppm dry weight) than concentrations obtained in this study. Also Pb levels in zooplankton sampled from the New York Bight were generally higher than our values.

Trace element body burdens have been determined in decapod crustaceans from an unindustrialized bay in South Africa (Fourie, 1976), the southern California Bight (Jan *et al.*, 1977) and England (Wharfe and Van den Brock, 1977; Wright, 1976). The levels of Cu, Fe and Zn observed in crustaceans from these studies are similar to those observed here. However, the concentrations of Cd, Cr, Ni and Pb are generally higher from these other areas than levels obtained here.

Trace metal concentrations have been determined in commercial fish from Australia (Bebbington *et al.*, 1977) and New Zealand (Brooks and Rumsey, 1974). Trace element body burdens have also been measured in fish from the Canadian Arctic (Bohn and McElroy, 1976), England (Wharfe and Van den Brock, 1977; Wright, 1976), the southern California Bight (Jan *et al.*, 1977), the New York Bight (Greig and Wenzloff, 1977) and Israel (Roth and Hornung, 1977). The levels of metabolically essential trace elements (Cu, Fe, Zn) are similar in all studies. The levels of Cd, Cr, Ni and Pb in the flesh of fish from the STOCS area are generally lower than levels observed in the cited studies even for apparently pristine areas. Levels of Pb observed in Pacific Tuna muscle by Patterson and Settle (1977) are among the lowest measured in any fish. These Pb levels are similar to those from this study.

The above comparisons suggest that STOCS biota are essentially free of trace metal contamination. It is a reasonable assumption that these organisms are not being adversely affected by these low levels of incorporated trace metals. Also these low levels should pose no health hazard to humans ingesting the muscle tissue of the economically important species studied.

RECOMMENDATIONS

Of the sample types analyzed during this study, three are best suited for any future monitoring effort aimed at detecting perturbations over rather large areas of the STOCS resulting from offshore oil and gas exploration and production. These types are zooplankton, *Stenotomus caprinus* liver and *Penaeus aztecus* hepatopancreas. Three criteria were used in selecting these sample types. All are widely distributed within the STOCS study area and are generally available in sufficient numbers most of the year. Each contain easily detectable amounts of all of the trace elements of interest. All exhibit relatively consistent spatial and temporal patterns of trace metal levels with acceptable intra-station variability (i.e. %CV <40). In any future monitoring program, sufficient sample replication is essential to accurately detect change. Based on expected variability, 10-20 samples of each type should be analyzed from each station to be compared. Since we cannot now accurately predict which trace elemental levels will be elevated as a result of offshore petroleum-related activities, the same multi-element analytical approach should be used. Calcium can be eliminated from the list of elements investigated.

If the goal of the monitoring effort is to detect perturbations at specific sites, the above recommendations would not be effective. Because of the mobility of these organisms, the spatial resolution of that approach is poor. The best approach for site specific studies would be to use a bivalve mollusk such as *Spondylus americanus* or *Mytilus* sp. Carefully matched individuals of these sedentary, filter-feeding organisms could be placed in metal-free enclosures at both test and control sites. Using data from the STOCS Benchmark Study, control

stations that were identical to the test stations could easily be selected. The caged bivalves would be allowed to "sample" the ambient trace metal levels at each station for several weeks before being retrieved and analyzed. To interpret properly such organismal trace element data, it is important to know the environmental levels of the elements at the collection sites. Trace element concentrations in the sediments, suspended matter and water at these stations should also be determined as part of this monitoring study.

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CHAPTER SEVEN

PHYTOPLANKTON AND PRODUCTIVITY

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ABSTRACT

This report summarizes the highlights of the STOCS phytoplankton element integration. The general sampling effort between 1975 and 1977 is compared. Factors from both the STOCS program and supplementary sources are analyzed for pattern, relationship and possible causality. The results provide: 1) verification of decreasing plant biomass offshore and north-to-south; 2) evidence of seasonality in net biomass and in nanno and net productivity; 3) an overview of phytoplankton community irregularity that is probably dependent on complex hydrography; 4) good relationships among phytoplankton indices and with some suggestive physical/chemical factors including salinity and incident solar radiation; 5) significant explanation of biological variability based on physical/chemical factors especially salinity and Secchi depth; and 6) geographic bounds dividing the south Texas shelf along Transect II into three zones at 0-14 nautical miles (Texas rivers) at 15-32 nautical miles (mixing between inshore and offshore waters) and at 33-48 nautical miles (Mississippi River); chlorophyll *a* is inversely related to salinity inshore but not offshore of the 32 nautical mile boundary.

INTRODUCTION

Historical data on the phytoplankton of the South Texas Outer Continental Shelf (STOCS) area is generally confined to the Bureau of Land Management (BLM) program. The three final reports (Van Baalen, 1976; Kamykowski *et al.*, 1977; Kamykowski *et al.*, 1979) describe, in detail, the spatial and temporal patterns of the components of the phytoplankton work element and some relationships between these components and the physical/chemical environment. In addition, Kamykowski and Batterton (1978) summarize four diurnal studies of the vertical structure and temporal variability of a 30 m water column located near Station 4/II. Additional information that may be related to the STOCS area is available in El Sayed *et al* (1972) and SUSIO (1973).

The measurements made within the work elements are backed by an extensive literature. Water column light measurements including Secchi depth determinations are reviewed by Strickland (1958). Jerlov and Steeman-Nielsen (1974) provide a recent discussion of optical oceanography. Sterdinger (*In* El Sayed *et al.*, 1972) discussed phytoplankton species enumerations in the eastern Gulf of Mexico. Parsons *et al* (1977) review field applications of the chlorophyll a, ATP and ^{14}C techniques. Steeman-Nielsen (1975) specifically summarizes various aspects of marine photosynthesis; Malone (1971) considers the implications of relative photosynthesis in the net and nannophytoplankton fractions. Finally, Pratt and Denman (1975) demonstrate the utility of continuously measured *in vivo* fluorescence to characterize phytoplankton spatial heterogeneity.

METHODS

Techniques

The detailed techniques used during each year of the STOCS program

were provided in the previously mentioned final reports. In general, the analyses for chlorophyll a/phaeopigments, ATP, ^{14}C uptake, plant nutrients (except ammonium) and *in vivo* fluorescence followed the methods given in Strickland and Parsons (1968). Ammonium ion was analyzed according to Solorzano (1969). Phytoplankton species enumeration utilized the Utermöhl (1971) procedure except during 1975.

Sampling

The details of the sampling effort in each of the four years is provided in Table 7.1. Program evolution is evident in the changes in sampling intensity and emphasis. The first year of the program (1973) had three cruises; the next two years (1976, 1977) had nine cruises each. The 1978 effort was a special purpose study of the nepheloid layer (NEPHY). The consistent measurements through the program were light extinction, phytoplankton species enumeration and chlorophyll a determinations; the latter was divided into two size fractions (< 20 μm; > 20 μm) in 1976 and 1977. ATP was measured in 1975 and 1976. ^{14}C uptake and *in vivo* fluorescence were measured in 1977 and 1978. The latter year also had data on transmissometry and detailed plant nutrient profiles.

Limitations of Analyses

Four limitations were superimposed on the data analyses: 1) attention was focused on interactions between phytoplankton and the physical/chemical environment since other elements were concerned with phytoplankton effects on higher trophic levels; 2) the data considered were limited to 1976, 1977 and 1978 because of sampling similarity in the former two years and the nepheloid layer emphasis of 1978; 3) surface samples were emphasized to determine the influence of freshwater runoff; and 4) the 18 cruises along Transect II were concentrated upon because of the rapidity of

TABLE 7.1

A SUMMARY OF THE SAMPLING EFFORT EXPANDED ON EACH OF THE FACTORS MEASURED WITHIN THE STOCS PHYTOPLANKTON ELEMENT BETWEEN 1975 AND 1978

	Seasonal	Monthly	Nephy*
LIGHT EXTINSTION			
1975	I-IV:1-3	-	
1976	I-IV:1-3	II:1-3	
1977	I,III,IV:1-3 II;1-6,HR,SB	II:1-6	
1978*	-	-	II:4
PHYTOPLANKTON SPECIES			
1975	I-IV:1-3(S,HP)	-	
1976	I-IV:1-3(S,HP)	II:1-3(S,0.5HP)	
1977	I-IV:1-3(S,HP)	II:1-3(S,0.5HP)	
1978	-	-	II:4(B)
CHLOROPHYLL a/PHAEOPIGMENTS			
1975	I-IV:1-3(S,HP,B)	-	
1976	I-IV:1-3(S,HP,B)	II:1-3(S,HP,B)	
1977	I-IV:1-3(S,HP,B)	II:1-3(S,HP,B)	
1978	-	-	II:4(CONT)
ATP			
1975	I-IV:1-3(S,HP,B)	-	
1976	I-IV:1-3(S,HP,B)	II:1-3(S,HP,B)	
1977	-	-	
1978	-	-	-
CARBON UPTAKE			
1975	-	-	
1976	-	-	
1977	I-IV:1-3(S)	II:1-3(S)	
1978	-	-	II:4(B) (4/29-30:,/24-25)
***IN VIVO* FLUORESCENCE, TEMPERATURE, CONDUCTIVITY**			
1975	-	-	
1976	-	-	
1977	II	II	
1978	-	-	II:4(S-B)
TRANSMISSOMETER			
1978			II:4(S-B)

TABLE 7.1 CONT.'D

	Seasonal	Monthly	Nephy
NUTRIENTS [NO_3, NO_2, NH_4, PO_4, $Si(OH)_4$]			
1978			II:4(S-B)

* Dates for NEPHY were 7/29-30; 8/24-25; 9/25-26; 11/8-9
SB-Southern Bank
HR-Hospital Rock
S-Surface
HP-Half the depth of the photic zone
B-Bottom
CONT-Continuous

phytoplankton turnover.

Statistical Analyses

Table 7.2 lists the biological and physical/chemical factors collected within the STOCS program that were analyzed for relationships. The derived relationships included diversity measured by the Shannon-Weaver index, equitability and probability of interspecific encounter (P.I.E.) described in Hurlbert (1971). Table 7.3 lists the additional data from other sources that were included in the analyses. The present report is a brief summary of the most interesting results based on the application of the following techniques listed in order of appearance:

1) Analysis of variance based on allowances developed by Link and Wallace (*In* Tate and Clelland, 1957);
2) Scatterplots of factor vs. Julian day (SPSS);
3) Cluster analysis (UTCLST 2 procedure with Canberra Metric Distance criterion);
4) Linear correlation analyses among the factors (SPSS);
5) Multiple polynomial regression analysis with estimates of percent variance explained (SPSS);
6) Serial application of linear correlation analysis to the continuous samples along Transect II (SPSS);
7) Scatterplots of salinity vs. chlorophyll a with polynomial fit.

Strict statistical significance at the 5% level is identified as such where applicable; otherwise, the term "trend" is used to describe the results.

RESULTS AND DISCUSSION

Spatial-Temporal Patterns of Phytoplankton Biomass

Table 7.4 summarizes the application of an Analysis of Variance based

TABLE 7.2

A LIST OF THE BIOLOGICAL AND PHYSICAL/CHEMICAL FACTORS MEASURED WITHIN THE STOCS STUDY THAT ARE CONSIDERED ON THIS REPORT

BIOLOGICAL	PHYSICAL/CHEMICAL
Secchi Depth	Temperature
Nanno Chlorophyll *a* (< 20 μm)	Salinity
Net Chlorophyll *a* (>20 μm)	Silicate
Total Chlorophyll *a*	Phosphate
Nanno Chlorophyll/Phaeopigment	Nitrate
Net Chlorophyll/Phaeopigment	Dissolved Oxygen
Total Chlorophyll/Phaeopigment	
Nanno Carbon 14 Uptake	
Net Carbon 14 Uptake	
Total Carbon 14 Uptake	
Nanno Carbon 14/Chlorophyll	
Net Carbon 14/Chlorophyll	
Total Carbon 14/Chlorophyll	
Number of Species	
Number of Individuals	
Diversity	
Equitability	
P.I.E.	

TABLE 7.3

A LIST OF THE SUPPLEMENTARY DATA FROM OTHER SOURCES CONSIDERED IN THIS REPORT

INCIDENT SOLAR RADIATION (kilojoules/m^2)

1) Brownsville, Texas
2) Lake Charles, Louisiana
3) Average of 1 and 2 above

-Source: National Climatic Center, Asheville, N.C.

WIND SPEED AT CORPUS CHRISTI AIRPORT (mph)

-Source: National Climatic Center, Asheville, N.C.

RIVER DISCHARGE (ft^3/sec)

1) Mississippi River

-Source: U.S. Geological Survey, Baton Rouge, Louisiana

2) Texas Rivers: a) Trinity
b) Brazos, San Bernard and Colorado
c) Guadalupe, San Antonio, Mission, Nueces
d) Rio Grande

-Source: U.S. Geological Survey, Austin, Texas

DELTA SIGMA-t ($\delta\sigma_T$)(gm/cm^3)

-σ_T = (p - 1) x 1000, p-water density

-Source: Dr. Ned Smith, obtained by subtracting surface σ_T from bottom σ_T at each station

TABLE 7.4

ANALYSIS OF VARIANCE BASED ON ALLOWANCES APPLIED TO THE NANNO, NET AND TOTAL CATEGORIES OF CHLOROPHYLL a COLLECTED FROM THE SURFACE, HALF-PHOTIC ZONE AND BOTTOM DURING THE SEASONAL CRUISES OF 1976 AND 1977

		Offshore	North-South
Surface:	Nanno	1 > 2, 3	N.S.
	Net	1 > 2, 3	I III, IV
	Total	1 > 2, 3	I, II > IV
Half-Photic:	Nanno	1 > 2, 3	II > IV
	Net	1 > 2, 3	N.S.
	Total	1 > 2, 3	I, II > IV
Bottom:	Nanno	1, 2 > 3	N.S.
	Net	1 > 2, 3	N.S.
	Total	1, 2 > 3	N.S.

N.S. - Not significant

on allowances to the six seasonal cruises in 1976 and 1977. The nanno, net and total chlorophyll categories are treated separately within the surface, half photic and bottom sample sets. The offshore gradient of chlorophyll a is statistically significant for all categories of all depths. The bottom samples exhibit a slightly different pattern than the surface and half the depth of the photic zone: the nanno and total categories are similar at Stations 1 and 2 instead of 2 and 3. The north-south gradient is not as pervasive as the offshore gradient. The northern part of the STOCS area is significantly higher in chlorophyll a at the surface in the net and total categories, and at half the depth of the photic zone in the nanno and total categories. The bottom samples are similar along all transects for all categories.

Figures 7.1 through 7.3 summarize the temporal and depth patterns in the nanno (a), net (b) and total (c) categories of chlorophyll a at the three stations of Transect II. Station 1/II is temporally characterized by a continuous background concentration of nanno-chlorophyll a; concentration peaks occur in the April and Fall (Hurricane Anita) cruises of 1977. Net chlorophyll a is much more variable exhibiting a seasonal occurrence between November and May. The seasonality in total chlorophyll a concentration is dominated by the net fraction. Surprisingly, the water column is routinely inverted in chlorophyll a concentration, *i.e.* the maximum concentration occurs in the bottom sample.

Station 2/II exhibits even less variability in the nanno-fraction than Station 1/II. The concentration of nanno-chlorophyll a, however, generally exceeds that of the net fraction. Two exceptions are at the surface, April 1976 and near-bottom, July 1977. The total chlorophyll a concentration reflects the nanno trend except during the net fraction peaks. The vertical profile of chlorophyll a again routinely exhibits an increase with depth.

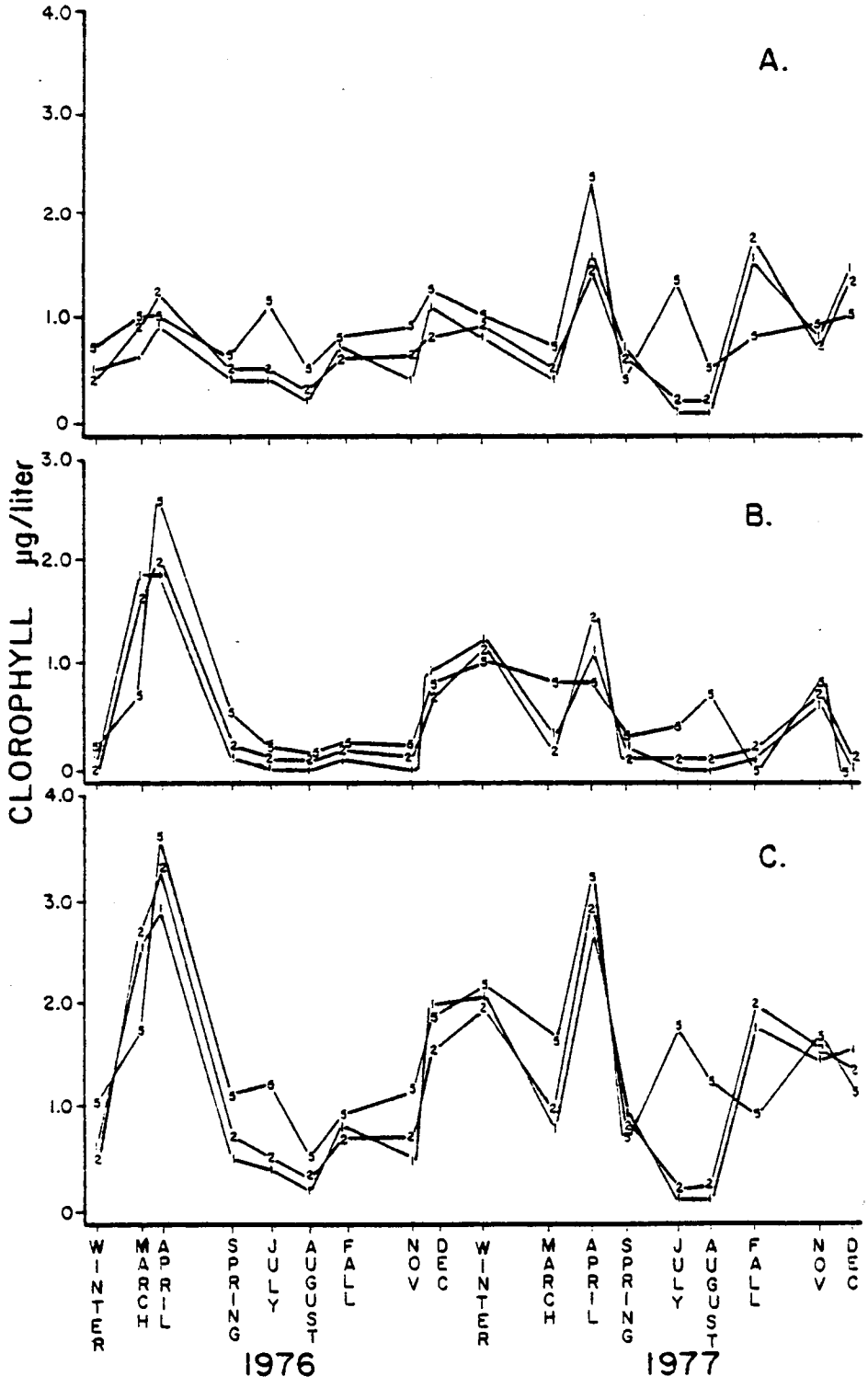

Figure 7.1 Station 1 Chlorophyll a (µg/ℓ) at the Surface (1), Half the Depth of the Photic Zone (2) and Bottom (5) in the a) Nanno, b) Net, and c) Total Categories Plotted Against Julian Day.

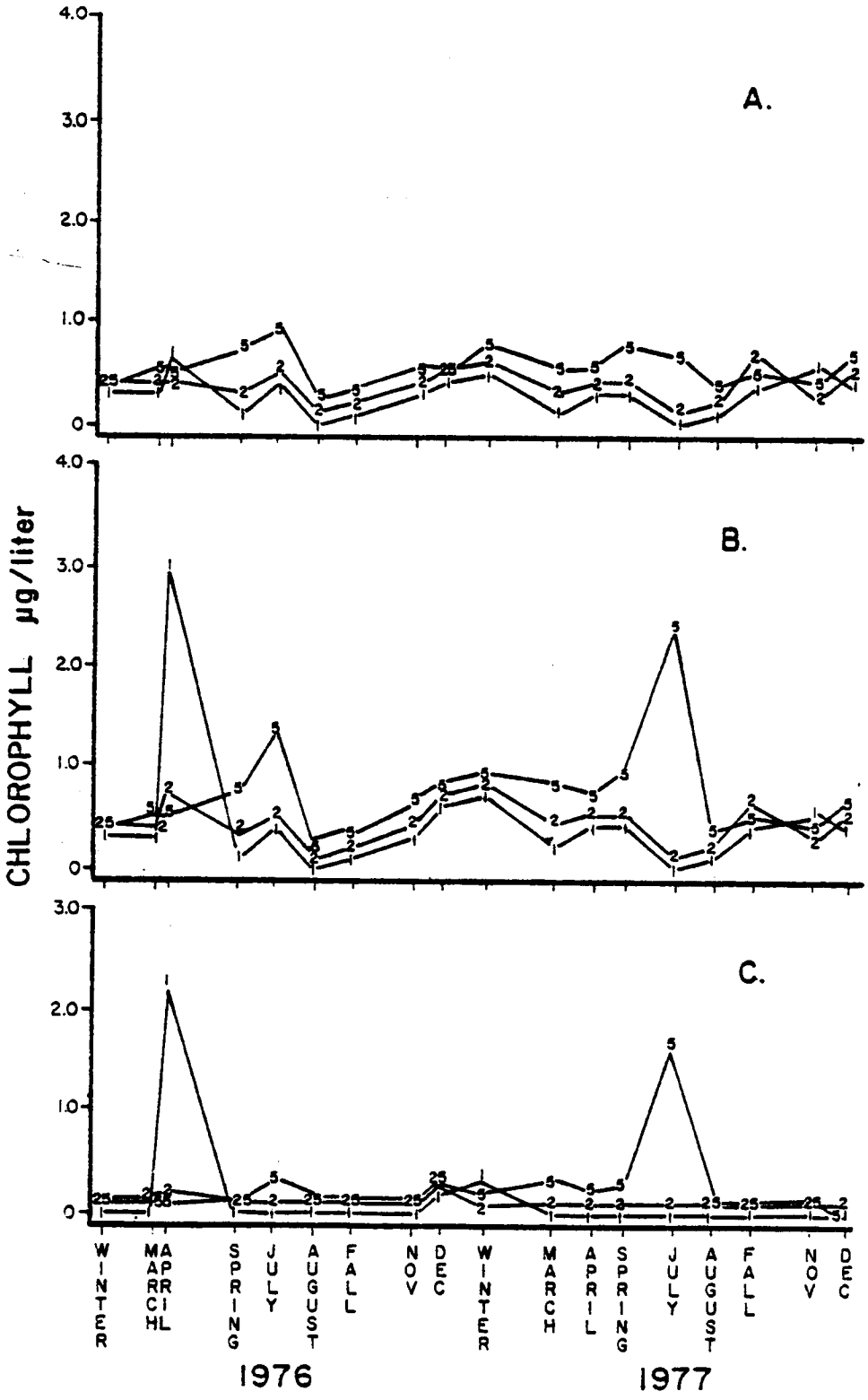

Figure 7.2 Station 2 Chlorophyll a (µg/ℓ) at the Surface (1), Half the Depth of the Photic Zone (2), and Bottom (5), in the A) Nanno, B) Net, and C) Total Categories Plotted Against Julian Day.

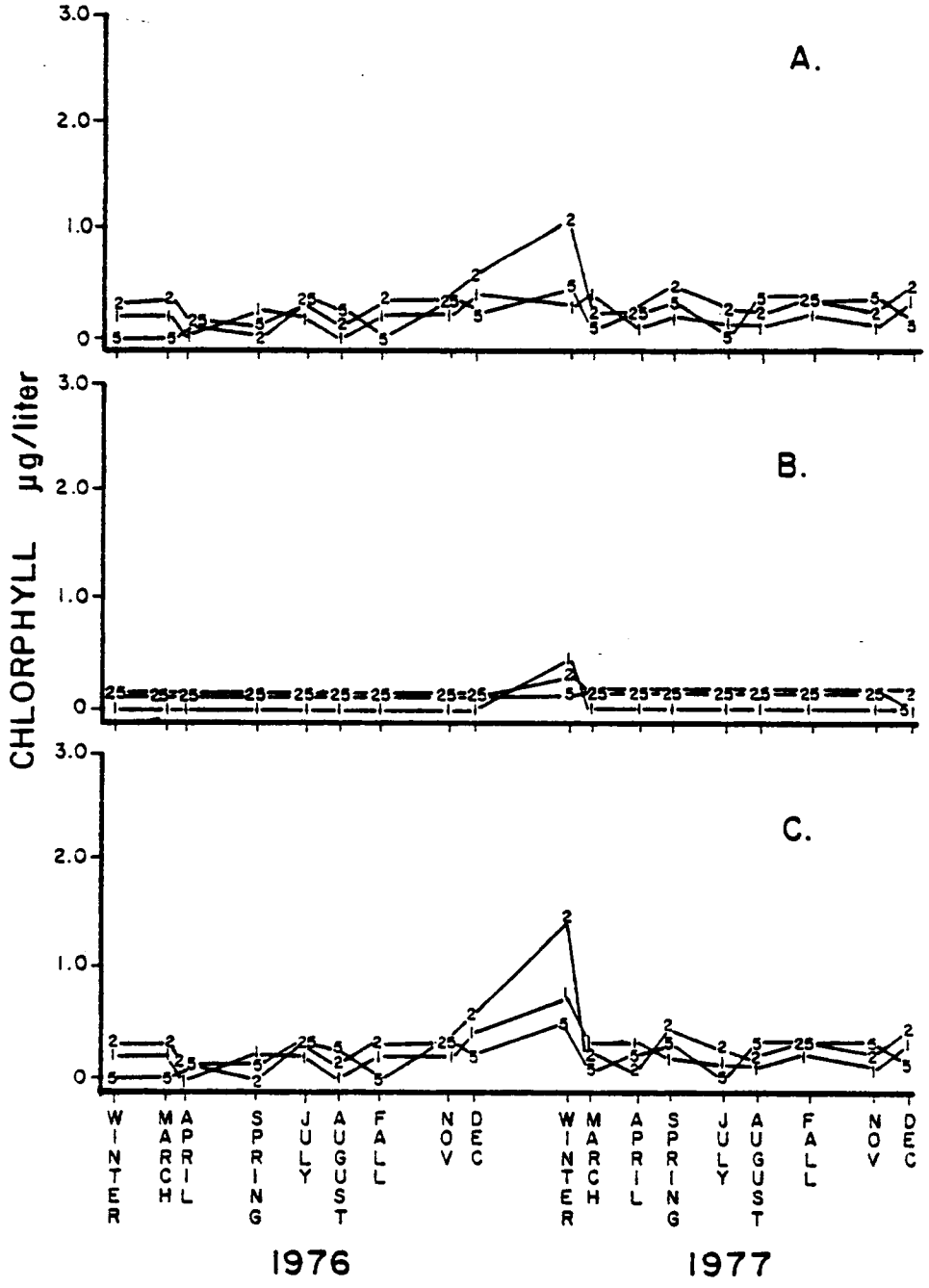

Figure 7.3 Station 3 Chlorophyll a (µg/ℓ) at the Surface (1), Half the Depth of the Photic Zone (2), and Bottom (5), in the A) Nanno, B) net, and C) Total Categories Plotted Against Julian Day.

Station 3/II exhibits a further decrease in nanno-chlorophyll a variability. An exception occurs at the half-photic zone, Winter 1977. The net fraction is extremely low except for the winter of 1977. The total chlorophyll a category reflects the even distribution of the other two categories throughout the sampling period except for the combined nanno and net peaks during Winter 1977. This unusual concentration of chlorophyll a at all depths is related to an upwelling during February 1977. This event may occur every year but is easily missed in a sampling program because of its probable short duration.

Nepheloid Layer

As stated previously, the highest concentration of chlorophyll a within the water column is often observed in the near bottom sample. This relationship is especially strong at Stations 1 and 2 in July (Figure 7.1C and 7.2C). The bottom of the water column is also characterized by a pervasive nepheloid layer (Berryhill *et al.*, 1977). Four cruises from 1978 provide detailed time-series information on the relationship between phytoplankton and the nepheloid layer. The basic conclusions of the study are:

1) The nepheloid layer is present throughout the sample period. It fluctuates in thickness and density within a 24-h period.
2) Phytoplankton are concentrated in the nepheloid layer during the summer months in the STOCS area. Active carbon fixation can occur since 10% surface radiation may reach the sediment interface in the zone within 30 nautical miles of shore.
3) Since nutrients are probably supplied to the layer at least partly from benthic diffusion, the phytoplankton dynamics of the layer may be affected by perturbations of the benthos caused by

oil-related activities.

4) The overall impact of this effect depends on organism sensitivity, the area perturbed, exchange intensity and the trophic significance.

Spatial-Temporal Patterns in Phytoplankton Activity

Table 7.5 summarizes an application of the Analysis of Variance based on allowances to the three seasonal cruises in 1977. The surface samples of the nanno, net and total carbon 14 uptake categories are treated separately. The offshore gradient is significant within all categories: nanno and total carbon 14 uptake show Station 1 greater than 2 and 3; net carbon 14 uptake only shows Station 1 greater than Station 3. A north-south gradient is significant only in the total category with Transect I significantly higher than Transect IV.

Figure 7.4 summarizes the temporal patterns in the nanno (a), net (b) and total (c) categories of carbon 14 uptake at the three stations of Transect II during 1977. Stations 2 and 3 dominate the winter nanno activity; Station 1 is dominant over the rest of the year. The inshore peaks in nanno activity occur in spring and fall. Station 1 dominates the net activity except during December and when Station 3 is dominant. The peaks in net activity are in April and November. The net peak precedes the nanno peak in the spring bloom and follows it during the fall bloom. The total category presents the composite of the size fractions and provides a picture of classic temperate zone phytoplankton activity.

Assimilation ratios are not presented here because of their complex relationship with the environmental mosaic of the south Texas shelf. More samples are required for a definitive interpretation of the data.

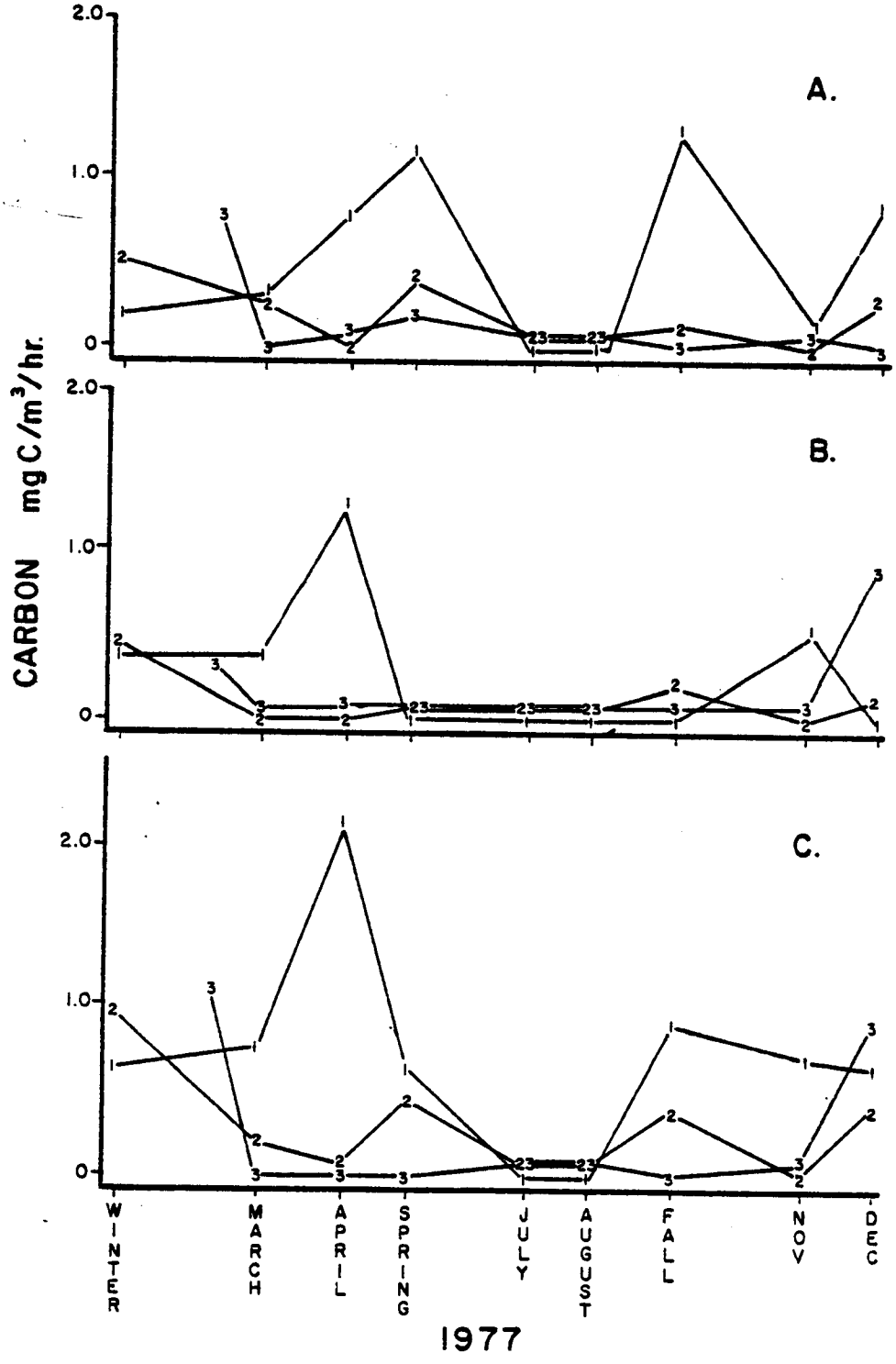

Figure 7.4 Stations 1, 2 and 3 Surface Carbon 14 uptake ($mgC/m^3/hr$) in the A) Nanno, B) Net and C) Total Categories Plotted against Julian Day.

TABLE 7.5

ANALYSIS OF VARIANCE BASED ON ALLOWANCES APPLIED TO THE NANNO, NET AND TOTAL CATEGORIES OF CARBON 14 UPTAKE COLLECTED FROM THE SURFACE DURING THE SEASONAL CRUISES OF 1977

	Offshore	North-South
Nannoplankton	1 > 2, 3	N.S.
Netplankton	1 > 3	N.S.
Total	1 > 2, 3	I > IV

N.S.-Not Significant

Phytoplankton Community Pattern

The results of the cluster analysis are presented in Figures 7.5, 7.6 and 7.7. Because of the community variability encountered, the station runs are subdivided into individual seasons or individual stations within each year. The results provide a view of the localized spatial or temporal patterns within the sub-units of the overall STOCS phytoplankton community. Both surface and half-photic zone samples are individually considered.

Figure 7.5 considers the spatial variability in phytoplankton community structure that occurs in the STOCS region during a given season. The ideal result is three bands parallel to shore. This pattern does not occur in any season. The closest approximation is the two band structure during winter 1976 in the surface samples. In general, a complex interdigitation of community structure occurs across the shelf.

Figure 7.6 considers the seasonality patterns within the bands that parallel the shore formed by simultaneously considering the similarly numbered stations within each transect (*i.e.* 1/I, 1/II, 1/III, 1/IV). The ideal result is depicted in the surface and half-photic zone cases obtained at Station 1 during 1977. Perfect seasonal grouping is seen with similar communities occurring at all transects at the same time. The complexity of the phytoplankton community structure in the STOCS area is evident in the frequent deviation from this simple pattern. In general, the progression of community structure through the seasons occurs at different rates at different locations on the shelf.

Figure 7.7 considers the fine scale temporal succession patterns in phytoplankton community structure along Transect II. The ideal breakpoints in the cruise groupings are difficult to define because of the multiple forcing functions that might be considered on this fine

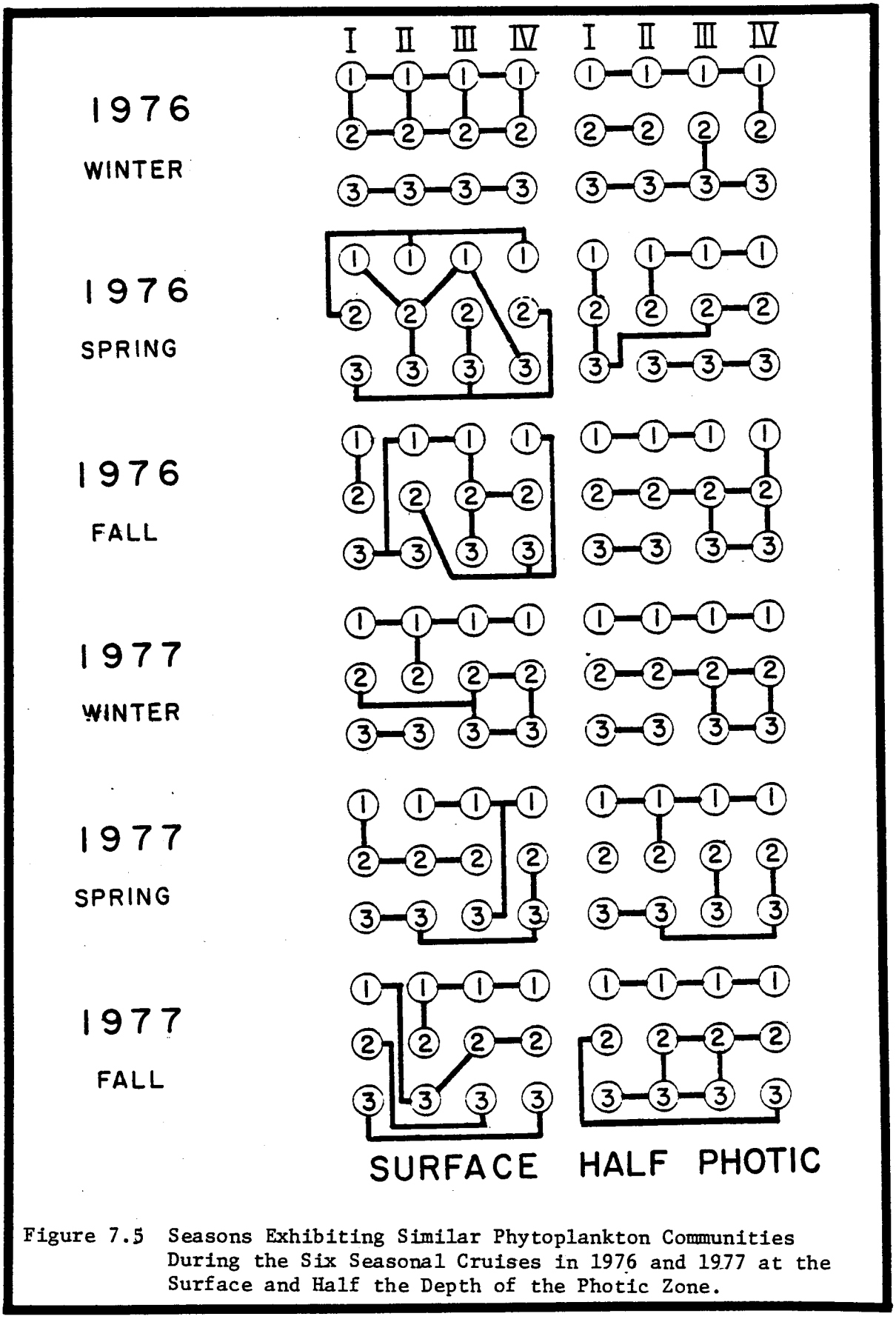

Figure 7.5 Seasons Exhibiting Similar Phytoplankton Communities During the Six Seasonal Cruises in 1976 and 1977 at the Surface and Half the Depth of the Photic Zone.

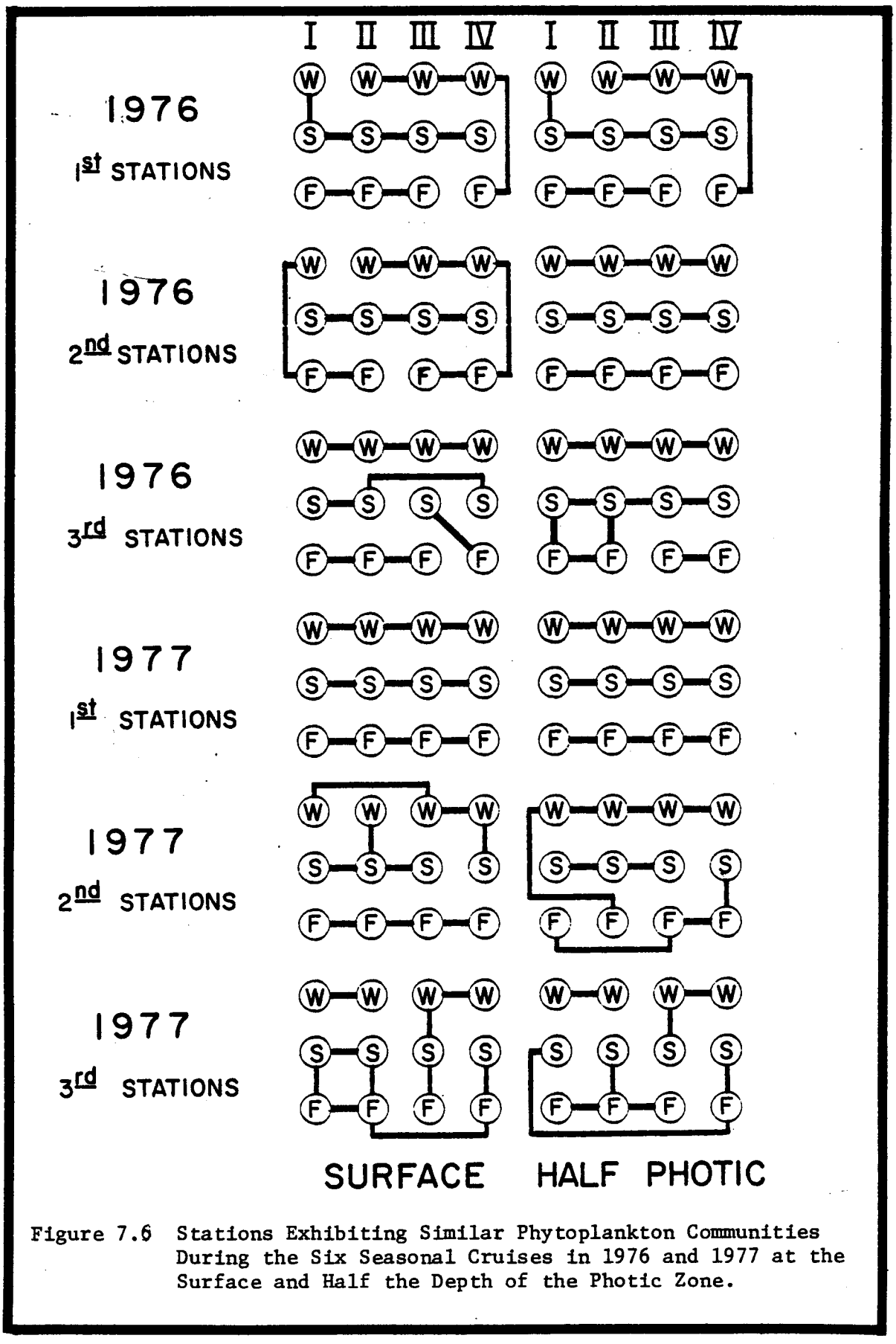

Figure 7.6 Stations Exhibiting Similar Phytoplankton Communities During the Six Seasonal Cruises in 1976 and 1977 at the Surface and Half the Depth of the Photic Zone.

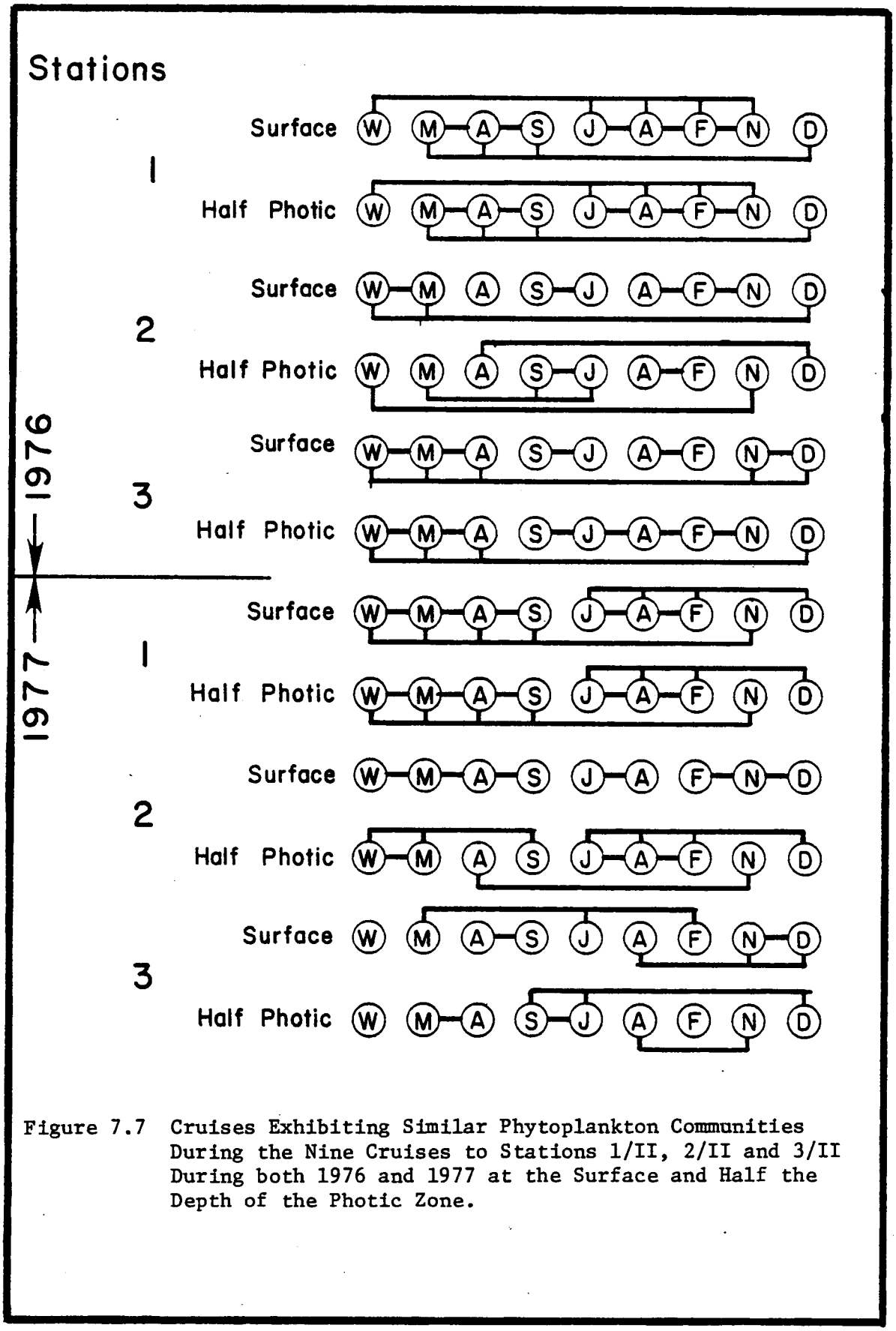

Figure 7.7 Cruises Exhibiting Similar Phytoplankton Communities During the Nine Cruises to Stations 1/II, 2/II and 3/II During both 1976 and 1977 at the Surface and Half the Depth of the Photic Zone.

scale: light intensity, day length, temperature, salinity, stratification, wind and nutrient sources. Intuitively, the simple groupings depicted at the surface and half the depth of the photic zone at Station 3 during 1976 are probably a base model. The remaining patterns at other stations in other years again demonstrate the complexity of the phytoplankton response to conditions in the STOCS area.

The species groupings derived from the cluster program are less informative than the station groupings. This results from both technical and biological reasons. Technically, the phytoplankton counts are generally limited to the size fraction above 20 μm. Since this fraction is dominant only between December and April, the groups formed only represent successions within this time period. The cruises are not sufficiently frequent to adequately distinguish community changes within this limited period. Information on summer community structure is also limited by the fact that the greatest concentration of phytoplankton occurs near bottom where species samples are not available. The biological reasons are related to the low sampling frequency compared to the rate of change of phytoplankton species composition. The species lists available for grouping are usually very different from one cruise to the next. Considering these problems, Figure 7.8 depicts the seasonal patterns of the phytoplankton classes and Figure 7.9 depicts the seasonal pattern of selected phytoplankton species or genera from the net phytoplankton observed at the surface along Transect II during 1976 and 1977. The graphs are ordered by decreasing numerical abundance.

Figure 7.8 demonstrates that diatoms, dinoflagellates, and silicoflagellates are generally most abundant between the November and Spring cruises, through the winter months. The remaining time interval is represented by a minor dinoflagellate peak, coccolithophorids and

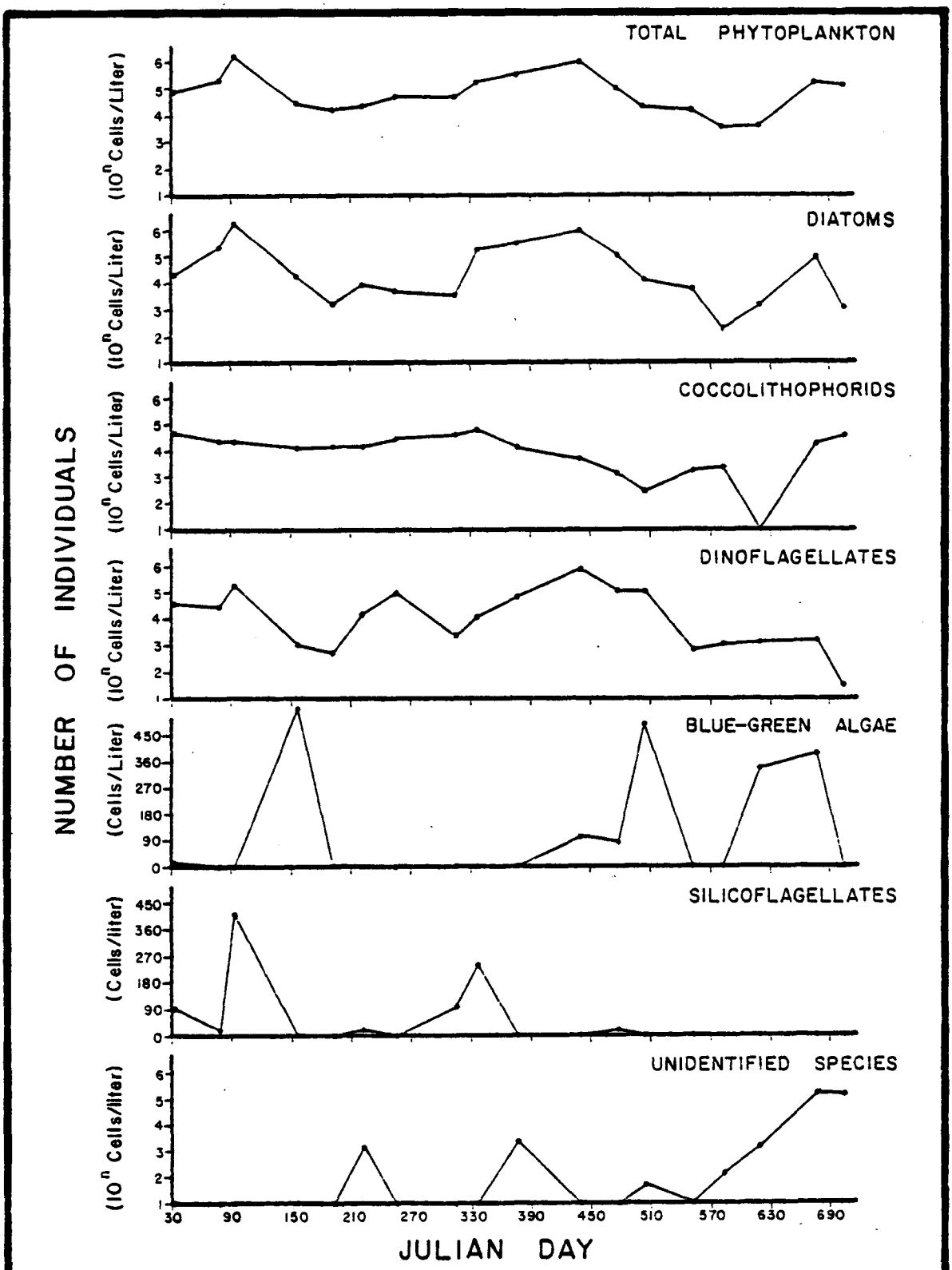

Figure 7-8. Comparison of Seasonal Abundances of the Different Classes of Phytoplankton Observed During the Eighteen Cruises Along Transect II During 1976 and 1977. Each Point Represents the Sum of the Surface Abundances at Stations 1/II, 2/II and 3/II Within a Given Cruise. Number of Individuals (cells/ℓ) are Plotted Against Julian Day. The Graphs are Ordered by Decreasing Abundance.

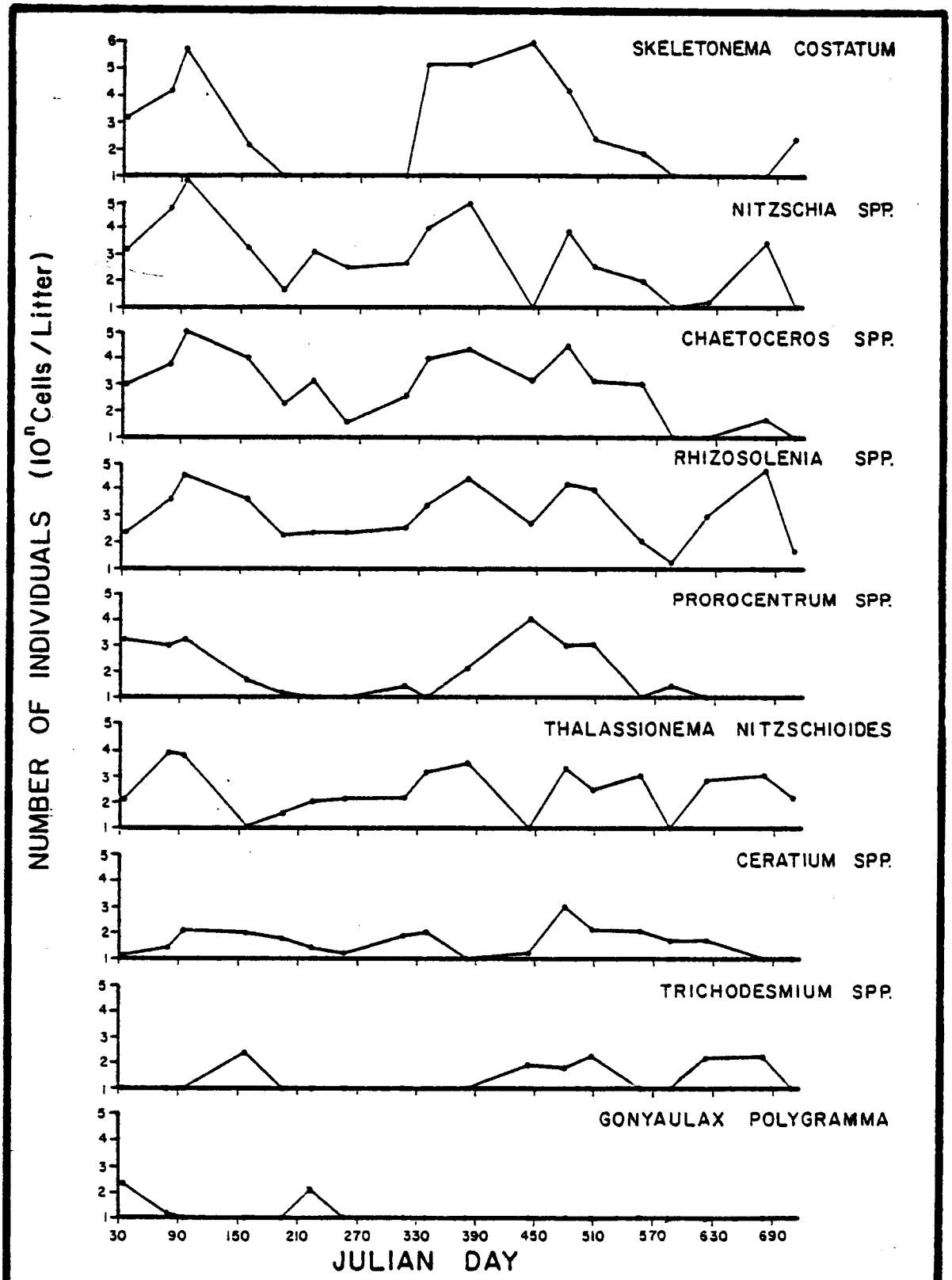

Figure 7-9. Comparison of the Seasonal Abundances of Different Species of Genera of Phytoplankton Observed During the Eighteen Cruises Along Transect II During 1976 and 1977. Each Point Represents the Sum of the Surface Abundances at Stations 1/II, 2/II and 3/II Within a Given Cruise. Number of Individuals (Cells/ℓ) are Plotted Against Julian Day. The Graphs are Ordered by Decreasing Abundance.

blue-green algae.

Figure 7.9 demonstrates the seasonal preference of selected species or genera. The two years are different in the order of species appearance. In 1976, a relatively clear succession occurrs: Winter - *Gonyaulax polygramma* and *Prorocentrum micans*; March - *Thalassionema nitzschioides*; April - *Skeletonema costatum, Nitzschia* sps., *Chaetoceros* sps.; Spring - *Trichodesmium*; August - *Gonyaulax polygramma* and *Thalassionema nitzschioides*. In 1977, more co-occurrence is evident: Pre-March - *Skeletonema costatum, Nitzschia* spp. and *Prorocentrum micans*; Post-March - *Chaetoceros* spp., *Rhizosolenia* spp., *Thalassionema nitzschioides, Ceratium* spp. and *Trichodesmium* spp., August - *Thalassionema nitzschioides*; Fall - *Trichodesmium* spp.; November - *Rhizosolenia* spp.

The patterns present a confused picture of the phytoplankton community. This probably results from the complex hydrography in the STOCS area. Better information may be obtained by eliminating geographic stations and relating species assemblages in similar water masses (see discussion of River Discharge later).

Correlation Diagrams

The general interrelationships in the surface samples among the various factors listed in Table 7.2 are presented in Tables 7.6 and 7.7. Table 7.6 is a correlation trellis diagram among the biological factors. Using correlation coefficients beyond ± 0.600 as a conservative index of trend for those variables that have ecological meaning (underlined), the most important relationships exist between;

1) chlorophyll a (net, total)-number of individuals;

2) chlorophyll a (nanno, net, total)-carbon 14 (nanno, net, total);

3) chlorophyll a (nanno, net, total)-Secchi depth.

TABLE 7.6

CORRELATION TRELLIS DIAGRAM AMONG THE BIOLOGICAL FACTORS LISTED IN TABLE 7.2

	No. Species	No. Individuals	Diversity	P.I.E.	Equitability	Net Chlorophyll	Nan Chlorophyll	Total Chlorophyll	Net Phaeopigment	Nan Phaeopigment	Total Phaeopigment	Net C14	Nan C14	Total C14	C14/Net Chlorophyll	C14/Nan Chlorophyll	C14/Total Chlorophyll
No. Individuals	.353																
Diversity	.542	.123															
P.I.E.	.333	.096	.940														
Equitability	-.169	-.132	.632	.730													
Net Chlorophyll	.421	.783	.362	.325	.006												
Nan Chlorophyll	.094	.255	.173	.164	.060	.500											
Total Chlorophyll	.328	.649	.326	.297	.033	.912	.812										
Net Phaeopigments	.294	.401	.403	.312	.079	.517	.628	.647									
Nan Phaeopigments	.021	.190	.029	.010	.061	.248	.495	.402	.366								
Total Phaeopigments	.064	.226	.084	.054	.076	.313	.526	.461	.434	.993							
Net C14	.311	.285	.297	.231	.099	.676	.425	.600	.365	.213	.269						
Nan C14	.484	.114	.375	.249	.046	.343	.776	.663	.697	.275	.332	.170					
Total C14	.469	.321	.390	.268	.107	.702	.750	.820	.637	.304	.391	.828	.676				
C14/Net Chlorophyll	-.120	-.075	.088	.203	.183	-.257	-.109	-.196	.089	.323	.119	.185	-.338	.039			
C14/Nan Chlorophyll	.580	.265	.334	.127	-.089	.163	.202	.208	.638	.190	.286	.036	.682	.421	-.362		
C14/Total Chlorophyll	.362	.251	.177	.093	-.083	.178	.220	.227	.402	.243	.305	.614	.320	.650	.312	.467	
Secchi Depth	-.398	-.319	-.261	-.165	.038	-.513	-.638	-.657	-.600	-.335	-.370	-.396	-.294	-.573	.211	-.245	-.297

TABLE 7.7

CORRELATION MATRIX DIAGRAM BETWEEN THE BIOLOGICAL FACTORS AND SOME OF THE PHYSICAL/CHEMICAL FACTORS LISTED IN TABLES 7-2 AND 7-3.

	Salinity	Temperature	Silicate	Phosphate	Nitrate	Dissolved Oxygen	Sigma-t	Wind	Solar Radiation
No. Species	-.452	-.367	-.084	-.061	.276	.417	-.027	.218	-.321
No. Individuals	-.473	-.375	-.069	.090	.046	.597	-.123	.190	-.089
Diversity	-.458	-.065	-.037	-.201	.182	.187	.194	.223	.005
P.I.E.	-.327	.006	-.016	-.166	.138	.107	.151	.261	.036
Equitability	-.169	.239	-.041	-.319	-.033	-.118	.234	.166	.219
Net Chlorophyll	-.645	-.465	.174	.167	.097	.615	-.027	.286	-.282
Nan Chlorophyll	-.453	-.322	.433	.394	.296	.287	-.315	.060	-.291
Tot.Chlorophyll	-.650	-.466	.323	.299	.206	.551	-.168	.222	-.331
Net C14	-.172	-.388	.431	.091	.363	.228	-.296	.221	-.620
Nan C14	-.623	-.211	.115	.267	.398	.160	-.096	-.148	-.245
Total C14	-.423	-.412	.395	.229	.491	.280	-.325	.017	-.448
Net Assimilation Ratio	.383	.201	.124	-.505	-.019	-.273	-.317	-.006	.102
Nan Assimilation Ratio	-.468	-.415	-.229	-.027	.257	.385	.048	-.260	-.181
Tot.Assimilation Ratio	-.118	-.359	.100	.001	.425	.279	-.231	-.274	-.307
Secchi Depth	.544	.543	-.356	-.417	-.385	-.539	.309	-.110	.306

The previously stated relationship between net chlorophyll a and the species counts is quantified. Phytoplankton biomass and photosynthesis activity are generally related. Phytoplankton biomass also probably contributes significantly to water column turbidity.

Table 7.7 is a correlation matrix of the interrelationships between the biological and the physical/chemical factors (except river runoff). Again, using correlations beyond ± 0.600 as a conservative index of trend, the most important relationships exist between;

1) salinity - chlorophyll a (net, total); carbon 14 (nanno);

2) dissolved oxygen - chlorophyll a (net);

3) solar radiation - carbon 14 (net).

Salinity and solar radiation probably influence phytoplankton through improved growth conditions. Phytoplankton may increase the dissolved oxygen in the water through photosynthesis.

Polynomial Fits Yielding Percent Variability Explained

Tables 7.8, 7.9, 7.10 and 7.11 summarize the results of a multiple polynomial regression analysis applied to surface samples collected in 1976 and 1977. The biological factors as dependent variables and the physical/chemical factors as independent variables are analyzed for all stations together and for Stations 1, 2 and 3 separately. Secchi depth is considered a physical variable though the factor is influenced by both organic and inorganic elements. This factor is analyzed both for biological and physical/chemical dependencies at the end of each table.

The analysis applied to all stations simultaneously (Table 7.8) provides significant predictor relationships for many of the phytoplankton factors. Among the more interesting are:

1) Numbers of species: River Discharge: Mississippi (47%). Though

TABLE 7.8

ALL STATIONS:

SUMMARY OF MULTIPLE REGRESSION ANALYSIS RESULTS OF DEPENDENT PHYTOPLANKTON VARIABLES AGAINST INDEPENDENT PHYSICAL FACTORS. THE INDEPENDENT VARIABLES, THE EXPONENTIAL POWERS OF THE INDEPENDENT VARIABLES USED IN THE NON-LINEAR REGRESSION, AND THE PERCENT VARIATION EXPLAINED ARE LISTED IN ORDER OF IMPORTANCE IN THE ANALYSIS. THE UNDERLINED EXPONENT INDICATES THE POWER OF THE VARIABLE WHICH CONTRIBUTED THE MOST TO THE PERCENT VARIANCE EXPLAINED. INDEPENDENT VARIABLES WERE SIGNIFICANT AT THE $P<0.05$ LEVEL EXCEPT THOSE INDICATED BY AN ASTERISK (*) WHICH WERE SIGNIFICANT AT THE $P<0.1$ LEVEL. TOTAL VARIATION EXPLAINED FOR EACH DEPENDENT VARIABLE IS ALSO SHOWN.

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variable		Total Variation
Number of Species	River Discharge: Mississippi ($\underline{1}$,2,3,4) 47%	Secchi Depth (1,2,3,$\underline{4}$) 10%	57%
Number of Individuals	Dissolved Oxygen ($\underline{1}$,2,3,4) 79%		79%
Diversity	Salinity ($\underline{1}$,2,4) 27%	Secchi Depth (1,2,3,$\underline{4}$) 6%	33%
Net Chlorophyll	Salinity ($\underline{1}$,2,4) 49%	Dissolved Oxygen (1,3,$\underline{4}$) 26%	75%
Nanno Chlorophyll	Secchi Depth ($\underline{1}$,2,3,4) 74%		74%
Total Chlorophyll	Secchi Depth ($\underline{1}$,2,4) 56%	Salinity ($\underline{1}$,2,4) 17%	73%
Net C14	Avg. Solar Radiation (1,$\underline{2}$,3,4) 58%	Secchi Depth ($\underline{1}$,2,3,4) 36%	85%

TABLE 7-8 CONT.'D

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variable				Total Variation
Nanno C14	Secchi Depth (1,2,4) 58%	Salinity (1,3,) 9%			67%
Total C14	Secchi Depth (1,2,3,4) 72%	Nitrogen (1,2,3,4) 27%			99%
Net Assimilation Ratio*	Secchi Depth (1,2,3,4) 51%				51%
Total Ratio	Secchi Depth (1,2,3,4) 56%				56%
Secchi Depth	Temperature (1,2,3) 41%	Salinity (1,2,3,) 19%	Phosphate (1,2,3) 8%	Nitrate (1,2,3) 6%	74%
Secchi Depth	Nan Chlorophyll (1,2,3,4) 40%	Net Chlorophyll (1,2,4) 30%			70%

TABLE 7.9

STATION 1:

SUMMARY OF MULTIPLE REGRESSION ANALYSIS RESULTS OF DEPENDENT PHYTOPLANKTON VARIABLES AGAINST INDEPENDENT PHYSICAL FACTORS. THE INDEPENDENT VARIABLES, THE EXPONENTIAL POWERS OF THE INDEPENDENT VARIABLES USED IN THE NON-LINEAR REGRESSION, AND THE PERCENT VARIATION EXPLAINED ARE LISTED IN ORDER OF IMPORTANCE IN THE ANALYSIS. THE UNDERLINED EXPONENT INDICATES THE POWER OF THE VARIABLE WHICH CONTRIBUTED THE MOST TO THE PERCENT VARIANCE EXPLAINED. INDEPENDENT VARIABLES WERE SIGNIFICANT AT THE $P<0.05$ LEVEL EXCEPT THOSE INDICATED BY AN ASTERISK (*) WHICH WERE SIGNIFICANT AT THE $P<0.1$ LEVEL. TOTAL VARIATION EXPLAINED FOR EACH DEPENDENT VARIABLE IS ALSO SHOWN.

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variables		Total Variation
Number of Species	River Discharge: Mississippi ($\underline{1}$,2,3,4) 64%	Secchi Depth ($\underline{1}$,2,3,4) 18%	82%
Number of Individuals	Dissolved Oxygen ($\underline{1}$,2,4) 56%		56%
Net Chlorophyll*	Salinity ($\underline{1}$,2,4) 56%	Dissolved Oxygen ($\underline{1}$,3,4) 11%	67%
Nanno Chlorophyll	Secchi Depth ($\underline{1}$,2,3,4) 62%		62%
Total Chlorophyll*	Secchi Depth ($\underline{1}$,2,4) 49%	Salinity ($\underline{1}$,2,4) 19%	68%
Net C14	Avg. Solar Radiation ($\underline{1}$,2,4) 98%	Secchi Depth ($\underline{1}$,4) 2%	100%

TABLE 7.9 CONT.'D

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variables				Total Variation
Total C14	Secchi Depth (1,2,4) 71%	Nitrogen (1,2,4) 29%			100%
Total Ratio	Secchi Depth (1,2,3,4) 95%				95%
Secchi Depth	Salinity (1) 36%	Temperature (1,3) 26%	Nitrate (2,3) 24%	Phosphate (1,3) 14%	100%
Secchi Depth	Nan Chlorophyll (1,2,3,4) 53%	Net Chlorophyll (1,2,4) 29%			82%

TABLE 7.10

STATION 2:

SUMMARY OF MULTIPLE REGRESSION ANALYSIS RESULTS OF DEPENDENT PHYTOPLANKTON VARIABLES AGAINST INDEPENDENT PHYSICAL FACTORS. THE INDEPENDENT VARIABLES, THE EXPONENTIAL POWERS OF THE INDEPENDENT VARIABLES USED IN THE NON-LINEAR REGRESSION, AND THE PERCENT VARIATION EXPLAINED ARE LISTED IN ORDER OF IMPORTANCE IN THE ANALYSIS. THE UNDERLINED EXPONENT INDICATES THE POWER OF THE VARIABLE WHICH CONTRIBUTED THE MOST TO THE PERCENT VARIANCE EXPLAINED. INDEPENDENT VARIABLES WERE SIGNIFICANT AT THE $P<0.05$ LEVEL EXCEPT THOSE INDICATED BY AN ASTERISK (*) WHICH WERE SIGNIFICANT AT THE $P<0.1$ LEVEL. TOTAL VARIATION EXPLAINED FOR EACH DEPENDENT VARIABLE IS ALSO SHOWN.

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variables		Total Variation
Number of Species	River Discharge: Mississippi ($\underline{1}$,2,3) 45%	Secchi Depth ($\underline{1}$,2) 22%	67%
Number of Individuals	Dissolved Oxygen (1,2,3,$\underline{4}$) 97%		97%
Diversity*	Salinity ($\underline{1}$,2,4) 43%	Secchi Depth ($\underline{1}$,2,3,4) 22%	65%
Net Chlorophyll	Dissolved Oxygen (1,3,$\underline{4}$) 59%	Salinity ($\underline{1}$,2,4) 39%	98%
Nanno Chlorophyll	Secchi Depth ($\underline{1}$,2,3,4) 79%	Salinity (1,3,$\underline{4}$) 8%	87%
Total Chlorophyll	Salinity ($\underline{1}$,2,$\underline{4}$) 55%	Secchi Depth ($\underline{1}$,2,4) 36%	91%
Net C14	Secchi Depth ($\underline{1}$,4) 75%	Avg. Solar Radiation ($\underline{1}$,$\underline{4}$) 25%	100%

TABLE 7.10 CONT.'D

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variables				Total Variation
Secchi Depth	Temperature (1) 40%	Salinity (1) 9%	Nitrate (1) 3%	Phosphate (1) 1%	53%
Secchi Depth	Nan Chlorophyll (1,2,3,4) 74%	Net Chlorophyll (1,2,4) 15%			89%

TABLE 7.11

STATION 3:

SUMMARY OF MULTIPLE REGRESSION ANALYSIS RESULTS OF DEPENDENT PHYTOPLANKTON VARIABLES AGAINST INDEPENDENT PHYSICAL FACTORS. THE INDEPENDENT VARIABLES, THE EXPONENTIAL POWERS OF THE INDEPENDENT VARIABLES USED IN THE NON-LINEAR REGRESSION, AND THE PERCENT VARIATION EXPLAINED ARE LISTED IN ORDER OF IMPORTANCE IN THE ANALYSIS. THE UNDERLINED EXPONENT INDICATES THE POWER OF THE VARIABLE WHICH CONTRIBUTED THE MOST TO THE PERCENT VARIANCE EXPLAINED. INDEPENDENT VARIABLES WERE SIGNIFICANT AT THE P<0.05 LEVEL EXCEPT THOSE INDICATED BY AN ASTERISK (*) WHICH WERE SIGNIFICANT AT THE P<0.1 LEVEL. TOTAL VARIATION EXPLAINED FOR EACH DEPENDENT VARIABLE IS ALSO SHOWN.

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variables		Total Variation
Number of Individuals	Dissolved Oxygen ($\underline{1}$,2,4) 40%		40%
Net Chlorophyll	Secchi Depth ($\underline{1}$,2,3,4) 88%	Salinity (1,2,$\underline{4}$) 7%	95%
Total Chlorophyll	Secchi Depth ($\underline{1}$,2,3,4) 56%	Salinity (1,2,$\underline{4}$) 16%	72%
Net C14	Avg. Solar Radiation ($\underline{1}$,2,3,4) 78%	Secchi Depth ($\underline{1}$,3) 22%	100%
Nanno C14*	Secchi Depth ($\underline{1}$,2,4) 83%	Salinity ($\underline{1}$,3) 11%	94%
Total C14	Secchi Depth ($\underline{1}$,4) 72%	Nitrogen (1,4) 28%	100%
Net Assimilation Ratio	Not Enough Cases		
Nanno Assimilation Ratio	Secchi Depth ($\underline{1}$,2,3) 81%		81%

TABLE 7.11 CONT.'D

Dependent Variable	Significant Independent Variables and Explained Variation in Dependent Variables				Total Variation
Total Ratio	Secchi Depth (1,2,3,4) 100%				100%
Secchi Depth*	Temperature (1) 39%	Salinity (1) 6%	Phosphate (1) 3%	Nitrate (1) 2%	50%
Secchi Depth*	Net Chlorophyll (1) 22%	Nan Chlorophyll (1) 5%			27%

this relationship could be mere correlation, there is the possibility that Mississippi River water may carry a unique phytoplankton community into the STOCS region. As it mixes with local communities, the number of species increases.

2) Net C14: Average Solar Radiation (58%)

   Total C14: Nitrogen (27%)

   These relationships demonstrate the dependence of carbon 14 uptake on the variable physical/chemical environment.

3) Biological Factors: Secchi Depth, Salinity.

   These two factors dominate as significant dependent variables. Secchi depth itself is adequately predicted either from physical/chemical factor or from biological factors. Salinity is dependent on freshwater runoff, a major nearshore nutrient source in the STOCS area.

The remaining three tables (7.9, 7.10, 7.11) are presented to provide a quantitative estimate of the changes in physical/chemical influences at Stations 1, 2 and 3. Some of the more interesting comparisons are:

1) The dependence of number of species on River Discharge: (Mississippi) at Stations 1 and 2;
2) The decreasing influence of salinity at Stations 2 and 3;
3) The relationships between nanno chlorophyll and Secchi depth at Stations 1 and 2 but not 3;
4) The increased prediction of Secchi depth by biological factors relative to physical factors at Station 2.

Other comparisons may become more meaningful depending on viewpoint or increased data.

Impact of River Runoff on the STOCS Area

River runoff is a dominant force acting on the phytoplankton in the STOCS area. This is suggested by the correlation matrix in Table 7.7 and by the percent-variance-explained terms in Table 7.8. The continuous measurements for chlorophyll a, temperature and salinity collected along Transect II in 1977 are ideal for identifying the bounds and sources of this salinity dependence.

Figure 7.10 summarizes the 48 nautical mile long transects for chlorophyll a (a), salinity (b) and temperature (c) from the Port Aransas jetties to Station 1/II and then to Station 3/II. The figures result by recording discrete values for each factor at nautical mile intervals for each of the 12 sampling months. These discrete values are the basis for the contours of month vs. distance offshore in Figure 7.10. The patterns among these figures are discussed in the 1977 final report (Kamykowski *et al.*, 1978). The general conclusions are that temperature is poorly correlated with chlorophyll a except in the winter and that salinity is well-correlated with chlorophyll a inshore. The present discussion expands on the salinity-chlorophyll a relationships.

Figure 7.11 is a plot of distance offshore vs. correlation coefficient between chlorophyll a (Figure 7.10A) and salinity (Figure 7.10B). Each correlation coefficient is computed by matching the 12 sampling points available for a given distance offshore. A total of 49 correlation coefficients (0 to 48 nautical miles offshore) are plotted. The trends of the correlation coefficients provide a useful interpretive tool. Three major sections are evident in the plot: 1) 0 to 14 nautical miles offshore; 2) 15 to 32 nautical miles offshore; and 3) 33 to 48 nautical miles offshore. Interpretation of these sections is aided by a consideration of river discharge.

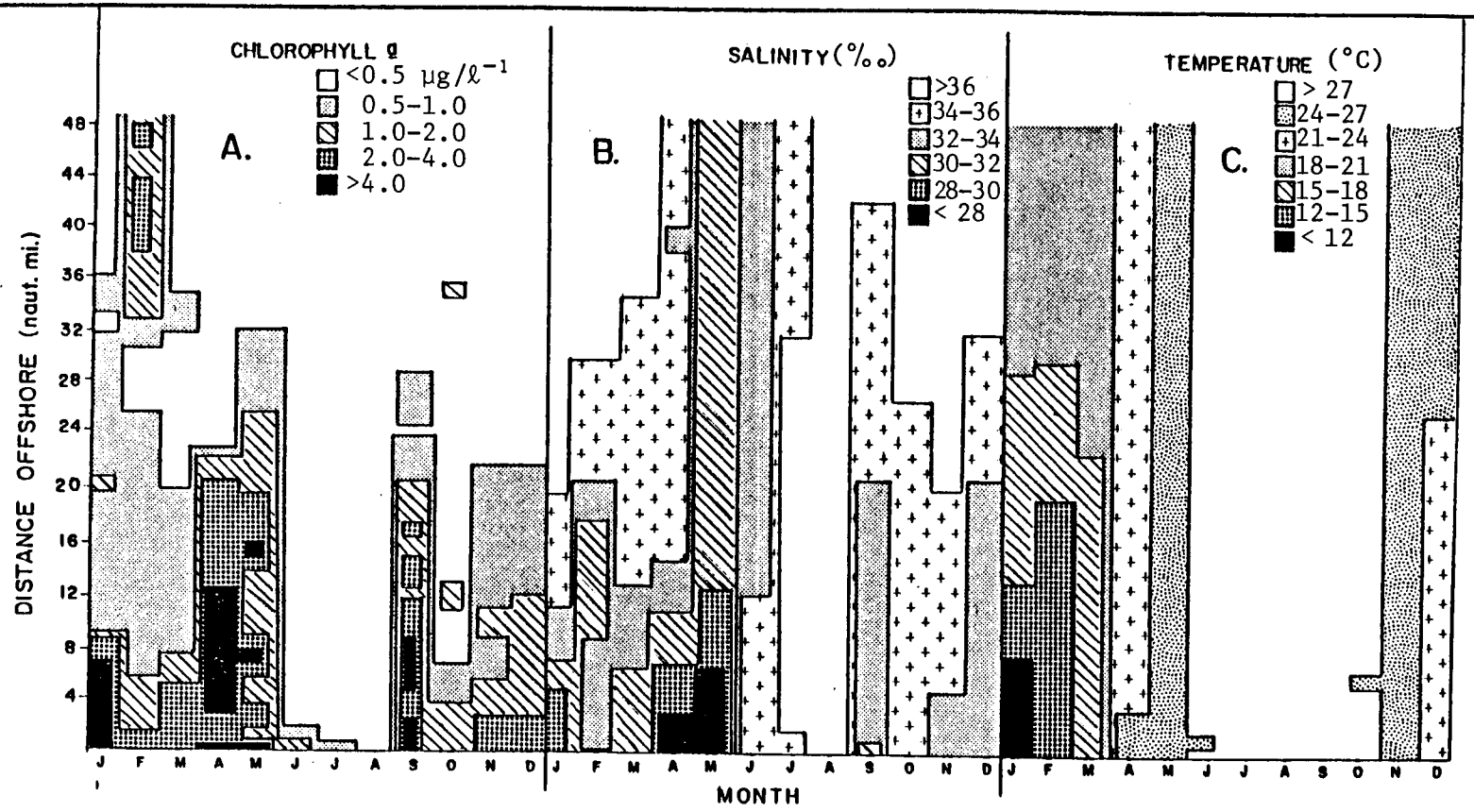

Figure 7.10 Contours of Chlorophyll a (µg/ℓ), Salinity (‰), and Temperature (°C) Based on Data Points Collected Every Month in 1977 at Each Nautical Mile Along a Transect Extending from the Port Aransas Jetties to Station 1/II and then to Station 3/II.

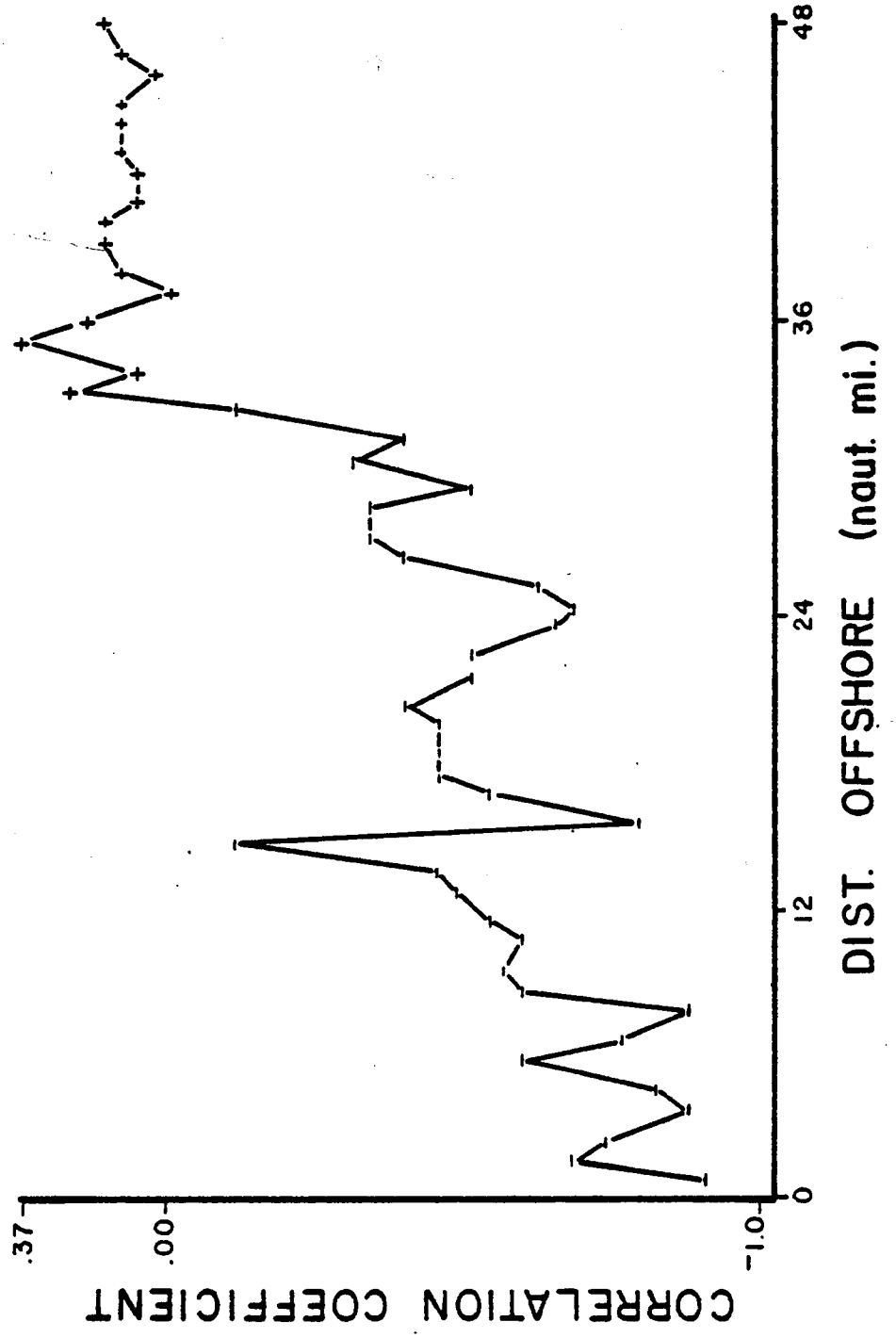

Figure 7.11 Correlation coefficients plotted against distance offshore (nautical miles) obtained by interrelating the 12 chlorophyll a points with the 12 salinity points for each nautical mile in Figure 7.10. The Y-axis extends from perfect negative correlation (-1.0; lower bound) to the highest positive correlation observed (+0.37;upper bound).

Table 7.3 lists the rivers used in the analysis. Five point sources in the northwestern Gulf of Mexico are used: 1) Mississippi River; 2) Galveston Entrance (Trinity); 3) Brazos, San Bernard and Colorado River; 4) Aransas Pass (Guadalupe, San Antonio, Mission and Nueces); and 5) Rio Grande. The Mississippi River discharge is represented by a single day's outflow six weeks prior to sampling the STOCS transect. This single day is representative of the average Mississippi River discharge in that time period. The six week lag allows transport between the Mississippi mouth and STOCS Transect II at a rate of 0.5 knots. The Texas rivers are represented by the monthly average flow most representative of the date of sampling the STOCS transect. The greater time span is required because of the more variable flow in these smaller rivers. The monthly average compensates for the variable distances from STOCS Transect II.

Figures 7.12 through 7.16 exhibit serial correlations of the 12 discharge estimates from each respective point source with the 12 salinity and chlorophyll _a_ determinations available for each nautical mile offshore. Polynomial fits are provided for easier interpretation of trends. This analysis examines whether temporal discharge fluctuations are related to the temporal salinity (negative correlation) or chlorophyll _a_ (positive correlation) fluctuation at a given distance from shore. The general conclusions moving from north to south are:

Mississippi River:

Salinity - highly correlated between 21 and 48 nautical miles offshore; relationship declines within 22 nautical miles of shore.

Chlorophyll - consistently higher correlations between 14 and 31 nautical miles offshore.

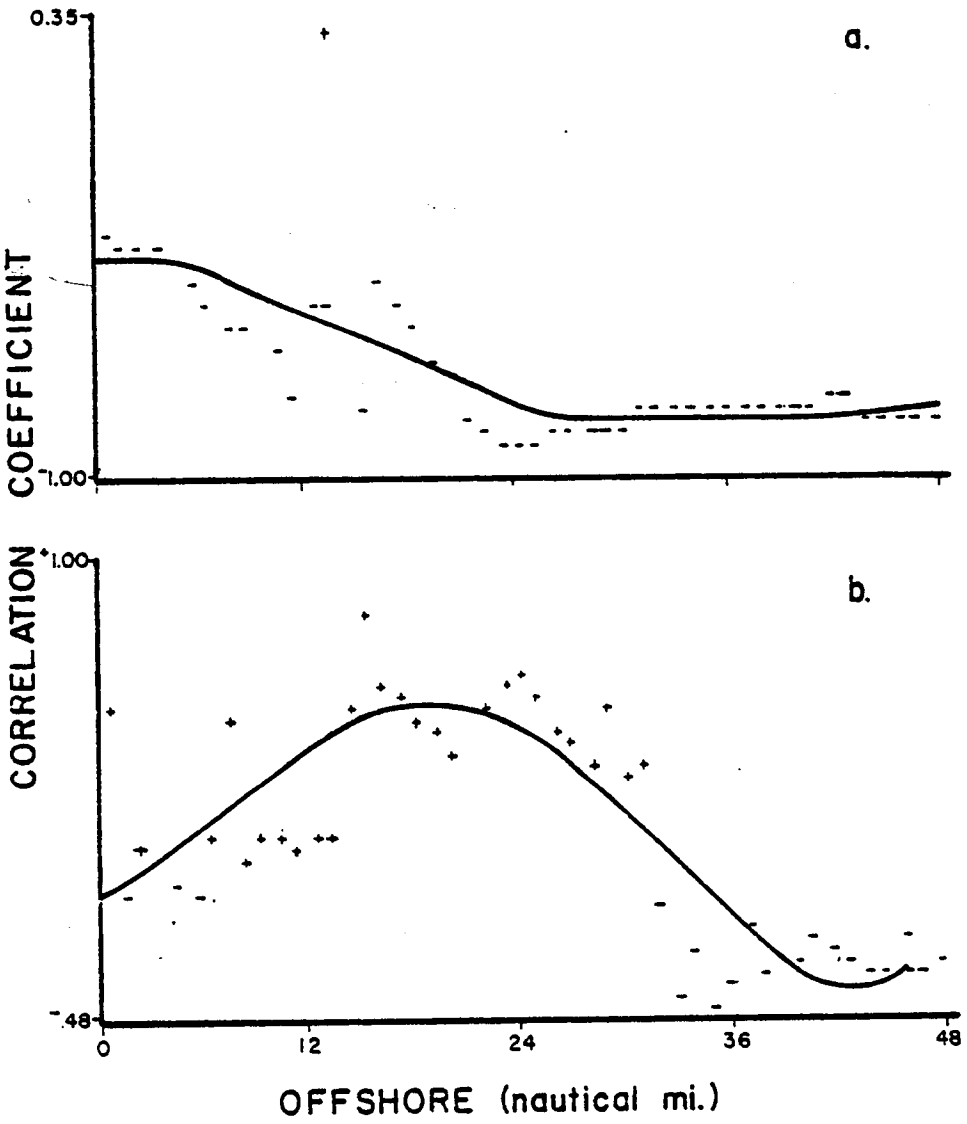

Figure 7.12 Correlation coefficients plotted against distance offshore (nautical miles) obtained by interrelating monthly Mississippi River Discharge (6 week lag) with a) monthly salinity in Figure 7.10 and b) monthly chlorophyll a in Figure 7.10 for each nautical mile between 0 and 48 nautical miles offshore. The salinity Y-axis extends from a perfect negative correlation (-1.0; lower bound) to the highest positive correlation observed (+0.35; upper bound). The chlorophyll a Y-axis extends from the perfect positive correlation (+1.0; upper bound) to the lowest negative correlation observed (-0.48; lower bound). Polynomial fits are provided to aid in visual interpretation.

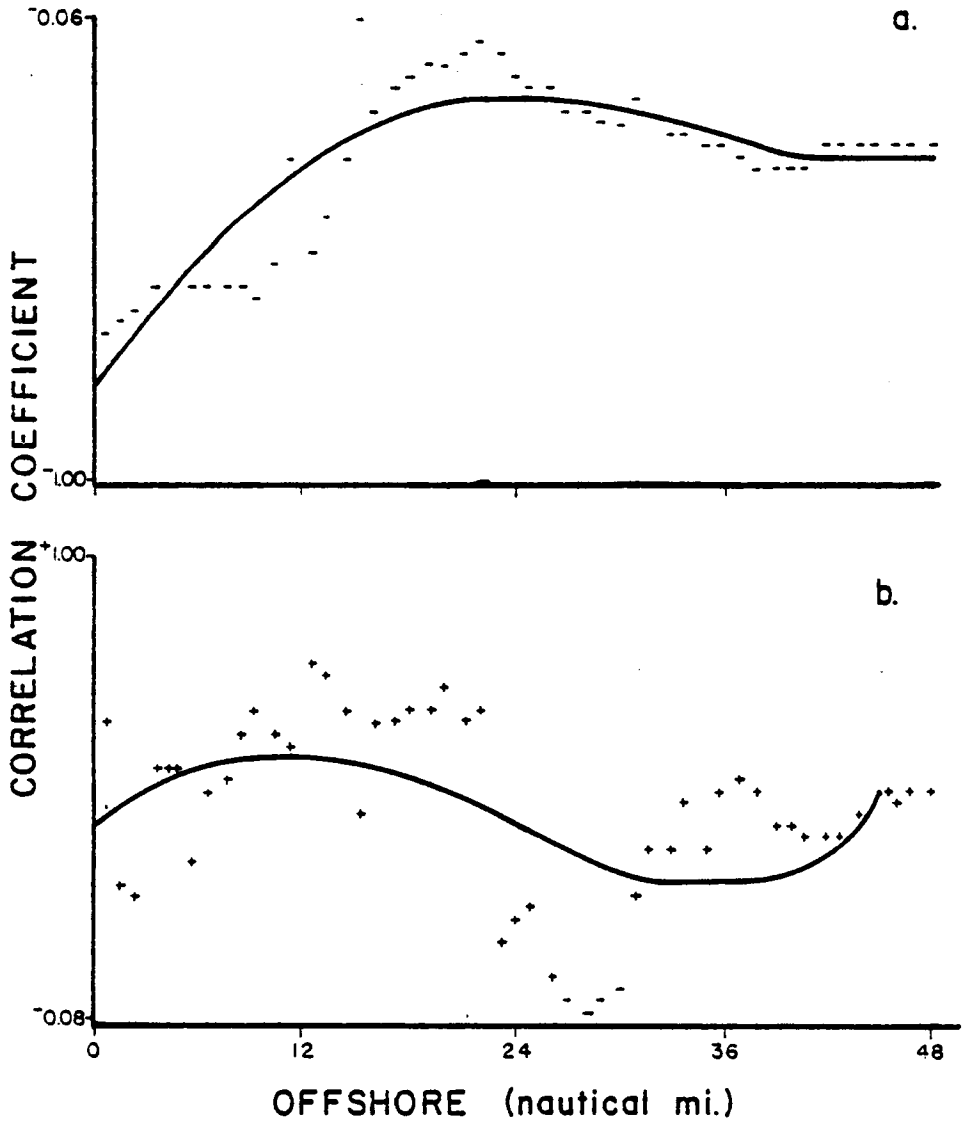

Figure 7.13 Correlation coefficients plotted against distance offshore (nautical miles) obtained by interrelation monthly Galveston Entrance (Trinity River) discharge (6 week lag) with a) monthly salinity in Figure 7.10 and b) monthly chlorophyll a in Figure 7.10 for each nautical mile between 0 and 48 nautical miles offshore. The salinity Y-axis extends from a perfect negative correlation (-1.0; lower bound) to the highest positive correlation observed (0.06; upper bound). The chlorophyll a Y-axis extends from the a perfect positive correlation (+1.0; upper bound) to the lowest negative correlation observed (-0.08; lower bound). Polynomial fits are provided to aid in visual interpretation.

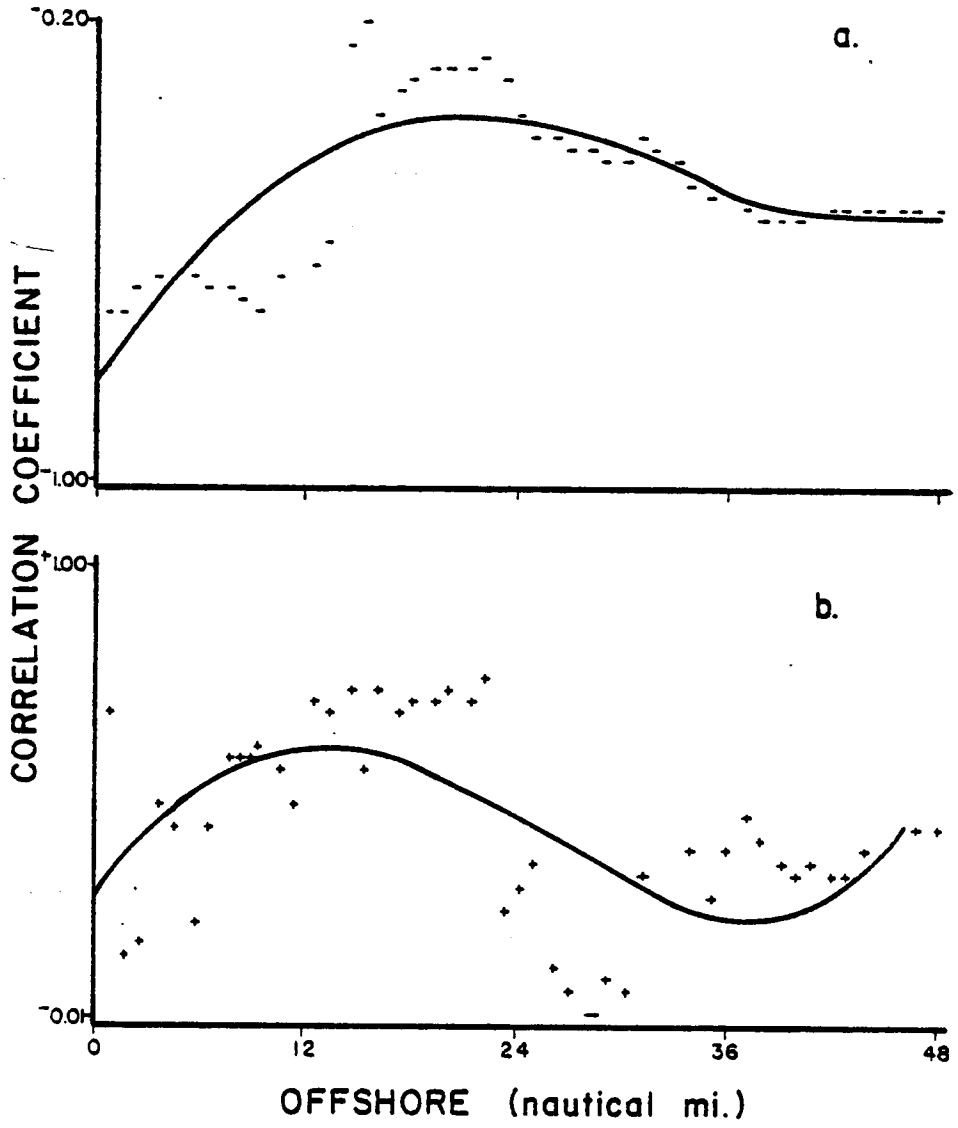

Figure 7.14 Correlation coefficients plotted against distance offshore (nautical miles) obtained by interrelating monthly Brazos-San Bernard-Colorado complex discharge (6 week lag) with a) monthly salinity in Figure 7.10 and b) monthly chlorophyll a in Figure 7.10 for each nautical mile between 0 and 48 nautical miles offshore. The salinity Y-axis extends from a perfect negative correlation (-1.0; lower bound) to the lowest negative correlation observed (-0.20; upper bound). The chlorophyll a Y-axis extends from the a perfect positive correlation (+1.0; upper bound) to the lowest negative correlation observed (-0.01; lower bound). Polynomial fits are provided to aid in visual interpretation.

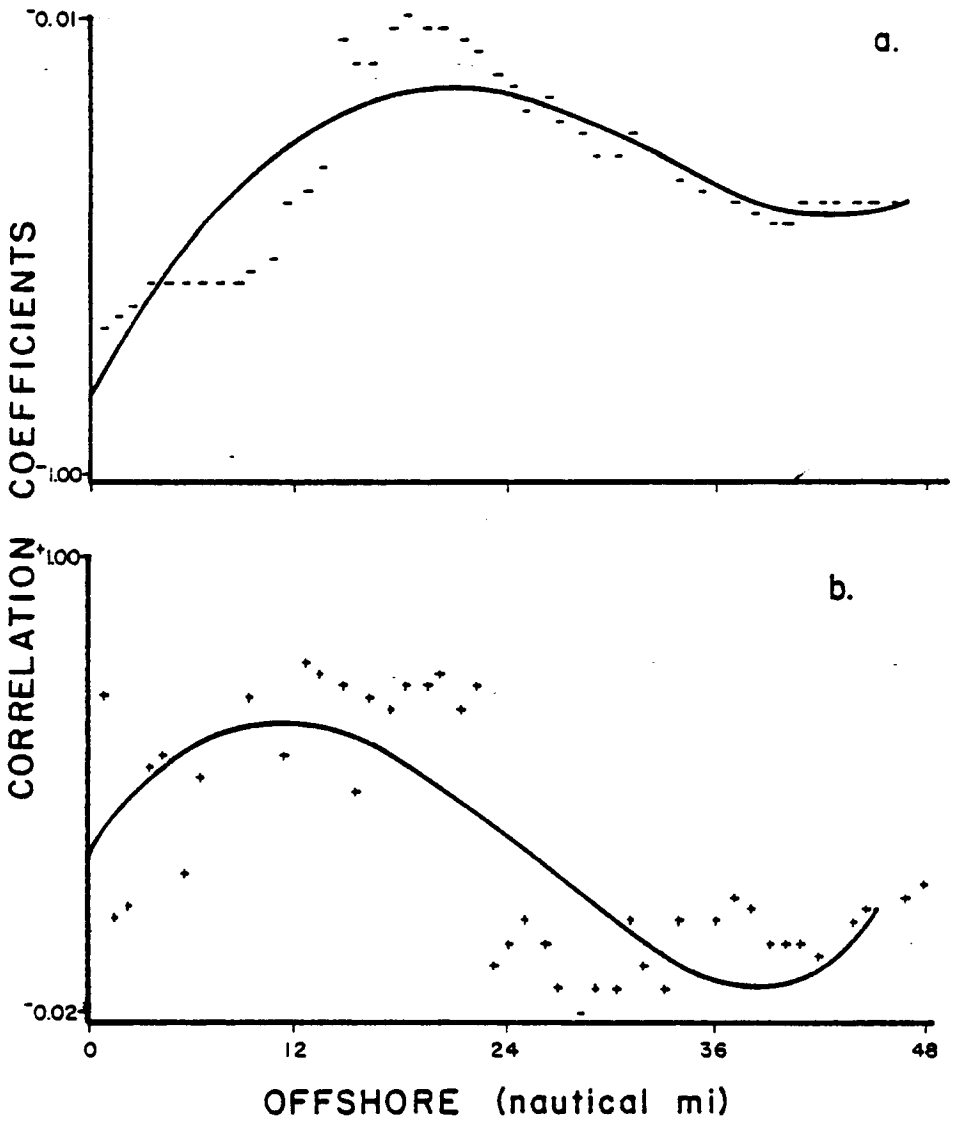

Figure 7.15 Correlation coefficients plotted against distance offshore (nautical miles) obtained by interrelating monthly Aransas Pass complex (Guadalupe, San Antonio, Mission, Nueces Rivers) discharge (6 week lag) with a) monthly salinity in Figure 7.10 and b) monthly chlorophyll a in Figure 7.10 for each nautical mile between 0 and 48 nautical miles offshore. The salinity Y-axis extends from a perfect negative correlation (-1.0; lower bound) to the lowest negative correlation observed (-0.01; upper bound). The chlorophyll a Y-axis extends from the a perfect positive correlation (+1.0; upper bound) to the highest negative correlation observed (-0.02; lower bound). Polynomial fits are provided to aid in visual interpretation.

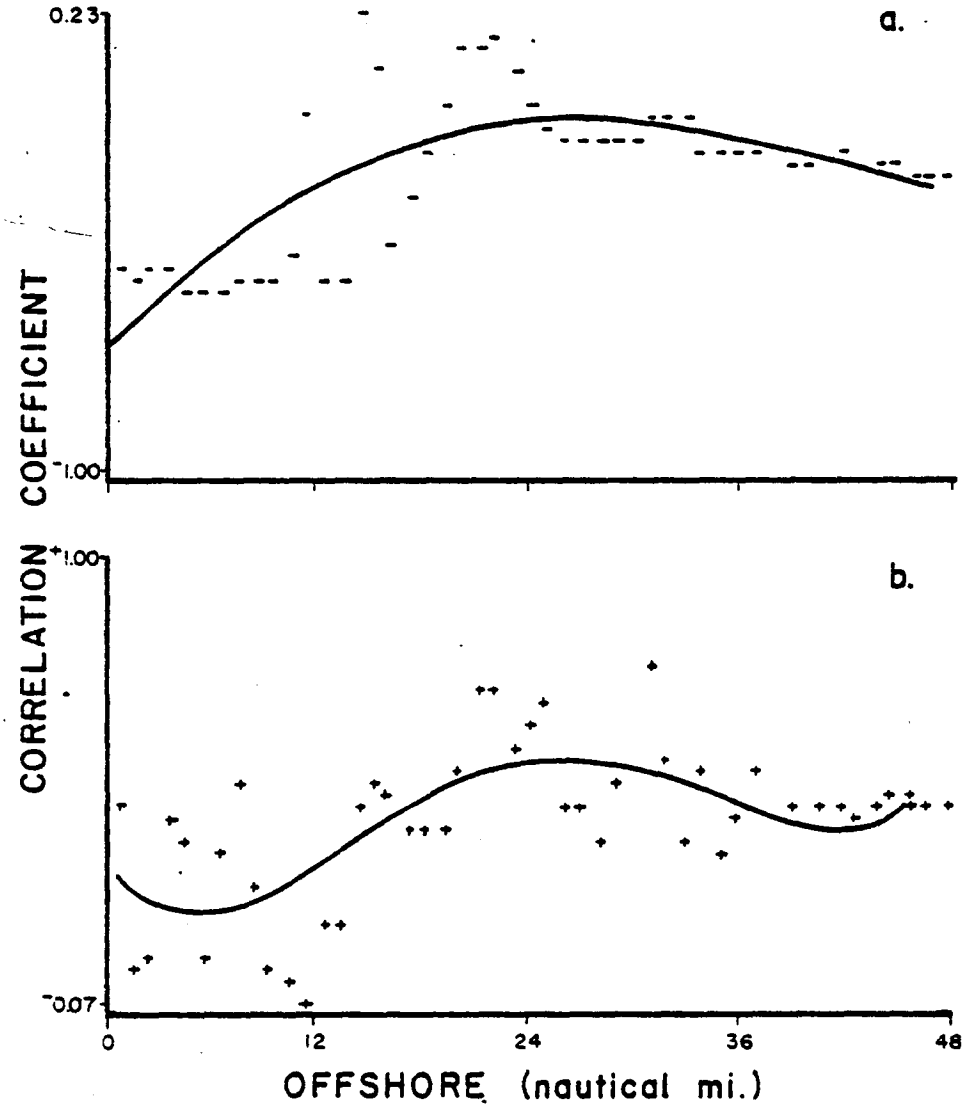

Figure 7.16 Correlation coefficients plotted against distance offshore (nautical miles) obtained by interrelating monthly Rio Grande discharge (6 week lag) with a) monthly salinity in Figure 7.10 and b) monthly chlorophyll a in Figure 7.10 for each nautical mile between 0 and 48 nautical miles offshore. The salinity Y-axis extends from a perfect negative correlation (-1.0; lower bound) to the lowest negative correlation observed (-0.23; upper bound). The chlorophyll a Y-axis extends from the a perfect positive correlation (+1.0; upper bound) to the highest negative correlation observed (-0.07; lower bound). Polynomial fits are provided to aid in visual interpretation.

Galveston Entrance (Trinity River):

Salinity - consistently higher correlation between 0 and 10 nautical miles offshore; low correlation offshore.

Chlorophyll - consistently higher correlation between 8 and 22 nautical miles offshore;

Brazos, San Bernard and Colorado Rivers:

Salinity - consistently higher correlation between 0 and 10 nautical miles offshore; some improvement in relationship offshore which may be a spurious seasonal relationship.

Chlorophyll - consistently higher correlation between 7 and 22 nautical miles offshore;

Aransas Pass Complex:

Salinity - consistently higher correlation between 0 and 10 nautical miles offshore; some improvement in relationship offshore which may be a spurious seasonal relationship

Chlorophyll - consistently higher correlation between 7 and 22 nautical miles offshore;

Rio Grande:

Salinity - consistently higher correlation between 0 and 10 nautical miles offshore; some improvement in relationship offshore which may be a spurious seasonal relationship;

Chlorophyll - consistently higher correlation between 21 and 26 nautical miles offshore.

These five point sources generally explain the sections in Figure 7.11 as seen in Figure 7.17. Between 0 and 14 nautical miles offshore,

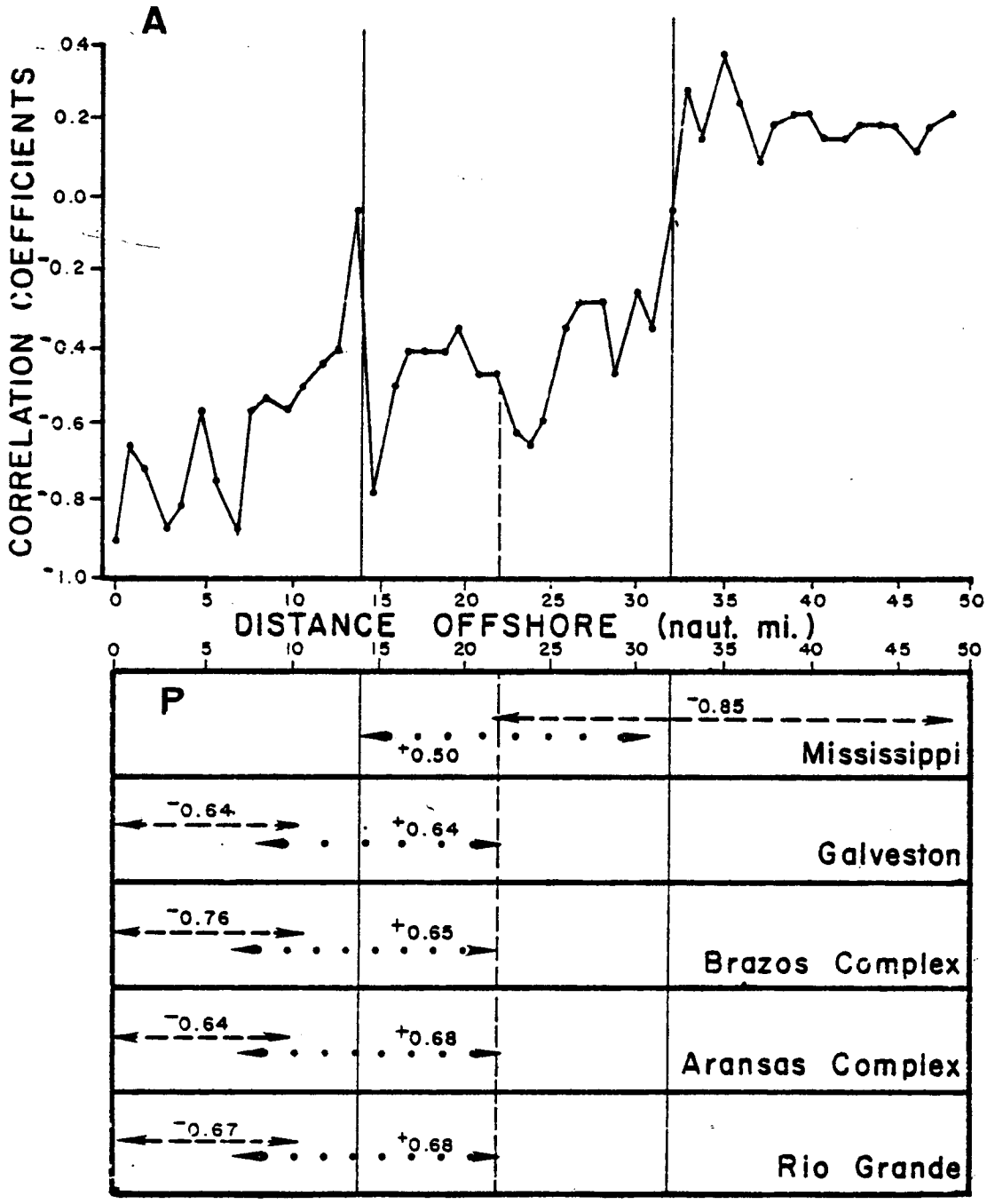

Figure 7.17

A. Plot of Distance Offshore (Naut. Mi.) vs. the Correlation Coefficients of Monthly Chlorophyll a and Salinity (12 points) for Successive Nautical Mile Distances Offshore in Figures 7.2 and 7.4, Respectively.

B. The Zones of Maximum Correlation Between Monthly Point Source Discharge and Either Monthly Salinity (Dashes) or Monthly Chlorophyll a (dots) for Five Significant Freshwater Sources in the Northwest Gulf of Mexico. For Example, Monthly Mississippi River Discharge in 1977 Exhibits an Average Correlation of -0.85 with Monthly Salinity Readings for Every Nautical Mile Between 21-48 Nautical Miles Offshore.

the shelf along Transect II is under the influence of the Texas rivers. The four Texas sources probably exercise an unequal influence on Transect II but they exhibit similar seasonal flow patterns. Though the shelf between 0 and 7 nautical miles offshore exhibits a strong correlation between chlorophyll and salinity, the chlorophyll-discharge relationship is inconsistent. This may be due to lingering pools of fresher water trapped against the coast or to the variable residence times of river discharge behind the barrier island prior to discharge through Aransas Pass. The clearer relationship between 7 and 14 nautical miles offshore may be due to the influence of the Brazos-San Bernard-Colorado system. Between 15 and 32 nautical miles offshore, a mixing zone exists between inshore and offshore water. This section appears to be composed of two sub sets: the zone between 15 and 22 nautical miles is significantly influenced by inshore water (see Aransas Pass chlorophyll plot in Figure 7.15); the zone between 22 and 32 nautical miles is significantly influenced by offshore water (see Mississippi salinity plot in Figure 7.12). The Mississippi River outflow is best related to chlorophyll *a* in the mid shelf region between 22 and 32 nautical miles offshore. Between 33 and 48 nautical miles offshore, no relationship exists between salinity and chlorophyll. This is the region of Mississippi River dominance as shown by the Mississippi salinity plot. For completeness, the involvement of Gulf of Mexico water should be mentioned as the third force involved in these patterns since salinities at all points of the transect reach 36.6‰ sometime during the year and the lowest salinities observed only reach 26 ‰.

As a final display of the relationship between salinity and chlorophyll *a* in the STOCS area, Figure 7.18 presents the salinity vs. chlorophyll *a* relationships that occur in the three sections observed in Figure

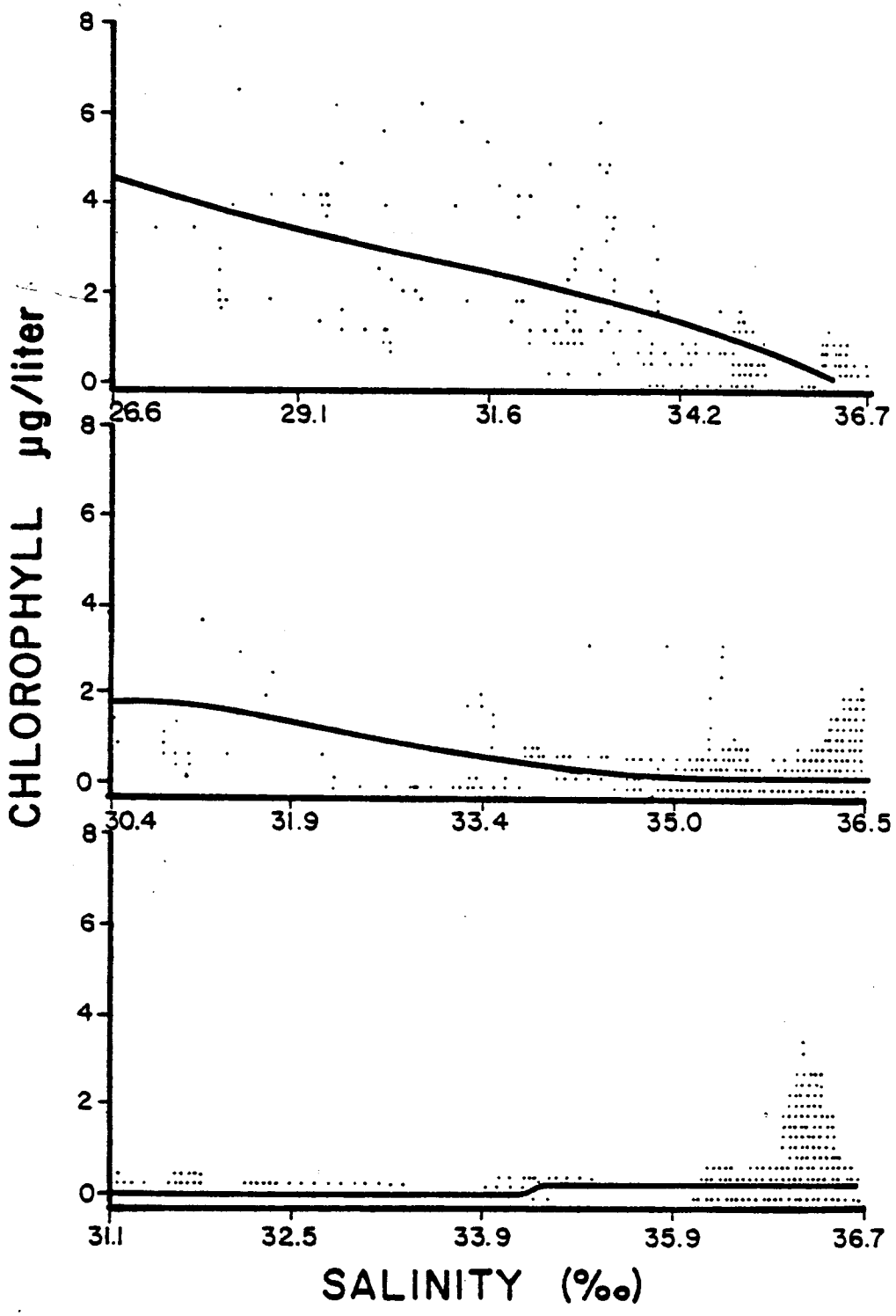

Figure 7.18 Scatterplots of salinity (‰) and chlorophyll a (mg/m^3) for sections of Figure 7.11 between 0 - 14 nautical miles, 15 - 32 nautical miles, and 33 - 48 nautical miles.

7.11. The relationship decreases in strength offshore, the sections bounded by 0 to 14 nautical miles and 15 to 32 nautical miles have significant inverse relationships; the highest offshore chlorophyll concentrations occur at high salinity.

CONCLUSIONS

1. Phytoplankton biomass and activity decrease offshore and from north to south in the STOCS area.

2. Phytoplankton biomass exhibits a strong seasonal cycle nearshore that decreases in intensity offshore. The net category is the primary cause of the seasonal cycle. Phytoplankton activity exhibits a seasonal cycle in both the nanno and net categories; the nanno peak follows the net peak in the spring and precedes it in the fall.

3. The distribution of phytoplankton communities is very irregular in the STOCS area. The composition of the species association in space and time is also irregular. This irregularity is probably related to the complex hydrographic regime.

4. Good relationships exist among the species counts, chlorophyll *a* carbon 14 uptake and Secchi depth. Some of the biological factors are strongly related to salinity, dissolved oxygen and incident solar radiation.

5. Significant percentages of variability are explained for a number of biological factors. The character of the independent variables change with geographic location on the shelf. Salinity and Secchi depth are the most consistent independent variables.

6. The South Texas shelf along Transect II divides into three sections based on salinity-chlorophyll *a* correlations: a) between 0 - 14 nautical miles offshore, Texas rivers dominate the patterns; b) between 15 and 32 nautical miles offshore two subsets of a mixing zone exist inshore

or offshore of 22 nautical miles; the inner zone is primarily Texas river water and the outer zone is primarily Mississippi River water; c) between 33 and 48 nautical miles offshore, the freshwater input is dominated by Mississippi River water.

7. Surface chlorophyll a increases are related to decreases in salinity between 0 and 32 nautical miles offshore. Between 33 and 48 nautical miles offshore, chlorophyll a increases are not related to salinity decreases.

RECOMMENDATIONS

1. Future plankton studies in the STOCS area should be based on temporally frequent samples because of complex hydrography.

2. Plankton studies should be coupled with chemical tracers (*i.e.* ion composition, humic acids) of northwest Gulf of Mexico rivers.

3. Plankton studies in the STOCS area should be coupled with satellite information on river plume dispersion.

4. A box model of nutrient fluxes into the STOCS area should be developed to quantify the relative contributions of the various boundaries.

5. Plankton studies should be part of a larger program to trace the effects of Mississippi River water back to its source.

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CHAPTER EIGHT

ANALYSIS OF A TWO YEAR STUDY OF NEUSTON

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ABSTRACT

The upper 15-20 cm of the water column was sampled during 1976-1977. Biomass and taxonomic studies of these samples revealed generally high variability. Most taxa showed distinct seasonal cycles with peaks in spring-summer samples. A few late fall-winter species were found. These cycles showed good year to year reproducibility. Diel migrations are apparent in most taxa with few truly euneustonic species apparent. Onshore-offshore variation was seen in some taxa, particularly the larval decapods. No significant correlations of neuston biomass to environmental parameters were found. The concentration of tar showed considerable variation, but in no obvious pattern.

INTRODUCTION

The neuston environment and its organisms are important to the water column ecosystem in that they occupy a relatively thin skin of the ocean surface where air-sea mixing initially occurs. Many potential pollutants probably enter the oceans through this route, and any biological impact might first manifest itself in changes in the neuston.

Although the neuston defies a strict biological definition in terms of species, there are certain taxonomic groups which are commonly found in the upper 15-20 cm of the water column during significant portions of each day. There is considerable variability not only in the abundance of neuston, either as total numbers of organisms or in terms of dry weight, but also in its taxonomic composition. This is due, in part, to diel vertical migration, but is also probably due to various types of environmental heterogeneity. Day-night sampling is, therefore, done to minimize the former variation, but the latter source of variability is not generally monitored.

In this report an attempt is made to identify the variations in numerical abundance of the various taxonomic categories of neuston in relation to diel, seasonal and geographic considerations as they existed during 1976 and 1977 in the sampling area. In addition, we have attempted to analyze relationships between species as co-occurring groups and to determine significant temporal patterns, as well as correlations with various environmental parameters.

Literature Survey and Previous Work

It is only within the last 15 years that much has become known about marine neuston, although the neuston of freshwater ponds and pools has

been studied since Naumann first applied the term to surface film organisms in 1917 (Zaitzev, 1970). Marine neuston has been studied fairly extensively in the Black Sea and Sea of Azov (Zaitsev, 1961, 1968, 1970) and in the North Sea, Norwegian Sea, and subtropical Northeast Atlantic (Hempel and Weikert, 1972). Neuston studies in most other areas, however, have been limited, usually concentrating on specific taxonomic groups. These include studies of pontellid copepods of the Pacific (Heinrich, 1969, 1971), and ichthyofauna of the subtropical Eastern Atlantic (Hartman, 1970).

No complete quantitative faunal analysis of neuston samples has been published. Although Weikert's (1972) study of the zooplankton of the subtropical Atlantic comes close, it omits several major zooplankton groups such as coelenterates and tunicates and does not provide identifications of calanoid copepod species.

Two recent unpublished manuscripts present the most complete quantitative and detailed analyses of neuston organisms to date. The first, a study of neuston of the Northwest Atlantic (Morris, 1975), compares the zooplankton in the neuston with the near-surface zooplankton and reports on definite seasonal and diel cycles of neuston biomass. The area of study included the southeastern Gulf of Mexico and Caribbean Sea as well as the northwestern Atlantic between Bermuda and Nova Scotia. The second is a M.S. thesis by Berkowitz (1976). It is a comparison of neuston and near-surface zooplankton in the northwestern Gulf of Mexico in oceanic waters off Texas above the 1000-fathom bottom contour of the continental slope zone. The neuston in this area appears to be relatively impoverished compared to plankton concentrations one meter below the surface. The above two studies did not include detailed analyses of fish larvae and eggs or decapod larvae as in the present study.

Other neuston studies in the Gulf of Mexico are sparse and incomplete. Zaitsev (1970) reported on neuston from the Gulf of Mexico, which he found to be poor in areas of upwelling, where its biomass (wet, fresh weight) did not exceed 100-200 mg/m^3, but where the water converges in the center of the Gulf the wet-weight biomass reached 410 mg/m^3.

METHODS

Field and Laboratory

Day and night samples were collected at Stations 1-3 on Transect I-IV on each of the three seasonal cruises in 1976. On each of six monthly cruises, day-night samples were collected at Stations 1-3 on Transect II only (Figure 8.1). Samples were collected using a towed frame 2.0 m wide and 1.0 m high in 1976. The net mesh used was 505 µm. Samples were taken on the "benthic" cruises. There were 108 samples taken. In 1977 our frame was modified (after the winter seasonal cruise) to four continuous, but separate compartments, each of the same size (0.5 x 0.5 m) with individual 505 µm nets. Samples were collected on "water column" cruises. Day-night pairs were taken on Transect II only reducing the number of samples to 81. See Wormuth (1979a) for further sampling details.

Data Analysis

The data were analyzed with respect to the overall abundance of taxa, the frequency of occurrence and variability in abundance. For statistical evaluation the SAS package available on the Amdahl 470 V/6 computer at Texas A&M University was used. Various grouping techniques were used to look at community structure in the neuston. The first

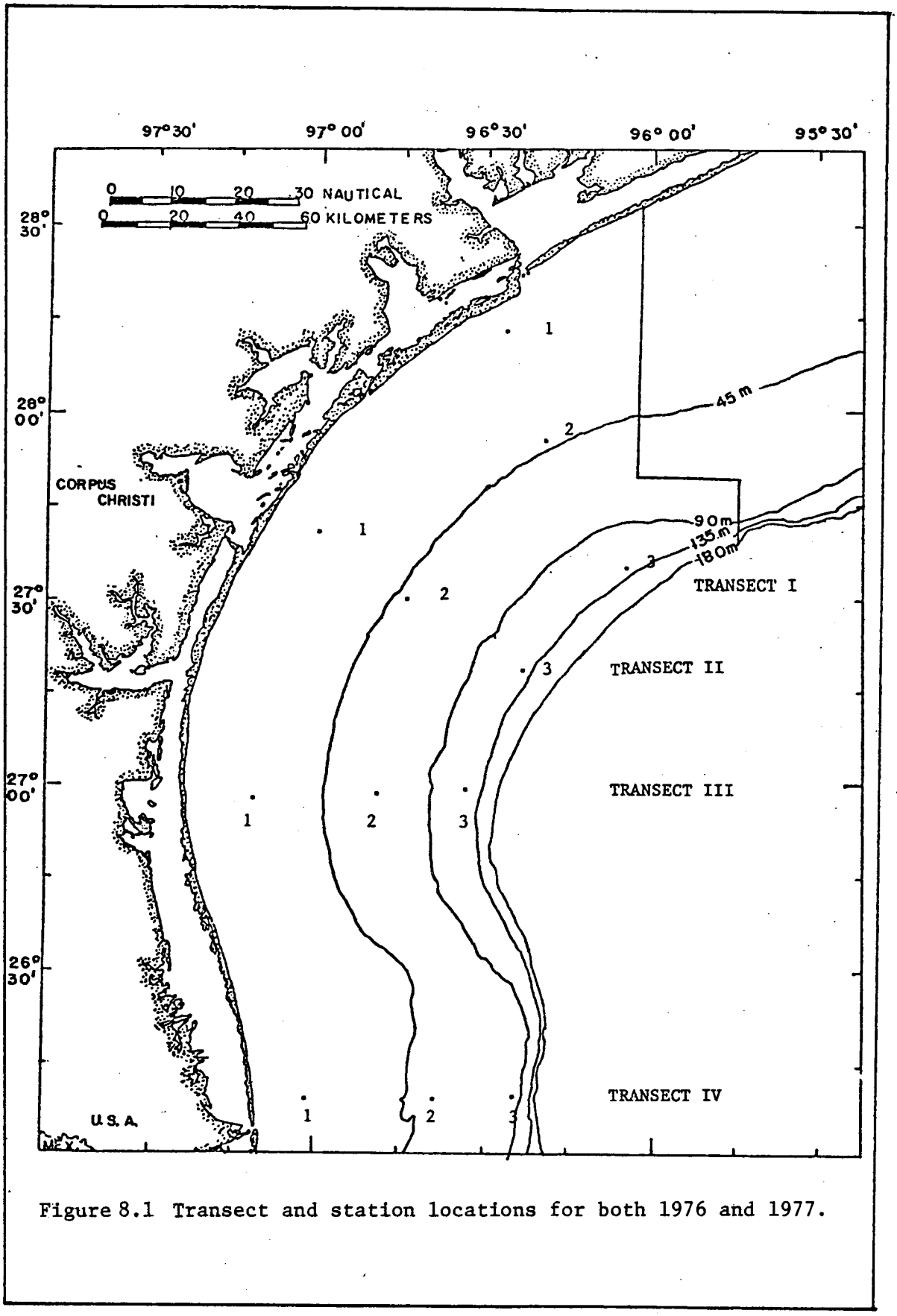

Figure 8.1 Transect and station locations for both 1976 and 1977.

was recurrent group analysis. This analysis forms species associations based only on presence and absence. The results for day and night samples separately and for both 1976 and 1977 have been presented in the final reports for those years. This analysis is insensitive to two things: numerical abundance and relationships of rare species. To examine these features factor analysis, an ordination procedure, was run. The data were log transformed initially. The procedure and various alternatives are discussed at length in Harman (1967). In essence this technique extracts sources of variation from a data set so that the variability in a matrix of 63 species or species groups and 81 stations can be explained by less than 63 different sources of variation (factors). The factors are ordered from largest to smallest.

In addition a set of factor scores can be calculated for each tow. These scores are derived from the equation:

$$Fqi = \sum_{j=1}^{n} a_{jq} \, z_{ji} / \lambda_q,$$

where n is the number of taxa, a_{jq} is the factor loading of the jth taxa on the qth factor and z_{ji} is the standardized log transformation of the count for j in haul i. Since other data (*i.e.* physical and biological parameters) are available for each tow, a new correlation analysis can be run.

RESULTS

General Characteristics

Each sample was routinely broken down into 173 categories representing various taxonomic levels from phyla to individual sexes of the same

species. Those categories which contributed significantly to the neuston, were in low abundance but frequent, or were interesting for some other reason, are listed in Table 8.1. Those taxa which included many species show high values and are overemphasized in this type of presentation included hyperiids, chaetognaths, immature calanoid copepods and fish eggs. Others split by sex tended to be underemphasized. Analyses of variance were run on these and other taxa. Those results were presented previously (Wormuth, 1979b) and showed different sources of variation to be significant for different taxa.

To examine general features of the neuston community we used factor analysis. In 1976 a total of six factors were retained. These accounted for 51% of the overall variance. No rotation of the factor matrix was performed. The species or species groups are listed in Table 8.2 according to their loadings on the six factors. Those species or species groups with high positive or high negative loadings were considered as identifiable groups.

A comparison of the factor scores for each tow and other data (*i.e.* physical and biological parameters) showed some interesting correlations (Table 8.3). These results suggested that Factor 1 (18% of variance) was related to variations in salinity. In other words, those taxa which group due to high loadings on Factor 1 appeared to vary positively in association with salinity values. A graphic illustration of this relationship will follow in the 1977 results. The Factor 1 group was also the largest and may represent a group of more offshore, oceanic taxa.

Factor 2 (10% of variance) scores correlated significantly with several parameters. The strongest was a negative correlation with temperature. This group was really only a single species with a winter-fall distribution. Factor 3 (8% of variance) scores correlated significantly

TABLE 8.1

MEAN ABUNDANCES OF SELECTED TAXA BY CRUISE AND TIME OF DAY. NUMBERS ARE IN NUMBER/$10^3 m^3$. UPPER (u) AND LOWER (ℓ) 95% CONFIDENCE LIMITS ARE GIVEN ONLY WHEN THEY DID NOT CROSS ZERO. NUMBER OF OBSERVATIONS ARE GIVEN UNDER THE COLUMN HEADED N

			Hyperidae			Lucifer faxoni			Brachyuran megalopa			Brachyuran zoea			Calanopia americana females			Centropages velificatus females			Nannocalanus Minor		
CRUISE		N	u	$\bar{x}$	ℓ	u	$\bar{x}$	ℓ	u	$\bar{x}$	ℓ	u	$\bar{x}$	ℓ	u	$\bar{x}$	ℓ	u	$\bar{x}$	ℓ	u	$\bar{x}$	ℓ
WINTER	Day	12	-	413	-	-	3988	-	-	447	-	255	152	48	-	58	-	-	480	-	-	616	-
	Twilight	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Night	12	31905	17176	2447	4381	2874	1367	-	11897	-	6650	3962	1273	2068	1331	594	2513	1537	560	14691	8520	2349
MARCH	Day	3	-	84	-	-	125	-	-	165	-	-	551	-	-	0	-	-	478	-	-	358	-
	Twilight	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Night	3	-	31349	-	-	5844	-	-	13620	-	-	11593	-	-	1661	-	-	2155	-	-	21792	-
APRIL	Day	3	-	343	-	-	230	-	-	23	-	-	327	-	-	27	-	-	108	-	-	40	-
	Twilight	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Night	3	-	14443	-	-	9684	-	-	1584	-	-	12903	-	-	3317	-	10563	5808	1052	-	16428	-
SPRING	Day	6	-	805	-	-	2609	-	-	696	-	-	1494	-	-	11	-	-	29311	-	-	-	-
	Twilight	7	-	36624	-	115152	60424	5695	-	430	-	-	6159	-	-	4165	-	-	59366	-	-	1071	-
	Night	11	151055	85268	19480	19761	13132	6502	22427	12698	2968	18182	12021	5859	-	930	-	72905	41955	11004	4082	2176	269
JULY	Day	1	-	-	-	-	35	-	-	105	-	-	738	-	-	-	-	-	1265	-	-	-	-
	Twilight	3	-	99	-	-	9285	-	-	2768	-	-	426	-	-	-	-	-	114	-	-	990	-
	Night	2	-	4554	-	-	3638	-	-	8129	-	-	2737	-	-	123	-	-	1294	-	-	1265	-
AUGUST	Day	2	-	75	-	-	101362	-	-	1659	-	-	3127	-	-	-	-	-	3319	-	-	-	-
	Twilight	1	-	89	-	-	757	-	-	-	-	-	178	-	-	445	-	-	757	-	-	133	-
	Night	3	-	29355	-	-	6426	-	-	11105	-	-	9214	-	-	5215	-	-	3885	-	-	240	-
FALL	Day	11	-	2653	-	5634	3130	625	-	325	-	-	-	-	-	24	-	-	1491	-	-	9	-
	Twilight	1	-	636	-	-	29771	-	-	14808	-	-	-	-	-	159	-	-	955	-	-	-	-
	Night	12	53563	28495	3877	5528	3502	1475	10800	6169	1538	4931	2775	619	-	4529	-	11929	6517	1105	-	526	-
NOVEMBER	Day	2	-	2411	-	-	15637	-	-	1269	-	-	379	-	-	677	-	-	5068	-	-	-	-
	Twilight	1	-	5451	-	-	1777	-	-	7229	-	-	355	-	-	829	-	-	177	-	-	2666	-
	Night	3	-	6184	-	-	1874	-	-	4001	-	-	701	-	-	4507	-	-	8144	-	-	489	-
DECEMBER	Day	2	-	817	-	-	22024	-	-	815	-	-	1838	-	-	3071	-	-	2405	-	-	-	-
	Twilight	1	-	41	-	-	57	-	-	-	-	-	131	-	-	8	-	-	1748	-	-	-	-
	Night	3	-	1898	-	-	1385	-	-	4452	-	-	2824	-	-	22433	-	-	11549	-	-	2554	-

TABLE 8.1 CONT.'D

CRUISE		N	*Temora stylifera* u	*Temora stylifera* $\bar{x}$	*Temora stylifera* ℓ	*Anomalocera ornata* immatures u	*Anomalocera ornata* immatures $\bar{x}$	*Anomalocera ornata* immatures ℓ	*Labidocera* immatures u	*Labidocera* immatures $\bar{x}$	*Labidocera* immatures ℓ	*Pontellopsis villosa* males u	*Pontellopsis villosa* males $\bar{x}$	*Pontellopsis villosa* males ℓ	Chaetognaths u	Chaetognaths $\bar{x}$	Chaetognaths ℓ	Fish larvae u	Fish larvae $\bar{x}$	Fish larvae ℓ	Fish eggs u	Fish eggs $\bar{x}$	Fish eggs ℓ
WINTER	Day	12	-	1592	-	20370	11782	3193	-	-	-	-	177	-	2998	1804	609	609	427	44	-	14767	-
	Twilight	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Night	12	3131	1904	676	9567	4793	19	-	347	-	-	40	-	11878	8776	5674	852	577	302	13663		472
MARCH	Day	3	-	1638	-	-	8264	-	-	1207	-	-	16	-	-	3130	-	-	430	-	-	9118	-
	Twilight	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Night	3	6726	6542	6357	-	13792	-	-	3169	-	-	110	-	-	21746	-	-	3068	-	-	6951	-
APRIL	Day	3	-	218	-	-	966	-	-	13743	-	-	-	-	-	309	-	-	233	-	-	2171	-
	Twilight	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Night	3	-	17273	-	-	9233	-	-	100612	-	-	145	-	10388	7731	5073	1061	722	382	-	5307	-
SPRING	Day	6	6817	3836	854	-	-	-	-	184046	-	3849	2367	884	7431	3821	210	-	341	-	-	4114	-
	Twilight	7	179432	97112	14792	-	-	-	-	26664	-	-	61450	-	18362	12468	6573	-	543	-	-	7182	-
	Night	11	77722	47760	17797	-	-	-	-	5360	-	-	989	-	34078	22998	11917	2597	1601	604	6348	3507	-
JULY	Day	1	-	4219	-	-	-	-	-	984	-	-	35	-	-	1336	-	-	8	-	-	1371	-
	Twilight	3	-	518	-	-	-	-	-	8089	-	-	516	-	-	2306	-	-	205	-	-	1497	-
	Night	2	-	6027	-	-	-	-	-	7006	-	-	24	-	-	4539	-	-	2555	-	-	6247	-
AUGUST	Day	2	-	671	-	-	-	-	-	113	-	-	2428	-	-	720	-	-	79	-	-	1706	-
	Twilight	1	-	3208	-	-	-	-	-	44	-	-	222	-	-	2718	-	-	133	-	-	757	-
	Night	3	-	1579	-	-	-	-	-	232	-	-	3714	-	-	4575	-	-	3584	-	-	5299	-
FALL	Day	11	1408	780	151	-	-	-	995	599	202	2861	2184	1506	-	2111	-	136	72	7	-	741	-
	Twilight	1	-	159	-	-	-	-	-	159	-	-	636	-	-	477	-	-	62	-	-	159	-
	Night	12	-	1311	-	-	-	-	2372	1393	414	-	2036	-	13456	8733	4009	1656	961	265	965	534	102
NOVEMBER	Day	2	-	507	-	-	20098	-	-	590	-	-	1943	-	-	5443	-	-	357	-	-	866	-
	Twilight	1	-	118	-	-	-	-	-	237	-	-	-	-	-	1777	-	-	125	-	-	59	-
	Night	3	-	365	-	-	2068	-	-	189	-	-	474	-	-	5412	-	-	424	-	-	429	-
DECEMBER	Day	2	-	1514	-	-	-	-	-	-	-	-	2968	-	-	5440	-	-	3859	-	-	477	-
	Twilight	1	-	41	-	-	-	-	-	41	-	-	90	-	-	362	-	-	113	-	-	-	-
	Night	3	-	3360	-	-	-	-	-	517	-	-	297	-	-	11350	-	-	1405	-	-	700	-

TABLE 8.2

FACTOR LOADINGS FOR TAXA IN 1976

Taxa	Fct 1	Fct 2	Fct 3	Fct 4	Fct 5	Fct 6
Limacina trochiformis	.61	-.17	-.20	-.22	.02	.22
Hyperiids	.77	-.15	-.40	-.07	-.17	-.08
Lucifer faxoni	.66	-.34	.12	-.01	.07	-.03
Brachyuran megalops	.55	-.08	-.37	-.03	-.40	.13
Brachyuran zoeas	.72	-.11	.01	.09	-.07	.06
Shrimp larvae	.70	-.11	.09	.15	.02	-.03
Mysids	.68	.15	-.35	-.08	-.15	-.24
Ostracods	.70	-.01	-.32	-.02	-.03	-.30
Calanopia americana males	.56	.17	-.27	.42	.16	-.17
Calanopia americana females	.65	.10	-.31	.42	.10	-.12
Centropages velificatus males	.55	-.35	.25	-.04	-.06	-.16
Centropages velificatus females	.62	-.33	.26	.02	-.08	-.06
Euchaeta spp. immatures	.53	.49	-.10	-.13	.03	-.14
Nannocalanus minor	.58	.29	-.14	-.43	.10	.13
Temora stylifera	.53	-.31	.30	-.28	-.05	.18
Immature copepods	.71	-.09	.28	.08	-.07	-.06
Copilia mirabilis females	.72	-.08	.21	-.05	-.14	-.21
Chaetognaths	.72	-.08	.20	-.05	-.14	-.22
Fish larvae	.62	-.52	.01	-.50	-.01	.02
Anomalocera ornata males	-.01	.79	.29	.22	-.17	-.11
Anomalocera ornata females	-.03	.76	.28	.22	-.16	-.15
Anomalocera ornata immatures	-.06	.79	.26	.17	-.16	-.11
Labidocera aestiva males	.40	.18	.65	.25	.11	-.10
Labidocera aestiva females	.33	.15	.68	.20	.15	.04
Pontella meadii males	-.09	-.09	.65	-.22	.17	-.26
Pontella meadii females	.01	-.07	.72	-.11	.18	-.18
Pontella immatures	-.19	-.18	.56	-.16	.03	.04
Fish eggs	-.02	.21	.52	.06	-.03	.18
Temora turbinata	.39	.32	-.01	.59	.13	-.11
Pontellopsis villosa males	.06	-.46	-.24	.56	.16	-.01
Pontellopsis villosa females	.12	-.55	-.30	.43	.15	-.03
Pontellopsis immatures	-.10	-.52	-.28	.56	.23	-.03
Creseis virgula	.26	-.06	.26	-.51	.07	.43
Euphausiids	.33	.29	-.25	-.43	.36	.01
Salps	.04	-.52	.01	-.49	-.01	.05
Pleuromomma pisecki females	.33	.36	-.06	-.25	.55	-.11
Eucalanus attenuatus	.53	.50	-.10	-.13	.43	-.14
Cladocerans	.04	.10	.33	.18	.02	.50
Larvaceans	.35	.33	.05	.20	.27	.47
Medusae	.20	.14	.12	.16	-.03	.38
Bivalve larvae	.44	.35	-.03	.11	-.22	.19

TABLE 8.2 CONT.'D

Taxa	Fct 1	Fct 2	Fct 3	Fct 4	Fct 5	Fct 6
Gastropod larvae	.42	.04	.01	.33	-.26	.31
Atlantidae	.42	-.14	-.00	.05	.18	.05
Creseis acicula	.24	-.39	-.08	.40	.07	.36
Barnacle naupli	.06	.28	.06	.17	-.17	.26
Barnacle cyprids	-.13	.40	-.17	.04	.06	.03
Echinoderm larvae	.06	-.18	.09	.26	.23	-.12
Stomatopod alima larvae	.44	-.11	.02	-.32	-.34	-.11
Rhincalanus cornutus	.33	.16	-.01	-.23	.11	-.13
Labidocera immatures	.13	-.32	.29	.20	.35	.04
Cyclopoids	.15	.11	-.40	-.08	.29	.19
Doliolids	.49	.40	-.10	.12	.15	.33
Labidocera scotti males	.21	-.48	.30	.15	.19	.05
Labidocera scotti females	.24	-.42	.40	.09	.09	.07
Eucalanus attenuatus females	.17	.19	-.20	-.06	.05	.25
Pontellopsis plumata	.18	.11	-.38	-.22	.26	-.07
Pleuromomma gracilis and *pisecki* males	.27	.22	-.06	-.22	.56	-.12

TABLE 8.3

CORRELATION COEFFICIENTS, NUMBERS OF OBSERVATIONS AND SIGNIFICANCE LEVELS FOR FACTOR SCORES AND ENVIRONMENTAL PARAMETERS FOR 1976.

	N	F1	F2	F3	F4
Temperature (^{o}C)	(54)	.04	-.81***	-.09	-.11
Salinity (%)	(54)	.32*	-.04	-.65***	.21
Net Phytoplankton (μg chlor. a l^{-1})	(54)	-.03	.36**	.28*	.40**
Zooplankton Biomass (mg dry weight m^{-3})	(108)	.02	-.23*	.47***	-.03
Neuston Biomass (mg dry weight $10^{-3}m^{-3}$)	(108)	-.06	-.22*	.36***	-.23*
Nannoplankton (μg chlor. a l^{-1})	(54)	.17	.30	.21	.16
F1	(108)		.02	-.33**	.02
F2	(108)			.05	.00
F3	(108)				.03
F4	(108)				

* .01 > p <.05
** .001> p <.01
*** p <.001

and positively with zooplankton and neuston biomass and negatively with salinity. This group of taxa was not large enough to account for a lot of the neuston biomass. Factor 4 (6% of variance) scores were most significantly correlated with net phytoplankton. These correlations do not imply cause and effect, but do suggest other parameters to be monitored.

A similar analysis was done for the 1977 data with the addition of five new taxa. The first four factors extracted accounted for 51% of the overall variance. The groups of taxa based on these four factors were quite similar to those found in 1976. Table 8.4 shows the correlation analysis for the environmental parameters and the first four factor scores. There is little doubt that Factor 2 (16% of the variance) was the same each year and showed the consistent negative correlation with temperature. The correlation analysis of Factor 1 scores in 1977 indicated that this factor was not well identified with any of the environmental parameters as the correlations were inconsistent with the 1976 results. In point of fact, no other correlations were consistent between the years and were therefore demonstrative of the lack of cause and effect relationship. The species groups, however, did show a high year to year similarity. Factor analysis of 1976 and 1977 combined gave no additional insight.

Species representative of each of these groups were plotted against those parameters which had significant correlation with the group factor scores. Figure 8.2 shows *Centropages velificatus* females for 1977 day samples against temperature. This plot shows that all of the higher abundances occurred at the higher temperatures, although many low values occurred there also. The relationship with salinity was much the same (Figure 8.3). The relationship with zooplankton biomass (Figure 8.4) showed a lot of scatter with a slight positive trend. This species

TABLE 8.4

CORRELATION COEFFICIENTS, NUMBERS OF OBSERVATIONS AND SIGNIFICANCE LEVELS FOR FACTOR SCORES AND ENVIRONMENTAL PARAMETERS FOR 1977.

	N	F1	F2	F3	F4
Temperature (^{o}C)	(54)	.21	-.75**	-.24	.26
Salinity (%)	(54)	-.43**	.02	.55***	.48**
Net Phytoplankton (μg chlor. a l^{-1})	(54)	-.12	.21	.09	-.48**
Zooplankton Biomass (mg dry weight m^{-3})	(54)	.42**	.07	-.19	-.45**
Neuston Biomass (mg dry weight $10^{-3}m^{-3}$)	(81)	.00	.02	.17	-.11
Nannoplankton (μg chlor. a l^{-1})	(51)	.06	-.07	.26	-.56***
F1	(81)		.00	.00	.00
F2	(81)			.00	.00
F3	(81)				.00
F4	(81)				

* .01 > p <.05
** .001> p <.01
*** p <.001

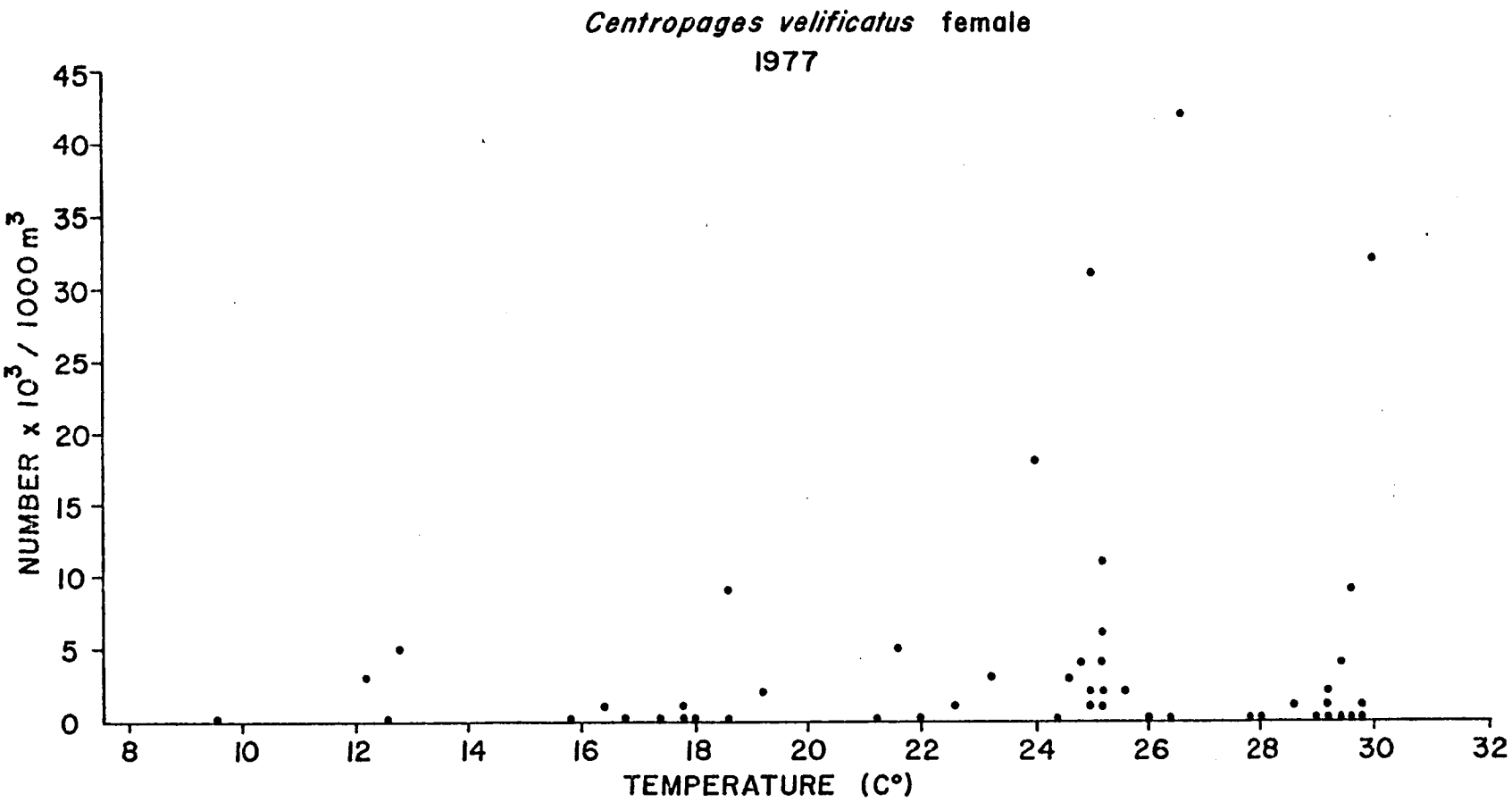

Figure 8.2 The relationship between temperature and abundance for Centropages velificatus females for 1977, day samples.

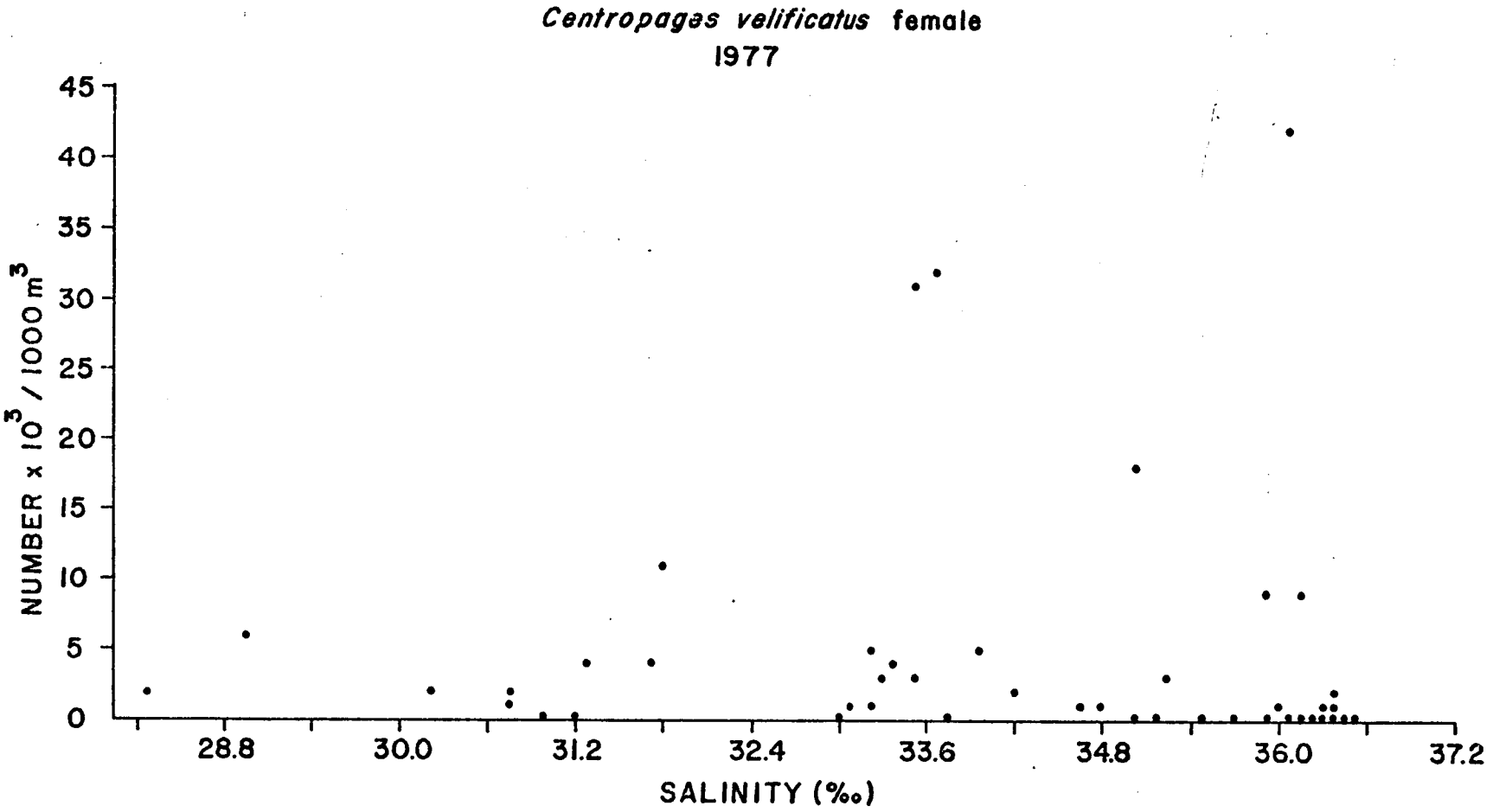

Figure 8.3 The relationship between salinity and abundance for Centropages velificatus females for 1977, day samples.

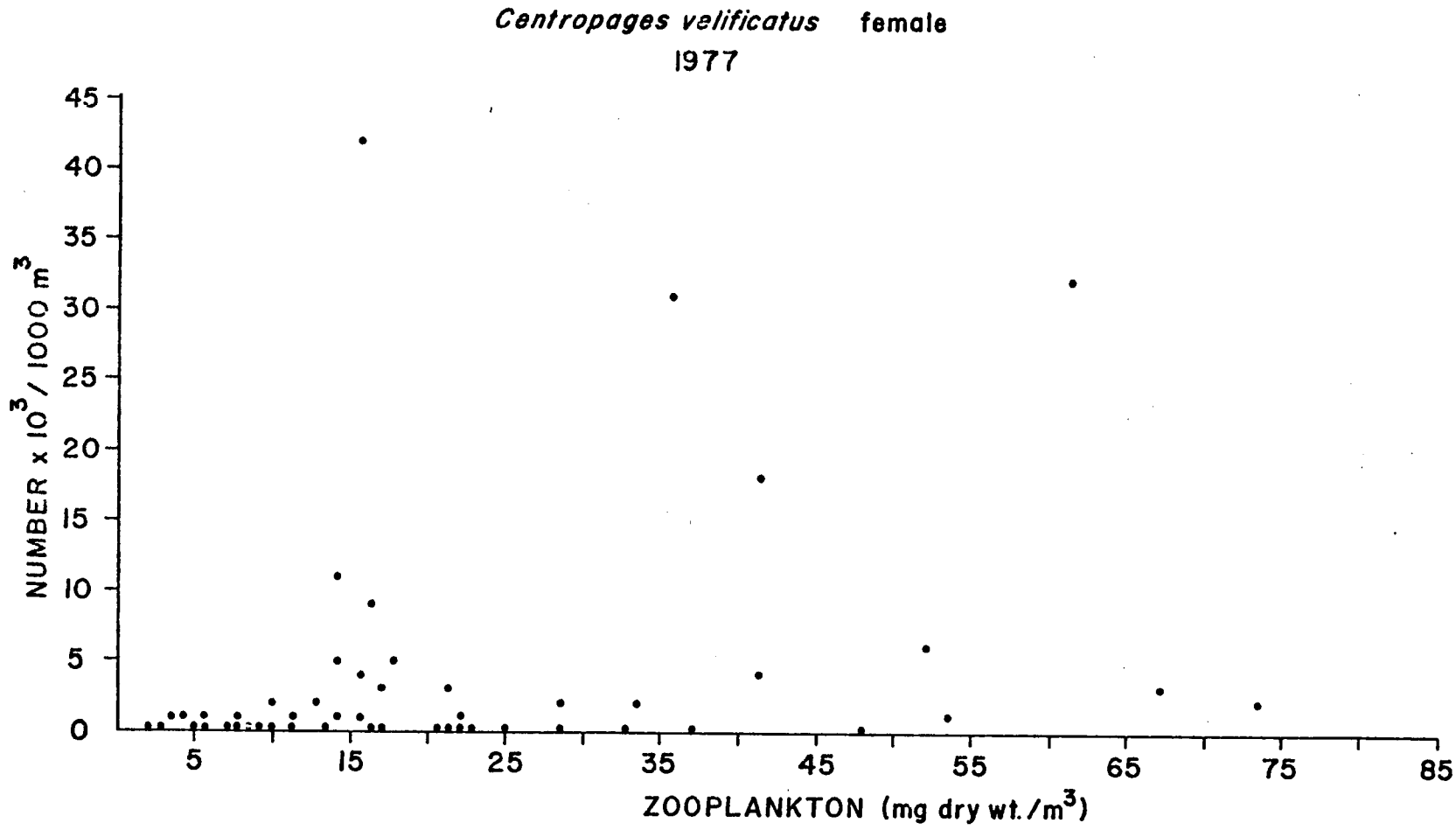

Figure 8.4 The relationship between zooplankton biomass and abundance for Centropages velificatus females for 1977, day samples.

appeared to be more of a summer species in the STOCS area as shown in Figure 8.5. Analysis of variance of this species presented in previous final reports showed significant differences for season as well as for station and time. Inspection of mean values for this species suggests the following:

1. abundance showed a maximum from spring (day 140) through the fall (day 250);
2. onshore abundances (Station 1) were greater than offshore (Stations 2 and 3);
3. night values were greater than day.

Anomalocera ornata was the only species to group on Factor 2. Since the factor scores showed significant negative correlation with temperature in both years, these two parameters are plotted against each other in Figure 8.6. It is clearly a colder water species. Once temperatures exceeded about 22°C this species was never caught. When plotted against Julian day (Figure 8.7), *A. ornata* appeared to be a winter species only. Analysis of variance showed significant seasonal and station differences. Inspection of mean values for the females showed:

1. a maximum in March (day 65); and
2. a steady decrease from Station 1 to Station 3.

A species representative of Factor 3 scores, *Labidocera aestiva*, showed significant seasonal and station variations (see Table 8.1). The males showed significant day-night differences, the females and immatures did not. This species' trends showed:

1. a maximum started around day 110 with a return to low values by day 190;
2. a decrease from onshore to offshore stations; and
3. higher night values for males only.

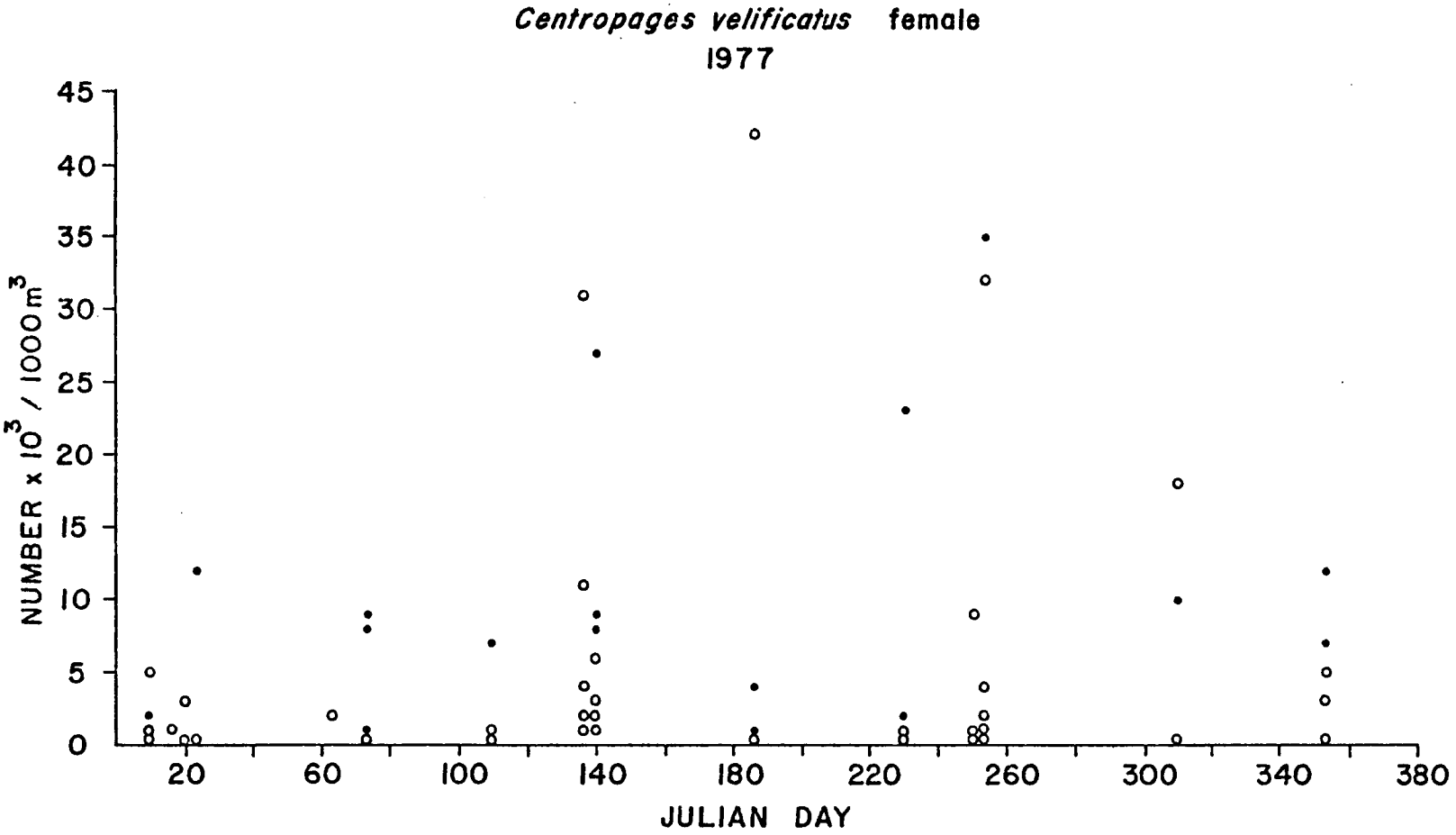

Figure 8.5 The temporal variation in abundance for Centropages velificatus females in 1977. The open circles are day tows, the solid ones are night tows. Coincident values are not distinguished.

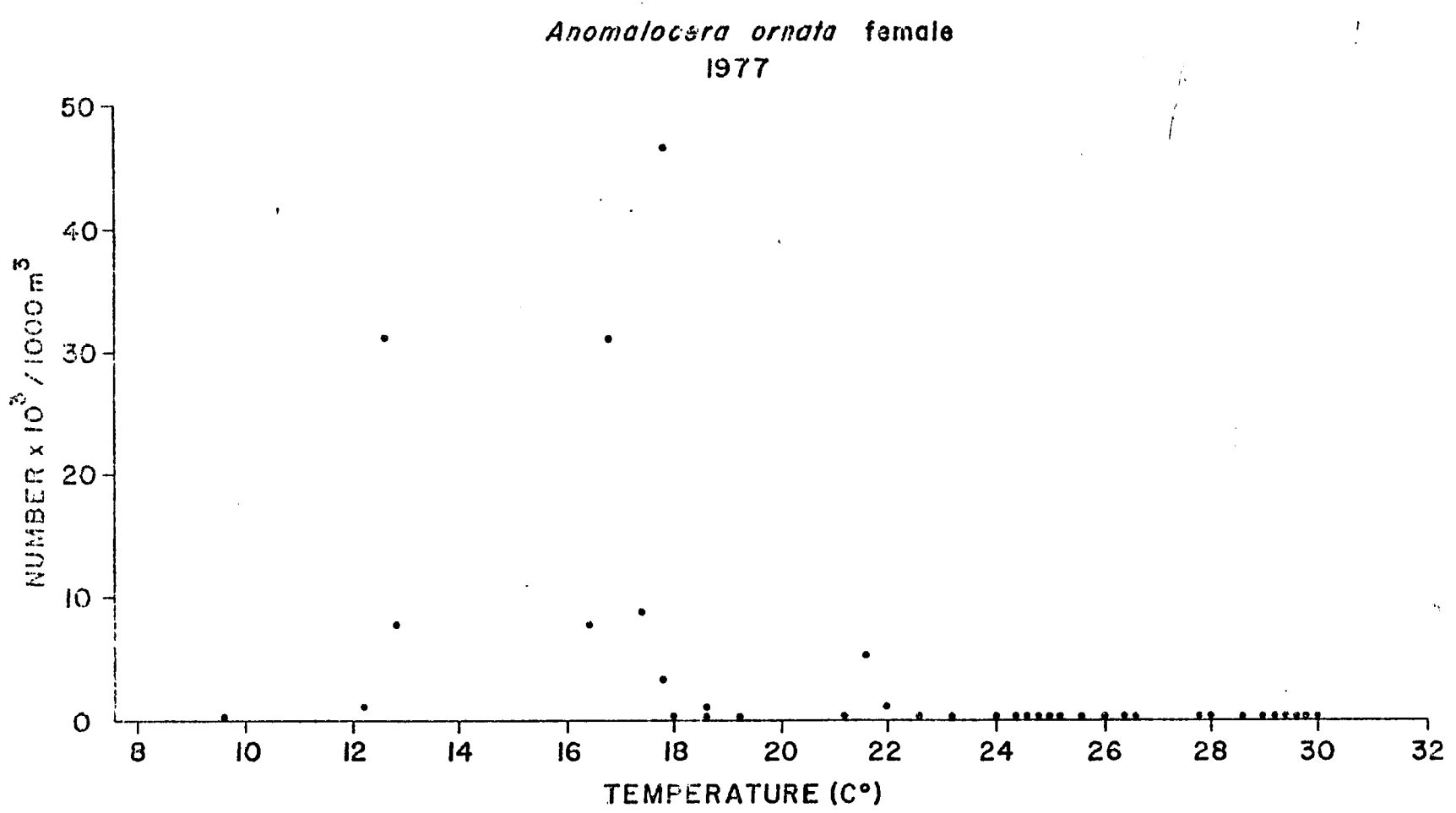

Figure 8.6 The relationship between temperature and abundance for Anomalocera ornata females for 1977, day samples.

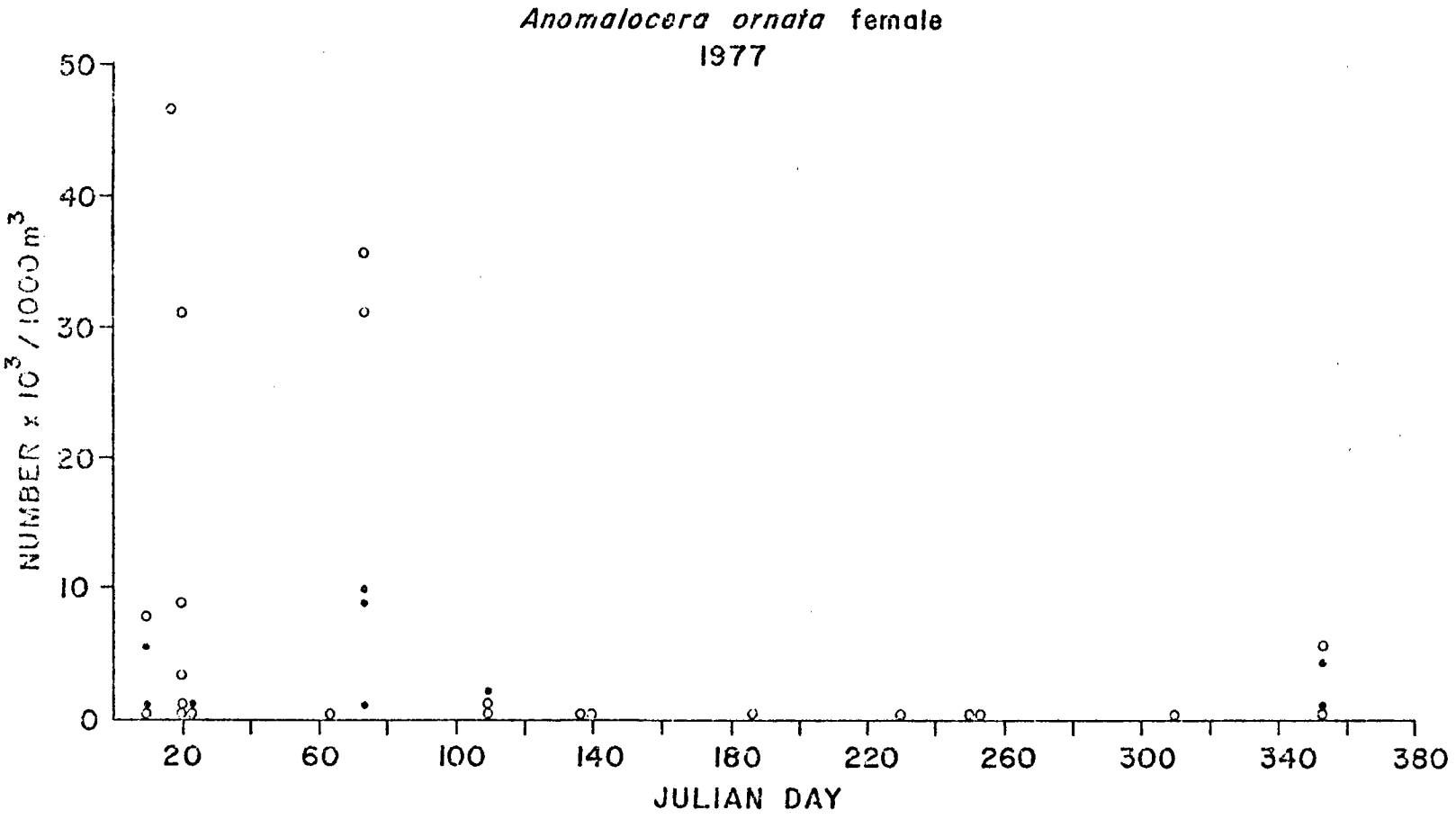

Figure 8.7 The temporal variation in abundance for Anomalocera ornata females in 1977. The open circles are day tows, the solid ones are night tows. Coincident values are not distinguished.

Seasonal Cycles

Taxa which have been identified to the species level or below occurred in fairly pronounced temporal cycles. There are a few winter species, but most are summer species. The surface temperature cycle along Transect II is shown for 1976 in Figure 8.8; 1977 was very similar. In the "winter months" the inshore station was coldest and there was a "gap" of about 4°C in the spring when many qualitative and quantitative changes appeared to take place. In addition the peak temperatures were not seen until late August and remained until at least mid-October. The same trend was seen in 1977 except that the temperatures did not fall off as quickly at the end of the year. Those species with seasonal cycles showed reasonable consistency between the two years.

Tar

Analysis of variance of tar concentrations showed significant effects of season and transect, but not station or time. To illustrate this, tar is plotted against Julian day in Figure 8.9. High values were seen during the March, Fall and November cruises. In part, this was due to single high values which shifted the means upwards. Figure 8.10 shows the effect of transect with highest averages on Transect I and a decrease to Transect IV. The number of observations on Transect II, however, is six times greater than any other transect.

Decapoda

The neuston decapod fauna was studied in great detail during 1976 and 1977. A total of 104 decapod taxa were identified consisting of 88 larval taxa and 16 non-larval taxa. Decapod larvae accounted for 53% of the mean concentration of total decapods and 6% of the total neuston and consisted of 34 natantian and 54 reptantian taxa representing 11 and 18 families

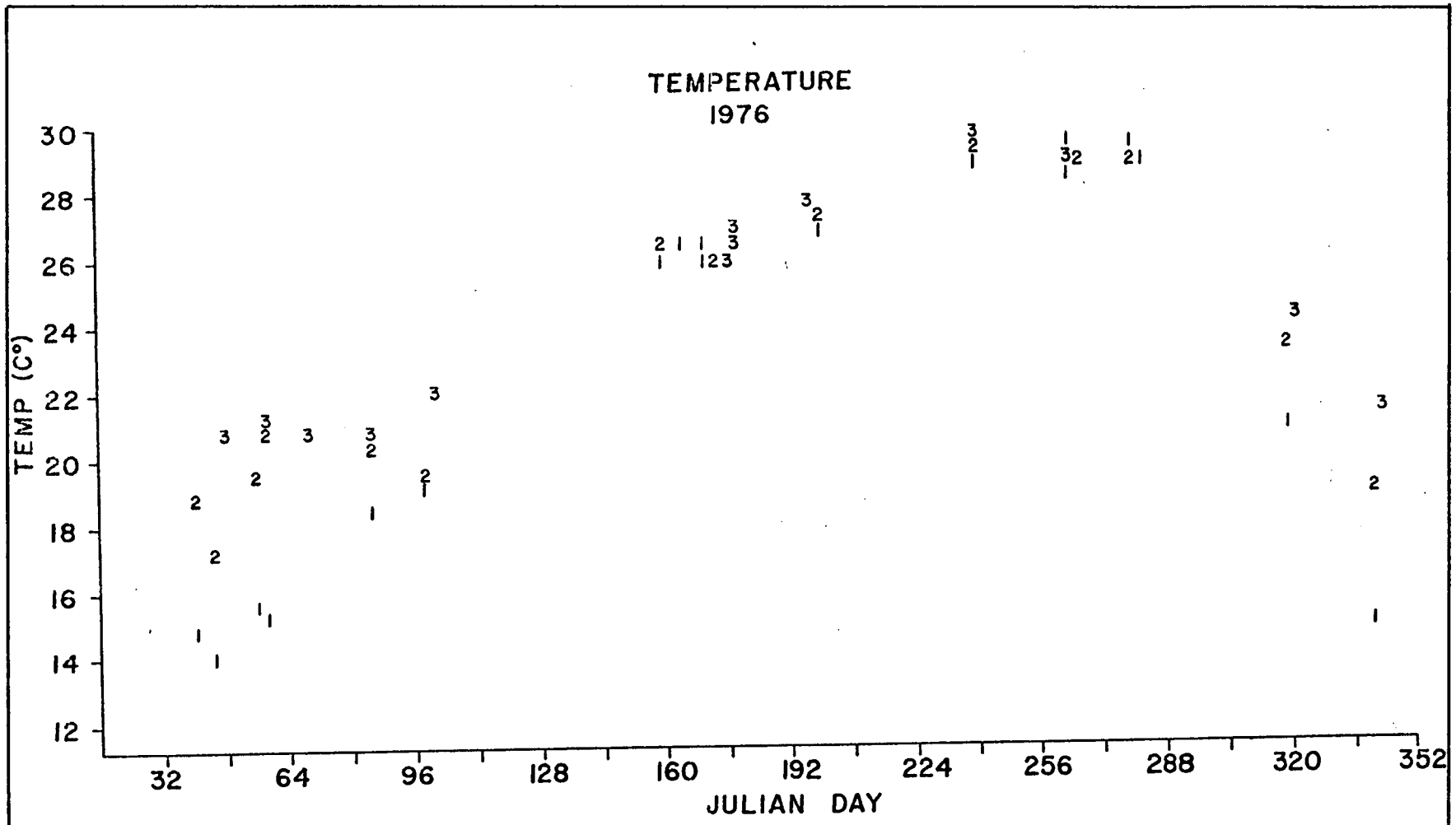

Figure 8.8 The annual temperature cycle at the surface for 1976 along Transect II. The numbers represent the station numbers.

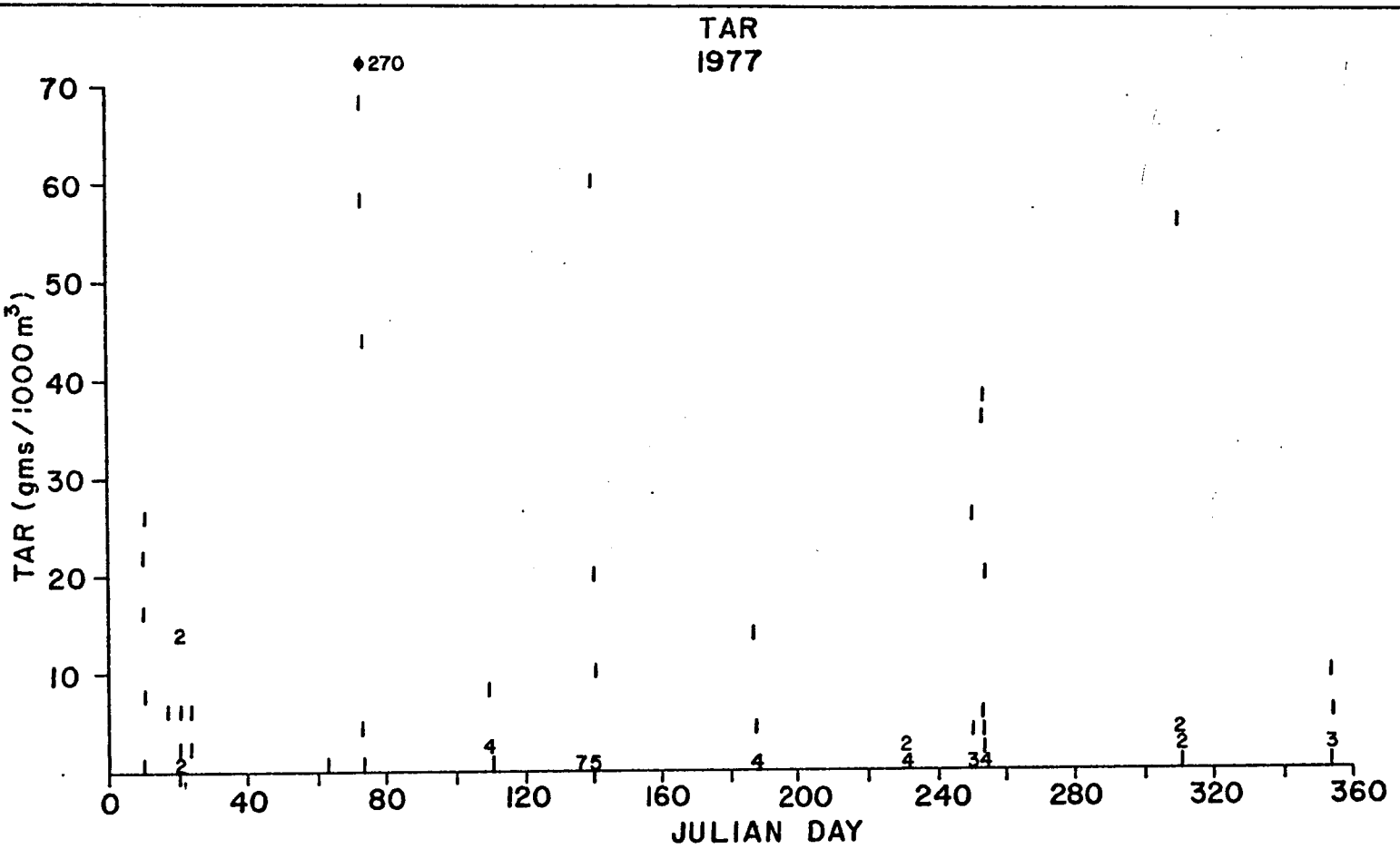

Figure 8.9 The annual variation in tar concentration for all tows in 1977. The numbers represent the number of coincident points.

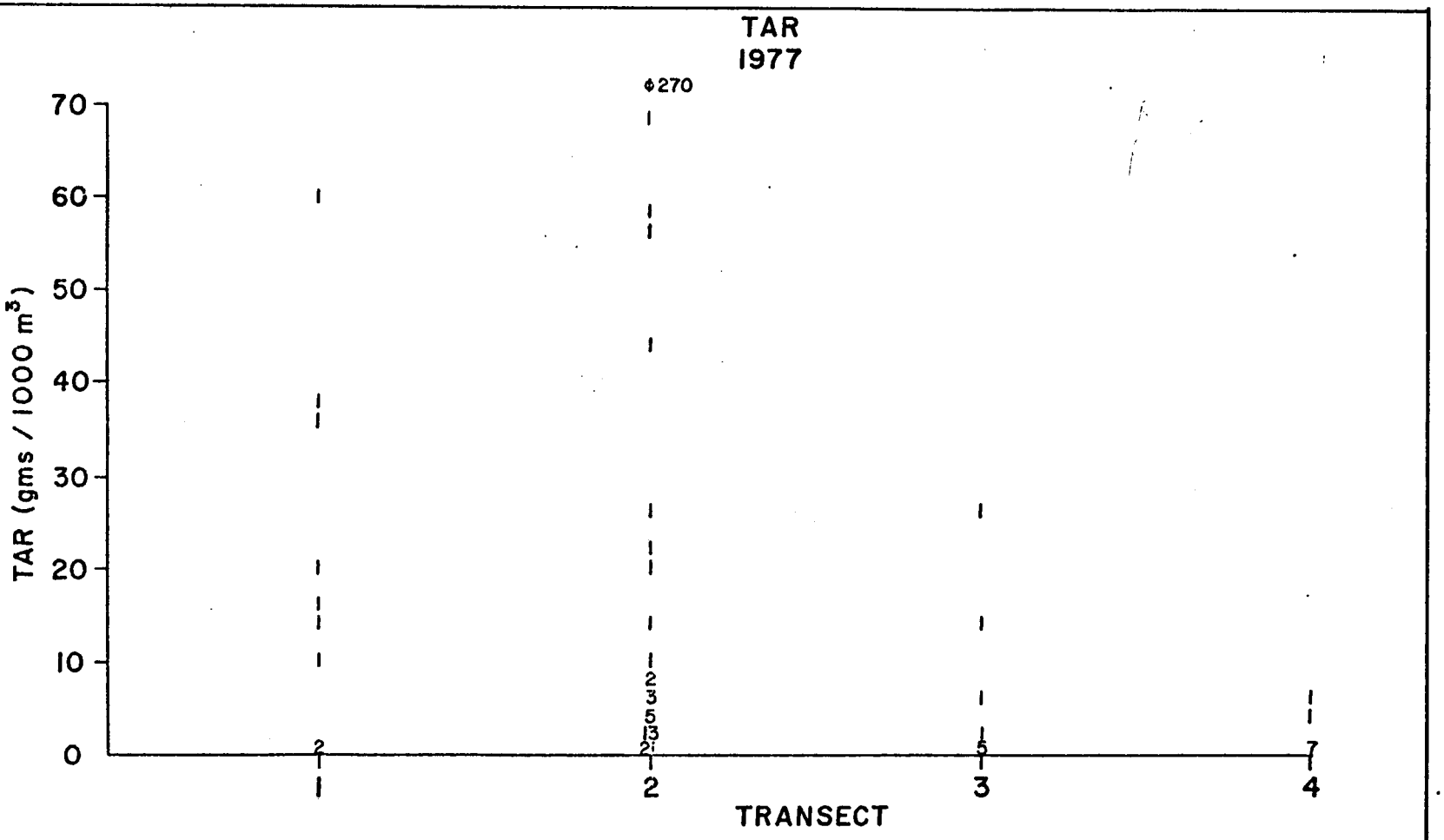

Figure 8.10 The variation in tar concentration by Transect. The numbers represent the number of coincident points.

respectively.

Non-larval decapods consisted of 10 natantian species and six reptantian species from six decapod families. The predominate non-larval species in both the 1976 and 1977 neuston was the holoplanktonic sergestid shrimp, *Lucifer faxoni*.

The neuston decapods will be discussed in relation to their numerical abundance, species diversity, and species composition. Within these categories the following spatial-temporal variations will be treated: diel, seasonal, distance from shore, and north-south geographical differences.

Numerical Abundance

Numerical abundance of decapod larvae at three stations along Transect II, the only transect sampled monthly, is plotted against time in Figures 8.11 (for 1976) and 8.12 (for 1977). Day-night differences were clearly shown with concentrations considerably greater at night in most samples. This is due to diel vertical migrations of larvae to the surface at night. Seasonal differences are also shown, particularly in the night neuston, where large spring peaks in abundance occurred in the April-June periods during 1976 and 1977, except at the offshore location (Station 3) in 1976 where the peak occurred in March. Smaller fall peaks in the August-October period also occurred at nearly all the stations in both years. An exception was Station 2 in 1976 where the peak occurred in December.

In comparing nearshore-offshore variability in numerical abundance, Figures 8.11 and 8.12 show similar periods of peak abundance of decapod larvae at the three stations along Transect II except for the offshore Station (3) in 1976 where, although there was a March peak, the June peak that was present at Stations 1 and 2 was missing at Station 3. A

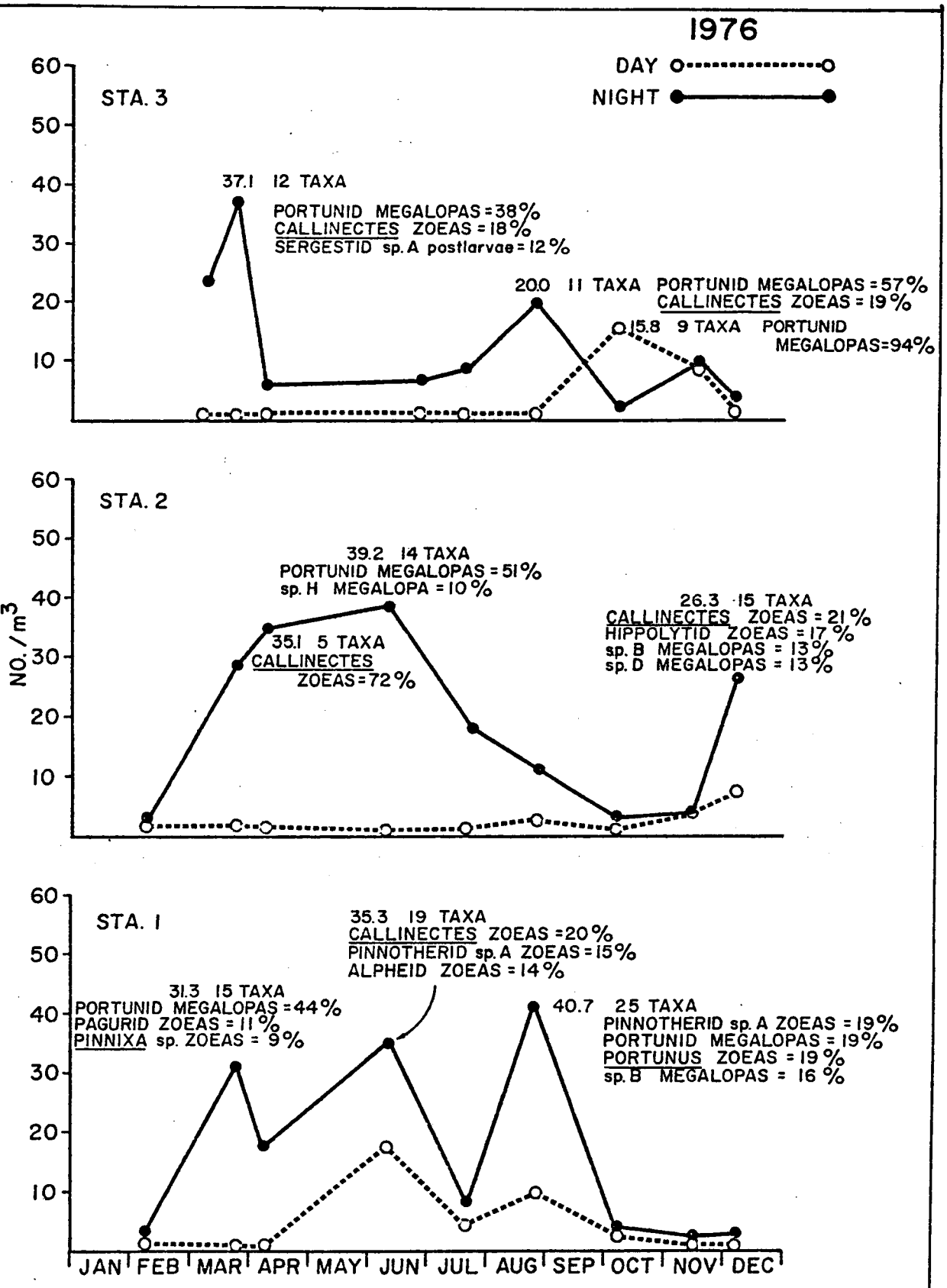

Figure 8.11 Numerical abundance of neuston decapod larvae plotted against time for 1976 at Transect II.

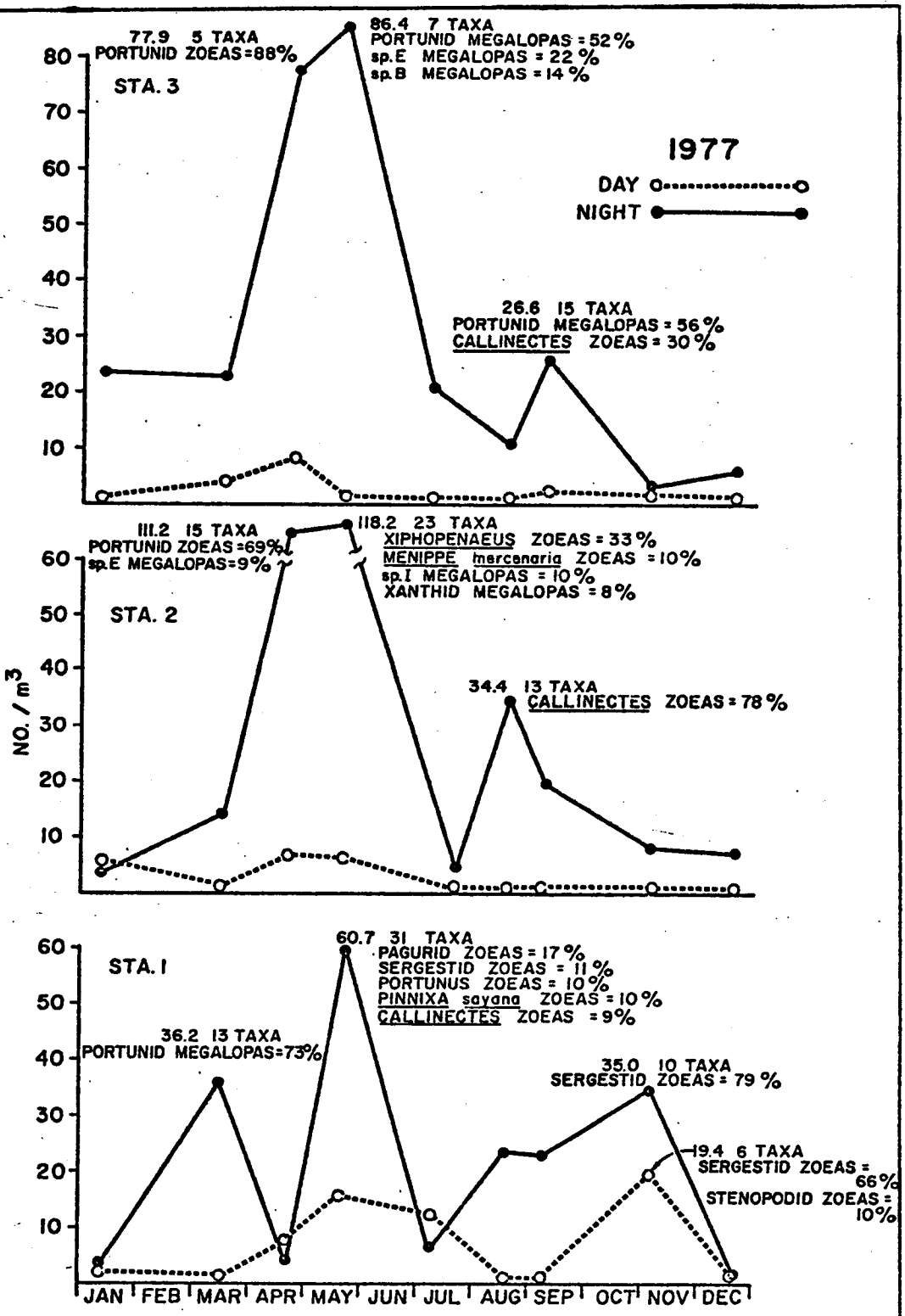

Figure 8.12 Numerical abundance of neuston decapod larvae plotted against time for 1977 at Transect II.

strong June peak was present, however, at Station 3 in 1977, suggesting the possibility of different conditions in the offshore waters between the two years. The levels of abundance during peak concentrations of decapod larvae were higher in 1977 at all three stations along Transect II compared to 1976. A listing of the dominant decapod larval taxa at each peak often show entirely different taxa accounting for the different peaks. Correlations of various species of decapods and decapod larvae with surface temperature and salinity showed no significant correlations. High concentrations of decapod larvae are ultimately related to spawning of benthic adults which may be related to a variety of benthic environmental conditions rather than to pelagic factors.

Variability in mean numerical abundance of decapod larvae by transects, *i.e.* , north-south geographic differences, is shown in Table 8.5 for each transect for 1976 and 1977 using seasonal samples only and with day and night samples averaged. The mean abundance at each transect varied considerably between 1976 and 1977 with Transects III and IV showing greater values in 1976 and Transects I and II showing greater values in 1977.

Species Diversity

Species diversity (*i.e.* number of taxa per sample) of decapod larvae was noticeably and consistently greater at night, with an average of 2 1/2 times more taxa in night samples (4.1 vs. 10.2 mean taxa per sample). Decapod larval species diversity was also greater in spring and fall than in winter and greater at nearshore stations than at offshore stations. The decrease in larval diversity with distance from shore could be expected as decapod larval input into the surface waters is greatest over inshore areas where benthic decapod adult populations are more diverse.

TABLE 8.5

MEAN DECAPOD LARVAE ABUNDANCE BY TRANSECT (No./1000 m^3)

	1976	1977	2-YR. AVG.
TRANSECT I	7,287	17,201	10,591
TRANSECT II	8,795	22,109	15,452
TRANSECT III	16,554	4,232	12,446
TRANSECT IV	16,187	9,718	14,031

Transect or north-south differences in species diversity were not pronounced. However, Transects II and III averaged somewhat greater decapod larval diversities over the two year period compared to Transects II and IV.

The numbers of decapod larval species in any single sample ranged from 0 (in several day tows) to a maximum of 31 (a night tow in the spring).

Species Composition

A total of 29 decapod taxa accounted for 91% of the decapod abundance in 1976 and 1977 neuston samples and are listed in order of dominance in Table 8.6, which also lists mean concentrations per 1000 m^3 and percent composition of total decapods and of total neuston for each species. Of these 29 dominant species, 25 are larval forms. Of the four non-larval species (*Lucifer faxoni, Leptochela bermudensis, Latreutes fucorum* and *Letreutes parvulus*), *Lucifer faxoni* was by far the most abundant - 45% of total Decapoda compared to less than 2.5% for the other three shrimp.

Lucifer faxoni ranked first in numerical abundance in both 1976 and 1977 samples. At Transect II *L. faxoni*, a species characteristic of near-shore or shelf waters, reached its greatest concentrations at the near-shore station (Station 1) in spring (May or June) and again in August during both years (Figures 8.13 and 8.14).

At Station 2, both years showed moderate spring peaks for *L. faxoni* in the period from April to June in night samples. The absence of a spring peak in 1976 and Station 3, together with a similar situation for decapod larvae in the same year indicates a possibility of the intrusion of more oceanic water, containing fewer decapod larvae and fewer of the shelf water indicators such as *L. faxoni*, in 1976 at Station 3. It is also interesting to note that *L. typus*, which is considered to be an

TABLE 8.6

DOMINANT DECAPOD TAXA IN 1976 AND 1977 NEUSTON

SPECIES	MEAN CONCENTRATION (Per 1000 m^3)			DOMINANCE					
				% of TOTAL DECAPODA			% OF TOTAL NEUSTON		
	1976	1977	2-YR. AVG.	1976	1977	2-YR. AVG.	1976	1977	2-YR. AVG.
Lucifer faxoni	10,705	11,490	11,042	47.2	43.3	45.38	5.78	5.04	5.42
Portunid megalopas	3,979	3,138	3,619	17.5	11.8	14.87	2.15	1.38	1.78
Callinectes zoeas	1,775	2,448	2,064	7.8	9.2	8.48	0.96	1.07	1.01
Portunus zoeas	890	1,579	1,186	3.9	5.9	4.87	0.48	0.69	0.58
Leptochela bermudensis	578	642	606	2.5	2.4	2.49	0.31	0.28	0.30
Pinnotherid sp. A zoeas	688	286	516	3.0	1.1	2.12	0.37	0.13	0.25
Sergestid sp. A postlarvae	696	213	489	3.1	0.8	2.01	0.38	0.09	0.24
Sergestid zoeas	3	899	387	<0.1	3.4	1.59	<0.01	0.39	0.19
sp. C & E megalopas	108	595	317	0.5	2.2	1.30	0.06	0.26	0.16
Alpheid zoeas	294	291	293	1.3	1.1	1.20	0.16	0.13	0.14
sp. B megalopas	236	313	269	1.0	1.2	1.11	0.13	0.14	0.13
Xiphopenaeus zoeas	0	546	234	0.0	2.1	0.96	0.00	0.24	0.12
Trachypenaeus zoeas	93	366	210	0.4	1.4	0.86	0.05	0.16	0.10
Pagurid zoeas	145	198	168	0.6	0.7	0.69	0.08	0.09	0.08
Pinnixa sayana zoeas	11	352	157	<0.1	1.3	0.65	0.01	0.15	0.08
Hexapanopeus zoeas	14	202	94	0.1	0.8	0.39	0.01	0.09	0.05
sp. D megalopas	73	79	76	0.3	0.3	0.31	0.04	0.03	0.04
Stenopodid zoeas	2	155	67	<0.1	0.6	0.28	<0.01	0.07	0.03
Latreutes parvulus	77	52	66	0.3	0.2	0.27	0.04	0.02	0.03
sp. H megalopas	103	0	59	0.5	0.0	0.24	0.06	0.00	0.03
Neopanope texana zoeas	7	126	58	<0.1	0.5	0.24	<0.01	0.06	0.03
Pagurid glaucothoe	52	59	55	0.2	0.2	0.23	0.03	0.03	0.03
Sergestid protozoeas	45	52	48	0.2	0.2	0.20	0.02	0.02	0.02
Sicyonia zoeas & protozoeas	84	2	48	0.4	<0.1	0.20	0.05	<0.01	0.02
Sergestid sp. B postlarvae	55	29	44	0.2	0.1	0.18	0.03	0.01	0.02
Penaeus zoeas & protozoeas	27	64	43	0.1	0.2	0.18	0.02	0.03	0.02
Diogenid zoeas	37	38	38	0.2	0.1	0.16	0.02	0.02	0.02
Pinnixa cf. cylindrica zoeas	20	4	13	0.1	<0.1	0.05	0.01	<0.01	0.01
Latreutes fucorum	19	6	13	0.1	<0.1	0.05	0.01	<0.01	0.01
Total Decapods	22,674	26,541	24,3[illegible]			91.56	12.2	11.6	11.9

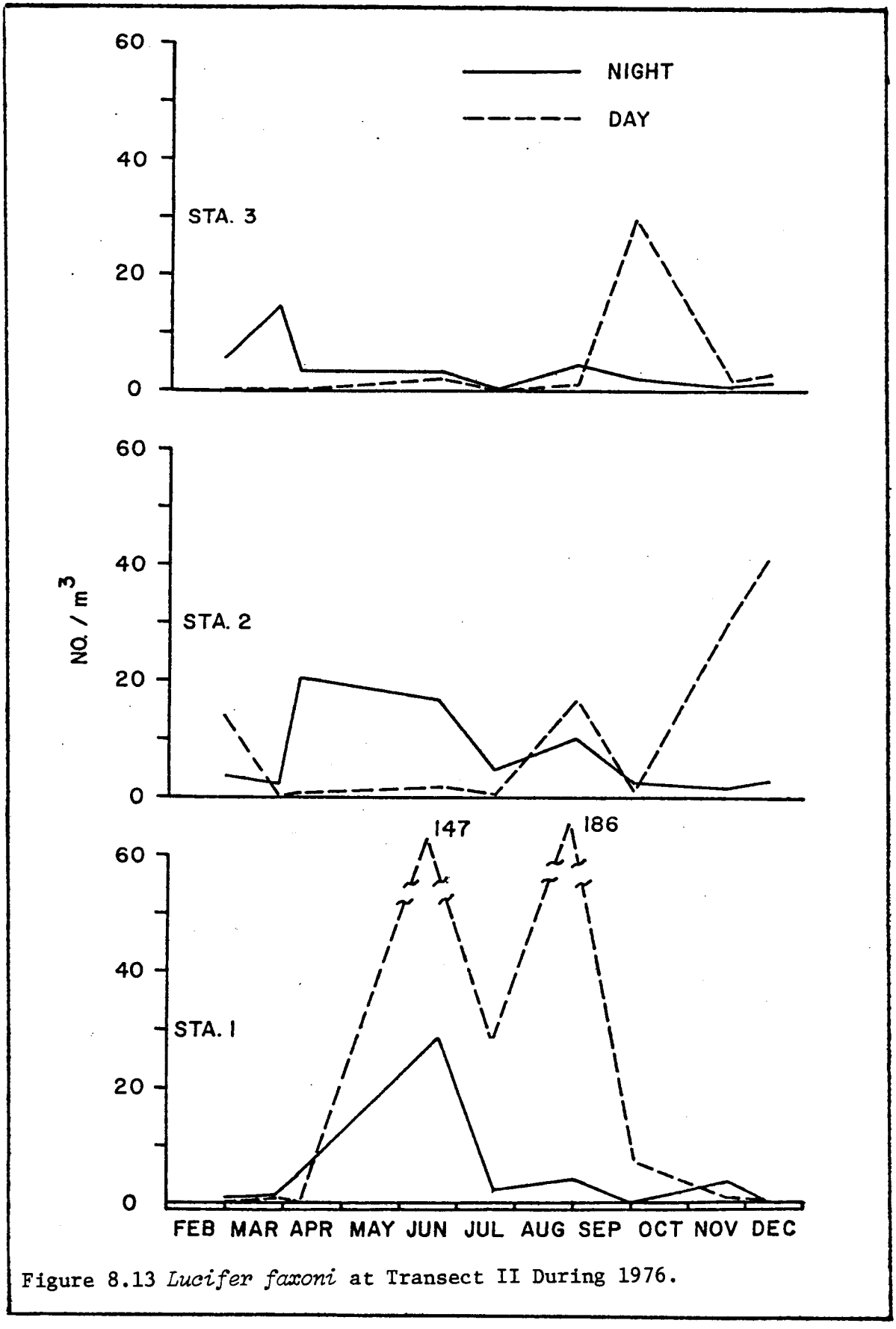

Figure 8.13 *Lucifer faxoni* at Transect II During 1976.

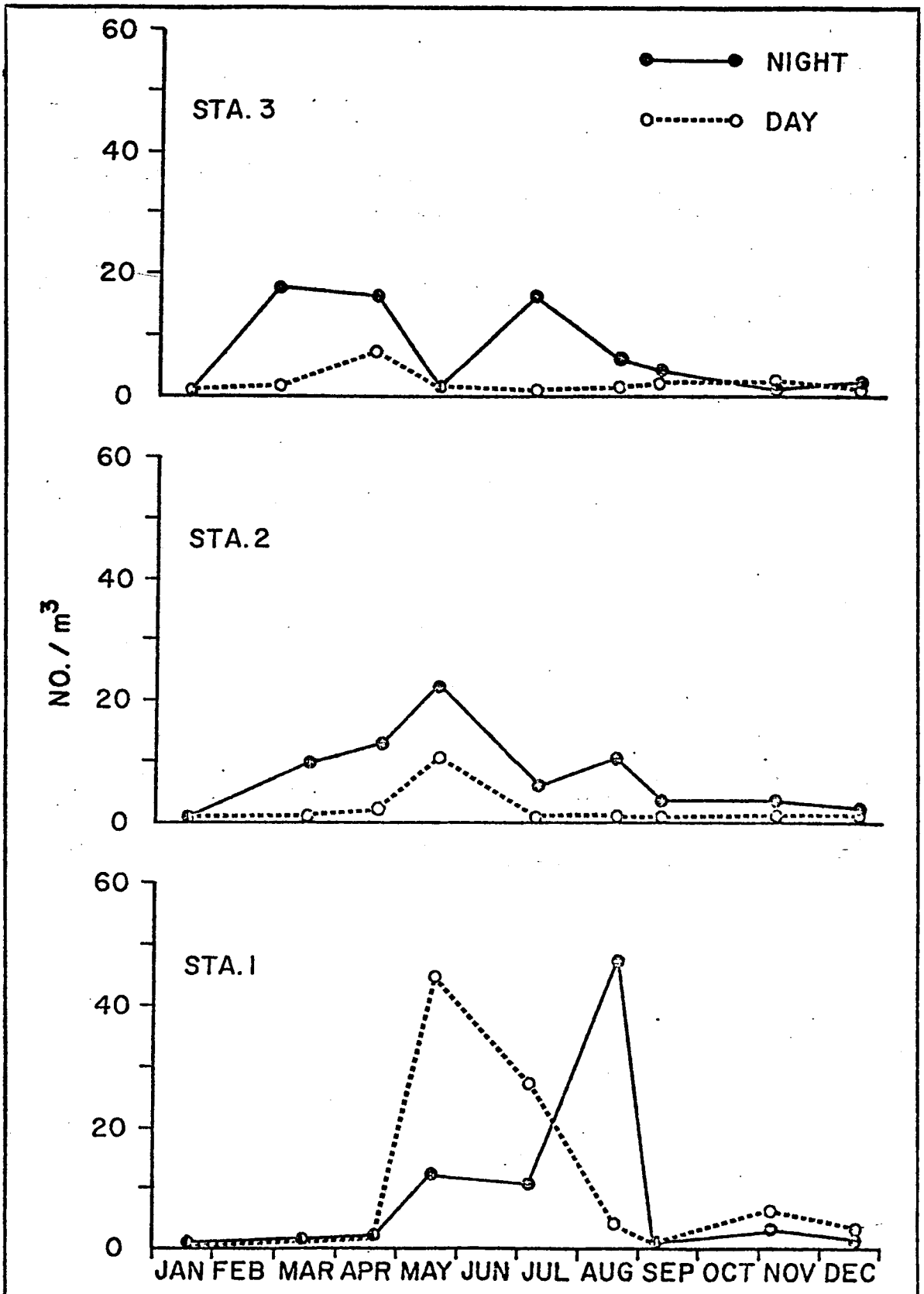

Figure 8.14 *Lucifer faxoni* at Transect II During 1977.

indicator of oceanic water (Bowman and McCain, 1967; Harper, 1968) was taken only at the offshore stations (Station 3) between June and November 1976 except for one occurrence at Station 3/II in July. *L. typus* was not present in the 1977 neuston samples. This would further suggest the presence of an oceanic water mass at Station 3 during 1976 that did not exist in 1977.

Lucifer faxoni reached greater concentrations more often at night than in day samples. The peak concentrations of *Lucifer* in "day" samples at Station 1 in June and August of 1976 (Figure 8.13) and in 1977 in May at Station 1 (Figure 8.14) actually occurred during twilight hours, at which time *L. faxoni* was found in much greater concentrations than during either day or night (Table 8.7).

The maximum abundance reached by *L. faxoni* during the two-year study was 415,656/1000 m^3 at Station 2, Transect IV in May 1977, a concentration greater than any values encountered at Transect II.

Leptochelia bermudensis and *Latreutes parvulus* both reached their greatest abundance in the spring to summer months (March-July) in 1976 and 1977. These are benthic caridean shrimp species which are found in the surface waters at night. *Latreutes fucorum*, associated with *Sargassum* was found in surface waters in both day and night samples. It was most abundant in April and May in 1976 and in November during 1977.

Nearly all of the dominant decapod larvae reached greatest concentrations sometime during the spring (March-June) period. Fourteen species showed additional or secondary peaks of abundance in other months and are categorized in Table 8.8.

Closer inspection of the dominant taxa accounting for peaks of abundance of decapod larvae at Transect II during 1976 and 1977 (Figures 8.11

TABLE 8.7

MEAN CONCENTRATIONS OF *Lucifer faxoni* IN DAY, TWILIGHT AND NIGHT HOURS (No./1000 m^3)

	1976	1977
Day	8,978	4,750
Twilight	34,513	43,889
Night	5,844	8,051

TABLE 8.8

DOMINANT DECAPOD TAXA BY SEASON

	Secondary Peak Concentrations 1976	No./1000 m^3 OF Decapod Larvae 1977
January-February Peaks		
Sergestid sp. A. postlarvae	3,000	1,700
Trachypenaeus zoeas	1,500	-
Pinnixa cf. *cylindrica* zoeas	900	260
August Peaks		
Pinnixa sp. A. zoeas	7,500	-
sp. B. megalopas	6,400	-
Portunus zoeas	4,800	5,600
Alpheid zoeas	-	2,500
September-October Peaks		
Portunid megalopas	-	58,000
Pinnixa sp. A. zoeas	-	18,000
Callinectes zoeas	-	7,000
Pagurid zoeas	-	7,400
Pinnixa sayana	-	6,000
Alpheid zoeas	3,000	-
Stenopodid zoeas	-	2,900
Hexapanopeus zoeas	-	2,700
Sergestid sp. A zoeas	-	1,900
Trachypenaeus zoeas	1,800	-
November Peaks		
Stenopodid zoeas	-	2,000
December Peaks		
sp. B. megalopas	3,600	-

and 8.12) showed that the Station 3 peaks during both years are accounted for almost entirely by portunid crab larvae (*Callinectes* and *Portunus* zoeas and megalopas). This is not to say that portunid larvae did not dominate at times at the nearshore stations, as in March and April of both years at Station 1 and 2, but other taxa tended to appear and dominate at the nearshore stations more often than at Station 3. For example, at Station 2 in May of 1977 *Xiphopenaeus* zoeas and three species of non-portunid crab larvae were dominant at Station 1. In May and November 1977 other taxa than Portunidae were dominant (*i.e.* pagurid crab zoeas, sergestid shrimp zoeas, *Pinnixa sayana* zoeas and Stenopodid zoeas).

The dominant decapod taxa arranged according to the stations at which they occurred more frequently and/or in greater abundance are shown in Table 8.9. Zoeas of the pinnotherid crab, *Pinnixa sayana*, are an example of a species that occurred most frequently and in greatest numbers at the nearshore station. Its abundance in 1977 samples according to station is plotted in Figure 8.15.

Portunid crab megalopa larvae are examples of a taxon that reached greater abundance at the offshore station (Station 3), and its abundance in 1977 samples is plotted according to station in Figure 8.16.

The majority of the individual decapod taxa showed no consistent affiliation for a particular transect, and therefore no discernable north-south distributional differences were identified. There was considerable variation in transect abundance for most of the species between 1976 and 1977 and very little consistency between the two years for this kind of north-south geographical difference. This is probably due to the fact that longshore currents which exist in the area transport the neuston organisms parallel to the shoreline and thus mask any north-south geographical differences.

TABLE 8.9

DOMINANT DECAPOD TAXA BY STATION

	Maximum Concentration No./1000 m^3
Station 1 (Nearshore or Shallow Species)	
Pinnotherid sp. A zoeas	18,377
Pagurid zoeas	10,575
Pinnixa sayana zoeas	10,000
Hexapanopeus zoeas	4,700
Sergestid sp. B postlarvae	3,496
Stenopodid zoeas	2,922
Pagurid glaucothoe larvae	2,185
Diogenid zoeas	1,440
Pinnixa cf. *cylindrica* zoeas	870
Stations 1 and 2 (Nearshore and Intermediate Species	
Lucifer faxoni	415,656
Neopanope texana zoeas	7,457
Station 3 (Offshore or Deep-Water Species)	
Portunid megalopas	91,290
Leptochela bermudensis	30,521
Common At All Three Stations (Ubiquitous)	
Callinectes zoeas	30,744
Portunus zoeas	27,000
sp. B megalopas	12,000
Sergestid sp. A postlarvae	15,777
Trachypenaeus zoeas	7,200
Alpheid zoeas	6,625
Penaeus zoeas & protozoans	2,845

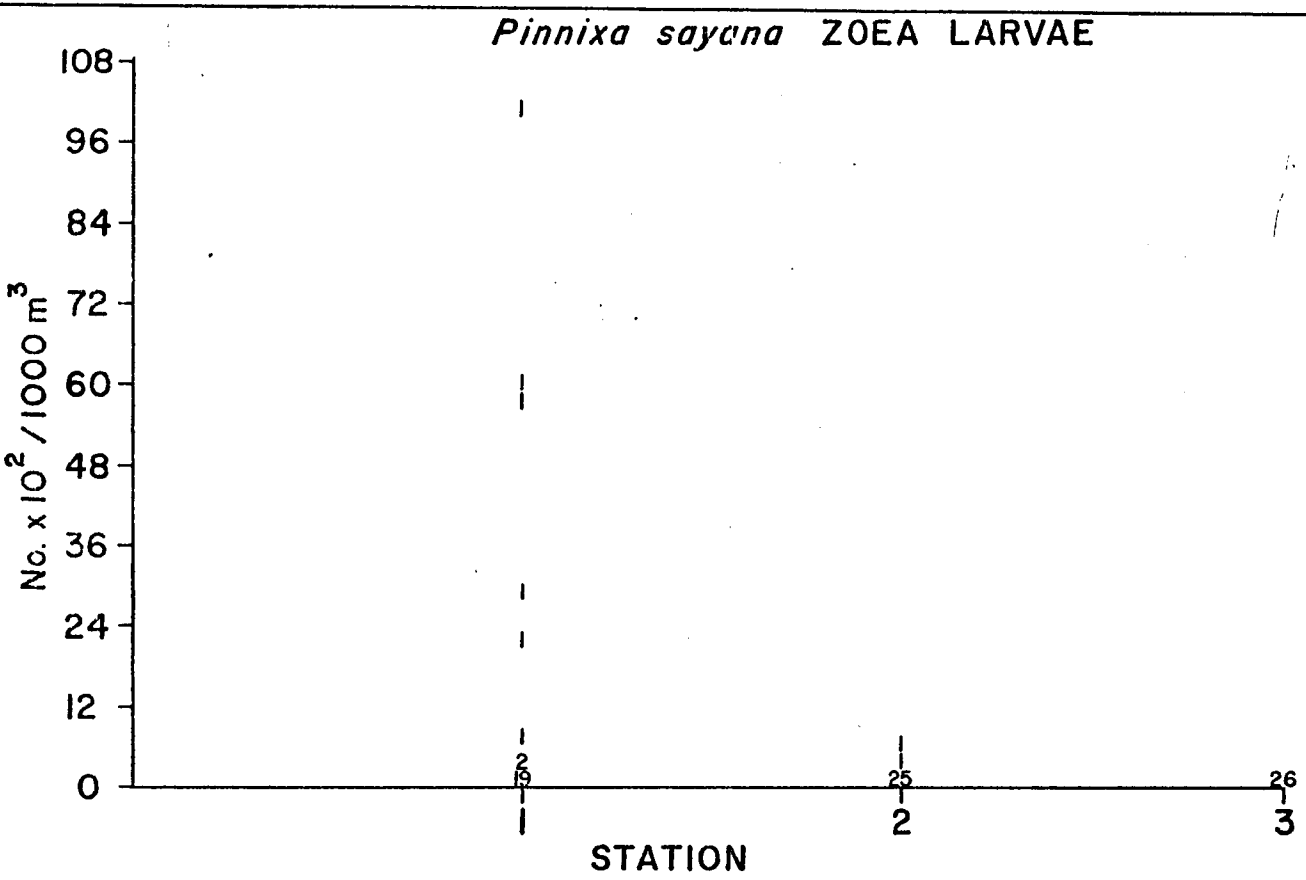

Figure 8.15 Numerical abundance of Pinnixa sayana zoea larvae by station in 1977. Numbers represent number of occurrences.

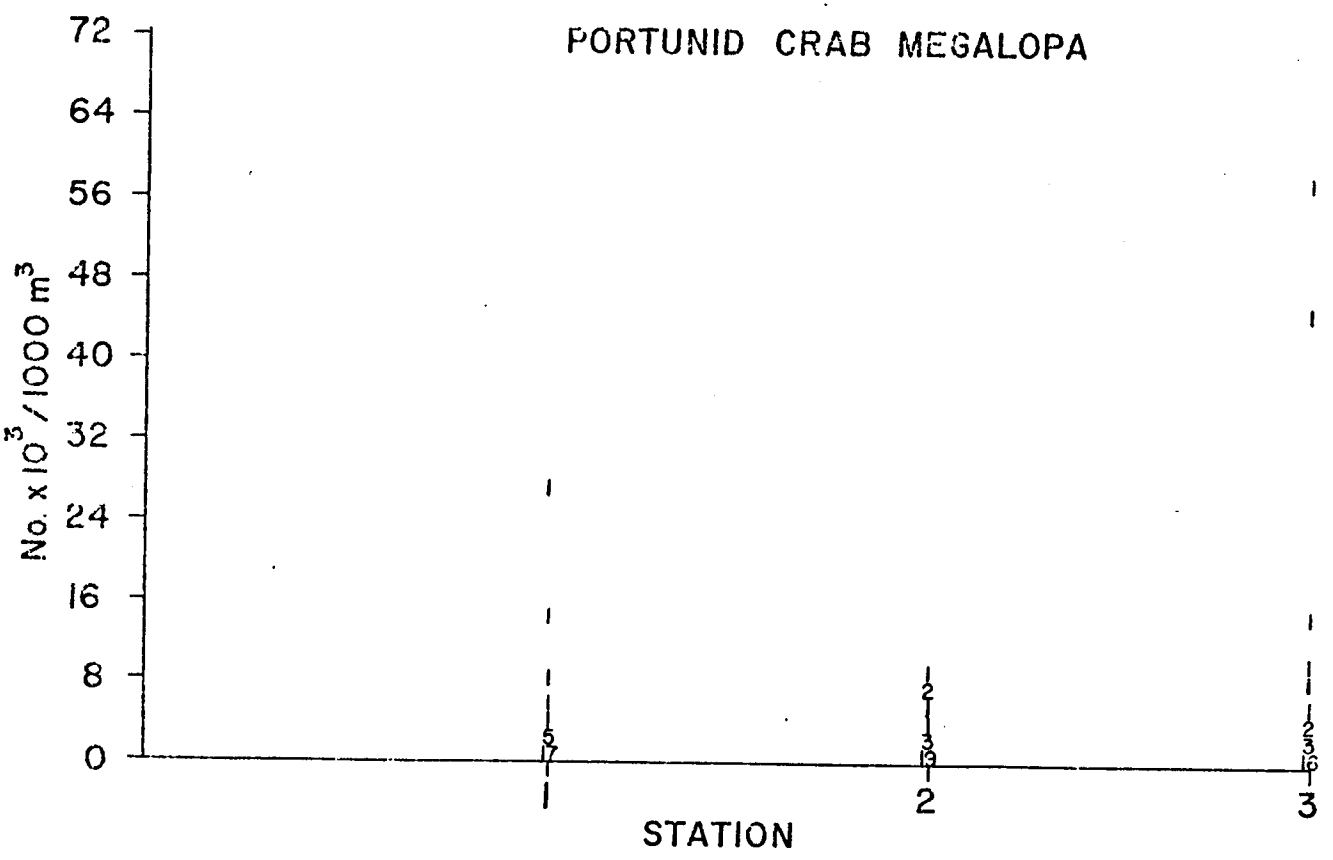

Figure 8.16 Numerical abundance of Portunid crab megalopa larvae by station in 1977. Numbers represent numbers of occurrences.

Fish

Diversity of fish taxa, when computed for each of the sampling years, was relatively high (H = 2.72 for 1976; H = 2.58 for 1977). In 1976 24 taxa individually contributed 0.1% or more to the total number of identifiable specimens. The most abundant taxa, those which individually represented 2.5% or more of the total were: *Antennarius* sp. (22.6%), *Harengula jaguana* (11.9%), *Mugil cephalus* (8.6%), *Mullidae* sp. (8.1%), *Opisthonema oglinum* (4.4%), *Cynoscion* sp. (4.2%), species of Gerreidae (3.8%), *Engraulus eurystole* (3.0%), *Micropogon undulatus* (2.9%), and *Citharichthys spilopterus* (2.5%). With the exception of *Antennarius* sp., which was captured at only three stations, these taxa were widely distributed over the survey area during at least one of the sampling seasons (winter, spring-summer, fall). Two of these taxa, *Cynoscion* sp. and the Gerreidae, may each have consisted of more than one taxon. Each of these taxa were represented by several species in the survey area but it was not possible to make specific identifications.

In 1977, 32 taxa individually contributed 0.1% or more of the total number of identifiable fish specimens. The most abundant taxa, representing 2.5% or more of the total were: *Mullidae* sp. (18.1%), *Etrumeus teres* (12.9%), *Harengula jaguana* (8.5%), species of Gerreidae (4.7%), *Trachurus lathami* (4.6%), *Rachycentron canadum* (4.0%) *Mugil curema* (3.3%), *Prionotus* sp. (3.2%), *Mugil cephalus* (2.6%) and *Menticirrhus* sp. (2.6%). All of these taxa, with the exception of *Rachycentron canadum*, were widely distributed over the survey area during at least one of the sampling seasons (winter, spring-summer, fall). The Gerreidae, *Prionotus* sp. and *Menticirrhus* sp. were each represented by several species in the survey area.

Species composition varied considerably between the two years of the

study; dominance affinity (Sanders, 1960) between the two years (42.3) was considered to be relatively low. Only four taxa, *Harengula jaguana*, *Mugil cephalus*, *Mullidae* sp. and the Gerreidae were within the most abundant group of taxa both years. *Mugil cephalus* was considerably more abundant in 1976 than in 1977 and *Mullidae* sp. was more abundant in 1977 than in 1976. Several species which were abundant in 1976 *i.e.*, *Antennarius* sp. and *Cynoscion* sp., did not significantly contribute to the number of specimens in 1977; each comprised less than 0.1% of the total in 1977. Likewise, *Rachycentron canadum* and *Menticirrhus* sp., were abundant in 1977 but did not contribute significantly to the total in 1976. Variance in abundance of *Antennarius* sp. and *Rachycentron canadum* may be explained by the clumped distribution of these taxa. Both taxa were captured in very high abundance at relatively few stations in 1976 and 1977 respectively. *Cynoscion* sp. and *Menticirrhus* sp. were less contagiously distributed than *Antennarius* sp. and *R. canadum* but more so than the other abundant taxa.

Diversity values were lower within stations (mean H' = 1.18) and seasons (mean H' = 2.28) than for either year of the survey since a relatively small number of taxa dominated individual samples and seasons. The reason for the low diversity was that most taxa showed distinct seasonal, diel and horizontal distributions. Fish taxa were largely partitioned into a cold water, a warm water and a ubiquitous component. The former two components each showed two temporal patterns. The cold water component consisted of fishes present from the fall through the winter (November through March) and those present from winter through the spring (December through June). The warm water component was divisible into a group present from the spring through summer (February-March through August or October) and a group present entirely during the summer (June through August).

Cold Water Component

Micropogon undulatus was the dominant taxon present in the fall and winter (Figure 8.17). It was captured from December through March in 1976 and in January, September, November and December of 1977. In 1976 concentration estimates (no./1000 m^3) were highest in March but in 1977 estimates were highest in September and November. Specimens ranged from 3.5 to 9.5 mm SL (Standard Length) and consisted of larvae. *Leiostomus xanthurus* showed a similar seasonal pattern.

Brevoortia patronus was captured from February through April and in November and December of 1976 and in January of 1977. The greatest numbers of specimens were captured from November through January. Specimens ranged from 4.5 to 20 mm SL and consisted of larvae.

Mugil cephalus was present during the winter and spring (Figure 8.18). In 1976 it was captured in December, February, March, April and June and in 1977 it was captured in January, May, September and December. Abundance estimates were greatest for December both years. Specimens ranged from 4 to 27 mm SL and consisted of larvae and juveniles.

Etrumeus teres was captured in February and March of 1976 and in January, March, April, May and August of 1977. In both years specimens were most abundant from January through March. Specimens ranged from 4.5 to 20 mm SL and consisted of larvae.

Citharichthys spilopterus was captured during all sampling months of 1976 and in January and March of 1977. It was abundant only from January through March. Specimens ranged from 5.8 to 11 mm SL and consisted of larvae.

Mugil curema and *Rachycentron canadum* were both abundant only during the spring.

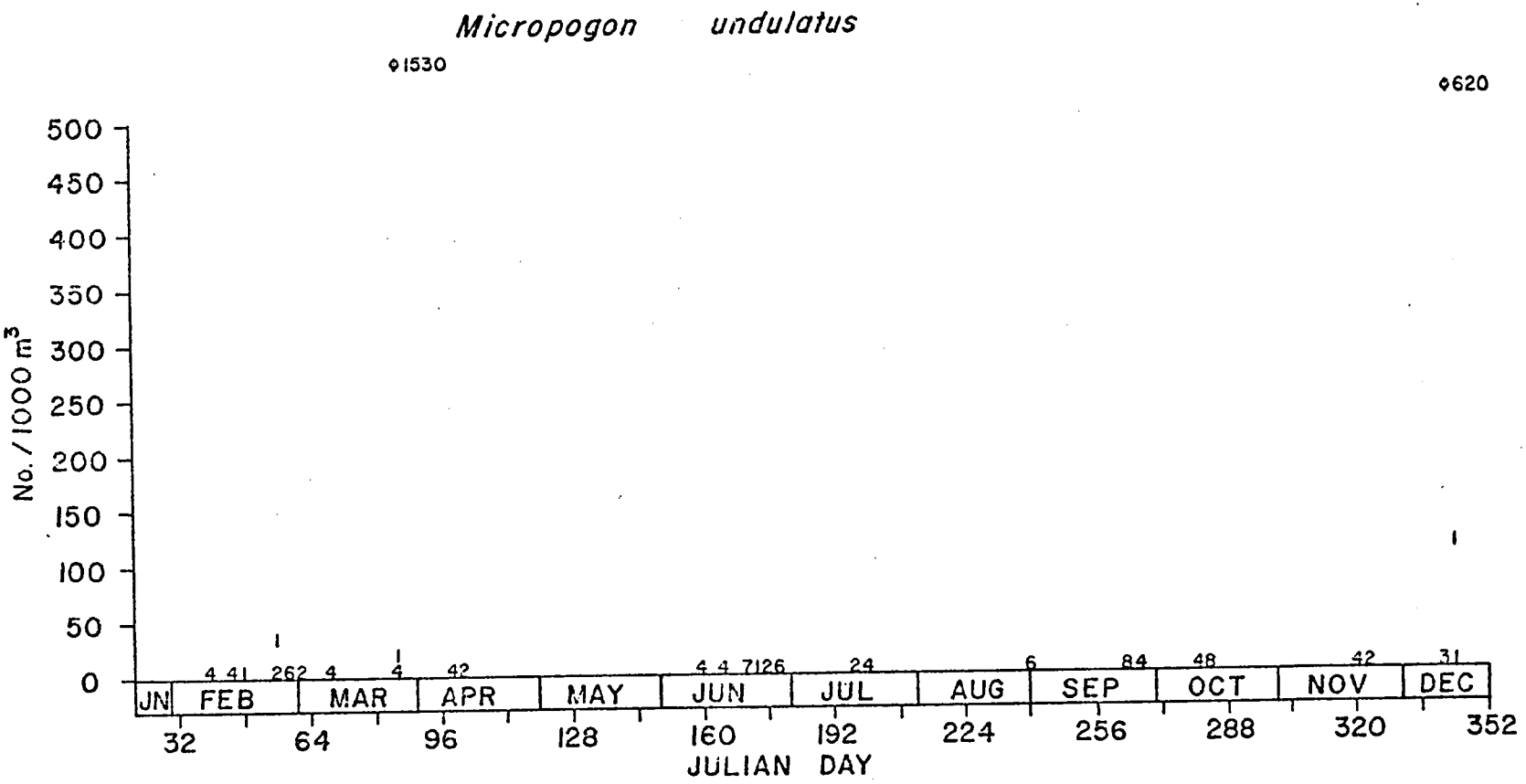

Figure 8.17 Micropogon undulatus, plot of abundance of specimens (number/1000 m^3) by Julian Day in 1976. Numbers along horizontal axis represent numbers of observations.

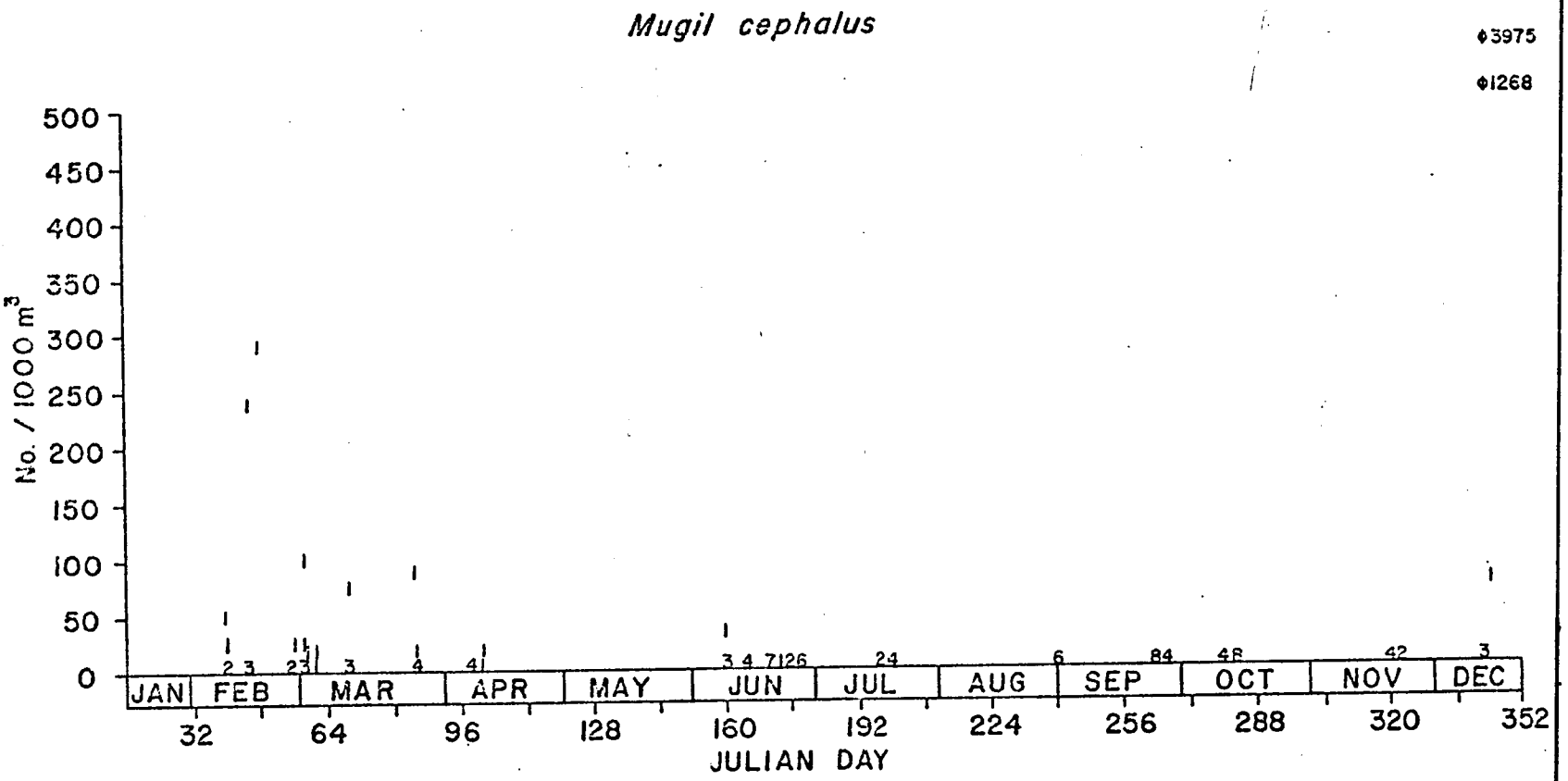

Figure 8.18 Mugil cephalus, plot of abundance of specimens (number/1000 m^3) by Julian day.

Warm Water Component

Opisthonema oglinum was captured during the spring and summer. It occurred in March, June and August of 1976 and in May of 1977. Highest abundances were recorded for June. Specimens ranged from 6 to 14 mm SL and consisted of larvae.

Engraulis eurystole was present over the entire year of 1976 (Figure 8.19), and in January, March, April, May and September of 1977, but was abundant only from April through August both years. Lengths ranged from 4.5 to 37 mm SL, representing larvae and juveniles.

Trachurus lathami occurred during all months sampled in 1976 and 1977 except in November and December. However, during both years abundance estimates were highest in May, June, August and September. Specimens ranged from 2 to 11 mm SL and consisted of larvae.

Anchoa hepsetus was present in all seasons but was most abundant during the spring and summer. Length of specimens ranged from 6 to 29 mm SL.

Harengula juguana was captured only during the summer (Figure 8.20). In 1976 it was present from June through August and in 1977 it was present from May through August. In 1976 large numbers were encountered throughout the summer but in 1977 the greatest number were captured in August.

Mullidae sp. displayed an almost ubiquitous seasonal distribution in that specimens were present and abundant during all sampling months except December, 1976 and January, 1977.

Temporal and Spatial Variation of Fish

Within the cold water and warm water components, taxa could be distinguished according to the distance that they occurred from shore. *Micropogon undulatus* and *Brevoortia patronus* were most abundant at the first station of each transect, in water shallower than 28 m.

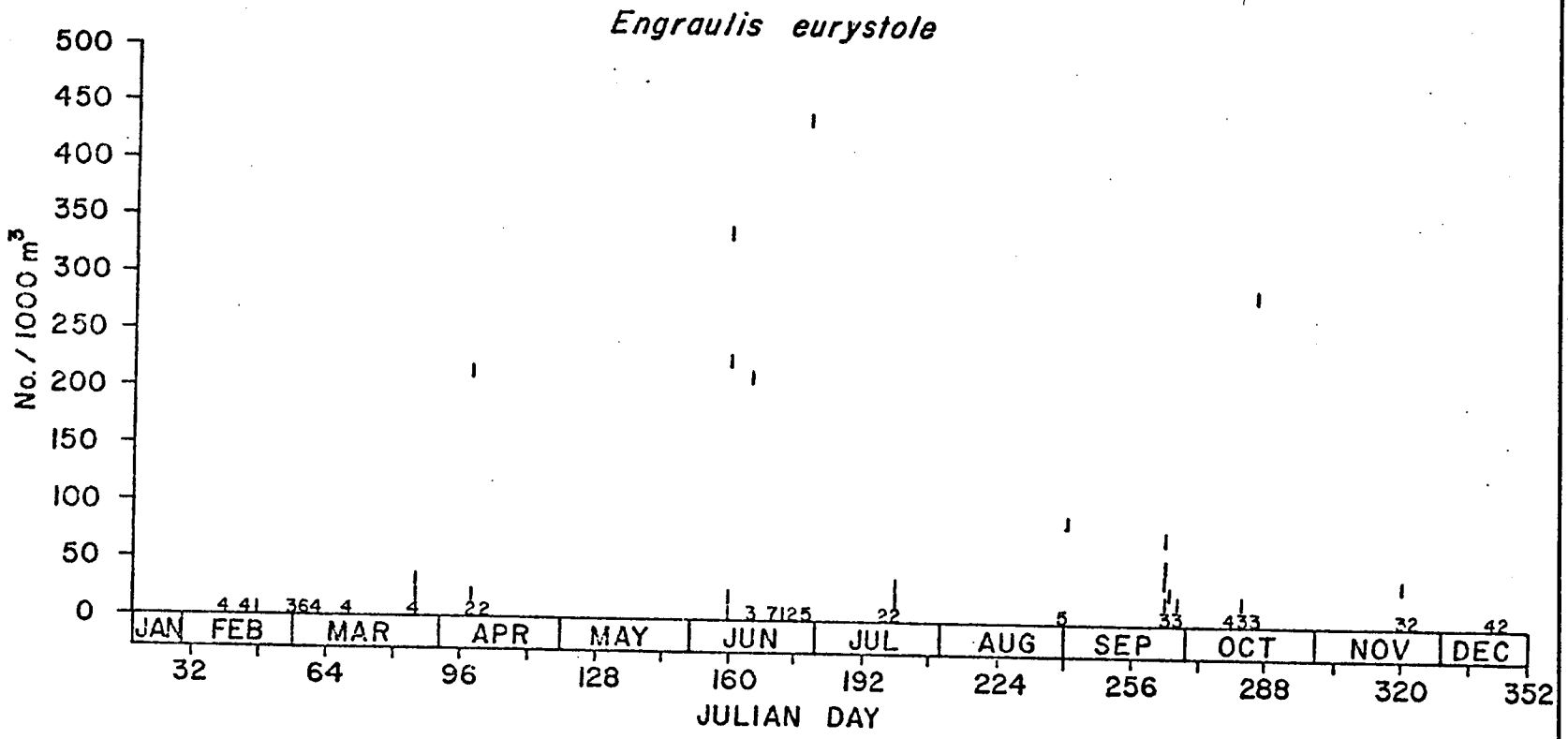

Figure 8.19 Engraulis eurystole, plot of abundance of specimens (number/1000 m^3) by Julian day.

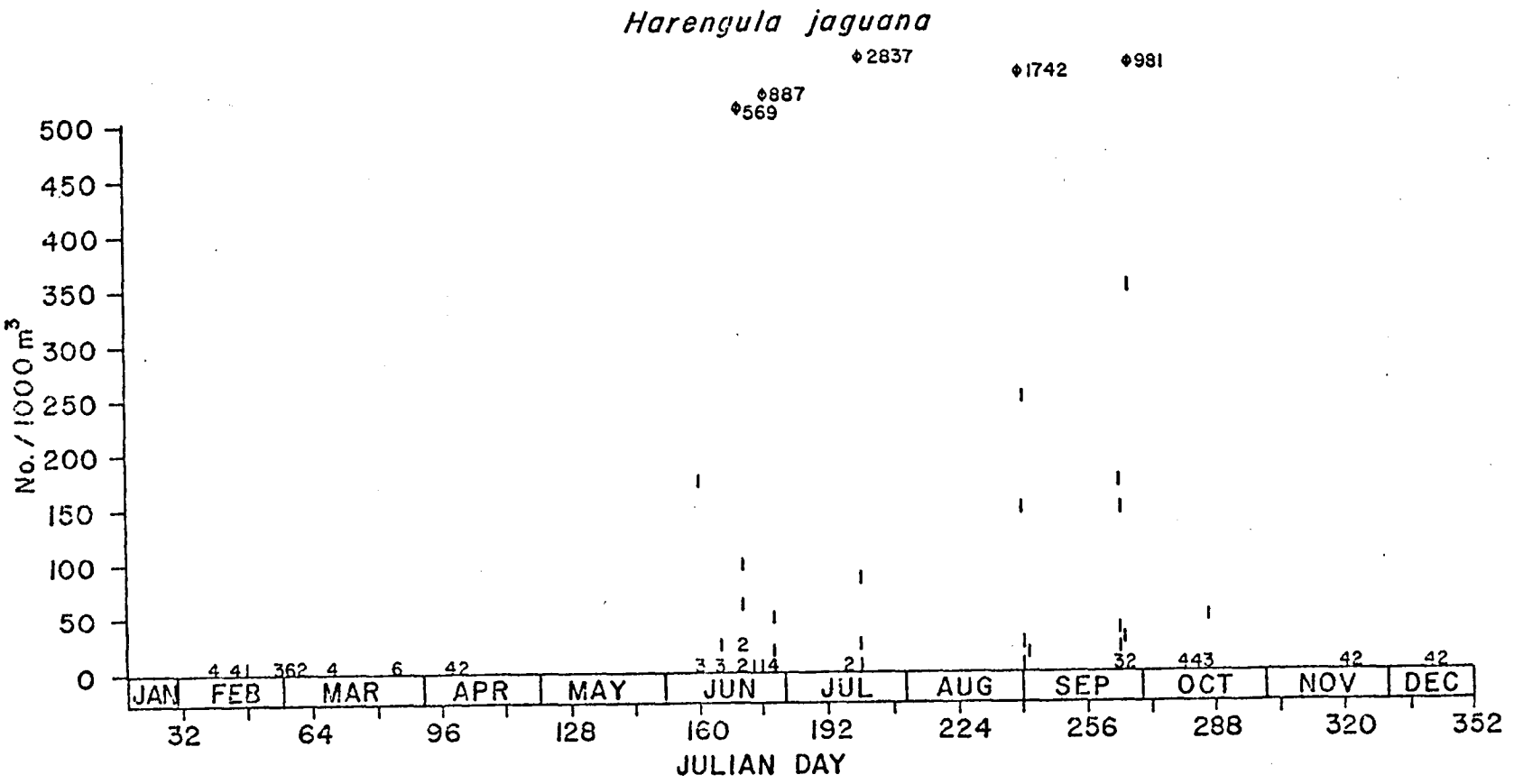

Figure 8.19 Harengula juguana, plot of abundance of specimens (number/1000 m^3) by Julian day.

Mugil cephalus, Etrumeus teres, Citharichthys spilopterus and *Mugil curema* were more abundant at the two seaward stations of each transect, in water deeper than 40 m. Among the warm water component *Opisthonema oglinum* and *Trachurus lathami* were most abundant at the first station of each transect and *Anchoa hepsetus* and *Harengula jaguana* were more abundant at the two outer stations. *Engraulis eurystole* was widespread, more frequently captured inshore but more abundant offshore.

Taxa of the two seasonal components also differed in their diel behavior. The majority of the taxa were more abundant during the night than during the day but others were either of equal abundance night and day or were more abundant during the day. *Micropogon undulatus, Harengula jaguana, Etrumeus teres, Anchoa hepsetus, Engraulis eurystole, Trachurus lathami,* and *Citharichthys spilopterus* were predominantly caught at night and *Brevoortia patronus, Opsthonema oglinum, Mugil cephalus, M. curema, Hirundichthys rondeleti* and *Parexocoetus brachypterus* were either caught in equal numbers night and day or were more abundant during the day. Diel differences in abundance were, in part, probably due to vertical migrations of fishes into and out of the neuston zone since larval fishes less than 15 mm SL are probably unable to successfully avoid the sampling gear (Colton *et al.*, 1961). In this thidu a large percentage of the larvae were less than 15 mm SL. Avoidance, if it was significant, would be most prevalent during the day when sampling gear would be visible.

Factor analysis and Horn's (1966) overlap test indicated that most of the abundant taxa were not correlated by presence and absence or abundance. However, two flyingfish, *Hirundichthys rondeleti* and *Parexocoetus brachypterus*, and *Opisthonema oglinum*, all warm water species, were highly correlated. *Anchoa hepsetus* and *Engraulis eurystole* were also

TABLE 8.10

CORRELATION COEFFICIENTS AND SIGNIFICANCE LEVELS FOR SELECTED PHYSICAL AND BIOLOGICAL PARAMETERS. THE NUMBERS OF OBSERVATIONS ARE IN PARENTHESES.

1976

	Salinity	Net P	Zoopl.	N.B.	N.	T.
Temperature (Om) (°C)	.09 (54)	-.58** (52)	.28 (52)	.10 (54)	-.23 (52)	-.21 (54)
Salinity (Om) (%)		-.36** (52)	-.57*** (52)	-.10 (54)	-.31* (52)	-.80 (54)
Net Phytoplankton (µg chlor. a l^{-1})			.26 (54)	.03 (54)	.55*** (54)	.06 (54)
Zooplankton Biomass (mg dry weight m^{-3})				.22 (54)	.18 (54)	.16 (54)
Neuston Biomass (mg dry weight $10^{-3}m^{-3}$)					.00 (54)	.56*** (81)
Nannoplankton (µg chlor. a l^{-1})						.04 (54)
Tar (gms/10^3m^3)						

1977

	Salinity	Net P	Zoopl.	N.B.	N.	T.
Temperature (Om) (°C)	.10 (53)	-.55*** (44)	-.15 (51)	-.23 (53)	-.20 (53)	-.22 (53)
Salinity (Om) (%)		.21 (55)	-.14 (54)	-.12 (81)	.53*** (81)	.10 (81)
Net Phytoplankton (µg chlor. a l^{-1})			.13 (47)	-.06 (55)	.37** (54)	.11 (55)
Zooplankton Biomass (mg dry weight m^{-3})				.22 (54)	.18 (54)	.16 (54)
Neuston Biomass (mg dry weight $10^{-3}m^{-3}$)					-.07 (81)	.56*** (81)
Nannoplankton (µg chlor. a l^{-1})						.13 (81)
Tar (gms/10^3m^3)						

* .01 > p <.05
** .001> p <.01
*** p <.001

highly correlated, occurring in spring and summer over the two deeper two sets of stations. *Brevoortia patronus* and *Leiostomus xanthurus* and *Leiostomus xanthurus* and *Micropogon undulatus* had overlaps of 0.57 and 0.51, respectively.

Environmental Relationships

In 1976 the neuston tows were on separate cruises from other water column work. Although we have run correlations with neuston biomass and other water column physical-biological parameters, we feel these results are not to be taken seriously. They are presented in Table 8.10 along with the results from the 1977 tows. The latter results should be considered as they were taken as concurrently with the neuston tow as possible. Few correlations were significant. Neuston dry weight was positively correlated with the dry weight of tar at a high level of significance in both years. This was the only significant correlation for neuston biomass.

DISCUSSION

The only significant correlation for neuston biomass was with tar biomass. There are at least two alternative explanations for this observation. The first has to do with surface circulation which creates convection cells, *i.e.* Langmiur cells (Pollard, 1977). If we consider tar to be a passively floating object, then we would expect it to be concentrated by this type of circulation into windrows. The direction of the swell is usually parallel to these windrows so that the course of towing is probably also parallel to the windrows. This positive correlation, then, may suggest that neuston, in general, are also concentrated into windrows to some extent. If this is true the next logical step would be to find

which taxa are most responsible for this correlation. These species might be "more neustonic" than other species.

Alternatively, it is possible that tar is just slightly positively bouyant and during rough weather is driven below the depth sampled by our nets. The neuston may also tend to go somewhat deeper at these times or be physically mixed deeper by surface forces. During calmer weather both may come to the surface again. There may be other explanations also. At this time we cannot test these alternatives.

Grouping results basically showed a large spring-summer, warm-water group, a winter group and several other small groups. Only Factor 2 which was responsible for the identification of the winter group, showed a consistent negative correlation with temperature for both years. The other factors showed no consistency. This suggested that we were not measuring the parameters responsible for those sources of variation. It should also be noted that overall there were many small, more or less equal, underlying sources of variation in the two years of data. This may be due to sampling inadequacies or to real variability in the neuston or both. With a single exception those taxa which grouped on Factor 1 showed considerable day-night differences. The other species in other groups showed no day-night differences as a rule. It should also be noted here that tows were to be taken during the day (0800-1700) and night (1900-0500). In reality a number of tows fell in the dawn-sunset period (13% of the total in 1976; 15% in 1977). There is a suggestion that this period was unique for some species, although the number of observations makes statistical testing very difficult.

The consistency in seasonal cycles from year to year was quite good. They clearly showed a few winter species, mainly *Anomalocera ornata*, *Micropogon undulatus* and *Leiostomus xanthurus* and many spring-summer

species. It was difficult to show consistent cycles due to the station-transect-diel variability, but general trends were obvious. Station variability was probably due to a decrease in a neritic influence in an offshore direction as shown in phytoplankton trends. Transect variability may have been due mainly to differences in influence of the Mississippi plume and other freshwater influences in the northern portion of the study area. Diel variation was due to vertical migrations of numerous taxa into the near-surface waters at night. Because we were sampling only about the upper 15 cm of the water column we were also strongly influenced by weather events either during or prior to a cruise and by internal waves.

The good agreement found among the sets of four samples per tow in March and April 1977 suggests that variability on the small scale was low. These four sample sets, however, did not constitute replicates. On the one occasion we took two replicate pairs, the agreement was low (18% Percent Similarity - day and 67% - night). These pairs were separated by 15-20 minutes (675-900 m). This distance falls beyond the spatial scales of Langmuir cells (Pollard, 1977).

If neuston studies are to be used in the future for baseline or monitoring studies, the importance of sampling consistently at the same time of day cannot be overemphasized. From the point of view of achieving the greatest variety (or species diversity) as well as greatest numerical abundance, night sampling is to be recommended. This is especially true for the decapod larvae and other diel vertical migrators.

The lack of correlation between decapod taxa and surface salinity or temperature, at least in the case of decapod larvae, is probably due to the fact that, ultimately, high concentrations of decapod larvae are dependent upon successful spawning of the benthic adults. This may be

related to environmental factors impacting the adults on the bottom or may simply be related to biological rhythms of the various benthic species. This probably explains the lack of correlation with pelagic factors. However, other studies have pointed out that various species of meroplanktonic larvae have different limiting salinity values beyond which they will not migrate into the upper water layers. For example, Lance (1960) showed that *Porcellana* crab zoeas are intensely positively phototactic in normal sea water, but an upper stratum of low salinity seawater prevents their upward migration. He demonstrated that *Porcellana* zoeas are reduced in abundance in the top 15 cm of seawater at 70-80% of normal seawater salinity (*i.e.* 24-28 ppt) and absent from the top layer in 65% of normal salinity (*i.e.* 22-23 ppt). The lowest surface salinities reached in the south Texas area during the 1977 study period were 27.996 ppt in May at Station 1/I and 28.763 ppt in May at Station 1/II. Similar salinity lows were reached at Station 1/II in 1976 in March and April. These salinities may not be low enough to be limiting to decapod larvae.

A large number of fish taxa occur in the neuston zone off south Texas for at least part of their life stages; most have distinct seasonal, diel and horizontal distributions within the neuston zone. The neuston fauna consisted of a cold water component, present either from fall through winter, or present from winter through early spring; a warm water component, present from late spring through summer or present entirely during the summer; and a ubiquitous component present and in high abundance most of the year. Within each of the seasonal components taxa were generally distributed either inshore or offshore and were present in the neuston zone either during the night or during both the day and night.

Spawning time can be gleaned from temporal distribution of the taxa. The cold water component, *Micropogon undulatus* and *Leiostomus xanthurus*

predominantly spawn during the fall and winter, while *Brevoortia patronus, Mugil cephalus, Etrumeus teres* and *Citharichthys spilopterus* spawn predominantly during the winter and early spring. The warm water component, *Opisthonema oglinum, Engraulis eurystole, Trachurus lathami* and *Anchoa hepsetus* predominantly spawn during late spring and summer, while *Harengula jaguana* spawns predominantly during the summer. These observations are supported by the literature (Finucane, 1976, 1977; Hoese, 1965; Houde, 1977a, b, c; Houde and Fore, 1973, Houde *et al.*, 1974; Lippson and Moran, 1974; Mansueti and Hardy, 1967; Springer and Woodburn, 1960).

The faunal composition of the neuston zone differed from that of the water column below the neuston zone. Finucane (1976, 1977) reported on the fishes captured in the water column from the same stations sampled in this study. Finucane stated that the families Gobiidae, Bothidae, Engraulidae, Bregmacerotidae, Clupeidae, Synodontidae, Carangidae, Myctophidae, Cynoglossidae, and Sciaenidae dominated the samples. In this study, Clupeidae, Antennariidae, Mullidae, Mugilidae, Sciaenidae, Gerreidae, Carangidae, Engraulidae, Exocoetidae and Bothidae were the most abundant families. Myctophidae and Cynoglossidae were rare in the present study. Other families represented in Finucane's studies *i.e.*, Sparidae, Lutjanidae, Sphyraenidae, and Gobiesocidae were not represented in this study. Several species *i.e. Micropogon undulatus, Etrumeus teres, Trachurus lathami, Engraulis eurystole, Leiostomus xanthurus* and *Harengula jaguana* were abundant in both studies; although within the neuston zone they were most abundant only during the night. These species, for the most part, spend daylight hours in the water column and migrate into the neuston zone during the night. Several species were either more abundant in the neuston zone than in the water column *i.e. Mugil cephalus* and *M. curema*, or occurred exclusively in the neuston zone *i.e. Hirundichthys rondeleti* and

Parexocoetus brachypterus. All of these species were equally abundant in the neuston zone day and night or were more abundant in the neuston zone during the day.

Fishes of the neuston zone can be classified as facultative neustonic taxa or euneustonic taxa. Those of the former category are found in the neuston zone during the larval stage while those of the latter category spend their entire life history in the neuston zone. Facultative forms dominate the neuston and a majority of these spend their juvenile and adult stages in the estuaries and inshore waters of the northern Gulf of Mexico. Most of the clupeids, mugilids, sciaenids, gerreids, carangids, engraulids and bothids reported in this study are found in the inshore waters and estuaries after transforming into juveniles (Gunter, 1945; Parker, 1965; Chittenden and McEachran, 1976). The antennariids and mullids also leave the neuston zone to assume a benthic existence as juveniles and adults, however, these forms are more abundant in the deeper waters of the continental shelf (Hildebrand, 1954; Chittenden and McEachran, 1976). Only the exocoetids are euneustonic and they were the only taxa which occurred in the neuston zone as large juveniles and adolescents. Possible time-lag correlations have not been examined thoroughly partly because our data and types of analyses available did not lend themselves to this type of study.

CONCLUSIONS

The neuston as a single component showed a lot of variability. This is due to the fact that it is made up of many diverse taxa, each responding to the environment in its own way. The best opportunity to explain, and hopefully to understand, these responses is to look at single species patterns. To enumerate our conclusions about those single species we

have studied in detail would be redundant. We can, however, highlight some general attributes seen in numerous taxa and list a few suggestions for improving our ability to understand this system.

Most of the more abundant and/or frequent taxa showed seasonal cycles. These cycles were in very good agreement between the two years. Most taxa showed peaks in warm water periods, but some cold water species were seen.

Diel differences were seen in most groups. This is the shortest time scale of variability we were able to document. Data which we have gathered and Berkowitz (1976) suggest this is an important variable. These studies do not necessarily indicate a sinusoidal-type fluctuation, but clearly an on-off-transition type change. Noon and midnight sampling should be carried out with twilight tows being an added luxury, not a substitute.

Distance from shore plays a role for many taxa, particularly in the decapod taxa, probably due in large part to the benthic distribution patterns of the adult species. Certain taxa can definitely be defined as nearshore (*e.g. Hexapanopeus, Pinnixa sayana,* Pinnotherid sp. A., and *Pinnixa* and *cylindrica* crab zoeas; diogenid and pagurid [hermit crab] larvae; and stenopodid shrimp zoeas). Others that are characteristically offshore are portunid crab megalopa, *Lucifer typus* and *Leptochela bermudensis* (offshore benthic caridean shrimp that swarm to the surface water at night).

Although transect variation could be seen in some taxa, it was less consistent and may have been due, in part, to unequal sampling. This is not surprising since neuston drift with currents and will not show the geographic fidelity of benthic organisms.

The single most important conclusion that can be drawn from our study is that several estimates of the within-station variability (found by replicates) would have helped the interpretation of the data considerably. This is a very cost effective strategy and should be followed in future studies.

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CHAPTER NINE

ZOOPLANKTON PROJECT

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ABSTRACT

Three years of data were analyzed for spatial/temporal related patterns of zooplankton distribution. Frequency of occurrence on cluster analysis showed that copepods formed two depth-oriented groups. Stations formed depth-related clusters on the basis of copepod species composition; and station clusters produced by-monthly data indicated that the species group composition changed semi-annually at the shallow and mid-depth stations.

Parametric analyses were used to determine if the zooplankton varied significantly between water depths, transects and seasons. One-way analysis of variance showed that changes in zooplankton variables were most often significantly related to water depth. Depth and season were treated as paired factors in two-way analysis of variance. In more than half the cases where zooplankton variables changed significantly with depth and/or season, the test for interaction between depth and season was also significant.

The results of multiple regression analysis failed to show clear relationships between zooplankton and environmental variables. Environmental variables which most frequently explained part of the variation in zooplankton variables were ichthyoplankton, salinity and phytoplankton at Stations 1, 2 and 3, respectively.

INTRODUCTION

In December 1974 a Bureau of Land Management (BLM) study was initiated to provide an inventory of many biological and physical conditions which characterize the south Texas outer continental shelf (STOCS). The zooplankton, well recognized as a vital component of the neritic trophic complex, was intensively studied during the three-year period, 1975-1977 (Park, 1976a, 1977, 1979).

The need for a comprehensive study of zooplankton in the STOCS area is apparent from the lack of published accounts concerning the zooplankton of the Gulf continental shelf. The most closely related sampling effort in the area was performed by the Galveston Laboratory of the National Marine Fisheries Service (NMFS) in the early 1960's (Temple, 1976; Temple and Fischer, 1965, 1967). Initially reported from that sampling effort were the seasonal abundances and distributions of larval stages of penaeid shrimp. Subsequently, the distribution of the decapod genus *Lucifer* was reported by Harper (1968), and the zooplankton taxonomic composition and distribution was reported by Park (1976b; 1978) from (NMFS) samples collected within the STOCS area.

Descriptions of the zooplankton populations inhabiting areas adjacent to the STOCS are somewhat more numerous. The lagoon and bay systems of the south Texas coast have received considerable attention, especially in the past 20 years. Among the studies dealing with estuarine zooplankton are those by Simmons (1957) and Henderson (1958) in the upper Laguna Madre, Breuer (1962) in the lower Laguna Madre, Cooper (1967) in the San Antonio estuarine system, and Holland *et al* (1974) in the Corpus Christi, Copano and Aransas Bay systems. To the north, zooplankton investigations off Galveston Island include a study of standing crop (dry weight and ash-

free dry weight) distribution by Drummond and Stein (1954), a study of the vertical distribution of copepods (Allison, 1967), and a study of the summer and fall vertical distribution of chaetognaths (Adelman, 1967). In the oceanic sector adjacent to the STOCS area the wet volume of zooplankton standing stock was reported by Arnold (1958) and the wet weight by Bogdanov *et al* (1968). Taxonomic and distributional studies of the oceanic Gulf zooplankton (primarily copepods) include those of Fleminger (1956), Park (1970), Ferrari (1973), Livingston (1974) and Howey (1976).

The Gulf shelf extending from the Texas-Louisiana border to the Tortugas, like the south Texas coast, has not been studied as intensively as adjacent bays and estuaries. Among the earliest efforts to appreciably extend our understanding of Gulf neritic zooplankton in terms of seasonal and spatial distribution were those by Davis (1949) and King (1950). Davis (1949) examined archived samples and compiled a basic inventory of plankton species occurrence and relative abundance. King (1950) systematically sampled stations in estuarine, coastal and offshore areas for 10 months to show a "typical plankton picture of the period". Grice (1960) identified copepods collected seasonally (4 seasons) from six coastal transects distributed along the Florida Gulf coast from Pensacola to Knights Key. Austin and Jones (1974) studied the relationship between seasonal variations of physical oceanographic parameters and the displacement volume of zooplankton at a station on the Florida Middle Ground.

While unique in many aspects of intensity and purpose, the STOCS zooplankton study is not without precedent in the warm temperate (Hedgepeth, 1953) faunal province of the Gulf and western North Atlantic. Caldwell and Maturo (1976) studied the zooplankton community over the Gulf continental shelf from Horn Island to Tampa, Florida. Bowman (1971)

reported the distribution of calanoid copepods from two years (1953 - 1954) of seasonal samples collected from 16 transects, spaced 40 miles apart between Cape Hatteras and southern Florida.

The foregoing discussion of pertinent literature is reasonably comprehensive and it leads one to share the conclusions of Roberts (1974) who compiled a literature review for zooplankton work between Cape Hatteras, North Carolina and Cape Canaveral, Florida. His conclusions were that many gaps in available information still exist in the areas of zooplankton community description, the effects of pollutants on the zooplankton, environmental and trophic relationships, depth distributions of zooplankton species and life histories *i.e.* growth rates, reproductive rates, generation times and mortality rates for zooplankton species.

This compilation of investigative reports together with other accounts of Gulf zooplankton, too numerous to mention, represents a myriad of sampling, analytical and reporting strategies which defies synoptic comparison with STOCS zooplankton data. However, it does provide a body of background information useful to the interpretation of STOCS zooplankton data.

Specific objectives of this study were:

1) to characterize the study area in terms of the zooplankton standing stock, spatially and temporally;
2) to identify numerically prominent forms and determine what if any patterns of change occur from station to station and season to season;
3) to determine which, if any, species form groups on the basis of occurrence and abundance and how these groups may be used to show faunal relationships between stations and seasons;
4) to characterize relationships between zooplankton composition, abundance and distribution and other biological and physical parameters.

METHODS AND MATERIALS

Stations

Twelve stations (Figure 9.1) were equally distributed among four transects (I to IV) perpendicular to the south Texas coast from just north of Port Aransas to Brownsville, Texas. The three stations on each transect were numbered 1, 2 and 3. Station 1 was nearest to shore and located in about 15 to 25 meters depth; Station 2 was the intermediate depth station located in about 40 to 65 meters depth; and Station 3 was located at the shelf's edge in about 90 to 135 meters depth.

Sampling

Detailed descriptions of the gear and techniques used to collect samples and the sample analysis procedures may be found in Park (1976a, 1977 and 1979). Only a brief summary of those methods are presented here. Tows were oblique (surface to near bottom to surface) and of about 15 minutes duration. A standard 1-m NITEX net with 0.233 mm mesh was used to collect each sample. The mouth of the net was fitted with a centrally located digital flowmeter (Model 2030, GENERAL OCEANICS) to provide an estimate of the volume of water filtered, and a time-depth recorder (Model 1170-250, BENTHOS) was attached near the mouth to record the sampling depth.

In the laboratory, samples were split with a FOLSOM plankton splitter to achieve adequate subsamples for archiving and analysis. Dry weight biomass measurements were made from subsamples dried to a constant weight at $55^{o}C$; and ash weight measurements were made by ashing the dried subsamples to a constant weight at $550^{o}C$. Zooplankton taxa were sorted, identified and counted in a BOGOROV plankton sorting tray.

Modifications to the Study

Zooplankton samples were collected seasonally in winter (January/February),

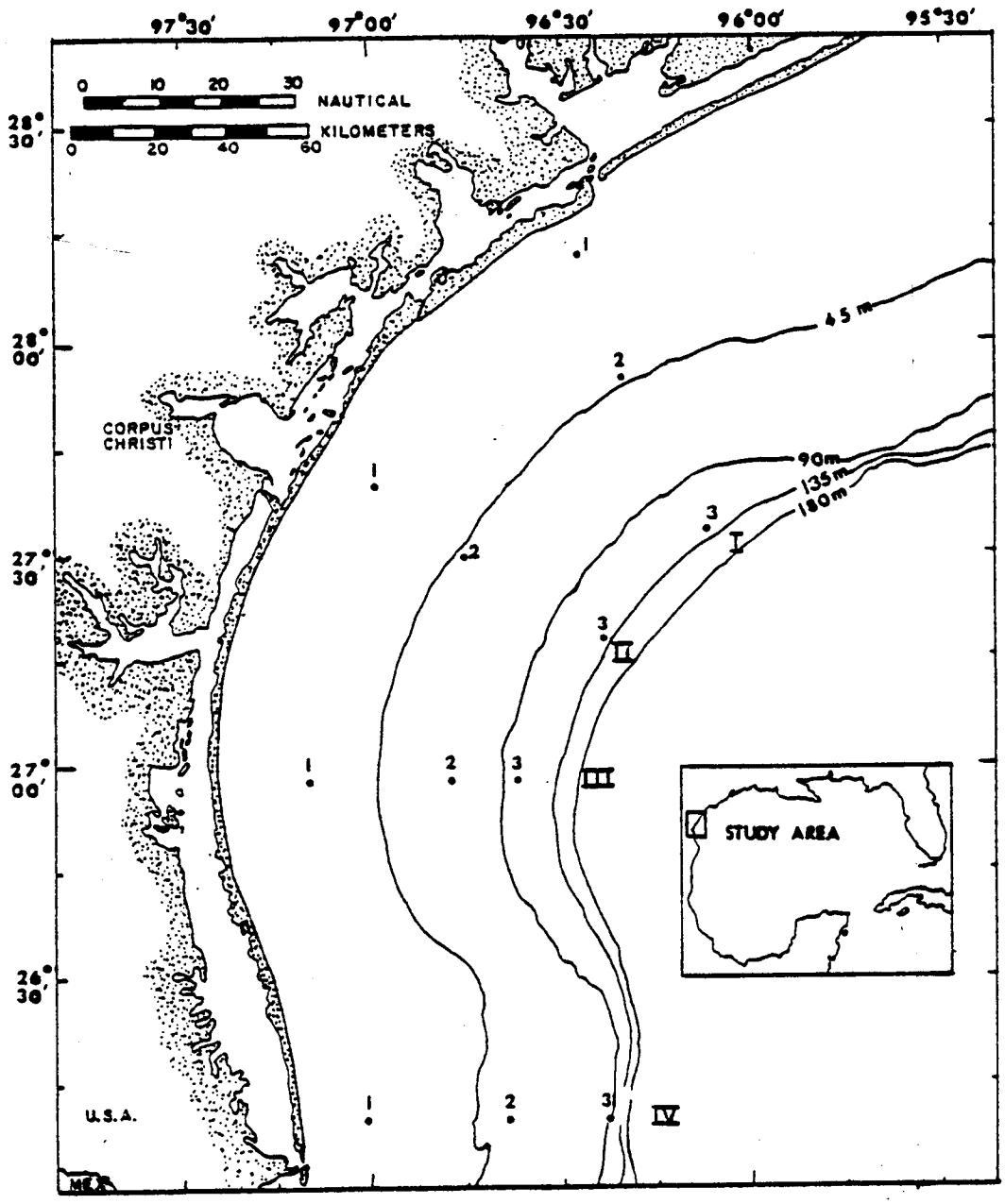

Figure 9.1 Station Locations for the South Texas Outer Continental Shelf Zooplankton Study. Depth in Meters.

spring (May/June) and fall (September) in 1976 and 1977 and about a month earlier in each season of 1975. Following the analysis of data collected in 1975 some changes in the data gathering approach were deemed appropriate. Initially (1975) two replicate tows were made in daylight and at night for each station. Analysis of variance showed that only 2 of the 12 stations produced significant differences between day and night samples indicating that oblique tows adequately sampled the water column. Consequently, a labor saving, diel-flexible program was adopted in which only one series of replicate samples was taken per station. The 1975 data also revealed considerable variation in numerical densities of organisms between replicate tows; therefore, in 1976 and 1977 three replicate samples were collected at each station and the two with the most similar volumes of water filtered and/or sampling depths (determined from depth recorder readings) were analyzed. In general, this provided greater confidence in the efforts at replication.

In 1976 and 1977 the sampling frequency on Transect II was increased by "monthly" cruises in March, April, July, August, November and December (two cruises between seasonal cruises) for a better examination of short-interval changes in the zooplankton community. Relationships between the zooplankton and other ecological parameters often appeared to be better defined by the increased sampling frequency.

Data Organization and Analysis

Organization

Biomass data were reported in terms of dry weight and ash-free dry weight corrected for volume of water filtered. Each major taxon was reported in terms of density (number$\cdot m^{-3}$) and relative abundance (percentage) within the total zooplankton. Copepoda, numerically the best repre-

sented zooplankton group, were separated into suborders (Calanoida, Cyclopoida and Harpacticoida) then grouped by sex if mature. Total counts of immature (copepidid) stages and the total counts of adult males in each suborder were each treated as subgroups of their respective suborder. Adult females were identified to species and counted. Most of the species were identified using the taxonomic works of Rose (1933), Owre and Foyo (1967) and Park (1970). Species of Copepoda were reported in terms of numerical density and the relative abundance of each species within the total copepods counted.

In keeping with the study objective to provide an inventory of zooplankton abundance and distribution, yearly summary reports were based on the analysis of density and percentage data groups by season, transect and station. Copepod species diversity indices and coefficients of equitability were calculated using the Shannon-Weiner function (Lloyd and Ghelardi, 1964).

Analysis

Many features of the BLM-STOCS zooplankton community were suggested by the subjective data grouping techniques used to summarize the data each year. The extensive amount of data representing the zooplankton community and a wide variety of physical and other biological parameters suggested that it would be worthwhile to attempt a more in-depth, integrated analysis.

Community relationships were examined using the Bray-Curtis (1957) coefficient of dissimilarity, community ordination (Orloci, 1966) and the frequency of occurrence of the more abundant copepod species. Similar results were obtained from Bray-Curtis cluster analysis and ordination analysis. Therefore, only the results of the Bray-Curtis analysis are

presented. Copepod species were the only taxa used in community analysis of STOCS data. The other taxa were omitted because few forms were identified to the species level. Grant (1977) showed that similar community relationships appeared in the Bray-Curtis cluster analysis when all the zooplankton species were clustered and when only the Copepoda were clustered.

When community analyses involve large numbers of species, some form of species reduction is often used to make computation and presentation of the results easier (Clifford and Stephenson, 1975). Grant (1977) used <9% occurrence as the cutoff point for species clustered, and Bowman (1971) restricted his analysis to "...13 species which were consistently present in the samples in significant numbers". The species used in cluster analysis of STOCS data were the 10 most abundant species in 50% or more of the samples. The species not used in cluster analysis were listed in Park (1976a, 1977, 1979). Cluster analysis was performed on seasonal data which represented the entire study area from December 1974 to September/October 1977 and on monthly data which represented Transect II from January 1976 to December 1977.

Basic statistics including one and two-way analysis of variance and Scheffe's multiple range test (Sokal and Rohlf, 1969) provided measures of confidence for observed seasonal and spatial variation in zooplankton groups or taxa. Multiple regression analysis was used to explain zooplankton variation in terms of certain environmental variables.

RESULTS

Community Relationships

The frequency distribution (Figure 9.2) and means and confidence intervals (Table 9.1) of copepod species used in Bray-Curtis cluster analysis

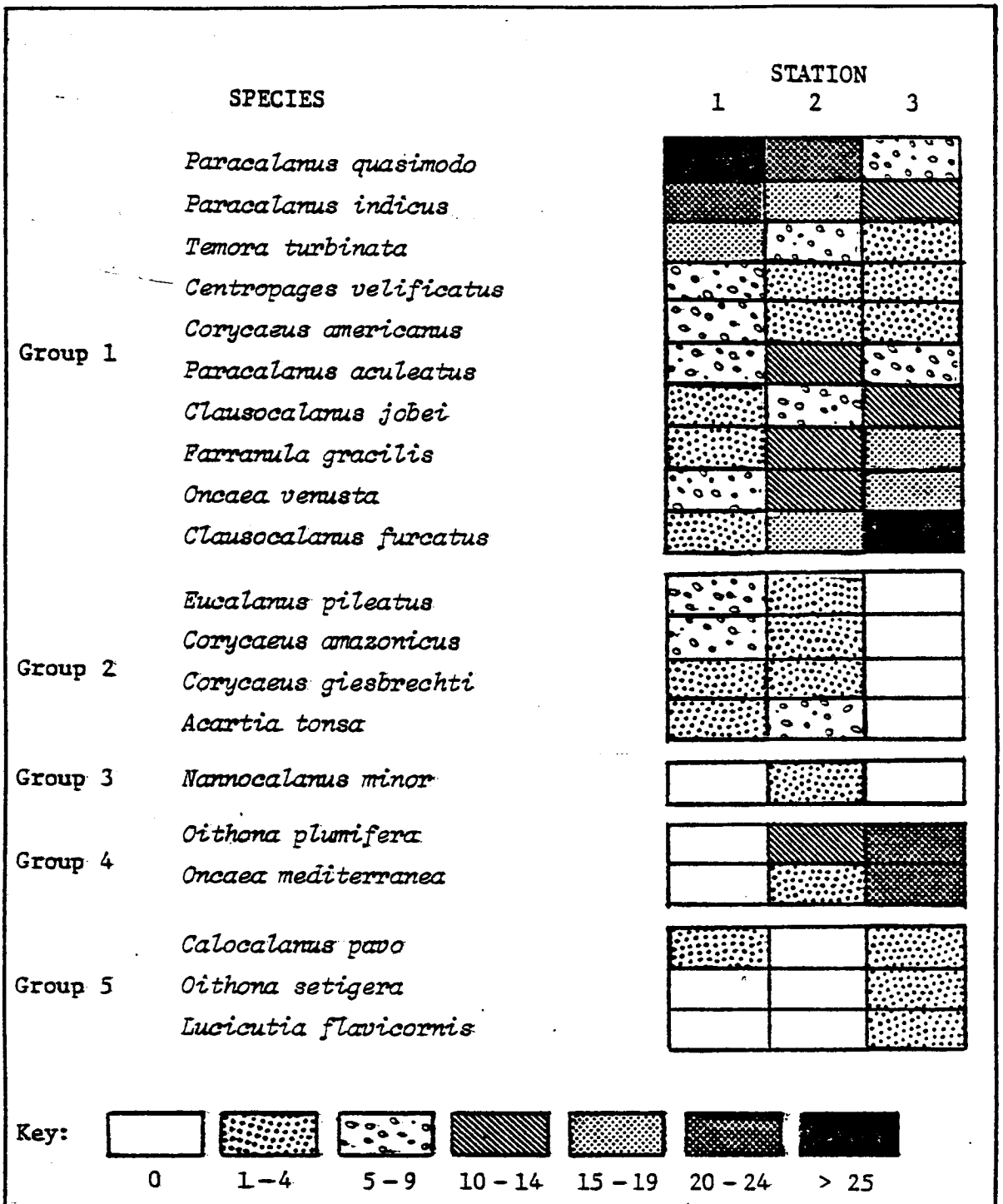

Figure 9.2 The frequency of occurrence of female copepod species used in cluster analysis for each bottom depth (= station 1-3 in order of increasing depths). Maximum number of occurrences = 36.

TABLE 9.1

THE MEAN DENSITY (NUMBER · M^{-3}) AND CONFIDENCE INTERVAL FOR THE COPEPOD SPECIES USED IN CLUSTER ANALYSIS OF THE SEASONAL DATA. N = 36.

SPECIES		STATION 1	STATION 2	STATION 3
Acartia tonsa	$\bar{x}$	33.1	13.9	0.2
	CI	-11.3 - 77.6	- 0.8 - 28.6	0.0 - 0.5
Calocalanus pavo	$\bar{x}$	4.3	2.6	4.8
	CI	- 1.0 - 3.6	1.3 - 4.0	3.5 - 6.1
Centropages velificatus	$\bar{x}$	27.2	17.9	2.9
	CI	12.3 - 42.1	1.3 - 34.6	1.0 - 4.8
Clausocalanus furcatus	$\bar{x}$	12.9	40.3	50.9
	CI	5.5 - 20.2	21.5 - 59.0	31.3 - 70.6
Clausocalanus jobei	$\bar{x}$	4.8	33.0	20.0
	CI	0.3 - 9.3	6.9 - 59.1	10.9 - 29.1
Corycaeus americanus	$\bar{x}$	36.4	14.2	2.7
	CI	6.6 - 66.2	5.3 - 23.0	0.3 - 5.1
Corycaeus amazonicus	$\bar{x}$	22.9	11.3	2.7
	CI	8.5 - 37.3	6.6 - 16.0	1.4 - 4.0
Corycaeus giesbrechti	$\bar{x}$	9.8	7.6	5.5
	CI	3.4 - 16.2	3.4 - 11.9	2.9 - 8.1
Eucalanus pileatus	$\bar{x}$	27.6	13.1	2.6
	CI	16.5 - 38.7	8.0 - 18.2	1.8 - 3.5
Farranula gracilis	$\bar{x}$	4.9	18.6	22.5
	CI	- 2.3 - 12.2	9.4 - 27.8	8.0 - 37.0
Lucicutia flavicornis	$\bar{x}$	0.1	2.1	5.3
	CI	0.0 - 0.2	1.0 - 3.3	3.5 - 7.2
Nannocalanus minor	$\bar{x}$	1.2	3.8	5.7
	CI	0.3 - 2.1	2.2 - 5.3	3.5 - 7.9
Oithona plumifera	$\bar{x}$	4.1	22.9	28.9
	CI	2.5 - 5.7	17.5 - 28.3	19.2 - 38.6
Oithona setigera	$\bar{x}$	0.1	0.6	5.3
	CI	0.0 - 0.2	0.3 - 1.0	3.8 - 6.9

TABLE 9-1 (cont'd)

Oncaea mediterranea	$\bar{x}$	1.9	14.5	32.5
	CI	0.6 - 3.2	7.9 - 21.0	23.7 - 41.2
Oncaea venusta	$\bar{x}$	17.3	35.4	30.4
	CI	5.8 - 28.8	20.9 - 50.0	20.1 - 40.6
Paracalanus aculeatus	$\bar{x}$	25.4	27.8	13.9
	CI	12.0 - 38.8	16.6 - 39.1	8.4 - 19.4
Paracalanus indicus	$\bar{x}$	169.8	55.8	14.6
	CI	96.8 - 242.8	37.5 - 74.1	2.9 - 26.2
Paracalanus quasimodo	$\bar{x}$	137.1	48.5	11.6
	CI	89.9 - 184.3	33.9 - 63.1	4.6 - 18.7
Temora turbinata	$\bar{x}$	83.5	20.3	5.9
	CI	34.1 - 132.8	8.5 - 32.1	2.3 - 9.6

provide assistance in interpreting the results of cluster analysis. All of the species occurred at all three depths across the STOCS (Table 9.1). However, most species showed either shoreward or seaward dominance in mean density and frequency of occurrence (Figure 9.2).

Seasonal Data

The dendrogram (Figure 9.3) of clustered seasonal data showed that copepod species formed groups according to the depths where they were most abundant or where they most frequently occurred. Groups A and B consisted of species which generally increased shoreward in density or frequency of occurrence; and the species in Groups C and D generally increased seaward.

Clusters of stations/seasons according to species composition in the seasonal data (Figure 9.4) showed that the shallowest (Station 1) and deepest (Station 3) station depths were different according to species composition. Mid-depth (Station 2) samples were about equally divided between the shallow and deep station clusters. Seasonal groups within station clusters could be described as winter, spring or fall, however, in most station cluster at least two and sometimes all three seasons were represented.

Monthly Data

Cluster analysis of the monthly data produced four species groups (Figure 9.5) similar in composition to the species groups produced from the seasonal data. However, the relationships between groups changed so that a nearshore (Group C) and an offshore (Group D) group were better related to each other than to the groups (Groups A and B, respectively) to which they were related in the seasonal analysis. This difference in species group relationships between seasonal and monthly data may be explained by cycles in the density of individual species which were only

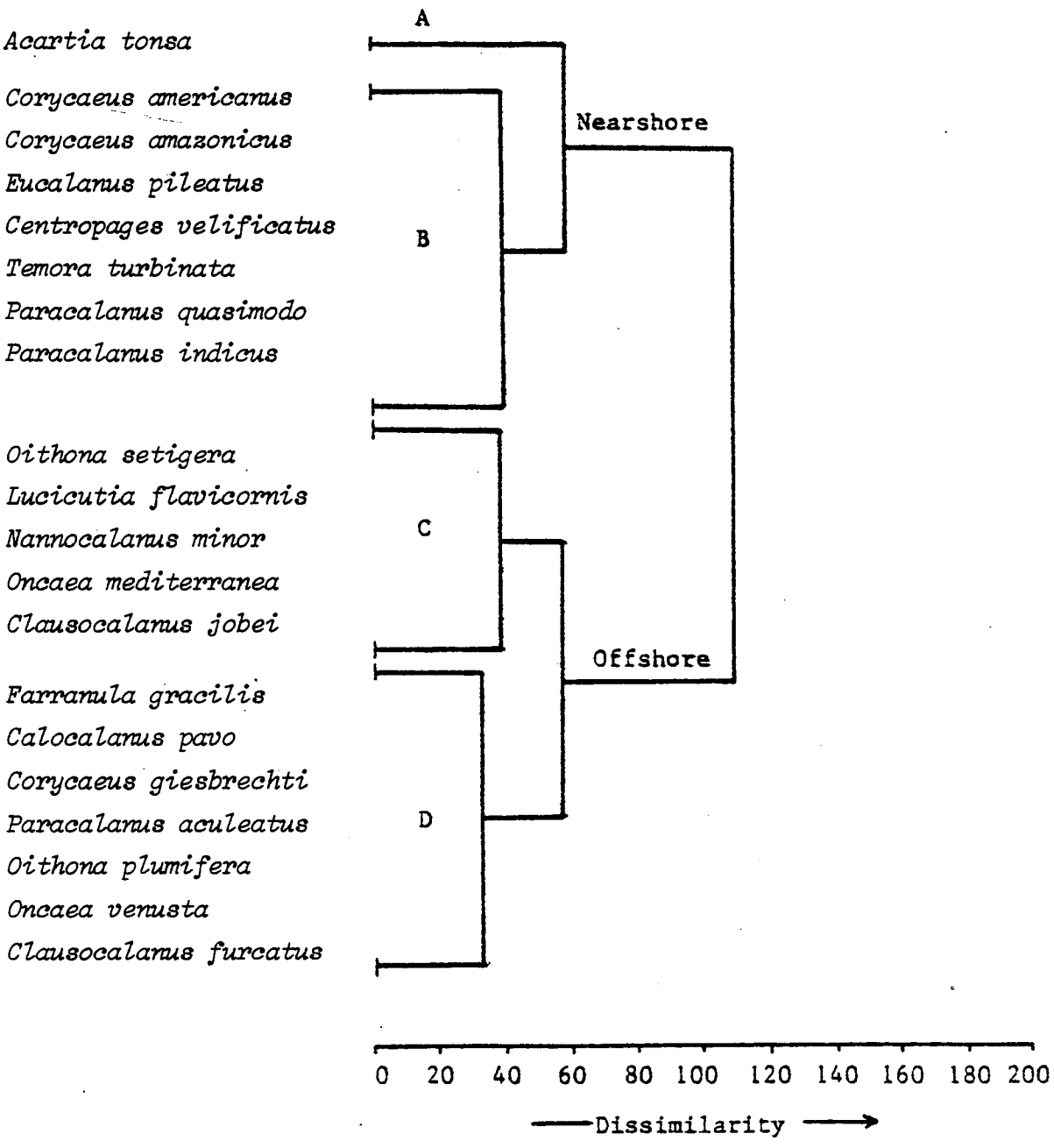

Figure 9.3 Copepod species clusters based on a matrix of 19 species and 108 seasonal samples. Clusters were formed by the Bray-Curtis coefficient of dissimilarity.

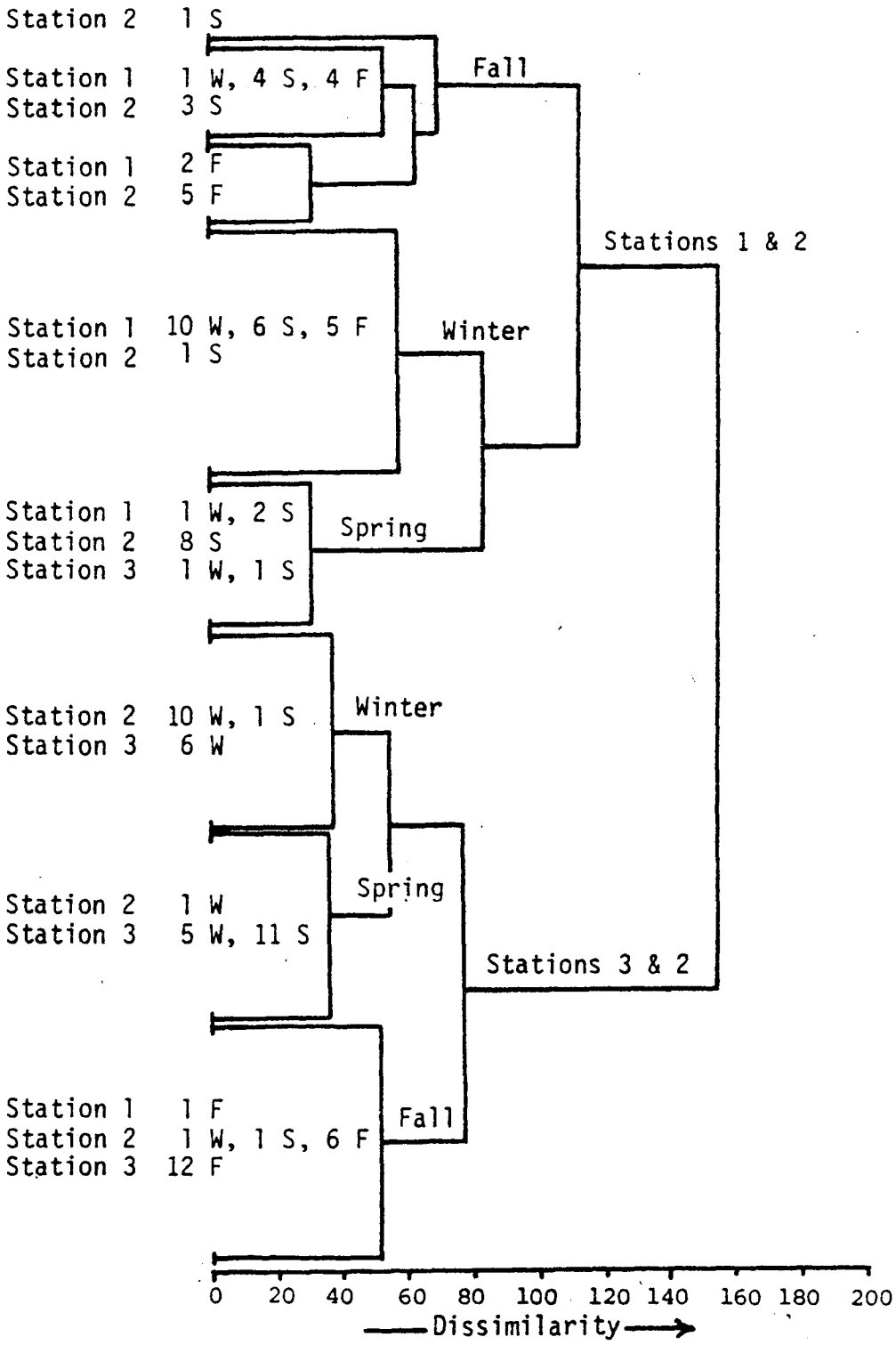

Figure 9:4 Site/season clusters based on a matrix of 19 species and 108 seasonal samples using the Bray-Curtis coefficient of dissimilarity. The seasons are winter (W), spring (S) and fall (F). Numbers preceding seasons are the number of samples from each station/season combination. The total possible samples in each station/season combination is 12.

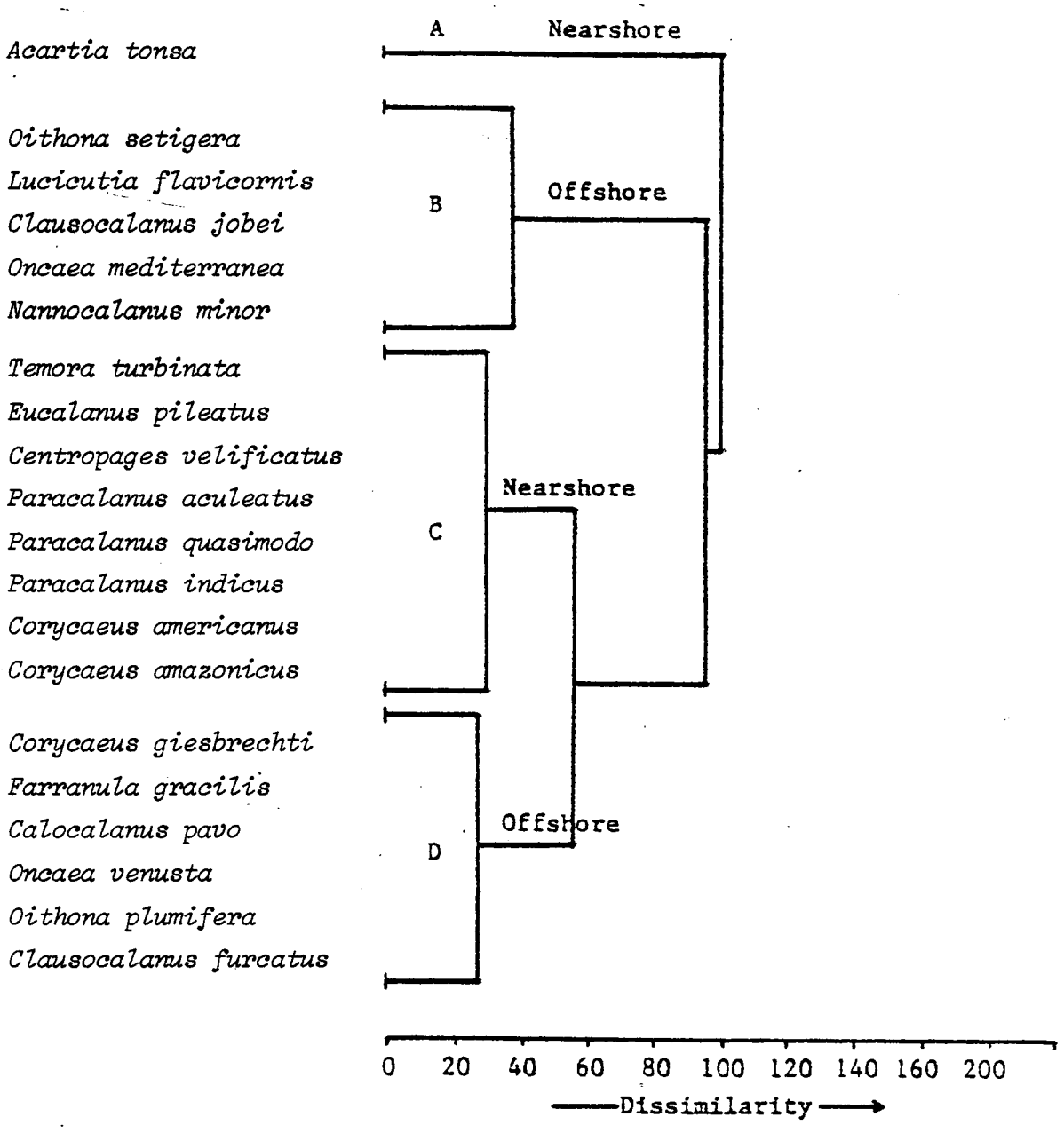

Figure 9.5 Copepod species clusters based on a matrix of 19 species and 54 monthly samples. Clusters were formed by the Bray-Curtis coefficient of dissimilarity.

revealed by the monthly sampling.

Analysis of the stations/months clustered according to species composition (Figure 9.6) showed that at the shallow and mid-depth stations changes in the species composition caused the data to be grouped into approximately semi-annual periods (January/February to May/June and July to December). The species composition at the deepest station (Station 3) did not change according to a recognizable seasonal cycle.

The data matrix of species densities averaged by station/month groups in Table 9.2 shows how the species composition changed between semi-annual periods. Changes in species composition at the shallow station involved species with typically nearshore distribution. *Acartia tonsa, Corycaeus amazonicus, Paracalanus indicus* and *Paracalanus quasimodo* showed a marked decline in mean density between the early and late semiannual periods. *Centropages velificatus, Eucalanus pileatus* and *Temora turbinata* increased in mean density between the early and late semiannual periods. The mid-depth station was characterized by reductions in the mean density of *Acartia tonsa, Corycaeus amazonicus, Paracalanus indicus* and *Paracalanus quasimodo* between the early and late semi-annual periods similar to the results at the shallow station. However, species which increased the most in mean density between the early and late semi-annual periods were *Clausocalanus furcatus, Farranula gracilis, Oithona plumifera* and *Oncaea venusta*. These were all species with typically offshore distributions. This means that at the shallow station changes in species composition between seasons involve typically nearshore forms whereas at the mid-depth station the species composition changes from typically nearshore species to typically offshore species between the early and late semi-annual periods.

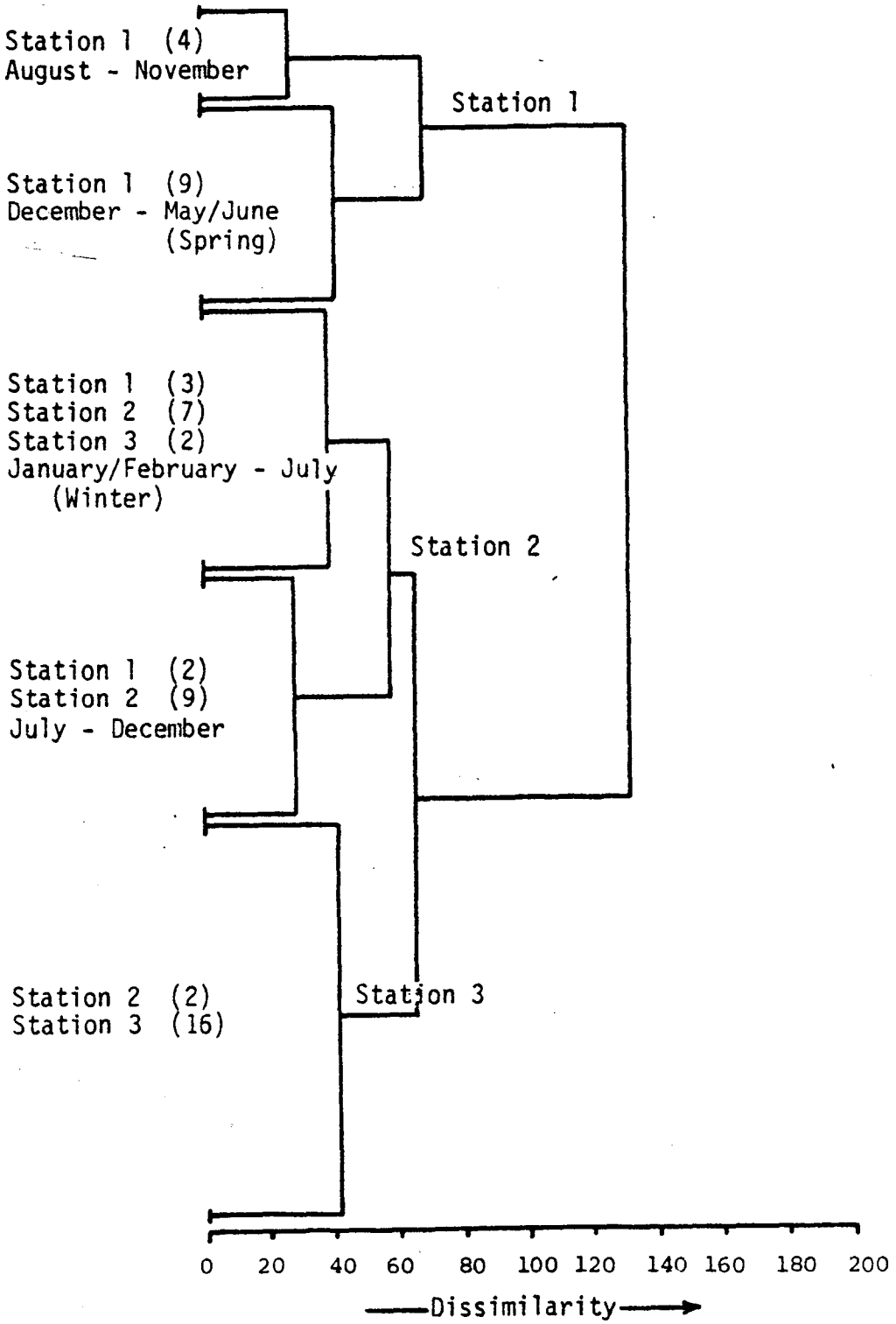

Figure 9.6 Site/season clusters based on a matrix of 19 species and 54 monthly samples using the Bray-Curtis coefficient of dissimilarity. Numbers in parentheses are the number of samples. The total possible samples for each station = 18.

TABLE 9.2

THE MEAN DENSITY OF EACH COPEPOD SPECIES IN THE MONTHLY (1976-1977) DATA MATRIX WITH 19 SPECIES. DENSITIES AVERAGED BY SAMPLES/SITE GROUPS ESTABLISHED BY BRAY-CURTIS CLUSTER ANALYSIS.

Species Group	Species (mean numbers · m^{-3})	Site Group: Station 1 Aug.-Nov. 4/6 Samples (I)	Station 1 Dec.-Jan. 9/10 Samples (II)	Station 2 Jan.-Jul. 7/10 Samples (III)	Station 2 Jul.-Dec. 9/10 Samples (IV)	Station 3 16/18 Samples (V)
A	Acartia tonsa	*	147	24	0	1
	Oithona setigera	0	0	1	*	6
	Lucicutia flavicornis	0	*	3	1	6
B	Clausocalanus jobei	*	5	16	5	14
	Oncaea mediterranea	0	2	16	5	31
	Nannocalanus minor	0	1	5	3	5
	Temora turbinata	155	35	19	32	6
	Eucalanus pileatus	51	3	16	3	2
	Centropages velificatus	17	5	42	12	2
	Paracalanus aculeatus	48	14	18	71	11
C	Paracalanus quasimodo	75	418	89	41	11
	Paracalanus indicus	21	283	106	25	6
	Corycaeus americanus	2	69	24	1	1
	Corycaeus giesbrechti	13	7	8	14	4
	Farranula gracilis	3	0	4	80	15
	Calocalanus pavo	0	*	2	6	3
D	Oncaea venusta	4	2	27	37	21
	Oithona plumifera	2	5	14	42	24
	Clausocalanus furcatus	2	7	26	166	53

* Present but <0.5 · m^{-3}

Spatial and Temporal Factors Related to Zooplankton Distribution

Zooplankton variables, including biomass ($mg \cdot m^{-3}$), density ($number \cdot m^{-3}$) of taxonomic groups and density of individual species, were analyzed by non-parametric grouping strategies for spatial and seasonal patterns of variation during each of the three years of the study (Park, 1976a, 1977, 1979). Parametric analyses were used to determine if apparent patterns of distribution reflected statistically significant changes in certain zooplankton variables with changes in water depth (=distance from shore), transect or season.

Water Depth

Water depth was the variable which was most consistently associated with changes in zooplankton parameters. Linear correlation showed that representative zooplankton variables (biomass, female copepod density, number of copepod species and species diversity) were significantly correlated to depth. Linear correlations were used to determine which if any of several physical and phytoplankton variables measured at the surface, at one-half the depth of the photic zone, and at the bottom of the water column were significantly correlated to the representative zooplankton variables. In general, the results suggested that variation in the zooplankton could not be reliably associated with changes in the physical and phytoplankton variables across the three water column depths. Therefore, statistical analyses were based on the surface values of physical and phytoplankton variables.

The effect of water depth on zooplankton groups or species was tested by one-way analysis of variance with seasonal data grouped by station and season. The results were presented in terms of Scheffe's multiple range test (Table 9.3). Table 9.3 shows which zooplankton groups or species

TABLE 9.3

RESULTS OF SCHEFFE'S MULTIPLE RANGE TEST ON DATA GROUPED BY DEPTH-RELATED STATIONS AND SEASONS. NUMBERS REPRESENT STATION DEPTHS ARRANGED IN ORDER OF INCREASING MEAN DENSITY OF EACH VARIABLE. SHALLOW STATIONS = 1, MID-DEPTH STATIONS = 2, AND DEEP STATIONS = 3. PARENTHESES SEPARATE SIGNIFICANTLY DIFFERENT STATIONS.

Variables	Winter	Spring	Fall
Biomass (mg · m^{-3})		(3)(2,1)	(3,2)(1)
Ichthyoplankton (number · m^{-3})	(1,3)(2)		
Adult Female Coepoda (number · m^{-3})			
Number of Species	(1)(2)(3)	(1)(2)(3)	(1,2)(3)
Density	(3,2)(1)	(3,2)(2,1)	
Diversity	(1)(2,3)	(1)(2)(3)	(1)(2)(3)
Equitability			(3)(2,1)
Copepod Density (number · m^{-3})			
Total Adult Males	(3,2)(1)	(3,2)(2,1)	
Total Immatures	(3,2)(2,1)	(3,2)(2,1)	(3,2)(1)
Total Calanoida	(3,2)(1)	(3,2)(2,1)	(3,2)(1)
Adult Females	(3,2)(1)	(2,3)(1)	(3,2)(1)
Acartia tonsa			
Calocalanus pavo	(1,2)(3)	(1,2)(2,3)	
Centropages velificatus	(3,2)(1)	(3,2)(2,1)	(3,2)(1)
Clausocalanus furcatus			(1,2)(2,3)
Clausocalanus jobei		(1,3)(2)	(1,2)(3)
Eucalanus pileatus		(3)(2,1)	(3,2)(1)
Lucicutia flavicornis	(1)(2)(3)	(1,2)(3)	(1,2)(3)
Nannocalanus minor	(1)(2)(3)		(1,2)(2,3)
Paracalanus aculeatus	(1,3)(3,2)	(3)(1,2)	
Paracalanus indicus	(3,2)(1)	(3,2)(1)	
Paracalanus quasimodo	(3,2)(1)	(3,2)(1)	(3,2)(1)
Temora turbinata	(3,2)(1)	(3,2)(1)	(3,2)(1)
Adult Males			
Immatures	(3,2)(2,1)	(3,2)(2,1)	(3,2)(1)

TABLE 9.3 (cont'd)

Total Cyclopoid Copepoda		(3,2)(2,1)	(1,2)(2,3)
Adult Females			(1,2)(3)
Corycaeus americanus	(2,3)(1)		
Corycaeus giesbrechti			
Farranula gracilis			(1,2)(2,3)
Oithona plumifera	(1)(3,2)	(1)(3,2)	(1)(2)(3)
Oithona setigera	(1,2)(3)	(1,2)(3)	(1,2)(3)
Oncaea mediterranea	(1)(2,3)	(1)(2,3)	(1,2)(3)
Oncaea venusta		(3,2)(1,2)	(1,2)(2,3)
Adult Males	(3,2)(2,1)	(3,2)(2,1)	
Immatures		(3,2)(2,1)	
Other Taxa (number · m^{-3})			
Cladocera	(3,2)(1)	(3,2)(1)	(3,2)(2,1)
Ostracoda	(3,2)(1)	(3,1)(2)	
Amphipoda		(3)(1,2)	
Crustacean Larvae		(3,2)(2,1)	(3,2)(1)
Cnidaria		(1,3)(2)	
Mollusca	(3,2)(1)		
Chaetognatha		(3,1)(1,2)	(3,2)(2,1)
Larvacea			

varied significantly with depth (=Stations 1, 2 and 3 arranged in order of increasing depth) during each season. The stations were listed in order of increasing mean values for each zooplankton variable tested. In general, where significant depth-related variations in the zooplankton occurred, the shallow stations and deep stations were usually significantly different. The mid-depth stations were grouped with either the shallow or deep stations for most zooplankton variables.

The density of most copepod species were significantly different between depths during at least one season. These results tend to support the results of cluster analysis which suggested that copepod species groups could be characterized as either nearshore or offshore groups.

Transect

Statistical analysis of seasonal zooplankton data grouped by transects indicated that few zooplankton variables changed significantly from transect to transect. One-way analysis of variance and Scheffe's multiple range test indicated that none of the variation in zooplankton variables between transects was significant. Two-way analysis of variance with transect and season as paired factors indicated that more zooplankton variables changed significantly between seasons than between transects (Table 9.4). The values of certain representative zooplankton variables were averaged over the three-year period and the mean for each variable was similar from transect to transect. Statistical analysis of transect effect on the zooplankton and the results from averaging representative zooplankton variables over three years indicated that zooplankton productivity was fairly uniform from transect to transect. However, when the means and confidence intervals for representative zooplankton variables were plotted for each bottom depth contour by each seasonal cruise (Figures 9.7 and 9.8), the

TABLE 9.4

TWO-WAY ANALYSIS OF VARIANCE OF ZOOPLANKTON VARIABLES WITH BOTTOM DEPTH-SEASON AND TRANSECT - SEASON AS PAIRED FACTORS. THE NUMBERS FOLLOWING EACH VARIABLE ARE F-VALUES. F-VALUES >.05 (<95% CONFIDENCE) HAVE BEEN OMITTED

	Paired Factors			
Variable	Bottom Depth	Season	Transect	Season
Biomass (mg · m^{-3})	.001	.001		.016
Total Zooplankton (number · m^{-3})	.001	.001		.006
Ichthyoplankton (number · m^{-3})	.036	.001		.001
Adult Female Copepoda				
Number of Species	.001	.001		
Density (number · m^{-3})	.001			
Diversity	*.001	*.001		
Equitability		.015		.026
Copepoda (number · m^{-3})				
Adult Males	.001			
Immatures (Copepidid Stages)	.001			
Calanoid Copepoda	.001			
Adult Females	.002			
Acartia tonsa				
Calocalanus pavo	*.001	*.001	.001	
Centropages velificatus	.001	.021		
Clausocalanus furcatus	.001	.005	.023	.007
Clausocalanus jobei			*.029	
Eucalanus pileatus	.001	.017		
Lucicutia flavicornis	*.001	*.001		.001
Nannocalanus minor	.002			
Paracalanus aculeatus	*.018	*.001		*.001
Paracalanus indicus	*.001	*.037		.019
Paracalanus quasimodo	*.001			
Temora turbinata	.007			

TABLE 9.4 (cont'd)

Adult Males				
Immatures	.001			
Cyclopoid Copepoda	.045		.041	
Adult Females			.015	
Corycaeus americanus	*.041	*.018		.022
Corycaeus giesbrechti	*.020	*.001		.001
Farranula gracilis	*.001	*.001	.026	.001
Oithona plumifera	.001	.006		.029
Oithona setigera	.001			
Oncaea mediterranea	*.001			
Oncaea venusta		.001		.001
Adult Males	.002			
Immatures (Copepidids)	*.002		*.022	
Other Taxa (number · m^{-3})				
Cladocera	*.040	*.001		*.001
Ostracoda	.005		*.042	
Amphipoda	*.001	*.014	.003	.020
Crustacean Larvae	*.007	*.005		.010
Medusae	*.002			
Mollusca		.029	*.047	*.017
Chaetognatha	*.001	*.002		.020
Larvacea		.004	.016	.003

* Test for 2-way interaction was significant at or above the 95% confidence level.

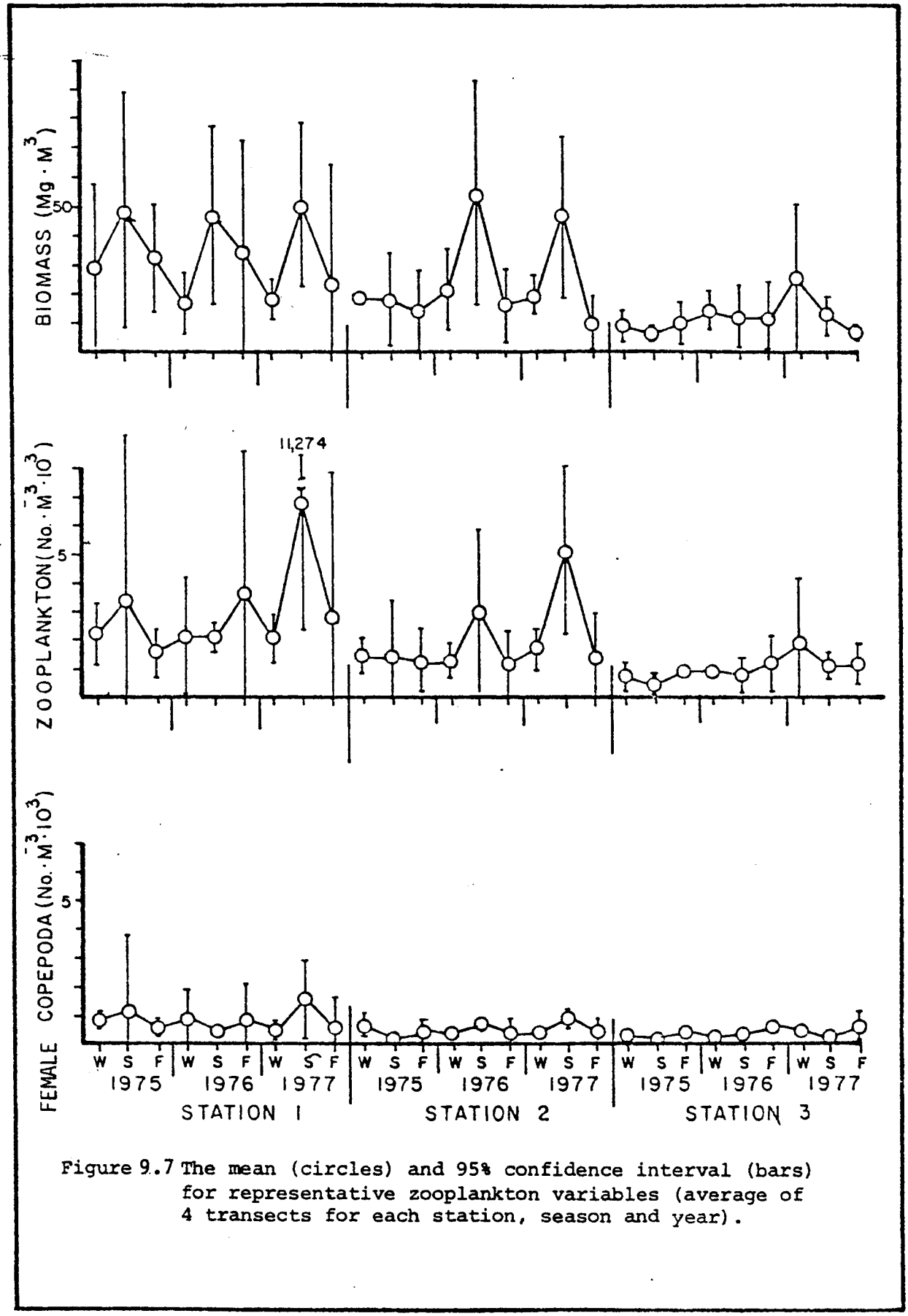

Figure 9.7 The mean (circles) and 95% confidence interval (bars) for representative zooplankton variables (average of 4 transects for each station, season and year).

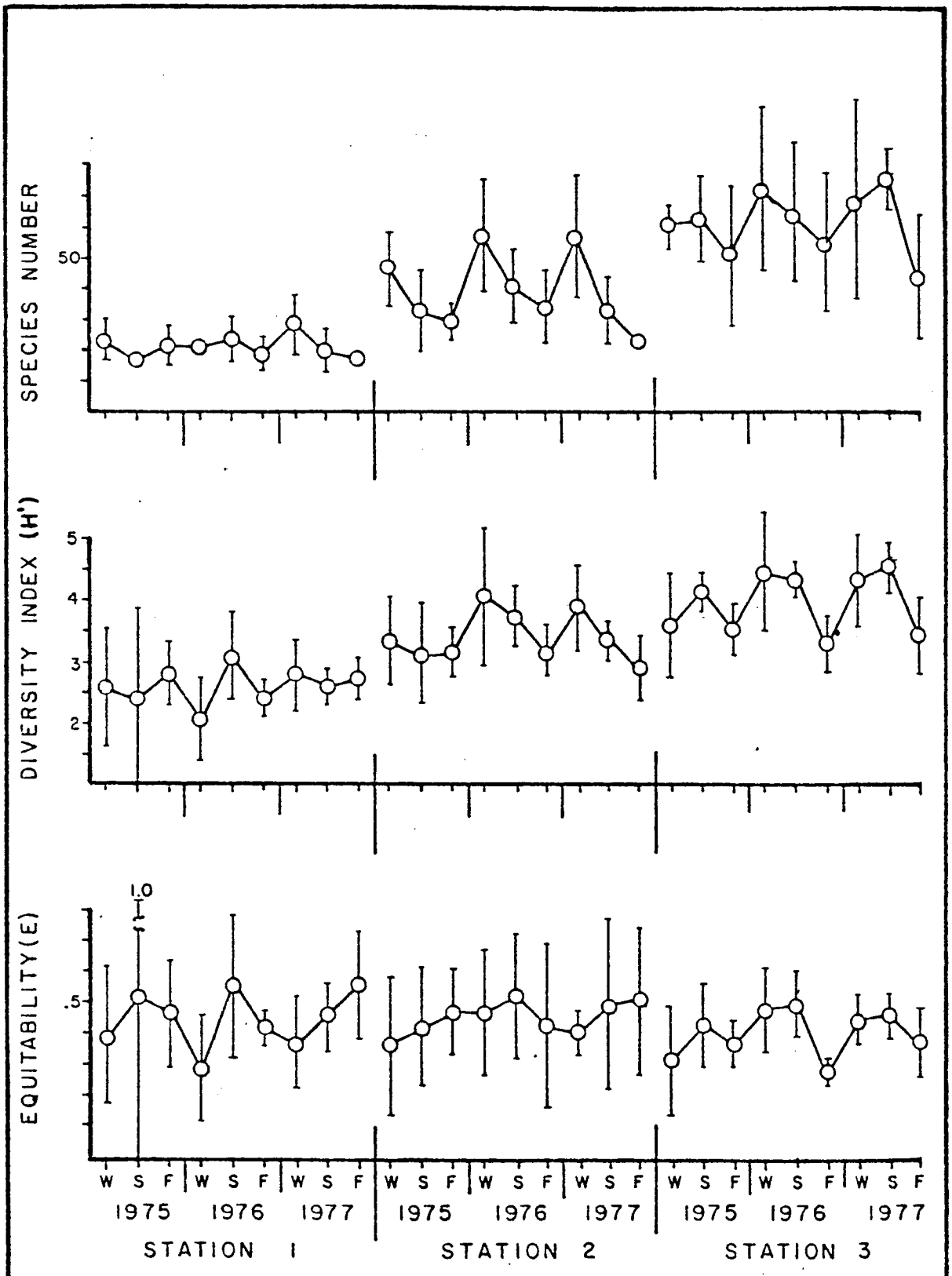

Figure 9.8 The mean (circles) and 95% confidence intervals (bars) for representative zooplankton variables (average of 4 transects for each station, season and year).

variation between transects (95% confidence intervals) was often quite large.

Season

Seasonality in zooplankton distribution was illustrated by the results (Table 9.3) of Scheffe's multiple range test where more zooplankton variables showed significant differences between depths in the spring. The implied effect of season on significant variations in the zooplankton with water depth was tested by two-way analysis of variance (Table 9.4). Among the zooplankton variables which showed significant variables with depth and season, the test for two-way interactions between the paired factors was significant for more than half the variables. This made the results difficult to interpret.

When only the means were considered for the variables in Figures 9.7 and 9.8 biomass weights decreased seaward and showed that the most consistent changes in weights between seasons occurred at the shallow stations. Mean total zooplankton densities followed the mean weights of biomass in a seaward decrease, but seasonal fluctuations at all bottom depths were poorly patterned. Mean densities of female copepods changes with the total zooplankton. The mean numbers of female copepod species increased with depth and showed a very consistent pattern of decreasing numbers through the seasons from winter to fall at Station 2. Species diversities followed the same patterns of change with depth and season that were observed in the number of species. The mean equitabilities, however, showed almost no pattern of change related to depth or season. The relatively low mean values obtained for equitability at each depth, indicated that a few species accounted for most of the copepod density across the shelf.

Relationships Between the Zooplankton and Certain Environmental Factors

Multiple regression analysis, with zooplankton variables as dependent variables and 14 physical and phytoplankton variables plus depth and ichthyoplankton as independent variables, was performed on the 1976 and 1977 data. Analyses were performed on the data base with all station depths combined and on the data separated according to station depth. In general, the results from the data separated by station depths showed higher percentages of zooplankton variation explained by physical or phytoplankton variables than the results from analysis of the combined data set. This could be related to the gradient nature of the transects. Table 9.5 shows the results of multiple regression analysis for each dependent variable with 50% or more of the total variation explained at one or more station depths.

Although the analysis was based on the data grouped by depth, depth was used as a variable because it increased slightly between shallow stations from Transect I to IV. This provided an additional variable which represented transect effect. In general, where the variation in the zooplankton was explained by variation in physical and phytoplankton variables, the amount of variation explained was low and distributed among several physical and/or phytoplankton variables.

At the shallow stations ichthyoplankton density, salinity and station depth were the independent variables which most consistently explained part of the significant variation in zooplankton variables. The largest amount of variation explained by ichthyoplankton density was 36.6% which was positively correlated with adult female copepod density. The largest percentage of zooplankton variation explained by salinity was 27% which was negatively correlated to the adult female calanoid copepod group.

The zooplankton variables with the largest percentages (50-80%) of

Table 9.5

MULTIPLE REGRESSION RESULTS OF DEPENDENT ZOOPLANKTON COMMUNITY VARIABLES AGAINST INDEPENDENT PHYSICAL AND PHYTOPLANKTON VARIABLES. THE INDEPENDENT VARIABLES, THEIR CORRELATION SIGN (+, -), AND THEIR EXPLAINED VARIATIONS ARE LISTED IN ORDER OF ENTRY INTO THE STEPWISE-REGRESSION ANALYSIS. ONLY SIGNIFICANT ($P < 0.05$) INDEPENDENT VARIABLES ARE SHOWN. ONLY DEPENDENT VARIABLES WITH > 50% TOTAL VARIATION EXPLAINED FOR ONE OR MORE STATION DEPTHS ARE SHOWN.

Dependent Variable	Shallow Stations	Mid-Depth Stations	Deep Stations
Biomass mg · m^{-3}	- Phosphate 19% Total Variation 19%	- Salinity 39% - Net Chlorophyll*a* 11% Total Variation 50%	- Phytoplankton Density 56% + Dissolved O_2 7% Total Variation 63%
Number of Adult Female Copepod Species		- Temperature 51% + Depth 12% - Total Phaeopigments 9% + Net Phaeopigments 5% + Dissolved O_2 4% + Nanno Chlorophyll*a* 3% Total Variation 84%	
Adult Female Copepod Density (no. · m^{-3})	- Salinity 22% + Ichthyoplankton 37% - Depth 7% + Number of Phyto-plankton species 7% (+) Total Phaeopigment 5% Total Variation 78%	- Salinity 30% + Total Phaeopigments 8% Total Variation 38%	

TABLE 9.5 (cont'd)

Adult Male Copepod Density (no. · m^{-3})	+ Nanno Phaeopigments	23%	- Salinity	30%	+ Phytoplankton Density	32%
	+ Ichthyoplankton	23%	- Net Chlorophylla	15%	- Salinity	11%
	- Salinity	11%	+ Total Phaeopigments	7%	+ Total Phaeopigments	8%
			- Silicate	3%		
			+ Ichthyoplankton	4%		
			- Dissolved O_2	2%		
	Total Variation	57%	Total Variation	89%	Total Variation	51%
Total Calanoid Density (no. · m^{-3})	+ Total Phaeopigments	20%	- Salinity	30%	+ Phytoplankton Density	35%
	+ Ichthyoplankton	19%	- Total Phaeopigments	11%		
	- Salinity	19%	- Depth	11%		
	- Depth	6%	+ Net Chlorophylla	7%		
	+ Number of Phyto-plankton species	5%	- Silicate	7%		
			+ Nanno Phaeopigments	5%		
			- Secchi Depth	6%		
			+ Ichthyoplankton	5%		
	Total Variation	59%	Total Variation	82%	Total Variation	35%
Adult Female Calanoid Density (no. · m^{-3})	- Salinity	27%	- Salinity	30%	+ Phytoplankton Density	26%
	+ Ichthyoplankton	30%	+ Total Phaeopigments	11%		
	+ Total Phaeopigments	9%	- Depth	11%		
	- Depth	6%				
	+ Number of Phyto-plankton species	5%				
	+ Net Chlorophylla	3%				
	Total Variation	80%	Total Variation	52%	Total Variation	26%

TABLE 9.5 (cont'd)

Calocalanus pavo Density (no. · m^{-3})			+ Net Chlorophylla 35% + Temperature 13% - Ichthyoplankton 8% - Total Phaeopigment 7% - Salinity 5% Total Variation 68%
Nannocalanus minor Density (no. · m^{-3})		+ Phytoplankton Density 39% - Temperature 12% Total Variation 51%	
Paracalanus indicus Density (no. · m^{-3})		- Temperature 33% - Phosphate 8% Total Variation 41%	+ Phytoplankton Density 66% Total Variation 66%
Paracalanus quasimodo Density (no. · m^{-3})	+ Net Chlorophylla 38% - Phosphate 12% Total Variation 50%		+ Phytoplankton Density 41% + Net Chlorophylla 9% - Phosphate 10% Total Variation 60%
Adult Male Calanoid Density (no. · m^{-3})	+ Nanno Phaeopigments 41% + Ichthyoplankton 20% Total Variation 61%	- Salinity 46% + Net Chlorophylla 6% + Total Phaeopigments 8% + Nanno Phaeopigments 6% + Ichthyoplankton 5% Total Variation 71%	

TABLE 9.5 (cont'd)

Total Cyclopoid Density (no. · m^{-3})	- Phosphate 25% + Ichthyoplankton 11% - Salinity 10% + Depth 12% Total Variation 58%	- Salinity 32% - Net Chlorophyll*a* 16% + Total Phaeopigments 8% - Dissolved O_2 8% - Silicate 11% Total Variation 75%	
Corycaeus americanus Density (no. · m^{-3})	- Salinity 17% + Ichthyoplankton 18% - Depth 8% Total Variation 43%	- Salinity 53% - Net Chlorophyll*a* 18% - Silicate 7% + Nanno Phaeopigments 5% + Ichthyoplankton 4% - Secchi Depth 3% + Total Phaeopigment 2% Total Variation 92%	+ Phytoplankton Density 24% - Salinity 26% Total Variation 50%
Corycaeus giesbrechti Density (no. · m^{-3})		- Dissolved O_2 33% + Silicate 12% + Net Phaeopigments 14% Total Variation 59%	+ Net Chlorophyll*a* 53% - Temperature 8% + Phytoplankton Density 5% Total Variation 66%
Farranula gracilis Density (no. · m^{-3})	+ Secchi Depth 31% + Salinity 9% - Phosphate 11% Total Variation 51%		

TABLE 9.5 (cont.'d)

Adult Male Cyclopoid Density (no. · m^{-3})	- Salinity 19% + Ichthyoplankton 18% + Depth 13% Total Variation 50%	- Salinity 54% - Net Chlorophylla 19% - Silicate 6% + Total Phaeopigments 6% - Dissolved O_2 4% Total Variation 89%	+ Net Phaeopigment 27% - Salinity 13% + Phytoplankton Density 10% Total Variation 50%
Immature Cyclopoid Density (no. · m^{-3})	+ Ichthyoplankton 18% + Depth 12% + Temperature 10% Total Variation 40%	+ Net Phaeopigment 23% + Total Chlorophylla 9% - Salinity 9% + Phytoplankton Density 9% Total Variation 50%	
Cladocera Density (no. · m^{-3})	- Salinity 16% + Ichthyoplankton 30% + Depth 17% Total Variation 63%		+ Temperature 25% Total VAriation 25%
Crustacean Larvae Density (no. · m^{-3})	+ Ichthyoplankton 24% - Secchi Depth 19% + Nanno Phaeopigments 9% Total Variation 52%	- Salinty 16% - Dissolved O_2 15% + Net Phaeopigment 25% Total Variation 56%	+ Net chlorophylla 52% - Salinity 8% Total Variation 60%
Larvacea Density (no. · m^{-3})		- Number of phyto-plankton species 16% + Phytoplankton Density 20% - Net Chlorophylla 10% - Phosphate 7% Total Variation 53%	+ Salinity 37% + Silicate 9% + Phytoplankton Density 9% + Total Phaeopig-ments 7% + Net Chlorophylla 7% Total Variation 69%

the total variation explained by physical and phytoplankton variables were found among the copepods grouped by suborders or sex. Relatively little of the variation in individual copepod species was explained. Among the other major taxa, part of the total explained variation in the Cladocera and crustacean larvae (63 and 52%, respectively) was explained by several independent variables collectively but ichthyoplankton density explained the largest (30 and 24%, respectively) portion in both cases.

At the mid-depth stations salinity and phytoplankton variables consistently explained part of the significant variation in zooplankton variables. The largest percentage of variation explained by salinity was 50% which was negatively correlated to the total densities of adult male copepods. Salinity also accounted for over 50% of the explained variation in the density of the adult male cyclopoid group and in density of the cyclopoid copepod species *Corycaeus americanus*. Most of the cases where the total explained variation exceeded 50% were found among the Copepoda grouped by suborder or sex. These results tend to agree with the results described for the shallow stations, however, variation in the density of more copepod species was explained at the mid-depth stations.

Copepod species which commonly showed relationships with physical and phytoplankton variables at the mid-depth stations were species which were usually most dense at the shallow stations. This indicated that successful occupation at the mid-depth stations by species might be influenced by limiting factors in the environment. For instance, 92% of the variation in *Corycaeus americanus* was explained by seven independent variables collectively, with 53% of the variation negatively correlated to salinity. To a lesser degree, the variation in the nearshore copepods *Acartia tonsa, Centropages velificatus, Paracalanus indicus* and *Eucalanus pileatus* was also explained by variation in environmental parameters. Phytoplankton

variables, especially total phaeopigments were more frequently implicated as sources of explained variation in zooplankton variables at the mid-depth stations than at the shallow stations.

At the deep stations, phytoplankton density most consistently explained part of the significant variation in zooplankton variables. Phytoplankton density accounted for a portion of the variation in the calanoid copepods *Paracalanus indicus* (66%) and *Paracalanus quasimodo* (41%) and to a lesser degree, the variation in the Copepoda grouped by suborder or sex. The variation in biomass was also largely (56%) explained by phytoplankton density.

In summary, ichthyoplankton density was the independent variable most frequently associated with zooplankton variation at the shallow stations. Salinity was the variable most frequently associated with zooplankton variation at the mid-depth stations; and phytoplankton density was the variable most frequently associated with zooplankton variation at the deep stations.

DISCUSSION

General Distributional Patterns

Zooplankton studies have revealed some characteristic features of the zooplankton population over the STOCS during the period from December 1974 to December 1977. Biomass, total zooplankton density and female copepod density showed patterns of variation perpendicular to the shore, decreasing seaward. Results similar to these have been reported in the literature. Within the Gulf of Mexico, Drummond and Stein (1954) showed that biomass (dry weight and carbon) decreased seaward. Howey (1976) reported that zooplankton biomass decreased seaward from the shelf, across the slope into oceanic waters. Data reported by Caldwell and Maturo (1976) showed seaward decreases in biomass (dry weight) and zooplankton numbers

(densities) off the northern Gulf coast of Florida. Sander and Moore (1978) summarized the frequently reported relationships of Copepoda to other taxa and to bottom depth by stating that copepoda usually constitute about 70% of zooplankton numbers and that, "... percentage contribution, biomass and/or number of copepods are generally greatest in proximity of land or island masses".

Copepod Distribution

The identification of copepod species groups in the STOCS area was based on the results of cluster analysis supported by frequency of occurrence and Scheffe's multiple range test. A nearshore and an offshore group was identified based largely on the different densities of species which appeared on all three depth contours. Other investigators have employed some forms of clustering strategies (Bowman, 1971; Grant, 1977) to describe species assemblages in neritic areas. The data used by Bowman (1971) and Grant (1977) were obtained from widely spaced stations which extended from areas more estuarine and/or oceanic than those surveyed for the STOCS project. Therefore, these investigators (Bowman and Grant) obtained somewhat more interpretable results based on mutually exclusive groups of copepod species.

The results of cluster analysis showed that nearshore and deep stations in the STOCS are different in terms of the numerically dominant species. Furthermore, the dominant species at both the shallow and mid-depth stations were different during the semi-annual periods from December to June and July to November. Semi-annual changes in copepod species composition based on the most abundant species have not been specifically described in literature pertinent to the BLM STOCS study area. Woodmansee (1958) reported that major abundances of certain copepods occurred between June

and November/December or November to mid-June in Biscayne Bay, Florida. Van Engel and Tan (1965) differentiated winter-spring (November to April) and summer-fall (May to October) copepod species assemblages based on the period of greatest abundance of 30 species in Chesapeake Bay.

Variability in Zooplankton Distribution

The results for representative zooplankton variables such as biomass, total zooplankton density and female copepod density revealed considerable variation in zooplankton distribution along bottom-depth contours from transect to transect during each of the nine seasonal cruises. The variability suggested the occurrence of pulsing inputs to the system which encouraged zooplankton production but which were so limited that the entire length of the study area was not uniformly affected. The calanoid species *Acartia tonsa, Paracalanus indicus, Paracalanus quasimodo* and *Clausocalanus furcatus* were often found in dense patches on one or two transects in the spring. Cladocerans of the genus *Penilia* appeared in a highly regionalized dense patch at Station 1/II in the spring of 1977 and in August 1976. Ostracoda, primarily of the species *Euconchoecia chierchiae*, were found in dense patches at various stations throughout the study. Several mechanisms which influence zooplankton population growth have been described in the literature. In the north Atlantic, thermocline inversion occurs in the spring when day-length increases and promotes phytoplankton blooms which are followed by zooplankton population growth. The work of Colebrook and Robinson (1961) showed that this is a cyclic phenomenon. In temperate or tropical regions nutrients are reported to be a limiting factor but light intensity is not. Therefore, phytoplankton and zooplankton may respond to nutrient increases throughout the year. Menzel and Ryther (1961) studied the relationship between nutrients, phytoplankton and

zooplankton in the Sargasso Sea and reported that plant production is limited by nutrient levels and the zooplankton ". . . keep up with the plants". Sander and Moore (1978) suggested that in tropical and subtropical areas at least some species (of copepods) are physiologically prepared to transform increased primary production into population growth throughout the year.

Relationships between the zooplankton and physical or phytoplankton variables have not been extensively studied in the Gulf of Mexico. Bogdanov *et al.* (1968) identified regions of upwelling and measured biomass production throughout the Gulf and Caribbean Sea. According to his (Bogdanov's) findings, upwelling is not a significant phenomenon off the south Texas coast and biomass is low (150-300 $mg \cdot m^{-3}$). Austin and Jones (1974) related fluctuations in zooplankton biomass to current and the influence of estuarine and neritic waters over the Florida Middle Ground.

Identification of nutrient sources and the mechanisms of current distribution in the STOCS area is a prerequisite to understanding variations in zooplankton density. Available data cannot satisfactorily identify these nutrient sources or mechanisms of nutrient distribution, however, some explanation may be inferred from the limited information available.

Drainage basin runoff is frequently implicated as a source of nutrient enrichment (Sander and Moore, 1978). Reduced springtime salinities at all three station depths in the STOCS area reflect some influence by drainage basin runoff. The Mississippi and Atchafalaya Rivers are the largest contributors of fresh water in the northern Gulf (Berryhill, 1975). Closer, but much more limited, sources of freshwater are represented by the numerous bay systems extending from the northern half of the study area north along the northwestern Gulf coast (Berryhill, 1975). It is possible that the patchy distribution of the zooplankton in the study area is

related to pulses of low salinity input from these bay systems. Evidence for estuarine influence in the STOCS area may be found in the composition of copepod species. *Acartia tonsa* is a calanoid copepod which is almost always reported among the most abundant copepod species inhabiting bays and estuaries in the Gulf and along the Atlantic coast from Florida to Cape Hatteras (Bowman, 1971; Breuer, 1962; Cuzon du Rest, 1963; Davis, 1949; Grice, 1960). In the STOCS area *Acartia tonsa* appeared in large numbers in 1975 at the nearshore and mid-depth stations on Transects I and II in the spring. In all three years *Acartia tonsa* was most abundant in the spring when salinities were low. Other typically estuarine copepod species (*Centropages hamatus, Labidocera aestiva, Oithona nana* and *Paracalanus crassirostris*) were also most abundant.

Events which influenced zooplankton production appears to be faithfully reproduced over an annual cycle, based on the results obtained by averaging representative zooplankton variables over the entire study area for each year. Data averaged for each transect over the three-year period showed that the southernmost transect (IV) was slightly less productive than those to the north but, in general, zooplankton productivity appeared to be fairly uniform from transect to transect. These findings may have resulted from purely coincidental sampling of each transect during periods of high and low zooplankton productivity. Much mofe information concerning water mass movements and more intensive zooplankton sampling should provide a better understanding of the mechanisms affecting zooplankton distribution in the STOCS area.

Relationships Between Zooplankton and Environmental Factors

Multiple regression analysis was used to identify possible relationships between zooplankton densities and physical, nutrient and phytoplankton

variables. A number of expected or at least plausible relationships were indicated, however, occasional relationships between trophically separated entities (*i.e.* phosphates and copepods) suggest that some of the plausible relationships may be deceptive. At the shallow stations, ichthyoplankton more frequently explained some of the variation in zooplankton variables than any of the other independent (physical or phytoplankton) variables. This may indicate that ichthyoplankton populations were responding to changes in zooplankton density. It is generally accepted that at least some species of planktonic fish take advantage of the zooplankton as a food source. Peters and Kjelson (1975) have demonstrated that post-larval and juvenile fishes eat copepods in controlled, laboratory experiments. Cuzon du Rest (1963) reported that abundances of fish larvae correlated with copepod abundances in the salt marshes of Louisiana; and Grice (1956) suggested that an observed springtime (May) decrease in zooplankton at Alligator Harbor, Florida might have resulted from predation by fish larvae, chaetognaths and ctenophores.

Salinity accounted for some of the explained variation in several zooplankton variables at the shallow stations but it more frequently explained some percentage of the zooplankton variation at the mid-depth stations. The number of relationships between zooplankton and phytoplankton variables also increased from shallow to mid-depth stations. The implied relationships between zooplankton variables and salinity at the mid-depth stations may indirectly reflect a response of the zooplankton to changes in primary production which are commonly associated with salinity changes in neritic waters.

The number of associations between zooplankton and phytoplankton variables increased seaward. At the deep stations, phytoplankton density generally accounted for the largest percentages of explained variation in

zooplankton variables. The implied direct relationship of zooplankton to phytoplankton at the deep stations reflect a close dependence of zooplankton on phytoplankton which is generally reported for oceanic, subtropical or tropical areas of the ocean (Menzel and Ryther, 1961; Sander and Moore, 1978). The combined results from the three depth contours suggested that offshore zooplankton populations may have been controlled by food availability while nearshore zooplankton populations may have been controlled by predation.

CONCLUSIONS

1. The BLM STOCS area may be separated into depth-related regions on the basis of copepod species composition. Two semi-annual periods may also be described on the basis of the numerically dominant species at the shallow and mid-depth stations. Species groups were based on density as well as occurrence at the three depths. The species which were most dense or occurred most frequently were found throughout the study area. Therefore, bottom depths and seasonality could not be defined in terms of distinctly separate species groups.

2. Statistical analysis showed that elements of the zooplankton occurred in significantly different densities between water depths and seasons. Some of the variation in certain zooplankton variables was explained by some environmental variables. However, the amount of variation explained was usually low and distributed among several environmental variables. Although statistical significance was found in several relationships between the zooplankton and water depth, season and certain environmental factors, the biological significance of these relationships was difficult to interpret.

RECOMMENDATIONS

Data from the three years of baseline studies have suggested the existence of certain features of the STOCS zooplankton which could be better evaluated by short-term, intensive sampling programs at selected stations. Three characteristics of the zooplankton suggested by analysis of the three years of zooplankton data should be more intensively studied.

1. The laboratory analysis of each zooplankton sample could be limited to those forms which appeared by their frequency of occurrence, density and distribution to be water mass indicators. This would allow more samples and replicates to be analyzed and thus improve the data base for statistical analyses.

2. Patchiness in zooplankton density distribution was evident in each seasonal cruise, however, when the data for most zooplankton variables were averaged by transect over the annual cycle, the transects appeared to be almost equally productive. Patchiness was most apparent at the nearshore and mid-depth stations. It is recommended that these stations be sampled more intensively during the period when the greatest change in zooplankton density or composition appeared in the monthly data (*i.e.* April through July).

3. Multiple regression analysis showed that certain environmental variables at each station depth consistently explained variations in the zooplankton. Discrete depth samples of the zooplankton with concurrent samples of hydrographic, ichthyoplankton and phytoplankton variables could more fully define the nature of these implied relationships.

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CHAPTER TEN

BENTHIC MYCOLOGY

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ABSTRACT

Mycological data from 18 STOCS sediment samples collected at six stations in the winter, spring and fall of 1977 were analyzed by ANOVA for significant seasonal and geographical variation. Among the variables studied were abundance of total fungi, oil-degrading fungi, and fungal oil degradation potential as isoalkane/n-alkane ratios. The association of these variables with other hydrological, chemical and biological variables was analyzed by regression and graphic methods.

The abundance and diversity of fungi were found to be greatest in the fall. The composition, abundance and longevity of the benthic fungal flora were probably controlled by threshold concentrations of available organic carbon. Fungi with spores requiring exogenous energy sources for germination appeared to be selectively maintained at the water-column thermocline during the summer after deposition from terrestrial sources by late-spring continental air masses. The abundance of fungi in the fall was associated with the total organic carbon concentration of the sediment with a threshold value of > 0.8% required for significant development.

Fungal crude oil degradation potential was greater in samples from inshore stations than from offshore stations. Degradation increased with an increase in sediment particle size and was greatest in the fall sample from the Rio Grande delta which might have recently received high nutrient fresh water outwash.

Although fungi were initially inhibited by South Louisiana crude oil (SLCO), more than half the isolates tested could degrade SLCO and fungal development was stimulated after a lag of one to two weeks.

INTRODUCTION

Fungi are ubiquitous in both terrestrial and marine environments. It is somewhat surprising, however, that the predominant genera and species found in sublittoral sediments are the same saprobic members of the Fungi Imperfecti that are commonly found in terrestrial habitats (Sparrow, 1937; Steele, 1967). Despite their documented abundance and the fact that they occur in sediments as viable mycelial filaments (Johnson and Sparrow, 1961; Morita and Zobell, 1955), the free living higher fungi have been largely ignored by marine mycologists who have directed their attention to yeasts and less abundant, but uniquely marine groups of algal parasites and wood rotting fungi (Jones, 1976). The study of sediment fungi on the South Texas outer continental shelf (STOCS) is timely because of the rapid increase in petroleum development and production activities in the area. The ability of fungi to degrade alkane (Markovetz *et al.*, 1968) and aromatic (Cerniglia *et al.*, 1978) hydrocarbons is well documented, but the factors controlling the fungal degradation of crude oil in marine sediments are as yet largely unknown.

The purpose of the research reported here was to integrate mycological data collected from 18 sediment samples in 1977 (Szaniszlo, 1978) with corresponding hydrographic, chemical and biological data collected during the same period by other project elements. From the results of the statistical analyses, a conceptual model has been developed which explains the quantitative and qualitative changes observed in the STOCS fungal community and in its oil degradation potential. Because the proposed scheme had no predecessors upon which to build and is based upon only 18 samples collected in a single year, this model is speculative, but does provide a first approximation of the major mycological processes occurring in the

STOCS study area.

METHODS

Sampling

Surficial sediment samples were collected for mycological analysis at six STOCS locations on three seasonal cruises during 1977 (Winter, March 4-8, Spring, June 13-15; and Fall, October 15-18). Stations 1, 2 and 3 on Transect II provided information on a typical profile across the shelf and included a shallow inshore station (∿ 22 m), an intermediate (∿ 49 m) and an offshore deep-water station (∿ 131 m). These were the same stations sampled on monthly cruises in the water column mycology study. A second transect, roughly perpendicular to Transect II and comprising Stations 3/I, 2/III and 1/IV, provided for duplicate stations at each depth while offering the possibility of detecting longshore trends. The surficial sediment from a Smith-McIntyre grab was collected and processed immediately to yield the following information: 1) the kinds and abundance of fungi in the sediment; 2) comparative rates of oil degradation; and 3) the effect of crude oil on benthic fungi.

Processing

The abundance of fungi in the sediment was estimated by plating duplicate dilution series of each sample on duplicate plates of a non-selective medium, Mycological Agar rehydrated with artificial seawater containing antibiotics and 0.1% (w/v) yeast extract. Colonies were counted after 3, 7 and 14 days and abundance was calculated as colony forming units per ml wet sediment (CFU/ml). Representative isolates were transferred to slope culture for maintenance and to slide culture for identification of the predominant species. These isolates were used in experiments to determine the

ability of individual fungi to assimilate hydrocarbons from crude oil using a method developed by Nyns *et al.* (1968). The abundance of hydrocarbonoclastic fungi was determined by the methods used for total fungi, but with a selective medium, Wickerham's Yeast Nitrogen Base, rehydrated with artificial sea water containing 0.5% (w/v) South Louisiana crude oil (SLCO) and antibiotics.

For the study of oil degradation by natural mixed populations of benthic fungi 20 ml of sediment were added immediately after collection to flasks containing 0.5% or 0.1% (v/v) autoclave-sterilized SLCO in 80 ml artificial sea water. This culture medium was supplemented with antibiotics and low levels of nitrogen and phosphorus equivalent to the maximum nitrate and phosphate concentrations found in STOCS waters in 1976 (Sackett and Brooks, 1977). Similar preparations without sediment served as abiotic-weathering controls. After the cultures were shaken at 25°C for 20-45 days, they were frozen and sent to Dr. P. L. Parker at the U. T. Marine Science Institute for extraction and GC analysis of the residual hydrocarbons (Parker *et al.*, 1979). The ratios of branched alkanes to n-alkanes (pristane/n-heptadecane; phytane; n-octadecane; and $\underline{n}\text{-}C_{16}\text{-}C_{32}$/pr+ph) were used to compare the amount of fungal bio-oxidation in the various samples. Increases in pr/$\underline{n}\text{-}C_{17}$ and ph/$\underline{n}\text{-}C_{18}$ values were presumed to indicate fungal degradation of crude oil because the isoalkanes are more recalcitrant than n-alkanes to oxidation by fungi (Perry and Cerniglia, 1973). The $\underline{n}\text{-}C_{16}\text{-}C_{32}$/pr+ph ratio has been excluded from the discussion that follows since several species of fungi including *Penicillium* sp. and *Aspergillus* sp. produce relatively large amounts of $\underline{n}\text{-}C_{27}$ through $\underline{n}\text{-}C_{31}$ (Jones, 1969).

The effect of crude oil on natural mixed fungal populations was measured by periodically sampling sediment cultures prepared as for oil

degradation study. The number of colony forming units per ml culture medium was determined and the genera present were determined. Similar cultures with no oil added served as controls. Yeasts were tabulated separately in all of the above studies, but their frequency was too low for meaningful analysis, less than 10% of possible cases, and so they were combined with molds and the data treated as total fungi. Crude oil (SLCO) was also added to triplicate pure cultures of a STOCS isolate of the marine yeast *Candida diddensii* Fell and Meyer under various combinations of nutrient concentrations typical of the area. The effect of the oil was monitored by periodically determining the concentration of viable cells.

Statistical Analyses

One-way analysis of variance ANOVE was used to test for significant seasonal and geographical relationships in the following mycological variables: 1) total counts, 2) hydrocarbonoclastic (oil degrader) counts; 3) degrader/total ratio; 4) pristane/$\underline{n}$-C_{17}; 5) phytane/$\underline{n}$-C_{18} and 6) $\underline{n}$-C_{16}-C_{32}/ pristane + phytane. The association of mycological variables and other physical, chemical and biological variables (1977 data) were evaluated by calculating a correlation coefficient matrix and by regression of the mycological variables on the others using linear and fourth order polynomial equations, the solutions of which were plotted on computer generated scatter graphs coded by station and season. F and P values for the regression fit were also generated by the same program and $P < 0.05$ was taken as the criterion of significance. Where appropriate, t tests, X^2 contingency table analyses and rank correlations were also performed.

RESULTS AND DISCUSSION

Seasonality and Distribution of Fungi

Fungi were isolated from all of the 1977 sediment samples assayed and population densities ranged from a low of 5 CFU/ml in the winter sample from a deep station (3/I) to a high of 1600 CFU/ml in the fall sample from the other deep station (3/II)(Table 10.1). The average for the year in the STOCS study area was 236 CFU/ml sediment. There was a progression toward larger fungal populations beginning with the late-winter low and ending with a significant increase in the fall. The ANOVA F test for seasonal differences yielded a P value of 0.024. An exception to this trend was seen at the deep station on Transect I where fungal abundance was much greater in the spring than in the fall.

Station differences in abundance of fungi were not statistically significant ($P = 0.816$). In the fall samples there was, however, a notable trend toward greater numbers offshore (Table 10.1).

The annual pattern of increasing numbers of fungi through the fall was paralleled by an increase in generic richness, an index of community diversity (Table 10.1). Simple ordination analysis using genus presence or absence data to compare community composition in the various samples revealed a striking similarity among stations during winter and spring (Figure 10.1). This was due to the almost universal occurrence of the four common genera *Aspergillus, Penicillium, Cladosporium* and *Fusarium* (Table 10.2). An exception was the winter sample from the deep station on Transect II. The ordination plot showed a great divergence in community composition during the fall with some stations widely dispersed and others peripheral to the winter-spring cluster. This pattern reflected the large increase in randomly distributed rare genera (Table 10.2)

TABLE 10.1

FUNGAL ABUNDANCE (CFU/ml)* AND GENERAL RICHNESS IN STOCS SURFICIAL SEDIMENTS BY BOTTOM DEPTH AND SEASON**

Depth	Station/ Transect	SEASON Winter	Spring	Fall	Mean by Depth
Shallow	1/II	110	33	200	98
	1/IV	16	30	200	
Intermediate	2/II	11	20	910	248
	2/III	12	83	450	
Deep	3/I	5	350	160	359
	3/II	21	15	1600	
Season Mean		29 ± 40	89 ± 130	587 ± 571	
Generic Richness Avg. No. Genera/Station		5.8	7.0	10.3	

*Colony Forming Units/ml wet sediment
**One-way ANOVA with season as independent variable
F= 4.8331, df = 2.13, P= 0.024.

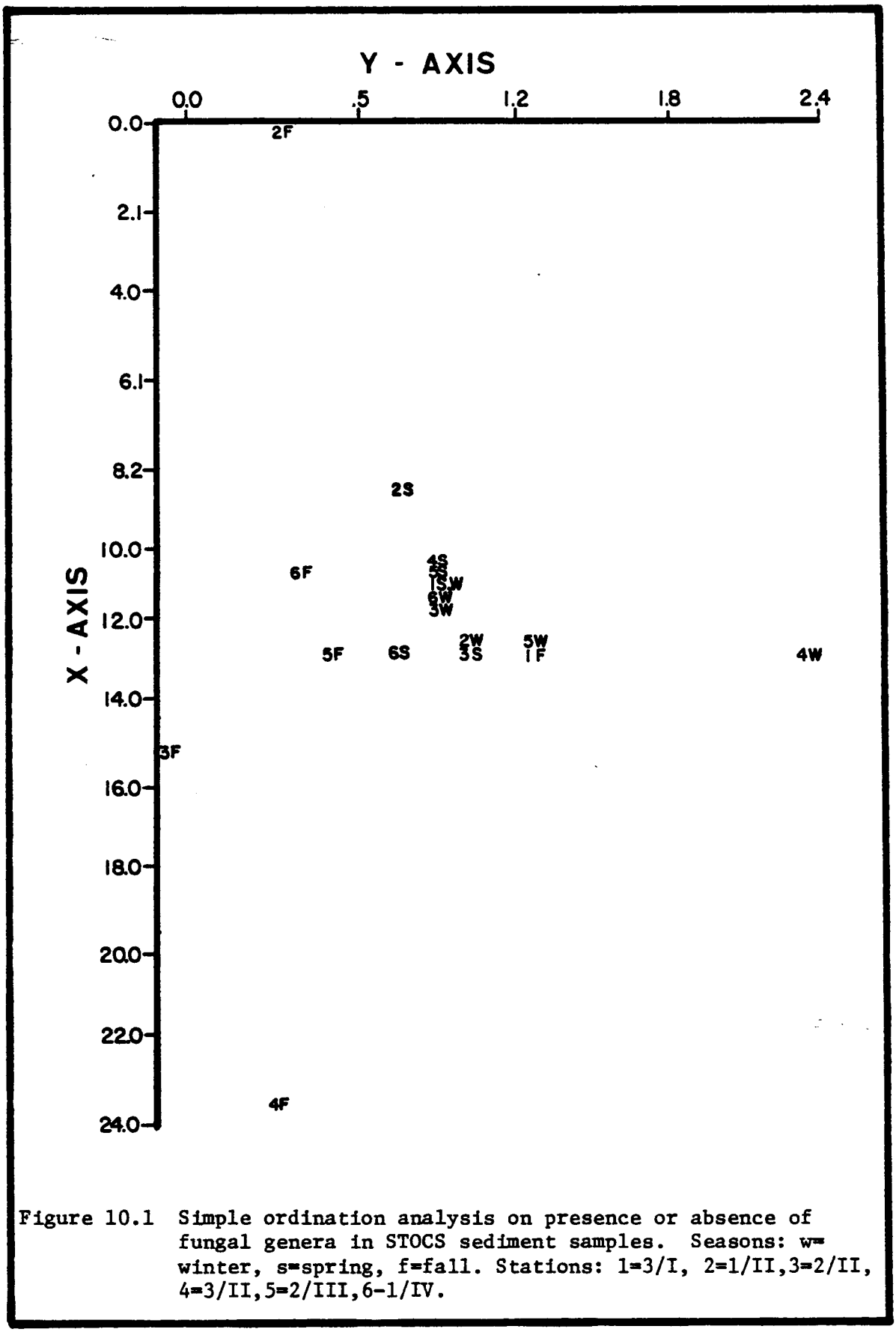

Figure 10.1 Simple ordination analysis on presence or absence of fungal genera in STOCS sediment samples. Seasons: w= winter, s=spring, f=fall. Stations: 1=3/I, 2=1/II,3=2/II, 4=3/II,5=2/III,6-1/IV.

TABLE 10.2

OCCURRENCE OF FUNGAL GENERA IN STOCS SEDIMENTS BY LOCATION AND SEASON

Species	3/I			1/II			2/II			3/II			2/III			1/IV		
	W	S	F**	W	S	F	W	S	F	W	S	F	W	S	F	W	S	F
Penicillium		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Fusarium	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	+	+
Apsergillus	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+
Cladosporium	+	+	+	+	+	+	+		+	+	+	+	+	+	+		+	+
Cephalosporium	+	+		+	+	+	+		+		+	+		+	+	+	+	+
Paecilomyces		+		+				+	+			+					+	+
Stachybotrys			+							+		+	+		+			
Coniothrium									+			+			+			+
Verticillium		+			+	+									+			
Alternaria									+				+			+		
*Candida**						+			+									+
Curvularia						+			+									+
Drechslera									+			+			+			
Periconia		+						+	+									
Trichoderma					+						+					+		
Allischeriella						+									+			
Arthrinium									+			+						
Aureobasidium				+						+								
Pestalotia		+								+								
*Rhodotorula**									+			+						
Syncephalastrum						+			+									
Cheatomium					+													
Chrysosporium											+							
Dichlaena					+													
Geotrichum										+								
Graphium																+		
Hypocrea															+			
*Rhodosporidium**				+														
Scopulariopsis															+			
Sporormia									+									

*Yeasts; **W=winter, S=spring, F=fall

The proportion of oil-degrading fungi, as measured by the ratio of counts on a medium containing crude oil as the sole carbon source to counts on Mycological Agar, proved unreliable with many samples giving values greater than one. The Nyns method of assaying the growth of pure isolates on crude oil yielded more reasonable results in which 52% of the 83 benthic fungi tested assimilated crude oil (Table 10.3). When the data were arranged by depth it was clear that a greater proportion of fungi from the shallow station had the capacity to degrade oil than those from intermediate depth stations.

Oil Degradation Potential

No consistent seasonal patterns in fungal oil degradation potential were discernible in the branched n-alkane ratios used as indices (Table 10.4). The one-way ANOVA F tests yielded P values of 0.915, 0.661 and 0.218 for pr/n-C_{17}, ph/n-C_{18} and (n-C_{16} to n-C_{32})/(pr + ph) ratios respectively when season was the independent variable. Likewise, geographical distribution of fungal oil degradation potential was not statistically significant by F test with P values of 0.225, 0.193 and 0.604 for the three dependent variables listed above. Closer examination of the data, however, revealed that degradation potential decreased offshore.

The average pr/n-C_{17} and ph/n-C_{18} values for shallow, intermediate and deep stations show a consistent decrease in degradation potential with depth (Table 10.5). When the indicator ratios from shallow and deep stations were compared by t test for unpaired observations the decrease was seen to be highly significant ($P < 0.001$). Even when the extremely high ratios in the fall sample from the shallow station on the Rio Grande delta were deleted, P remains < 0.001.

TABLE 10.3

GROWTH OF FUNGAL ISOLATES* IN CRUDE OIL
BY STATION AND DEPTH

Depth	Station/Transect	Growth	No Growth
Shallow	1/II	11	6
	1/IV	13	9
Intermediate	2/II	5	9
	2/III	3	7
Deep	3/I	3	3
	3/II	8	6

By depth $X^2 = 4.916$
$0.05 < P < 0.1$
D.F. = 2

*Isolated from benthic sediments on nonselective medium

TABLE 10.4

INDICATOR RATIOS OF N-ALKANE BIODEGRADATION IN SLCO[1] ENRICHED NATURAL MIXED FUNGAL CULTURES[2]

Ratio	Station 3/I	1/II	2/II	3/II	2/III	1/IV	Weathered Control	Incubation (days)
			WINTER					20
Pr/17[a]	0.980	1.004	1.051	0.886	1.161	1.002		
Ph/18[b]	0.483	0.478	0.515	0.462	0.501	0.559		
Σ16-32/Pr + Ph[c]	4.726	4.676	4.964	4.806	4.396	4.763		
			SPRING					40
Pr/17	0.692	1.428	1.081	0.731	1.274	1.491		
Ph/18	0.188	0.432	0.316	0.212	0.533	0.527		
Σ16-32/Pr + Ph	7.165	4.386	9.157	7.410	3.624	4.116		
			FALL					45
Pr/17	0.622	0.000[d]	0.676	0.623	0.656	3.614	0.640	
Ph/18	0.328	0.338	0.364	0.327	0.345	1.698	0.298	
Σ16-32/Pr + Ph	7.836	26.317[d]	7.143	7.250	9.783	1.117	8.552	
Pr/17 [e]	0.628	1.066	0.938	0.631	1.414	26.390	0.626	
Ph/18 [e]	0.301	0.463	0.494	0.324	0.674	4.569	0.296	
Σ16-32/Pr + Ph [e]	8.214	6.366	5.143	8.360	4.535	0.597	9.599	

[1] Southern Louisiana Crude Oil (SLCO) at 0.5% final concentration in shake cultures of sediment diluted 1:5 (v/v) artificial seawater.

[2] Established with benthic sediment samples.

[a] Pristane/n-C_{17}

[b] Phytane/n-C_{18}

[c] Σn-C_{16-32}/Pr + Ph

[d] Aberrant data: Pristane value of 0.0000.

[e] 0.1% SLCO

TABLE 10.5

FUNGAL OIL DEGRADATION INDICES FOR STOCS SEDIMENTS BY BOTTOM DEPTH

Depth	Indices	
	Pr/n-C_{17}*	Ph/n-C_{18}
Shallow	1.708 ± 1.090	0.672 ± 0.508
Intermediate	0.983 ± 0.258	0.429 ± 0.097
Deep	0.756 ± 0.146	0.333 ± 0.122
t (Deep vs. Shallow	-6.634	-10.951
df	9	10
$P_{0.001}$	-4.781	-4.587

*Pr/n-C_{17} value for Fall 1/II deleted t tests significant at P 0.001 when Fall 1/IV also deleted and when all points included.

Effect of Crude Oil on Benthic Fungi

Crude oil stimulated the growth of benthic fungi (Figure 10.2) The addition of SLCO to fall benthic sediment samples resulted, after 45 days, in an average 7-fold increase in fungal abundance at the 0.5% (v/v) oil level and a 3.6-fold increase at the 0.1% oil level relative to the control. There was, however, an initial inhibition of the natural mixed fungal populations in the 0.5% treatment. This initial toxicity was also seen in experiments with pure cultures of *Candida diddensii* in which pre-starved inoculum and low nutrient conditions duplicated as nearly as possible conditions in the STOCS ecosystem (Figure 10.3). Severe toxicity was observed in all cases with early survival rates ranging from 0 to 3% of the no-oil control. Maximum toxicity occurred between the third and sixth days with recovery and significant stimulation taking place by the 22nd day.

Abundance and Composition of STOCS Mycota

The abundance of fungi in the STOCS benthic system appears to be controlled by two primary factors, the replenishment of inoculum from the atmosphere via the water column, a seasonal phenomenon, and the availability of organic carbon, a site specific parameter.

In general, the genera of fungi found in the STOCS ecosystem are those whose spores are also abundant in the air over the adjacent continent (Chapman, 1979) and the species are those commonly found on terrestrial plant debris and in soil (Gilman, 1945; Raper and Thom, 1949; Raper and Fennel, 1965; Booth, 1971; Ellis, 1971; Domsch and Gams, 1972). The species most frequently encountered in our sediment samples were *Cladosporium cladosporioides* (Freson.) deVries, *Penicillium citrinum* Thom, *Aspergillus flavus* var. *columnaris* Raper and Fennel, *Aspergillus sydowi* (Bain and Sart.) Thom

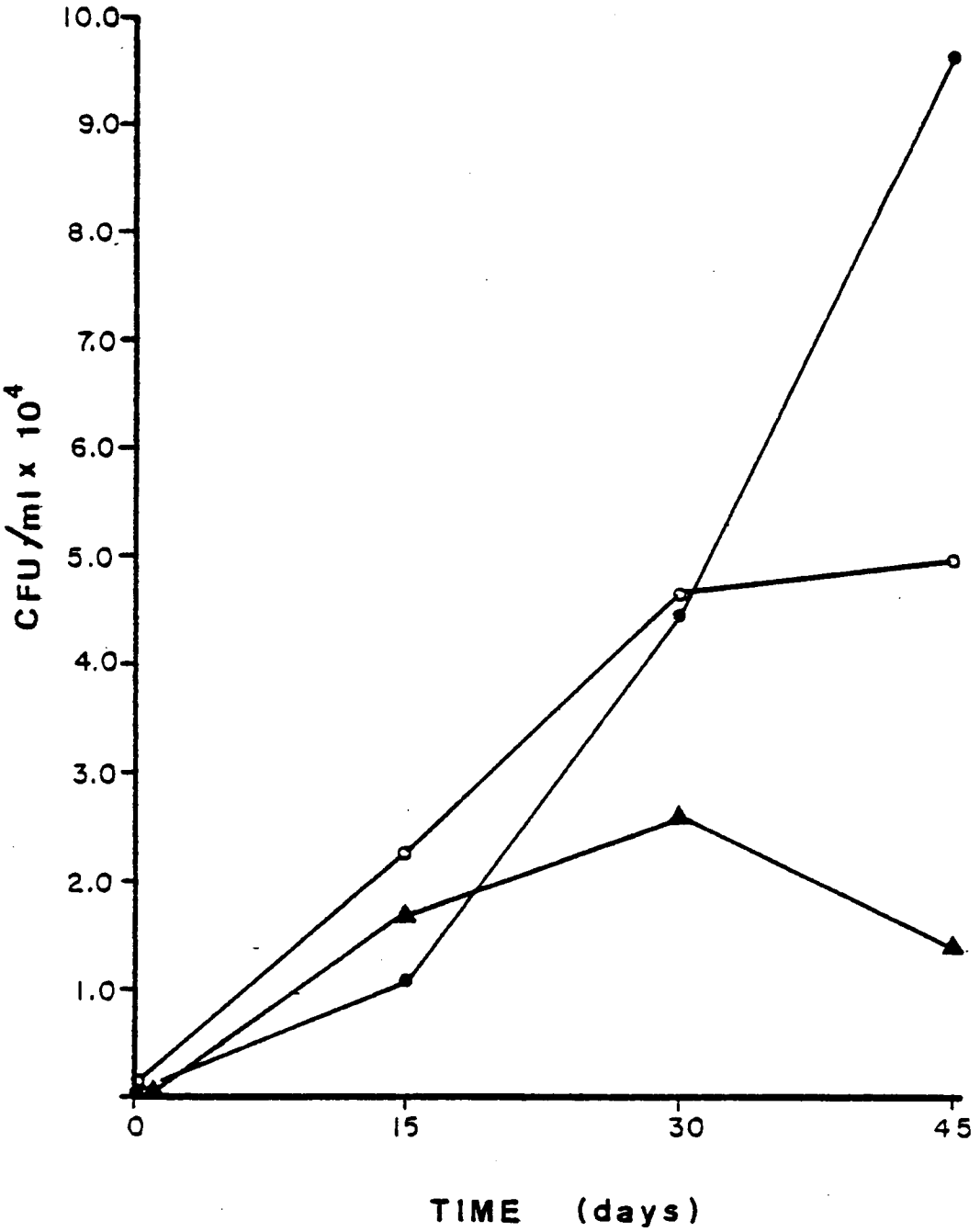

Figure 10.2 Effect of Crude Oil Concentration on Fungal Growth in Natural Mixed Cultures of STOCS Benthic Sediments Diluted (1:5) with Artificial Seawater. The Numbers are the Mean Values for all Samples from the Fall Cruise. (●) - 0.5% oil (SLCO); (○) - 0.1% oil (SLCO); (▼) - control to which no oil was added.

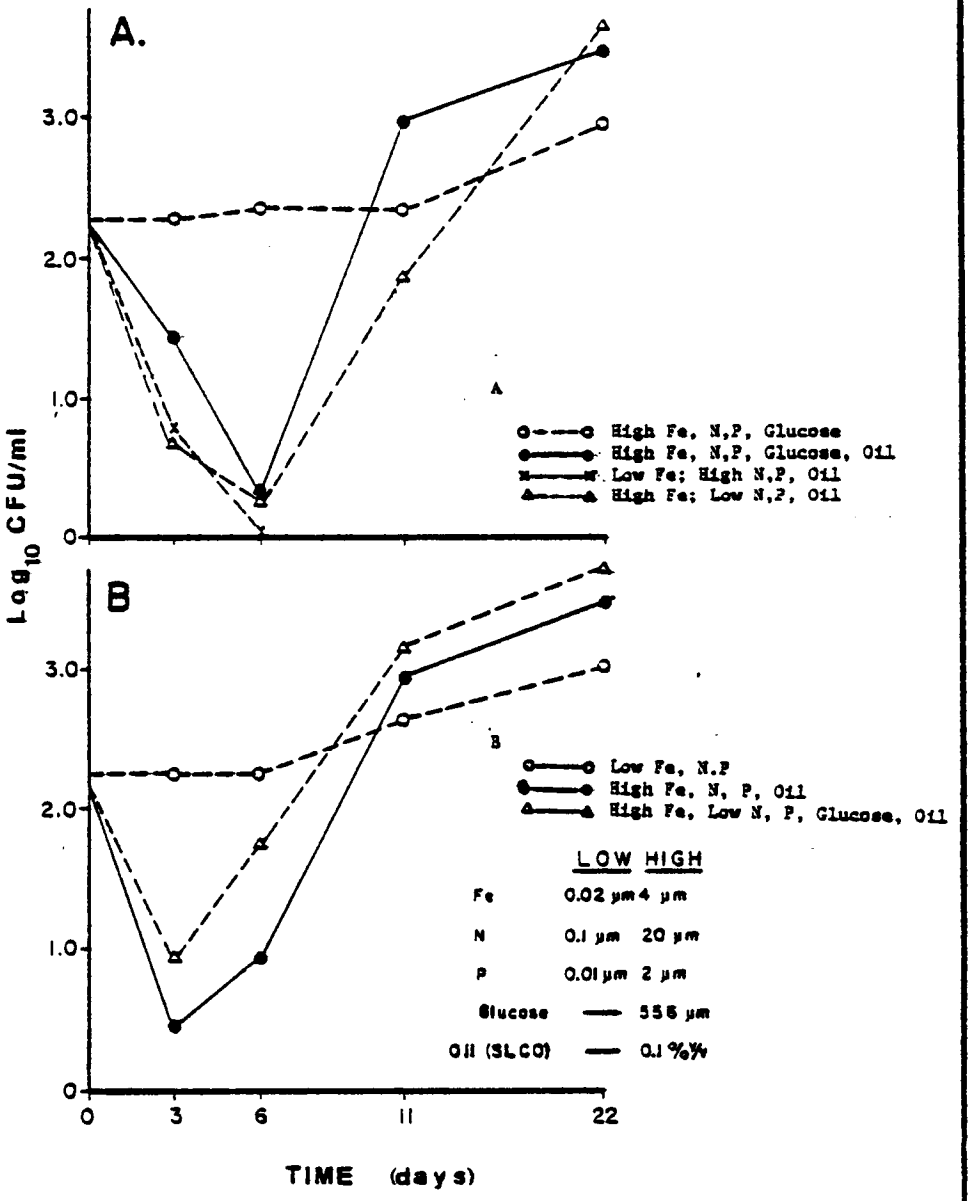

Figure 10.3 Effect of Crude Oil on Growth of *Candida diddensii* in Artificial Seawater Containing High and Low Concentrations of Fe, N, P, and Glucose Found in STOCS Waters.

and Church, *Fusarium ventricosum* Appel and Wollenweber and *F. moniliforme* var. *subglutanans* Wr. and Reink. No strictly marine genera were isolated from benthic samples, but marine species of the yeast genera *Rhodotorula* and *Candida* may have been present along with some unidentifiable species of *Fusarium* and *Cephalosporium* which also may have been uniquely marine. A similar predominance of terrestrial fungi has been reported from Atlantic and Pacific sublittoral sediments (Sparrow, 1937; Johnson and Sparrow, 1961; Roth *et al.*, 1964; and Steele, 1967).

The terrestrial origin of "marine" molds is suggested by their reported greater abundance near land masses (Ahearn *et al.*, 1968; Fell, 1967; Colwell *et al.*, 1967; and Steele, 1967). The fact that molds were more restricted than yeast to the vicinity of land in these studies might be a function of their continual reintroduction from terrestrial sources, either by air transport or freshwater outwash. Strong evidence against the outwash origin of "marine" molds came from a comparison of fungal population densities in sediments on the leeward and windward side of an Hawaiian island. The leeward sediment yielded 3.18 CFU/g but the windward sediment contained only 0.28 CFU/g even though it was in an area receiving heavy terrestrial outwash (Steele, 1967). This finding is confirmed in our studies by the relatively low fungal densities at the Rio Grande delta station (1/IV)(Table 10.1).

The generic composition of air spora over the North Atlantic was reported to be the same as that over North American agricultural lands with spores of *Cladosporium* predominating (Pady and Kapaica, 1955). They found in samples taken on the same airplane flight that the density of airborne fungal spores varied from 529 spores/ft^3 in a continental air mass to 0.5/ft^3 in a maritime air mass. The difference in the spore loads

of air masses holds the key to the seasonal distribution of molds in the STOCS ecosystem.

The large increase in benthic fungi isolated in the fall can be explained by the early fall arrival in the sediments of spores suspended throughout the summer at the thermocline/pycnocline following their deposition in the water column during late winter and spring. As the atmospheric spore load in Texas is reaching its annual maximum (Chapman, 1979) the last continental air masses of spring are moving out over the Gulf of Mexico off Corpus Christi in late April or early May (Orton, 1964). Until fall the area is covered by maritime air masses. These conditions are reflected in the abundance of fungi in STOCS near-surface waters. During March and April of 1977 fungi were uniformly very abundant with monthly averages of 40,000 and 16,000 CFU/l compared to only 13 CFU/l in July, 4 CFU/l in August, 21 CFU/l in November and 4 CFU/l in December (Szaniszlo, 1978). This distribution is probably somewhat extreme because the first half of 1977 was unusually wet in Texas while the second half was unusually dry (Climatological Data, Texas 1977, NOAA). Since fungal spores are small, usually ranging between 2 and 30 μ in their largest dimension, and light, with specific gravities of 0.56-1.36 (mostly 1.0-1.2)(Gregory, 1973), they settle very slowly in seawater which has a specific gravity of approximately 1.03. Sackett (1978) reported that the settling velocity of coccolith sized particles ranges from 0.05-10 m per day but were mostly 0.4-2 m per day.

The first signs of horizontal stratification of the water column were recorded on Transect II during late February in 1977 and by April both the thermocline and halocline were well established above all of the mycological sample sites with the exception of the inshore station (1) on Transect II

which exhibited a strong vertical salinity gradient (Smith, 1978). One month later a strong temperature-salinity pycnocline was evident across the shelf 10 to 15 meters below the surface. Rheinheimer (1974) reported that bacterial concentrations were greatest at the thermocline in stratified seawater and the data of Roth *et al* (1964) suggested that the same might occur with fungi. Brooks and Bernard (1979) have presented evidence that particles, including bacteria, were suspended at the pycnocline in the STOCS area during part of 1977. The near coincidence of a turbid layer shown by transmissometry and by bacterial activity indicated by methane concentration with the thermocline in deeper waters strongly suggest that fungal spores also could have been suspended at the pycnocline.

The breakdown of water column stratification began in September with mixing and cooling leading to a more or less homogeneous water column above the inshore stations reaching almost to the depth of the intermediate stations by the second week of September. A weakened thermocline above the outer stations persisted through November, but the integrity of the stratified layer was disrupted by an incursion of open-Gulf water documented by salinity changes (Smith, 1978) and an increase in numbers of foraminiferans and radiolarians (Casey, 1978). The breakdown coincides with the fall surge in fungal population densities in the sediment.

If the hypothesis regarding the suspension of fungal inoculum at the thermocline is valid, then anomalies in the general seasonal pattern of fungal abundance should correspond to anomalies in the general thermocline pattern. The extraordinarily high fungal counts in the spring (June) sample form the deep station (3) on Transect I and the high counts in the winter (March) sample from the inshore station (1) on Transect II will serve as test cases (Table 10.1). According to both salinity (Smith, 1978)

and radiolarian richness data (Casey, 1978), a strong incursion of open-Gulf water at intermediate depths occurred at the outer station on Transect I during the spring. This disturbance in the pycnocline might have been sufficient to permit the water column spore-load to reach the sediment at that point resulting in unusually high fungal counts. The unusually high abundance of fungi at the shallow station on Transect II during the winter (March) cruise might be explained by the delayed development of the thermocline-halocline at that inshore site (Smith, 1978), thus permitting the rapid transmission of spores from the air to the sediment.

The low concentration of organic carbon in the water column appears to control the composition of the benthic fungal community. Fungal spores can be classified, somewhat arbitrarily, as one of two physiological types: "nutrient competent" spores that contain endogenous carbon and energy reserves and thus germinate in nutrient poor water; and "nutrient incompetent" spores that require exogenous organic carbon for germination (Ko and Lockwood, 1967). Available organic carbon also determines the longevity of vegetative structures, *e.g.* spore germ tubes and mycelium, because when nutrients are exhausted these structures autolyse (Lloyd and Lockwood, 1966).

The large "nutrient competent" spores of such dematiaceous genera as *Alternaria* and *Curvularia* should germinate after deposition in the water column and soon thereafter autolyse, since the concentration of dissolved organic carbon (1.2-2.5 ppm) and particulate organic carbon (0.1-0.4 ppm) is very low in STOCS waters (Mauer and Parker, 1972). That this indeed occurred is demonstrated by the fact that *Alternaria* spores are as abundant in the air over Texas as those of *Penicillium* and *Aspergillus*, yet *Alternaria* and other large spored fungi are infrequently encountered in

STOCS sediments (Table 10.2). Jannash (1970) has shown that threshold concentrations of carbon sources limit bacterial activation in seawater. A similar phenomenon would be expected with small spored "nutrient incompetent" fungi. The low concentrations of these compounds found in the study area are below the germination threshold values of the predominate genera *Penicillium* and *Aspergillus, e.g.* > 6 ppm for *A. fumigatus* (Ko and Lockwood, 1967) thus permitting them to remain inactive until they reach the organic carbon rich sediments.

Organic carbon apparently continues to control fungal diversity in the sediment. This is suggested by the fact that the generic richness of fall samples was associated with total organic carbon content of the sediment as shown by the high rank correlation coefficient ($r = 0.843$).

The abundance of benthic fungi in the fall samples also was positively correlated with the percent total organic carbon in the sediment ($y = 75 + 2.042 \ln x$; $r = 0.829$; df 4; P 0.05)(Figure 10.4). A threshold effect is evident with abundance becoming a log function of percent total organic carbon above a concentration of about 0.80%. Experimental proof that the availability of organic carbon limited fungal growth in fall sediments is presented in Figure 10.2. The addition of carbon in the form of crude oil increased the population of fungi over that of the control. The dependence of fungal abundance on organic carbon concentrations is evidence that the fungi are physiologically active in marine sediments, a fact even recently disputed (Hughes, 1975).

No significant correlation was found between fungal numbers and total organic carbon (TOC) in the winter ($r = -0.563$, df 4) or spring ($r = 0.187$, df 4) (Table 10.6). The rather large negative correlation in the winter sample does, however, imply fungal mineralization of these compounds during

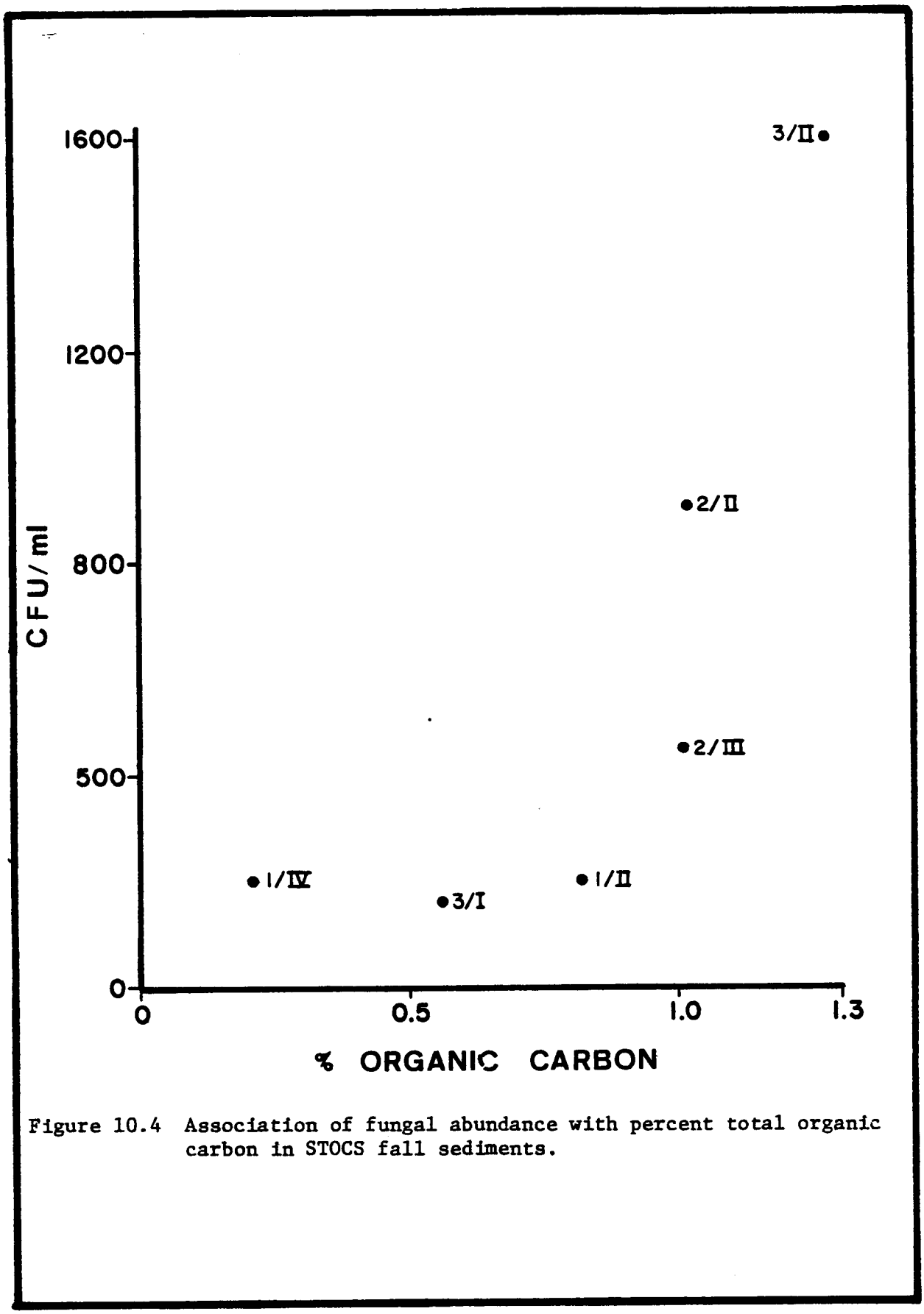

Figure 10.4 Association of fungal abundance with percent total organic carbon in STOCS fall sediments.

TABLE 10.6

AVERAGE PERCENT TOTAL ORGANIC CARBON IN STOCS 1977 SEDIMENT SAMPLES BY AREA AND SEASON (after Parker *et al* 1979)

Transect/ Zone	Season		
	Winter	Spring	Fall
I - Offshore	1.02	1.04	0.56
II-Nearshore	0.70	0.93	0.82
II-Mid-shelf	0.88	0.89	1.02
II-Offshore	1.12	1.13	1.28
III-Mid-shelf	1.02	0.97	1.01
IV-Nearshore	0.73	0.28	0.21

the winter months. Further evidence for fungal mineralization of sediment organic carbon during the summer is seen in the very high rank correlation coefficient (r = 0.828) between abundance of fungi in spring samples and decrease in TOC between the spring and fall sampling periods. The abundance of fungi present at a site during the summer therefore determines, to a degree, the number of fungi that can establish themselves at that site in the fall as shown by the high rank correlation coefficient (r = 0.810) between the inverse station rankings by abundance for the two seasons. In summary, the number of colony forming units present in the fall samples is directly correlated with the TOC concentration which is, in turn, determined by the fungal population at each site earlier in the year.

Although fungi are obviously active for a time in marine sediments, they appear to be short-lived, probably because of autolysis upon exhaustion of available organic carbon and the failure to form resistant resting structures, *e.g.* spores. It is well known among mycologists that spores are seldom formed in submerged culture (Burnett, 1968). There are two pieces of evidence that indicate a short life span. One is the fact that a sharp fall maximum in fungal populations (587 CFU/ml) is followed by a winter minimum (29/CFU/ml). These data are not, of course, from sequential fall and winter seasons. Other evidence comes from comparing abundances at each site in spring and fall. If fungal populations were long lived, high numbers of fungi in spring should have an additive effect on fall abundance at the same site since fungi are non motile and our methods would have detected both active and resting structures. The relationship is, however, inverse as documented above. The most outstanding case is found at Station 3/I where there was a decrease from 350 to 160 CFU/ml during the summer.

Geographical Distribution of Fungal Oil-Degradation Potential

The potential for oil degradation by fungi decreases with distance from shore. The trend is associated with decreasing coarseness of sediment and possibly with the greater capacity of inshore fungi to assimilate crude oil. Tables 10.7 through 10.9 contain the results of regression and correlation analyses relating the oil degradation indices and sediment texture variables. These results show that degradation was negatively correlated with fine texture indicators, *e.g.* percent clay, and positively correlated with coarse texture indicators, *e.g.* percent sand and Sand/Mud ratio. This relationship is most convincingly illustrated by the negative correlation of pristane/n-C_{17} ratio with phi, the negative log of mean particle size ($r = -0.680$, df 16)(Figure 10.5). Even when the extreme high and low values are deleted the correlation is still significant ($r = -0.498$, df 14, $P < 0.05$). Enhanced degradation activity in coarser sediments may result from growth stimulation by attachment of the microorganisms to particle surfaces (Rheinheimer, 1974; Marshall, 1976).

Caution should be used in interpreting these results, however, since they are dominated by the degradation in the fall sample from Station 1/IV in which the degradation indicator ratios are several times greater than in the next most active samples (Table 10.4). For example, the phytane/n-C_{18} ratio showed a significant correlation coefficient of 0.631 with percent sand, but an examination of the scatter plot indicated little if any association when the extreme degradation value is disregarded (Figure 10.6). It should be noted that the highest value for percent sand occurred at Station 1/IV in the spring rather than fall. The distortion was even more pronounced in the six data points from the 0.1% oil treatment of the fall sediment samples, where, for example, the correlation coefficient for

TABLE 10.7

REGRESSION ANALYSIS SIGNIFICANCE LEVELS (P) OF MYCOLOGICAL VARIABLES ON PHYSICAL, CHEMICAL AND OTHER BIOLOGICAL VARIABLES USING 1977 STOCS SEDIMENT AND BOTTOM WATER DATA FIT TO FOURTH ORDER POLYNOMIALS

Independent Variable	MYCOLOGICAL VARIABLE				
	Total Counts	Degrader Counts	Pristane/ n-C_{17}*	Phytane/ n-C_{18}*	n-C_{16-32}/ Pr + Ph*
Bottom depth	0.88	0.98	0.67	0.67	0.97
Temperature**	0.91	0.54	0.87	0.34	0.46
Salinity	0.76	0.88	0.99	0.99	0.73
Silicate	0.82	0.66	0.00	0.00	0.28
Phosphate	0.98	0.85	0.96	0.82	0.98
Nitrate	0.50	0.80	0.86	0.94	0.98
Dissolved Oxygen	0.50	0.20	0.99	0.98	0.77
Alkanes	0.73	0.79	1.00	0.75	0.99
Pr/C17	0.64	0.65	1.00	0.87	0.90
Pr/C18	0.91	0.83	0.86	0.28	0.17
Pr+Ph/n-alkanes	0.14	0.28	0.55	0.99	0.81
OEP (C14-20)	0.97	0.97	0.85	0.97	1.00
OEP (C20-32)	0.98	0.98	0.92	0.31	0.77
Ba	0.67	0.45	0.85	0.92	0.69
Cd	0.36	0.21	0.92	0.91	0.97
Cr	0.91	0.86	0.48	0.36	0.80
Cu	0.86	0.95	0.14	0.19	0.57
Fe	0.96	0.98	0.26	0.19	0.37
Mn	0.94	0.92	0.05	0.01	0.56
Ni	0.14	0.11	0.21	0.35	0.53
Pb	0.36	0.16	0.18	0.43	0.81
V	0.81	0.55	0.87	0.60	0.75
Zn	0.94	0.93	0.47	0.24	0.65
Grain Size	0.88	0.91	0.04	0.10	0.72
Skew Grain Size	0.65	0.61	0.00	0.00	0.41
% Sand	0.75	0.74	0.04	0.01	0.84
% Silt	0.91	0.90	0.00	0.00	0.55
% Clay	0.90	0.93	0.05	0.18	0.60
Sand/Mud	0.78	0.69	0.00	0.00	0.82
Organic Carbon	0.56	0.92	0.00	0.00	0.56

*0.5% oil treatment

**Temp., salinity, silicate, phosphate, nitrate and dissolved oxygen from bottom water; all others from sediment.

TABLE 10.8

CORRELATION COEFFICIENTS (r) AND R^2* VALUES FOR STATISTICALLY SIGNIFICANT (P 0.05) RELATIONSHIPS BETWEEN FUNGAL OIL DEGRADATION INDICIES (0.5% OIL) AND PHYSICAL, CHEMICAL AND BIOLOGICAL VARIABLES

Independent Variables	Mycological Variable			
	Pristane/n-C_{17}		Phytane/n-C_{18}	
	r	R^2	r	R^2
Silicate	+0.471	0.84	+0.580	0.94
Mn	-0.549	0.62	-0.613	0.74
Grand Size (phi)	-0.680	0.51	N.S.	0.43
Skewness Grain Size	+0.629	0.85	+0.530	0.90
% Sand	+0.682	0.52	+0.631	0.63
% Silt	-0.397	0.78	-0.421	0.87
% Clay	-0.622	0.49	N.S.	0.36
Sand/Mud	+0.694	0.70	+0.645	0.73
Organic Carbon	-0.500	0.77	-0.522	0.83
Bacteria Oil Degraders	+0.657	0.78	+0.746	0.91
% Degraders	+0.716	0.86	+0.820	0.92
% Bacteria Degradation	+0.207	0.73	+0.259	0.90

*R^2 based on fit to fourth order polynomials

TABLE 10.9

SIGNIFICANCE LEVELS (P) FOR REGRESSION ANALYSES BASED ON FIT TO FOURTH ORDER POLYNOMIALS FOR FUNGAL OIL DEGRADATION RATIOS (0.1% oil) *vs.* SELECTED PHYSICAL AND CHEMICAL VARIABLES FROM FALL SEDIMENT SAMPLES

Independent Variables	Sign	Degradation Ratio		
		Pristane/n-C_{17}	Phytane/n-C_{18}	n-C_{16-32}/Pr+Ph
Silicate	+	0.04	0.12	0.71
Fe	-	0.03	0.06	0.38
Mn	-	0.03	0.07	0.37
Ni	-	0.05	0.11	0.63
Pb	-	0.05	0.13	0.67
Zn	-	0.04	0.09	0.49
Grand Size (phi)	-	0.05	0.06	0.27
Skewness of Grain Size	+	0.01	0.02	0.07
% Sand	+	0.04	0.12	0.67
% Clay	-	0.04	0.09	0.26
Sand/Mud	+	0.04	0.12	0.67

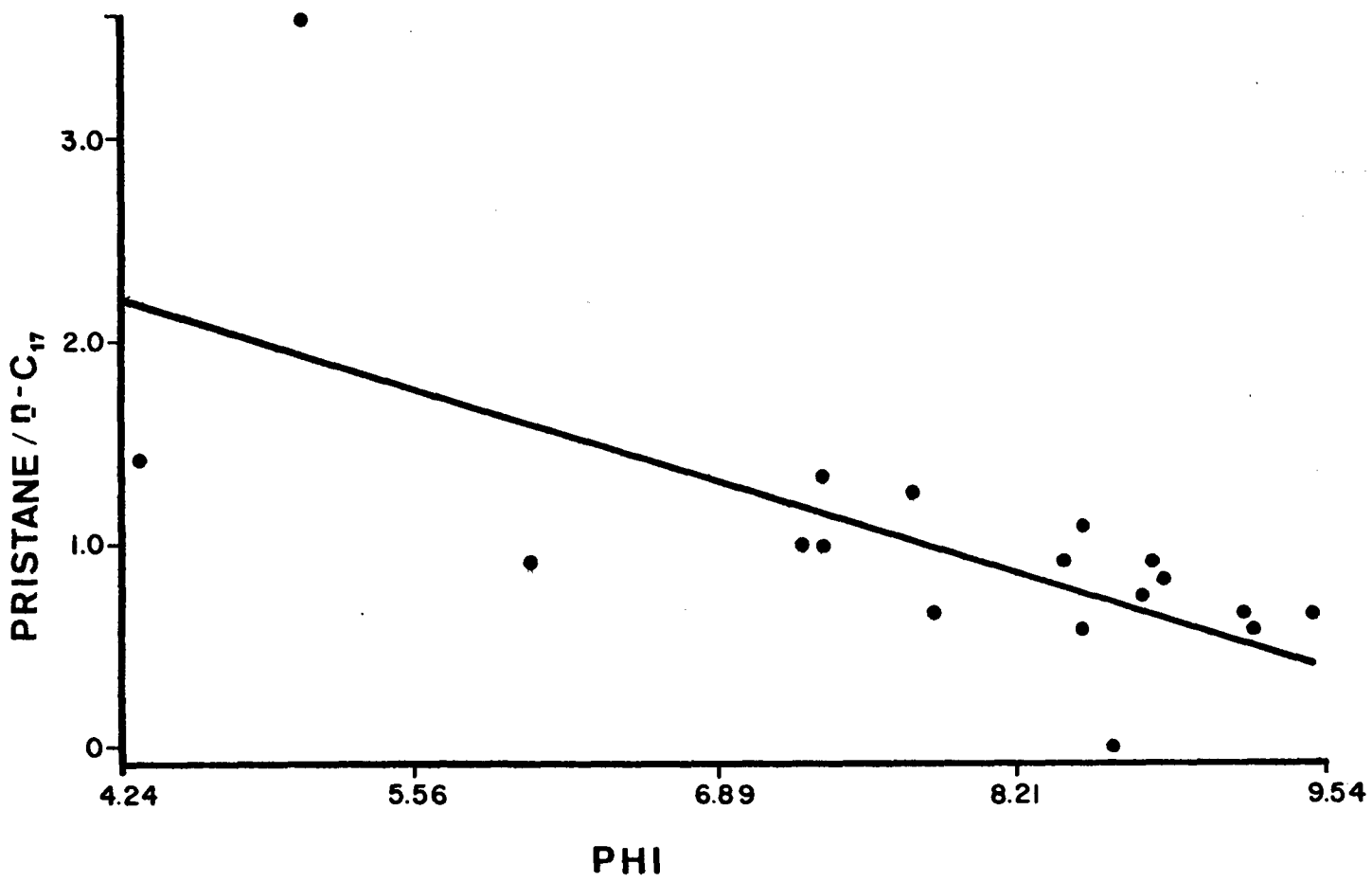

Figure 10.5. Association fungal degradation of 0.5% crude oil (pristane/$\underline{n}$-C_{17}) with phi (-log mean grain size) in STOCS sediment samples.

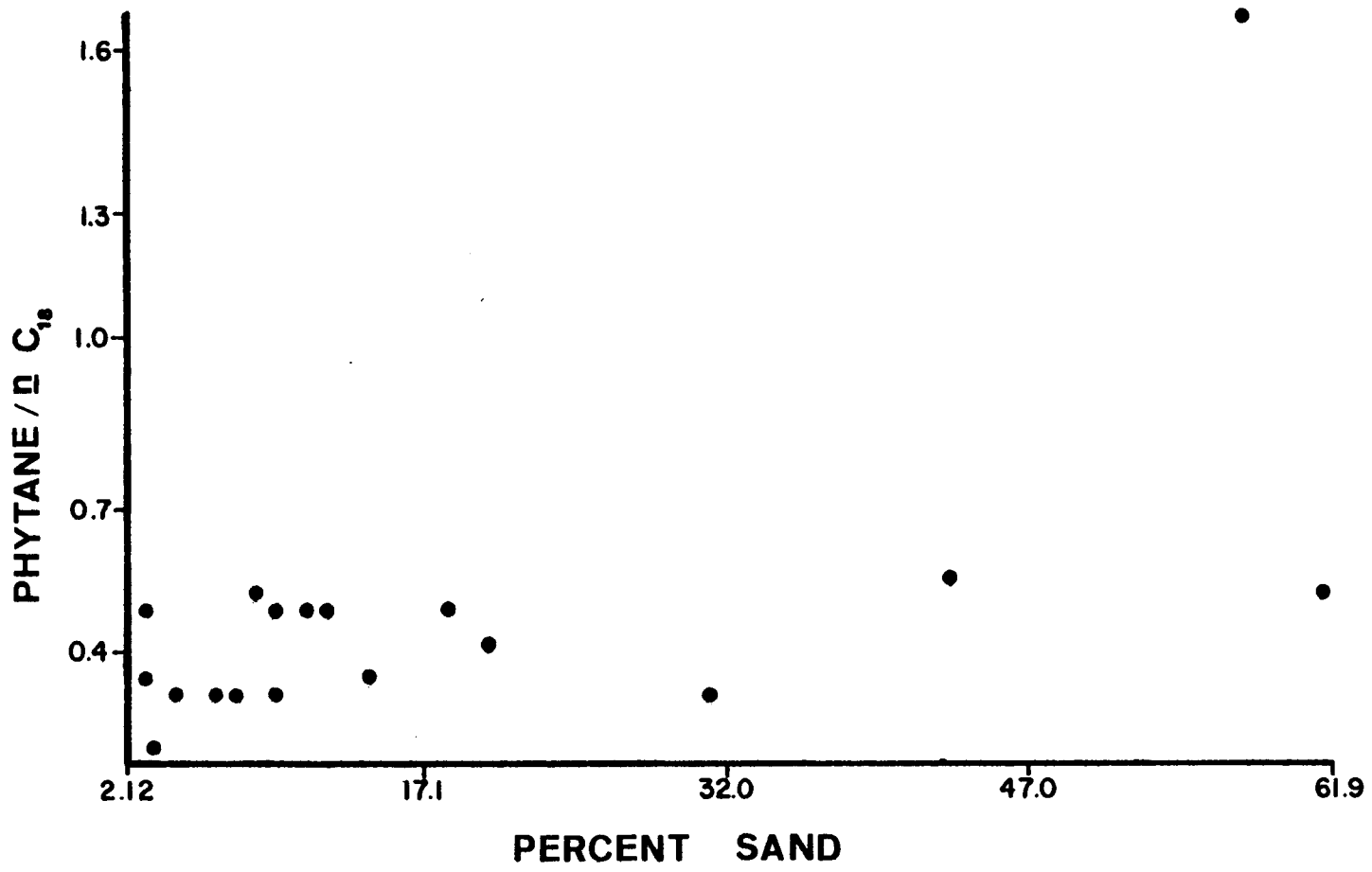

Figure 10.6 Association of fungal degradation of 0.5% crude oil (phytane/n-C_{18}) with percent sand in STOCS sediment samples.

pristane/n-C_{17} ratio and skewness of grain size was 0.862 and statistically significant at the 0.01 level (Figure 10.7). In summary, coarse sediment texture appears to be a necessary, but not sufficient condition for significant fungal oil degradation potential.

The inverse correlation between oil degradation and some trace metals *i.e.* Fe, Ni, Pb, and Mn (Tables 10.4, 10.7, and 10.8 and Figure 10.8) was due largely to the coincidence of extreme values at the delta station and the fact that these trace metals tended to be associated with sediments of high clay content (Table 10.10). The maximum concentrations of statistically important sediment trace metals corresponding to STOCS mycology samples (*e.g.* Ni 25, Pb 20, Mn 410 ppb) were well below the ED_{50} for spore germination of the typical imperfect fungi *Alternaria tenuis* (63.8, 2.3, and 1040 ppm, respectively) and *Botrytis fabae* (1.0, 4.6, and 1155 ppm, respectively)(Ross, 1975). Degradation potential was also inversely correlated with total organic carbon. Since TOC was also associated with sediment clay (Table 10.10) and its minimum concentration was at Station 1/IV, the site of maximum oil degradation, its relationship to crude oil degradation was probably incidental. A direct correlation, if any, would have been expected because of the enhancement of microbial hydrocarbon degradation by cooxidation of other substrates (Turner and Ahearn, 1970).

The only other variable to show a statistically significant association with the degradation ratios was bottom water silicate concentration (Figure 10.9), the extreme high value of which coincided with the highest degradation potential. Unlike the other variables with extreme values at Station 1/IV silicate was high only in the fall at that station and had very low values at the same site during the winter and spring of 1977. Since the silicate readings would have included suspended particles, the

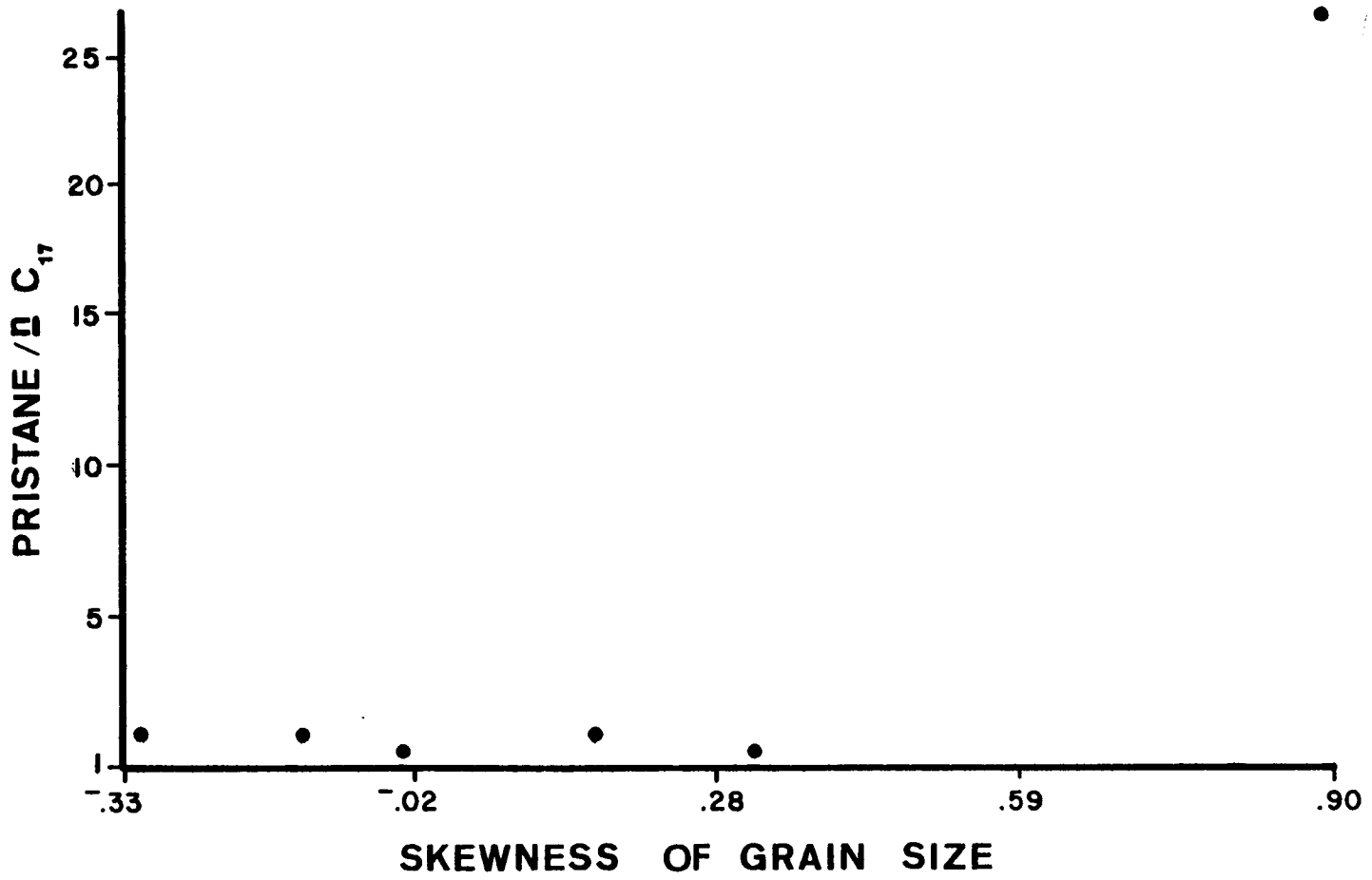

Figure 10.7 Association of fungal degradation of 0.1% crude oil (pristane/n-C_{17}) with skewness of grain size in STOCS fall sediment samples.

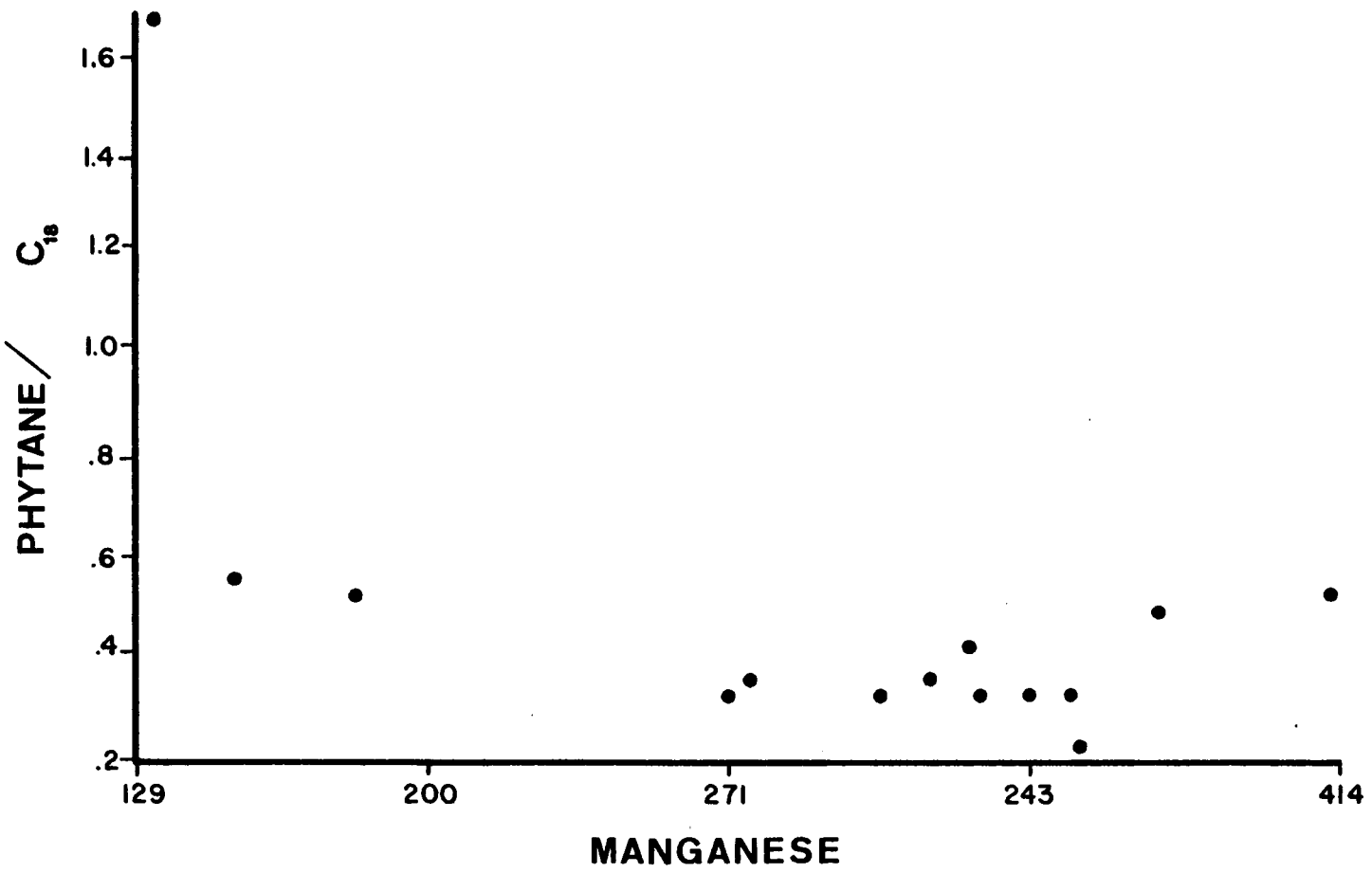

Figure 10.8 Association of fungal degradation of 0.5% crude oil (phytane/n-C_{18}) with manganese concentrations in STOCS sediment samples.

TABLE 10.10

CORRELATIONS AMONG PHYSICAL AND CHEMICAL PARAMETERS ASSOCIATED WITH OIL DEGRADATION BY FUNGI*

	Mean Grain Size (phi)	Skewness of Grain Size	% Clay	% Sand
Silicate	-0.069	+0.115	-0.112	+0.046
Fe	+0.639	-0.517	+0.608	-0.630
Mn	+0.530	-0.450	+0.520	-0.500
Ni	+0.651	-0.549	+0.611	-0.670
Pb	+0.576	-0.556	+0.563	-0.604
Mean Grain Size (phi)		-0.942	+0.976	-0.968
Skewness of Grain Size	-0.942		-0.971	+0.879
% Clay	+0.976	-0.971		-0.907
% Sand	-0.968	0.879	-0.907	
% Silt	+0.600	-0.419	+0.436	-0.774
Sand/Mud	-0.933	+0.869	-0.859	+0.970
Total Organic Carbon	0.528	-0.464	+0.528	-0.497

*All correlations significant at better than 1% except for silicate. Df=27 for metals and 34 for all other variables

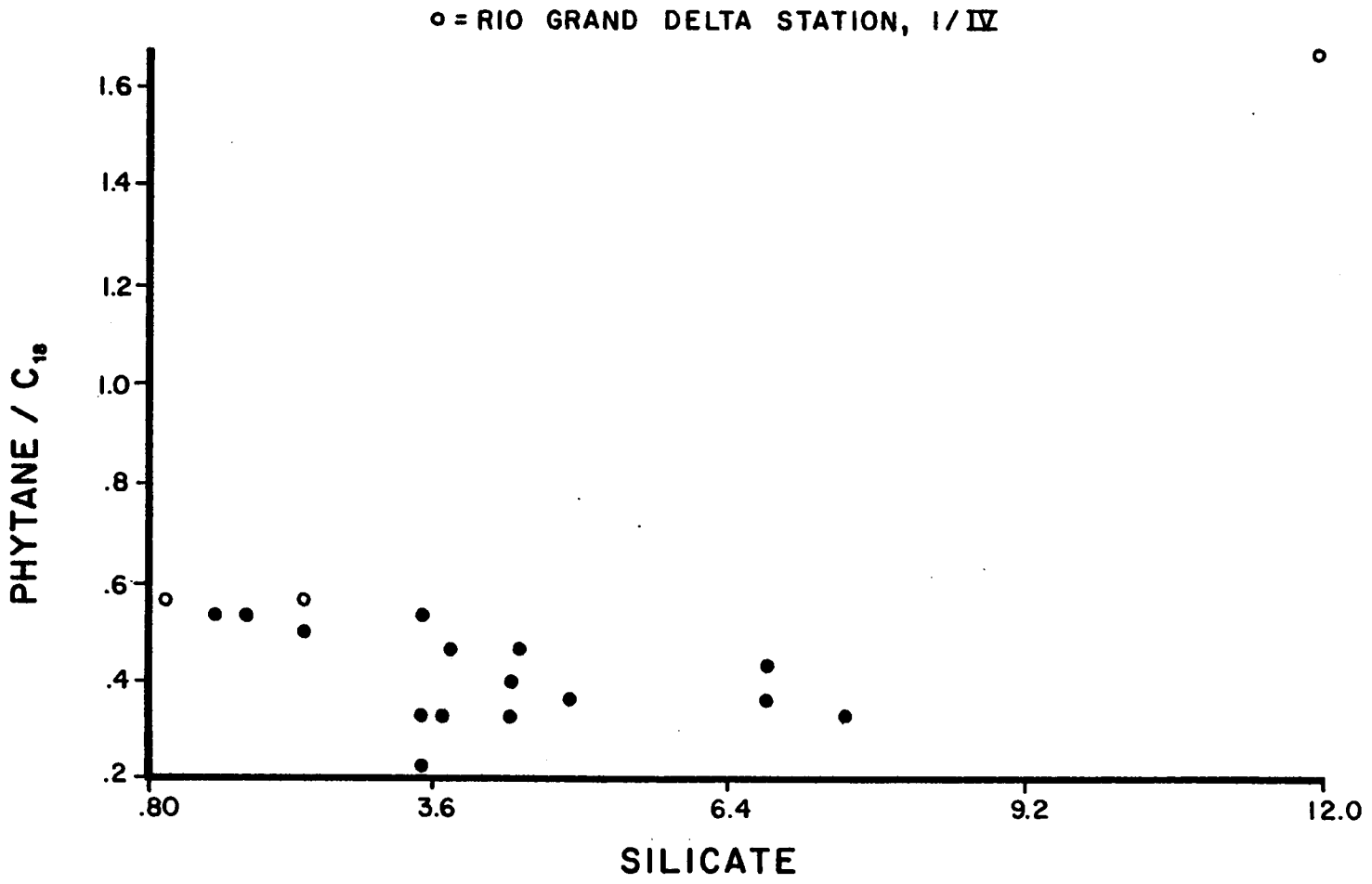

Figure 10.9 Association of fungal degradation of 0.5% CRUDE OIL (phytane/n-C_{18}) with bottom water silicate concentration.

unusually high reading might indicate that Rio Grande discharge water was active at that site only in the fall. A surge in discharge from the Rio Grande occurred in September of 1977 and was accompanied by a significant increase in nitrate concentration (USGS, Water Resources Data for Texas, Water Year 1977, vol. 3). At Brownsville on August 16 total nitrate was at 0.02 mg/ℓ, but increased to 0.08 mg/ℓ on September 13 and the algal population in the September sample was more than double the August count, again suggesting nutrient rich waters. The STOCS fall water column samples were collected in early September (6-12) and would not have detected the higher nutrient levels likely to have been present at the delta station, 1/IV, when the fall mycology sample was collected in mid-October. This might explain the low correlation between the degradation indices and nitrate and phosphate in our study.

Sediment factors limiting the degradation of oil by fungi may also have limited degradation in samples in which bacteria were present, as shown by the significant regression of mycological degradation ratios on mean percent degradation in bacteriological samples (Table 10.11). The amount of degradation in both cases may have been related, in part, to pre-existing factors that favored the development of hydrocarbonoclastic populations. This was suggested by the statistically significant association between counts of hydrocarbonoclastic fungi and mean percent degradation in bacterial samples and the association between proportion of oil-degrading bacteria and oil degradation by fungi. The statistical significance of these comparisons is, however, heavily dependent on the extremely high degradation values in the fall sample from the Rio Grande delta station.

Mycological variables failed to exhibit statistically significant relationships with a number of other physical, chemical and biological

TABLE 10.11

P VALUES FOR ASSOCIATIONS BETWEEN FUNGAL AND BACTERIAL OIL DEGRADATION VARIABLES BASED ON FIT TO FOURTH ORDER POLYNOMIALS*

Bacterial Variable	FUNGAL VARIABLE					
	Oil Degrader Count	Degrader/ Total	0.1% Oil		0.5% Oil	
			Pr/C_{17}	Ph/C_{18}	Pr/C_{17}	Ph/C_{18}
Proportion of Oil Degraders	0.12	0.86	0.00	0.00	0.03	0.06
Mean % Degradation	0.03	0.06	0.00	0.00	0.07	0.14
Oil Degrader Count	0.52	0.89	0.00	0.00	0.02	0.06

*All correlations positive.

variables, among them water depth, concentrations of nitrate, phosphate, and dissolved oxygen, as well as salinity and temperature. Also, associations with sediment concentrations of hydrocarbons and the metals Ba, Cd, Cr, Cu, V were not significant (Table 10.7). Among the biological variables investigated, but showing little correlation with fungal variables, were population densities and diversity indices of nematodes and harpacticoids.

CONCLUSIONS

Most filamentous fungi found in STOCS sediments in 1977 were common terrestrial imperfect fungi whose airborne spores were deposited in the water column during the late winter and spring months. The small "nutrient incompetent" spores of some species may have been suspended at the thermocline/pycnocline throughout the summer and deposited on the bottom in the fall.

The abundance of fungi in the fall sediment was directly correlated with total organic carbon at each site indicating that the fungi were physiologically active in the sediment. Indirect evidence suggested that fungal mineralization of organic carbon during winter, spring and summer controlled the abundance of fungi at each site in the fall. Fungi appeared to be short lived in STOCS sediment where available carbon became limiting. Over half of the benthic fungi tested were able to assimilate South Louisiana crude oil to overcome carbon limitation.

Crude oil degradation potential was greater in samples from inshore stations than in those from offshore stations and was associated with sediment texture parameters. Coarse surficial sediment appeared to be a necessary condition that was not sufficient along for significant oil degradation. The greatest oil degradation potential may have been

associated with nutrient rich river discharge. Although South Louisiana crude oil was initially toxic to fungi, growth was stimulated after two to three weeks.

Since organic carbon and not nitrogen or phosphorous limited fungal abundance in the STOCS ecosystem, it is reasonable to presume that at least some fungal oxidation of intruxive petroleum would occur anywhere in the area. Greater activity would, however, be expected inshore in coarse sediments subject to high nutrient freshwater outwash.

RECOMMENDATIONS

1. No special precautions are required to protect the STOCS fungal flora (as isolated and identified by the techniques employed) from petroleum development and production activities since it is composed almost entirely of terrestrial fungi and is replenished annually.

2. Determination of the proportion of fungal oil degraders by comparison of colony counts on oil-containing medium and on nonselective medium should be discontinued or modified since values greater than one have been obtained in this and other reported studies.

3. Ths sinking of oil slicks with sand after the application of lipophilic nitrogen and phosphorous fertilizers should be considered as a clean-up method since fungi in STOCS sediment samples were stimulated by SLCO and degradation potential was associated with coarse sediment texture.

4. Biological effects of heavy metals from offshore drilling activities could be easily detected by monitoring the development of resistant strains of fungi since, according to the literature, such strains arise very frequently and the "biological concentration factor" for most metals is much higher in fungi than in other organisms.

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CHAPTER ELEVEN

ANALYSIS OF BENTHIC BACTERIA

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ABSTRACT

An analysis of results from a one-year study on the benthic bacteria of the South Texas outer continental shelf (STOCS) was made. Aerobic heterotrophic bacteria or sediment exhibited significant spatial and seasonal variations. Bacteria were most numerous at nearshore stations, decreasing with increasing depth. This decrease is likely associated with a decrease in organic carbon quality (increase in refractory components) and temperature with depth. Bacteria were most abundant in the spring, corresponding to an expected seasonal high in the input of organic carbon to the sediments and increasing sediment temperatures.

The flow of energy in the benthos appears to be: organic carbon → bacteria → benthic animals. The constant ratio of benthic animals to bacteria, and not organic carbon, supports this proposed flow.

Hydrocarbon degrading bacteria are an indigenous component of the benthic bacterial population throughout the year. These populations exhibit significant spatial (highest nearshore) and seasonal (highest in the fall) variations. Their abundance is highly correlated with total alkanes in the sediment. Therefore, their distribution patterns may be due to seasonal and spatial variations in hydrocarbon input to the sediments.

The distribution of hydrocarbon biodegradation potential could not be fully assessed. Since biodegradation potentials are related to the abundance of hydrocarbon degrading bacteria and temperature more than other environmental parameters, variations in these will likely determine the distribution of oil biodegradation potentials.

Effects of oil studies *in vitro* indicate that oil increases the proportion of hydrocarbon degrading bacteria in the total population. Additional studies are required to fully assess the effect of this oil-induced change on nutrient cycling in the marine environment.

INTRODUCTION

Development of oil resources on the south Texas outer continental shelf (STOCS) is planned in the near future. An important aspect of environmental assessment prior to oil development in this region is the determination of the distribution and activity of bacteria, especially hydrocarbon degrading bacteria. Microbial surveys have preceded oil development in other offshore areas (Gunkel, 1973; Oppenheimer, 1978; Roubel and Atlas, 1978). Of equal importance in assessment is the determination of the effects of oil on bacteria, since these populations are important in nutrient cycling in the marine environment.

This report represents an analysis of results from a one-year study on the benthic bacteria of the STOCS. The report emphasizes: 1) the spatial and seasonal distribution of benthic bacteria and hydrocarbon biodegradation potential; 2) relationships between bacteria and environmental parameters; and 3) the effects of oil on benthic bacteria.

MATERIALS AND METHODS

Collection and On-Board Processing of Sediment

Sediment was collected with a Smith-McIntyre grab at Stations 1, 2 and 3 on four transects (Figure 11.1) during winter, spring and fall 1977 (4-8 March, 13-15 June, and 15-18 October, respectively). A mercury thermometer was inserted into the grab sample immediately after retrieval to record sediment temperature. The top one centimeter of sediment was then removed with a spatula and placed in a sterile 150 ml beaker. After mixing, 10 ml subsamples were removed from the beaker for bacteriological analyses.

Processing of sediment was initiated immediately after collection to minimize alteration of bacterial numbers (Zobell, 1946). Procedures

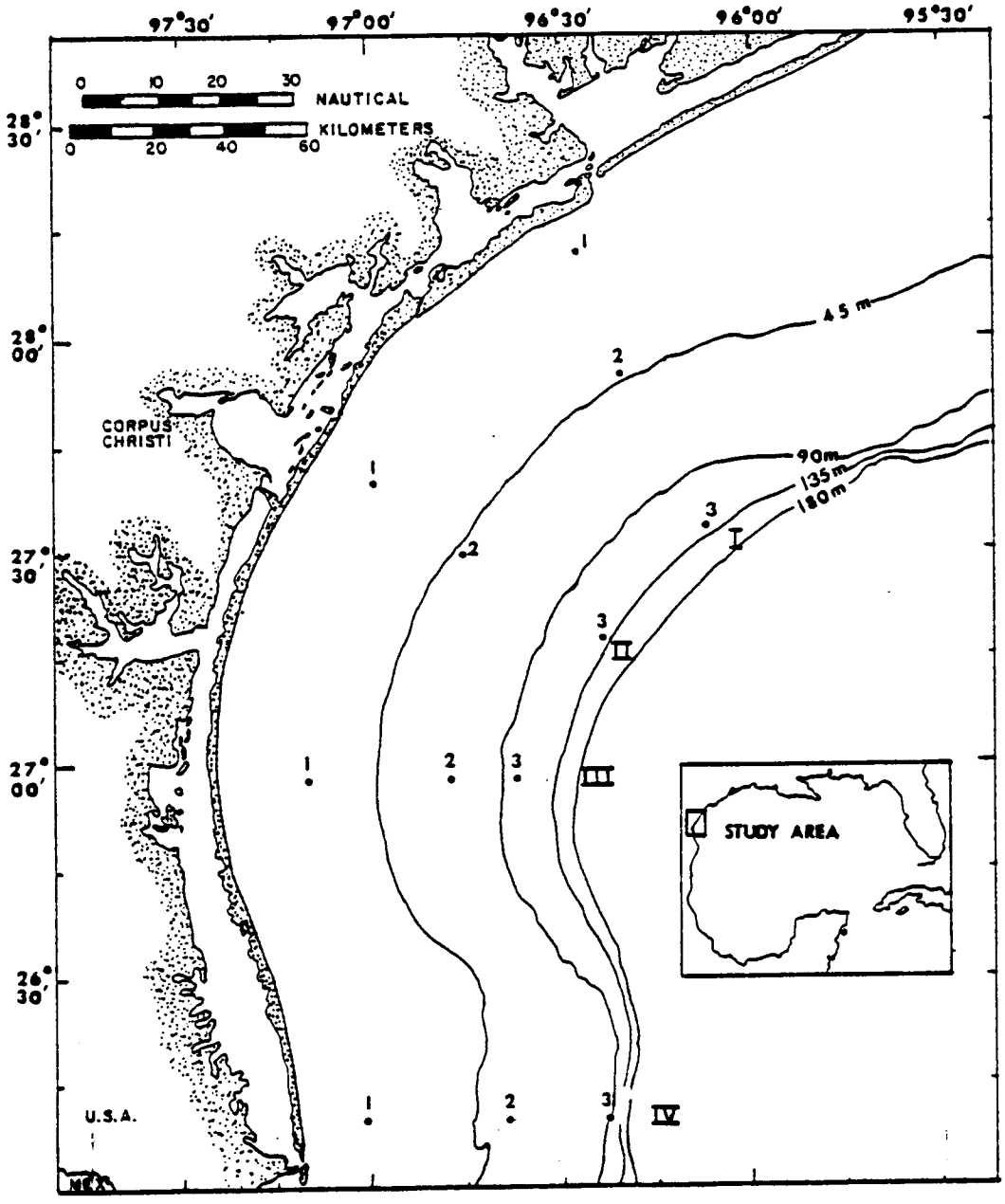

Figure 11.1 Location of Sampling Stations on the South Texas Outer Continental Shelf.

included: 1) inoculation of plates and tubes with dilutions for subsequent enumeration of total aerobic heterotrophic and hydrocarbon degrading bacteria; 2) inoculation of flasks for oil biodegradation studies; and 3) inoculation of flasks for oil effects studies. All inoculated plates, tubes, and flasks were secured for subsequent transfer to the laboratory.

Contamination of the culture medium during on-board processing and subsequent transfer was monitored. The number of bacteria arising on uninoculated marine agar plates was less than 10% of the number arising on inoculated plates at 95% of the stations occupied during the study.

Enumeration of Sediment Bacteria

Total Aerobic Heterotrophic Bacteria

Duplicate 10 ml subsamples were diluted in 90 ml artificial seawater (INSTANT OCEAN) and mixed by swirling for one minute. The resulting suspension (1 ml) was serially diluted in 9 ml artificial seawater and three dilutions plated in triplicate on Marine Agar 2216 (DIFCO). Bacterial colonies were enumerated with a Quebec Colony Counter after 10 days incubation at the seasonal mean *in situ* temperature (Table 11.1).

Hydrocarbon Degrading Bacteria

Two methods were evaluated for enumeration of hydrocarbon degrading bacteria. One method employed silica gel-oil medium (Seki, 1973), while the other method employed basal-oil medium and the most probable number (MPN) technique (Gunkel, 1973). The former method proved unsatisfactory, because it was difficult to distinguish the small bacterial colonies from sediment particles at low sediment dilutions. The latter technique proved satisfactory. Heavy growth occurred in the basal-oil medium in addition to visible oil degradation. Control tubes without added oil consistently exhibited negligible growth when inoculated with sediment dilutions.

TABLE 11.1

RANGE OF DEPTH (m) AND SEDIMENT TEMPERATURES (°C)
AT SAMPLING STATIONS DURING 1977

Station (All Transects)	Depth	Season		
		Winter	Spring	Fall
1	18-27	17-20	24-26	25-26
2	42-65	18-19	23-24	25-27
3	91-134	17-19	21-23	22-23
	MEAN	18.4	23.6	24.7

Therefore, the MPN technique was adopted for enumeration of hydrocarbon degrading bacteria in this study.

Duplicate 10 ml subsamples were each serially diluted in artificial seawater (as before) and 1 ml of four sediment dilutions placed into tubes containing 10 ml artificial seawater and 0.05 ml autoclaved south Louisiana crude oil. The artificial seawater was supplemented with 1 g NH_4NO_3 and 1 g KH_2PO_4 per liter. The pH of the medium was adjusted to 7.6 by the addition of 1N NaOH. After inoculation, tubes were incubated stationary for 30 days at the seasonal mean *in situ* temperature. Positive tubes were determined by visual observation of growth.

Oil Biodegradation Potential of Benthic Bacteria

Duplicate 10 ml subsamples were each added to 90 ml basal-oil medium. The basal medium consisted of INSTANT OCEAN supplemented with *in situ* concentrations of nitrogen and phosphorus. Nitrogen concentrations added ranged from 0.01 to 1.2 mg NH_4NO_3 per liter, while phosphorus ranged from 0.003 to 0.1 mg KH_2PO_4 per liter (Sackett and Brooks, 1976). The oil used was south Louisiana crude oil from the Gulf of Mexico. Gas chromatographic analysis revealed the presence of C_9 to C_{32} n-alkanes, which comprised 11% of the oil.

The concentration of oil used in biodegradation studies varied from season to season. For winter samples, 0.5% volume/volume (v/v) oil was added. This concentration proved to be too high for this period, because biodegradation rates were extremely low. Based on these results, the concentration of oil added was reduced to 0.05% v/v in the fall. For the spring, 0.5% v/v oil was used, because winter results were not available at that time. The concentration of oil effects the biodegradation rate (Zobell, 1973). When oil concentrations are low, each hydrocarbon is more

likely to be degraded. However, when concentrations are high, preferential utilization of hydrocarbons may occur in addition to oil toxicity. For this reason, degradation rates of the fall (with 0.05% v/v oil) cannot be reliably compared to those of the winter and spring (with 0.5% v/v oil).

The composition of the oil also varied from season to season. Oil used in the winter was autoclaved. Subsequent gas chromatographic analyses revealed 16% of the C_{14} to C_{32} n-alkanes were lost during autoclaving, 87% of which were C_{14} to C_{20} hydrocarbons. For this reason, unautoclaved oil was used during the spring and fall. No bacterial growth occurred when unautoclaved oil was streaked onto marine agar. Benthic bacteria in the study area utilized all n-alkanes from C_{14} to C_{32}, but exhibited a preference for low molecular weight hydrocarbons, *i.e.* C_{14} to C_{20} (see Results). These n-alkanes were those significantly reduced during autoclaving. Low biodegradation rates observed in winter may have been partly due to significant removal of "preferred" n-alkanes during autoclaving. Since unautoclaved oil was used in the spring and fall, rates from these seasons cannot reliably be compared to those from winter.

The basal-oil medium inoculated with sediment (and uninoculated weathering controls) were incubated at the seasonal mean *in situ* temperature for eight weeks, and then frozen. The oil remaining after this period was extracted by rinsing the sediment (after filtration) with 30 ml methanol followed by three 20 ml portions of methylene chloride. The latter portions were used sequentially to extract the liquid. All extracts were combined and then concentrated to either 40 ml or 10 ml (for fall samples) prior to gas chromatographic analysis. Extracts were analyzed on either a Hewlett-Packard 5830A or Varian 3700 gas chromatograph equipped with dual flame ionization detectors and programmable integrators. These were equipped with 30 to 50 m OV - 101 or SE-30 WCOT glass capillary columns.

The injector temperature was 270°C and the detector was 280°C. The column oven was temperature-programmed from 70 to 270°C at a rate of 3° per minute. The mean percent biodegradation of C_{14} to C_{32} n-alkanes was determined by comparing the peak areas of hydrocarbons recovered from samples inoculated with sediment to those of hydrocarbons recovered from uninoculated weathering controls.

Effects of Oil on Benthic Bacteria

Four 10 ml subsamples were each diluted in 90 ml basal medium. The basal medium consisted of INSTANT OCEAN supplemented with *in situ* concentrations of nitrogen and phosphorus as previously listed for oil biodegradation studies. Two of the four samples received 0.5% v/v autoclaved south Louisiana crude oil. The remaining two samples received no oil and served as controls. Samples were incubated stationary for eight weeks at the seasonal mean *in situ* temperature. At four weekly periods during the eight weeks, total aerobic heterotrophic bacteria were enumerated as described previously.

The effects of oil on the number and percent hydrocarbon degrading bacteria were determined during the spring and fall. The experimental procedures used were identical to those above. At four or five periods during the eight weeks, the number of hydrocarbon degrading bacteria were enumerated as described previously.

Statistical Analysis

Analysis of variance was performed using the Statistical Package for the Social Sciences (SPSS) on the CDC 6600 computer (University of Texas, Austin). Samples were grouped according to station, transect, and season. A significance level of $P \leq 0.05$ was considered necessary to establish a significant difference. Correlation coefficients were

generated in an R/N matrix using the same package. A correlation coefficient of $\geq \pm .50$ ($n \geq 12$) significant at the .05 level was considered necessary to establish a significant relationship between two parameters. Descriptive plotting was employed to aid in interpretation of bivariate relationships.

RESULTS

Benthic Bacterial Populations

Aerobic heterotrophic bacteria ranged from 4.6×10^4 to 1.3×10^6/ml wet sediment. Analysis of variance indicated a significant ($P < 0.01$) seasonal difference in benthic bacterial populations with highest numbers during spring and lowest during winter (Table 11.2). There was no significant difference between transects. There was, however, a significant difference between stations, with highest populations at Station 1, decreasing with increasing station number, or increasing depth (Figure 11.2). Mean populations of benthic bacteria at Stations 1, 2 and 3 (all transects and seasons) were 7.9, 4.3, and 2.2×10^5/ml wet sediment, respectively. The variation by station accounted for 47% of the total variance in benthic bacteria. The only deviation from this distribution was on Transect IV, where Station 3 contained an unusually high number of bacteria during the spring and fall.

Hydrocarbon degrading bacteria were isolated from all 72 samples collected during the study. Populations ranged from 8.0×10^1 to 1.1×10^5/ml wet sediment and were significantly correlated with total alkanes of the sediment (Figure 11.3). Analysis of variance demonstrated a significant ($P < 0.01$) seasonal variation in the number of hydrocarbon degrading bacteria, with highest populations during fall and lowest during winter (Table 11.2). There was a significant ($P < 0.01$) difference

TABLE 11.2

SUMMARY OF BENTHIC BACTERIAL POPULATIONS OF THE SOUTH TEXAS OUTER CONTINENTAL SHELF DURING 1977

Type	Season	Number of Samples	Mean ± 1S.D.
Aerobic heterotrophic bacteria (number/ml wet sediment)	Winter	24	$40.2 \pm 28.0 \times 10^4$
	Spring	24	$55.4 \pm 41.6 \times 10^4$
	Fall	24	$47.8 \pm 31.2 \times 10^4$
Hydrocarbon degrading bacteria (number/ml wet sediment)	Winter	24	$2.7 \pm 3.8 \times 10^3$
	Spring	24	$3.1 \pm 5.1 \times 10^3$
	Fall	24	$23.5 \pm 35.8 \times 10^3$
Percent hydrocarbon degrading bacteria	Winter	24	0.6 ± 0.5
	Spring	24	0.5 ± 0.4
	Fall	24	4.8 ± 6.1

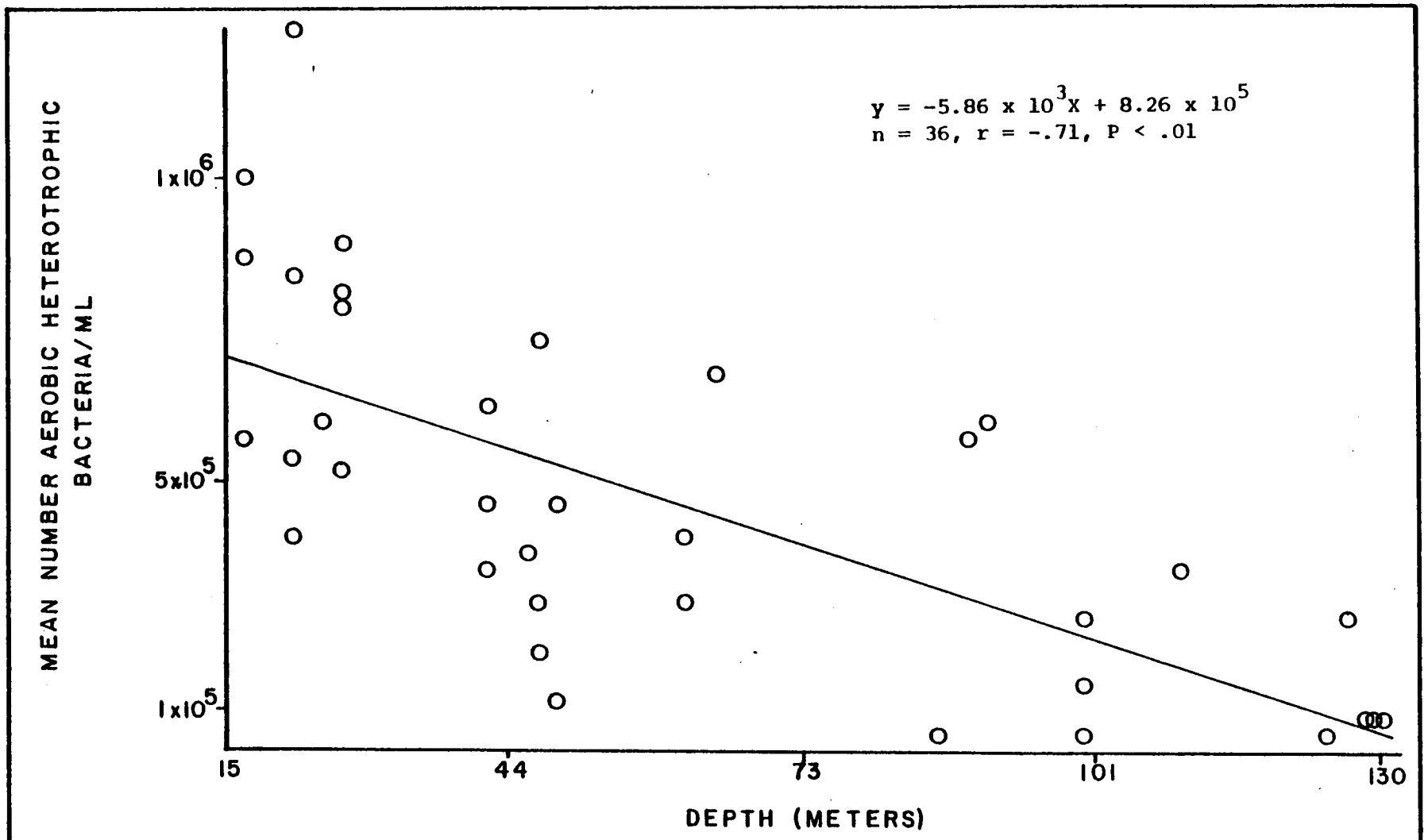

Figure 11.2 Relation Between Aerobic Heterotrophic Bacteria of Sediment and Bottom Depth.

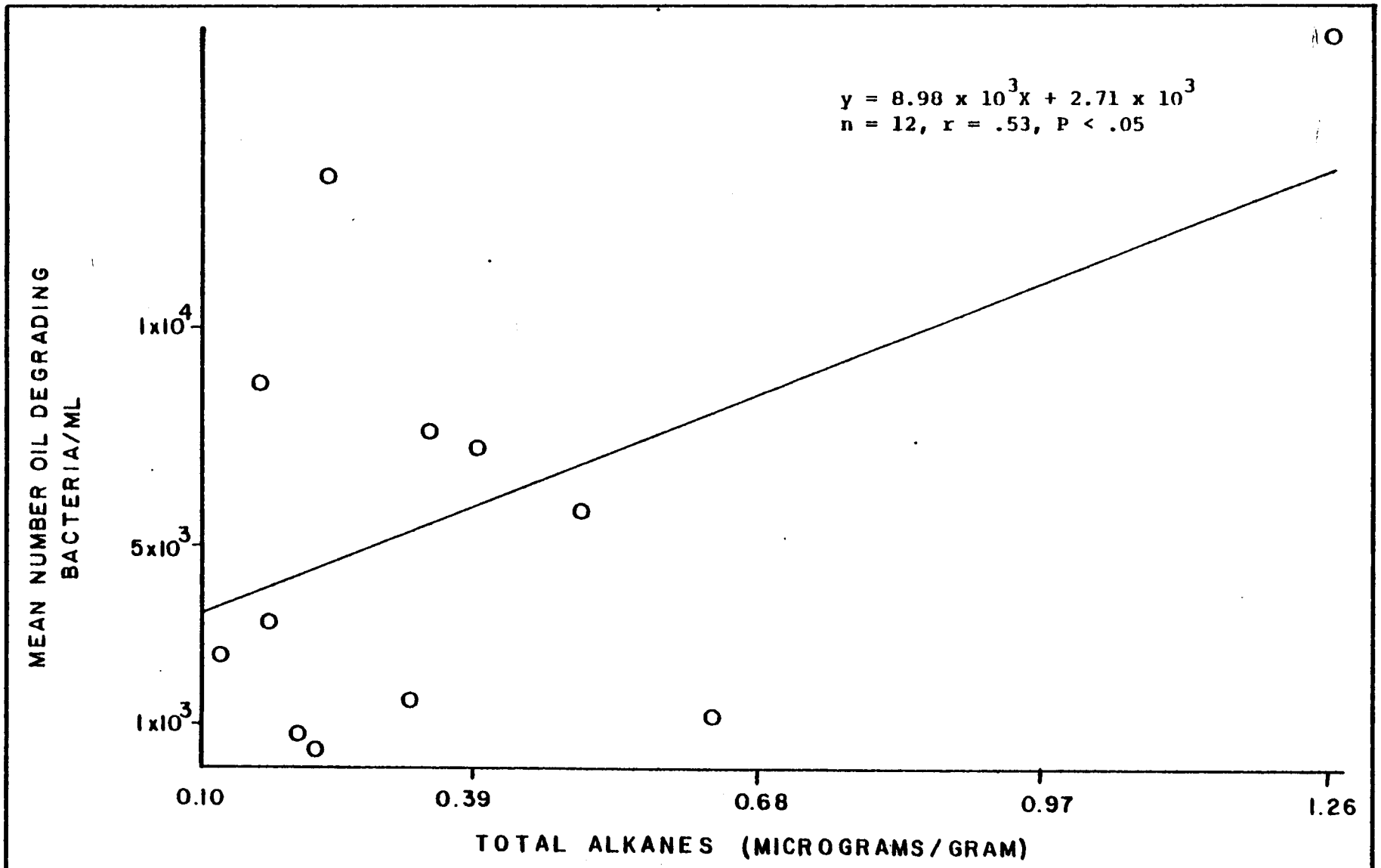

Figure 11.3 Relation Between Number of Oil Degrading Bacteria of Sediment and Total Alkanes.

between transects, with greatest concentrations on Transect I during winter and spring, and on Transect IV during fall. Hydrocarbon degrading bacteria were also significantly ($P < 0.01$) greater at Station 1, decreasing with increasing station number, or increasing depth. The mean number of hydrocarbon degrading bacteria at Stations 1, 2 and 3 (all transects and seasons) was 17.3, 9.3, and 2.6 x 10^3/ml wet sediment, respectively.

The percent hydrocarbon degrading bacteria ranged from 0.10 to 20.7% and was significantly correlated with total alkanes of the sediment (Figure 11.4). Analysis of variance demonstrated a significant ($P < 0.01$) seasonal variation in the percent hydrocarbon degrading bacteria, with highest percentages during fall and lowest during spring (Table 11.2). There was a significant ($P < 0.01$) difference between transects, with the highest percentages on Transect I during winter and spring, and on Transect IV during fall. There was no significant difference between stations.

The benthic bacterial populations of the study area are comparable to those of other offshore regions (Table 11.3).

Benthic Oil Biodegradation Potentials

Benthic bacteria are capable of degrading all n-alkanes from C_{14} to C_{32}, but exhibit a preference for low molecular weight hydrocarbons, *i.e.* C_{14} to C_{20} (Table 11.4). Biodegradation removed from 0.4 to 91.6% of these n-alkanes in oil added to sediment. There appeared to be a significant seasonal variation in oil biodegradation rates (Table 11.5). Variations may not be entirely seasonal, however, due to variations in composition and concentration of oil added. For this reason, seasonal comparisons of biodegradation rates are not valid and were not made.

Spatial variations in biodegradation of oil were examined for each season. No significant spatial variations occurred in the winter, probably due to consistently low rates of biodegradation (from 0 to 16.78%).

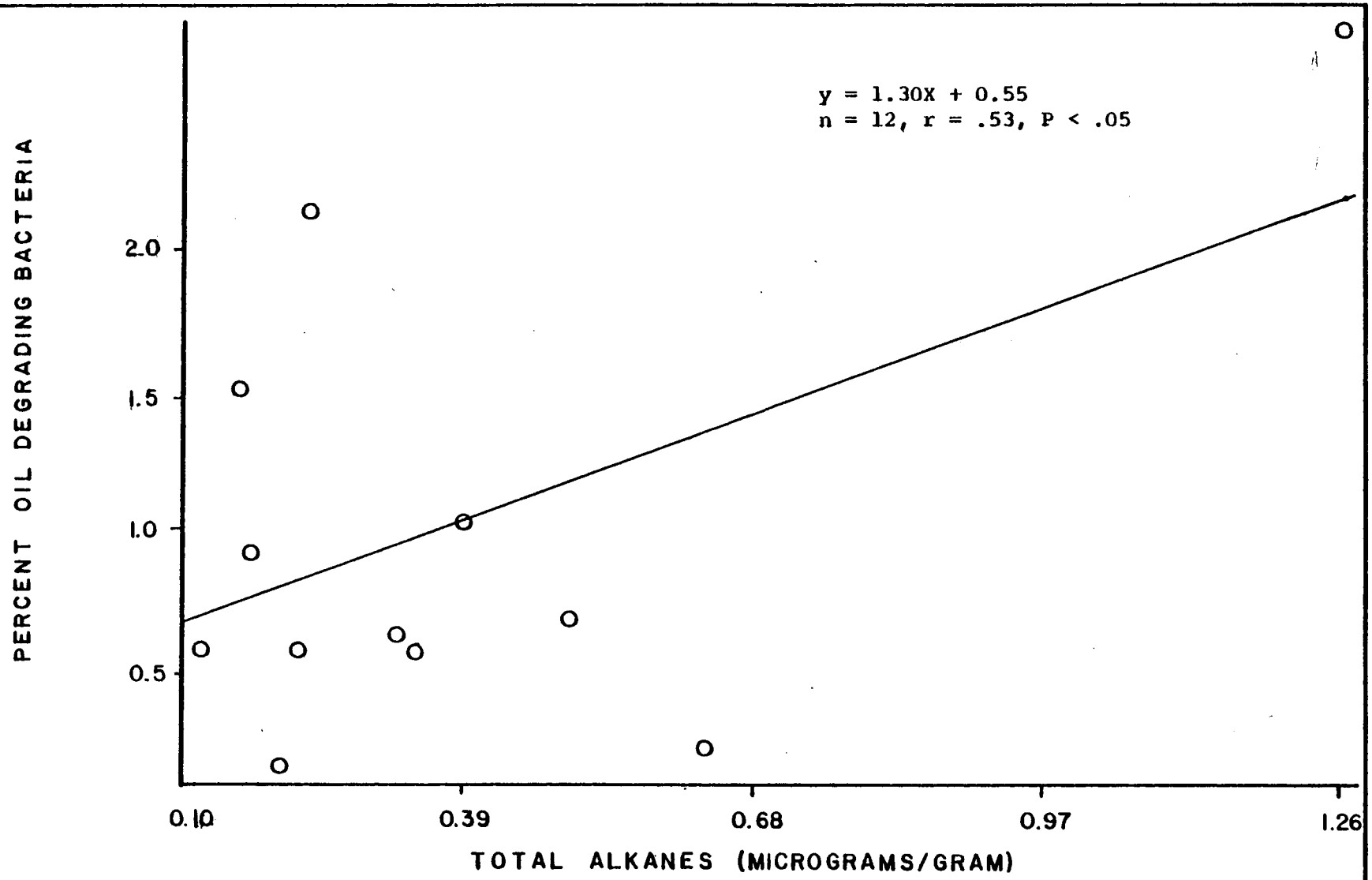

Figure 11.4 Relation Between Percent Oil Degrading Bacteria of Sediment and Total Alkanes.

TABLE 11.3

BENTHIC BACTERIAL POPULATIONS OF THE STUDY AREA COMPARED TO OTHER OFFSHORE REGIONS

Offshore Region	Bacterial Type	Range	Source
South Texas	Total aerobic heterotrophic (1)	4.6×10^4-1.3×10^6/ml	Present study
	Hydrocarbon degrading (2)	8.0×10^1-1.1×10^5/ml	
	Percent hydrocarbon degrading (3)	0.10-20.7	
Louisiana	1	2.0×10^3-6.4×10^7/ml	Schwarz etal.,
	2	2.7×10^2-8.9×10^5/ml	Unpublished data
	3	0.04-46.0	
South Atlantic (South Carolina, Georgia, Florida)	1	1.0×10^1-4.9×10^6/g	Oppenheimer, 1978
	2	0-1.2×10^6/g	
	3	0.0004-96	
Alaska (Beaufort Sea)	1	*NR	Roubal and Atlas,
	2	0.1-8.7×10^3/g	1978
	3	*NR	
North Sea	1	9.6×10^3-3.9×10^7/ml	Gunkel, 1973
	2	5.7×10^1-2.3×10^6/ml	
	3	*NR	

*NR - Not Reported

TABLE 11.4

THE n-ALKANE PREFERENCE OF BENTHIC BACTERIA DURING SPRING

Sample	Incubation Temperature (^{o}C)	*$\frac{\Sigma\ C_{14}\text{ to }C_{20}}{\Sigma\ C_{20}\text{ to }C_{32}}$
Weathering controls	22	1.47
(Uninoculated)	25	1.49
Inoculated with sediment from:		
1/1	25	1.19
2/1	25	1.38
3/1	22	1.38
1/11	25	1.11
2/11	25	1.41
3/11	22	1.37
1/111	25	1.33
2/111	22	1.37
3/111	22	1.40
1/1V	25	1.24
2/1V	22	1.34
3/1V	22	1.36

* Based on ppt *n*-alkanes recovered.

TABLE 11.5

SUMMARY OF THE OIL BIODEGRADATION POTENTIAL OF SEDIMENT OF THE STOCS DURING 1977

Season	Number of Samples	*Mean Percent Biodegradation (Mean ± 1 S.D.)
Winter	24	3.94 ± 3.77
Spring	24	37.10 ± 17.79
Fall	24	69.69 ± 9.93

*Based on percent recovery of C_{14} to C_{32} n-alkanes in weathering controls.

During the spring, there were significantly ($P < 0.01$) higher biodegradation potentials at Station 1, decreasing with increasing station number, or increasing depth. There was also a significant ($P < 0.05$) difference between transects, with lowest potentials on Transect III. During the fall, there were no significant spatial variations in biodegradation potential. The mean percent biodegradation of oil during the spring and fall was significantly correlated with the mean number of hydrocarbon degrading bacteria (Figures 11.5 and 11.6, respectively).

Effects of Oil on Benthic Bacteria

Oil significantly ($P < 0.01$) stimulated the growth of total aerobic heterotrophic bacteria at the majority of stations during the three seasons. Growth stimulation by oil occurred after one week and continued through eight weeks. Significant growth inhibition by oil was not observed.

The number of hydrocarbon degrading bacteria of sediment was significantly ($P < 0.05$) increased by the addition of oil. Stimulation of hydrocarbon degrading bacteria by oil was recorded after two days and continued through eight weeks.

The percent hydrocarbon degrading bacteria of sediment was significantly ($P < 0.01$) increased by oil after two days during the fall. After one week, oil typically had no effect on the percent hydrocarbon degrading bacteria.

DISCUSSION

Benthic bacterial populations are related to organic carbon content more than any other environmental parameter (Zobell, 1946). In the present study, total aerobic heterotrophic bacteria decreased with increasing depth (Figure 11.2), while total organic carbon increased ($r = .62$). A decrease in benthic bacteria concurrent with an increase in organic

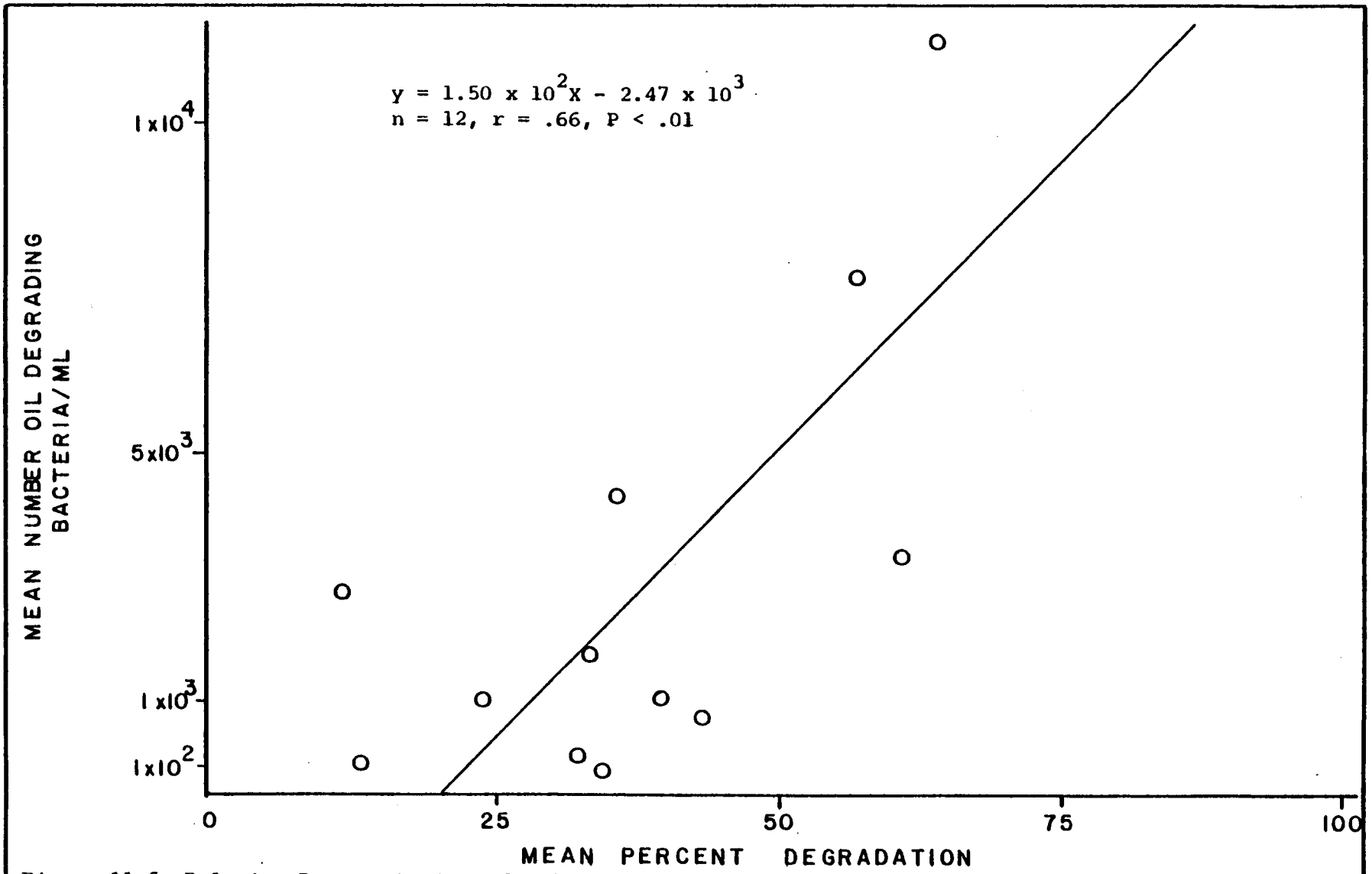

Figure 11.5 Relation Between Number of Oil Degrading Bacteria of Sediment and Mean Percent Degradation During the Spring.

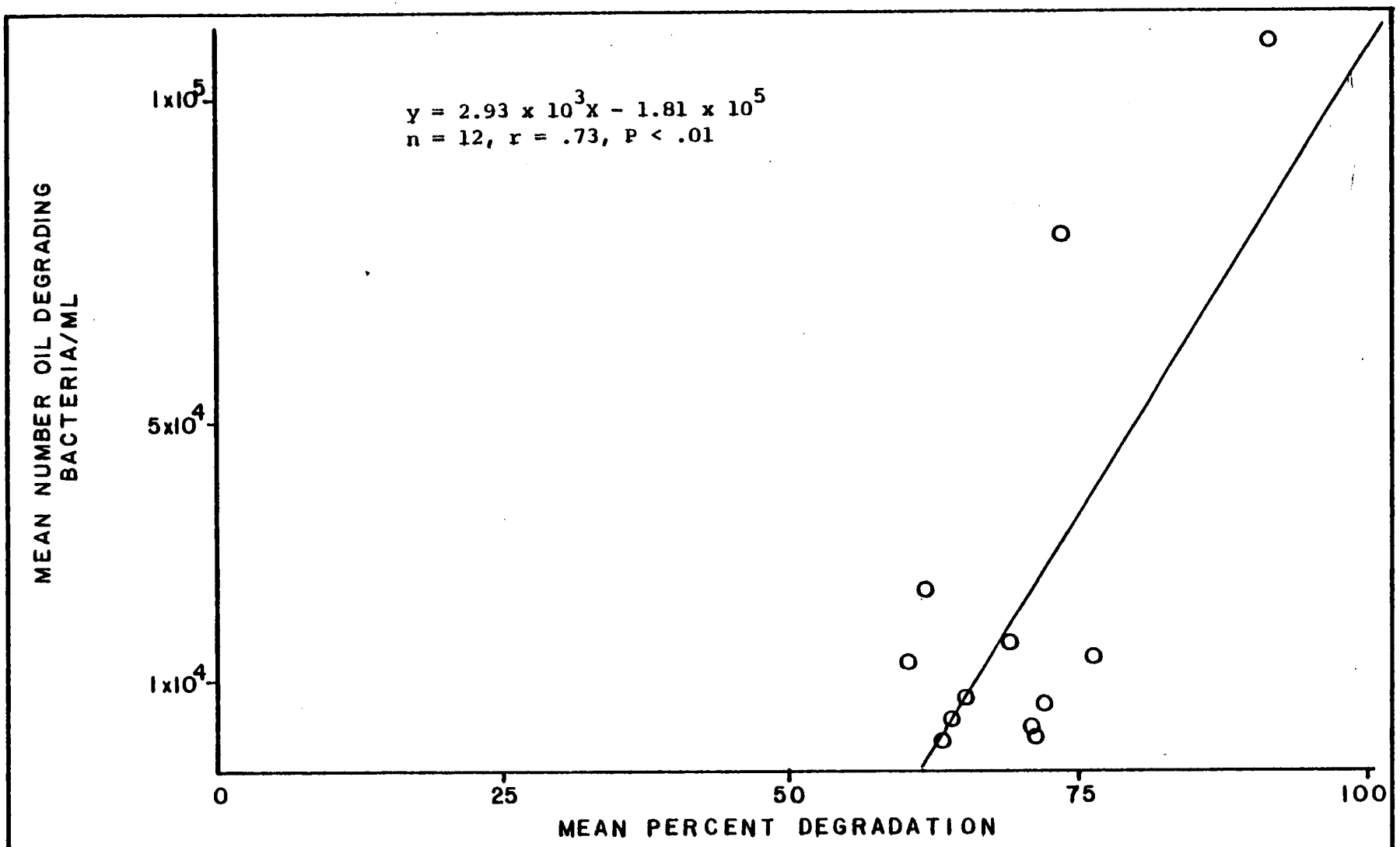

Figure 11.6 Relation Between Number of Oil Degrading Bacteria of Sediment and Mean Percent Degradation During the Fall.

carbon suggests no direct relationship between these two parameters. Apparently there are factors involved which regulate the utilization of the higher organic carbon content of deep station sediments. Temperature may be one factor. Temperature is important in regulating rates of organic carbon utilization and growth in bacteria (Stanier *et al.*, 1970). *In situ* sediment temperatures at deep stations were typically lower than those at shallow stations nearshore (Table 11.1). This difference in temperature will slow organic carbon utilization and growth at deep stations relative to shallow stations. Although this likely contributes to a decrease in bacteria with increasing depth, only 12% of the total variation in populations is explained by sediment temperature. Additional factors are probably involved. Several investigators (Reuszer, 1933; Sanders and Hessler, 1969) have suggested that the number of benthic bacteria along a transect perpendicular to land is more related to the quality rather than the quantity of organic carbon. This suggestion requires close examination in view of the present findings.

The organic carbon of offshore sediments is derived from three primary sources: 1) freshwater runoff; 2) the rain of "detritus" from the euphotic zone; and 3) *in situ* photosynthetic production (Sanders and Hessler, 1969). The contribution of the latter source is unknown for nearshore stations, but is zero for deep stations not exposed to light. During transport of organic carbon to the sediment via the first two sources, autolysis and microbial decomposition occurs (Sanders and Hessler, 1969). During decomposition, microorganisms utilize the most susceptible compounds first, such as simple proteins and carbohydrates, leaving the more refractory compounds, such as lignin, complex proteins, chitin, and cellulose (Zobell, 1946; Alexander, 1961). The longer the transport period, the greater the percentage of refractory material remaining. By this reasoning, organic carbon of deep stations should be more refractory than that of shallow

stations due to the longer period of time required for the material to reach the sediment. Unfortunately, no determinations of the types of organic compounds present in sediment were made to verify this hypothesis. There is indirect evidence, however, to support this hypothesis. A relatively low rate of carbon input to deep stations is expected, since these stations are more distant from riverine sources and primary production in the euphotic zone above is low (Kamykowski and Van Baalen, 1979). A relatively high rate of carbon input is expected at nearshore stations, since these stations are near riverine sources and primary production in the euphotic zone above is high (Kamykowski and Van Baalen, 1979). Despite expected lower input rates, deep station sediments contained a higher content of organic carbon than nearshore stations. An apparent explanation for this would be slow utilization rates of refractory organic carbon at deep stations and rapid utilization rates of less refractory organic carbon at nearshore stations.

The quantity of organic carbon appears to regulate the seasonal distribution of benthic bacteria. Highest river runoff (Texas Department of Water Resources, unpublished data) and highest rates of primary production (Kamykowski and Van Baalen, 1979) occur during the spring. Rates of organic carbon input to the sediments during the spring are expected to be greater than at any other time during the year. Benthic bacteria appear to have responded to this high input during the spring, since this is the period of maximal populations. Temperature also likely effects the seasonal distribution of benthic bacteria. Benthic bacterial populations were lowest during the winter, corresponding to seasonal low sediment temperatures (Table 11.1).

The biomass of meiofauna (Pequegnat, 1979) and macroinfauna (Holland

et al. 1979) in the study area decreased with increasing depth. Total bacterial populations decreased similarly, while total organic carbon increased. The constant ratio of benthic animals to bacteria, and not organic carbon, indicates that benthic animals are more related to bacteria than to organic carbon. This relationship suggests that benthic animals utilize bacteria as a food source and not organic carbon. Bacteria are considered a major food item for a wide variety of meiofauna (Coull, 1973) and macrofauna (Zobell and Feltham, 1938; Newell, 1965; Chua and Brinkhurst, 1973).

Sediment of the study area contained a resident population of hydrocarbon degrading bacteria. Greatest numbers were isolated from nearshore stations. Zobell (1969) also reported greatest populations of hydrocarbon degrading bacteria in nearshore areas. He attributed this distribution to the greater input of hydrocarbons to nearshore areas. A relationship between hydrocarbon degrading bacteria and hydrocarbons suggested by Zobell (1969) was observed in this study (Figures 11.3 and 11.4).

Hydrocarbon degrading bacteria also exhibited significant seasonal variations, with greatest numbers and percentages occurring during the fall. Roubal and Atlas (1978) examined hydrocarbon degrading bacteria in sediment from the Beaufort Sea. Populations were several orders of magnitude greater in the summer-fall period than in the winter-spring period. Oppenheimer (1978) examined hydrocarbon degrading bacteria in sediment from the south Atlantic off South Carolina, Georgia, and Florida. Highest percentages of hydrocarbon degrading bacteria occurred during the fall. The seasonality of hydrocarbon degrading bacteria observed in this and other studies may be related to the seasonal input of hydrocarbons to the sediment, since hydrocarbon degrading bacteria are significantly

correlated with hydrocarbon concentration (Figures 11.3 and 11.4). However, there are insufficient data on the seasonal distribution of hydrocarbons in the sediment to verify this.

The primary environmental parameters affecting oil biodegradation rates are oxygen concentration (Zobell, 1961; Kerr, 1977; Atlas, 1978), nutrient concentration (Bartha and Atlas, 1973; Mulkins-Phillips and Stewart, 1974), temperature (Atlas and Bartha, 1972; Mulkins-Phillips and Stewart, 1974), and the abundance of hydrocarbon degrading bacteria (Walker and Colwell, 1976a). Oxygen concentration in bottom water of the study area was always in excess of 2.9 ml/ℓ (Sackett and Brooks, 1979). Therefore, oxygen is probably not limiting to oil biodegradation, at least in the surficial sediments.

Oil biodegradation rates did not highly correlate with *in situ* concentrations of nitrogen and phosphorus in bottom water during winter, spring and fall. Likewise, *in situ* concentrations of nutrients added to the basal medium did not effect biodegradation rates. In the majority of cases, sediment samples receiving highest *in situ* concentrations of nutrients did not exhibit highest rates of oil biodegradation. *In situ* concentrations of nitrate in the study area ranged from 0 to 1.12 mg/ℓ, while phosphate ranged from 0 to 0.45 mg/ℓ (Sackett and Brooks, 1979). Variations of nutrient concentration in the above ranges apparently have little effect on oil biodegradation rates compared to variations in other parameters.

The effect of temperature on rates of oil biodegradation could not be assessed in the present study for two reasons: 1) rates from different seasons could not be compared because of variations in composition and concentration of oil added; and 2) incubation temperatures used for any

one season varied only 3°C. The importance of temperature in controlling the rates of oil biodegradation has been emphasized by many investigators (Atlas and Bartha, 1972; Zobell, 1973; Mulkins-Phillips and Stewart, 1974; Atlas, 1978). *In situ* sediment temperatures increased 10°C from winter to fall (Table 11.1). It is unlikely that this temperature increase during the year will enhance rates of biodegradation.

The growth of benthic bacteria was significantly stimulated by the addition of oil. The bacteria stimulated to the greatest extent were hydrocarbon degrading bacteria, as the percentage of these bacteria in the population increased after addition of oil. Stimulation of hydrocarbon degrading bacteria by oil has been described by other investigators (Hood *et al.*, 1975; Atlas and Bartha, 1973; Walker and Colwell, 1976b).

An oil-induced change in benthic bacterial populations to those more capable of degrading oil may affect natural bacterial activity. Marine bacteria mineralize a wide variety of organic substrates (Zobell, 1946), both dissolved (Wright, 1974) and particulate (Gosselink and Kirby, 1974). The effect of oil on this bacterial process is unclear. Several investigators have reported that oil decreased the numbers of bacteria that mineralize certain organic compounds (Walker *et al.*, 1974; Crow *et al.*, 1975). In addition, Hodson *et al* (1977) reported inhibition of glucose uptake and mineralization by four oils. In contrast to these studies which indicate the harmful effects of oil on bacterial activity, Knowles and Wishart (1977) saw no effect of oil on bacterial carbon dioxide evolution. Bartha and Atlas (1977) cited two studies where oil did not affect the rate of glutamic acid mineralization by marine bacteria. Clearly, much more work is required to assess the factors controlling the toxic effects of oil on marine bacteria.

CONCLUSIONS

Two study findings suggest that hydrocarbon degrading bacteria may be a useful indicator of sediment hydrocarbons in the study area: 1) the number and percent hydrocarbon degrading bacteria were significantly correlated with total alkanes of the sediment; and 2) the addition of oil to the sediment increased the number and percent hydrocarbon degrading bacteria after two days. These results indicate the direct relationship and rapid response of hydrocarbon degrading bacteria to hydrocarbons. Hydrocarbon degrading bacteria, therefore, may be an important variable to monitor in future assessments of hydrocarbon input to the sediments.

All 72 sediment samples collected during the study contained populations of hydrocarbon degrading bacteria capable of degrading C_{14} to C_{32} n-alkanes in added crude oil. However, the percent degraded varied widely, from 0.4 to 91.6%. The specific factors responsible for this large variation are not known with certainty. Future *in vitro* studies are necessary to establish the effects of specific factors (*i.e.* oxygen, nutrients, temperature) on oil biodegradation. Information obtained from such studies may provide a better understanding of the seasonal and spatial variations in hydrocarbon biodegradation potentials in the study area.

The addition of 0.5% v/v crude oil to sediments *in vitro* significantly increased populations of aerobic heterotrophic and hydrocarbon degrading bacteria. The latter were stimulated to the greatest extent, as the percentage of these bacteria in the population increased after addition of oil. If such an oil-induced change in benthic bacterial populations occurred *in situ*, it is unclear what effect this would have on benthic nutrient cycling. Information on the impact of oil on this process may be gained from future studies which examine the effects of oil on the uptake and mineralization of radioisotope-labeled organic compounds.

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CHAPTER TWELVE

MEIOFAUNA PROJECT

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ABSTRACT

Meiofaunal samples were taken over a two year period on four transects extending over the south Texas outer continental shelf (STOCS) and on two banks of the shelf. Stations were sampled three times each year (winter, spring and fall) on Transects I, III and IV and nine times each year on Transect II. A total of 786 samples were analyzed for meiofauna over the two years.

Transects I, III and IV showed a decrease in True Meiofaunal populations with depth, whereas Transect II did not. Bank populations were more numerous than transect populations of the nearest transect (II) at a similar depth. A three-way ANOVA with interactions was performed on the replicate counts of True Meiofauna at each station against the parameters of depth zone, time (sampling period) and transect. Qualitatively, Transect II was shown to be anomalous to the other transects, having small populations at its shallower stations and therefore grouping with the deeper stations of the other transects.

Nematode populations on the more frequently sampled Transect II were examined for exhibition of seasonality of abundance. Population peaks occurred in March, July-August and November.

Populations of the Nematoda, the Harpacticoida, the Kinorhyncha and the Polychaeta were discussed with respect to their abundance and taxonomic composition. The Nematoda were the most abundant group of the True Meiofauna (average 92%), followed by the Harpacticoida. Disregarding the Foraminiferida (because of inaccuracies in sorting techniques), the Polychaeta were the most abundant of the Temporary Meiofauna.

Abiotic and biotic factors relating to the True Meiofaunal abundance in the STOCS area were reported and discussed. Nematodes were highly correlated with sediment granulometry and increased substantially when the sand component exceeded 60% by weight. Where True Meiofaunal totals were less numerically abundant (at the outer stations of all transects and the inshore stations of Transect II), the sediments were finer. The possible use of the harpacticoid:nematode ratio for monitoring physical perturbations at a station was discussed.

Speculations on possible interactions between the meiofauna and other biota of the STOCS area were presented. Similarities in the patterns of abundance of the True Meiofauna and certain detritovores (*Penaeus aztecus* and the more abundant benthic detritovorous fishes) suggest an interaction between these groups, very possibly predation. An approach to the future investigation of the above interaction was recommended.

INTRODUCTION

Purpose

The first investigative objective of the South Texas Outer Continental Shelf (STOCS) study was to search for correlations between environmental variables and changes in meiofaunal populations. The second purpose was to determine any similarities or differences between the 1976 and 1977 attributes of meiofaunal populations. If population variances between the two years were large while fluxes in environmental parameters in the same time span were small, either sampling techniques were inadequate or meiofaunal populations were unstable and determined by factors not measured during the study. Few significant correlations were found. Clearly the meiofaunal study was not structured to reveal some of the potentially valuable relationships. For instance, it was noted by us that in some instances where trace metals were high, meiofaunal populations were low. Since we know nothing about meiofaunal susceptibility to mortality from the metals involved and since it is well known that metals tend to be higher and meiofaunal populations lower in fine grain sediments, it seemed likely that granulometry and not toxicity was involved.

More encouraging is the fact that our study found remarkable similarities between the two years with regard to several parameters of meiofaunal populations. This is an important fact, the details of which will be developed in the following sections.

METHODS

Sampling Transects and Stations

The meiofauna of the STOCS area was sampled with a Smith-McIntyre grab on four transects and two banks, Hospital Rock and Southern Bank, in 1976 and 1977. The locations of the transect stations and the banks are

shown in Figure 12.1. All stations of the transects and two stations of each bank were sampled during the three seasonal cruises both in 1976 and 1977. Stations 1-6 on Transect II were additionally sampled during six monthly cruises in both years, as were two stations on each of the two banks during 1976. The number of samples taken, with source and time of collection are shown in Tables 12.1 and 12.2. The 25 transect stations were divided into five depth zones (A-E) as shown in Figure 12.1. Hospital Rock (HR) and Southern Bank (SB) were located in zone C.

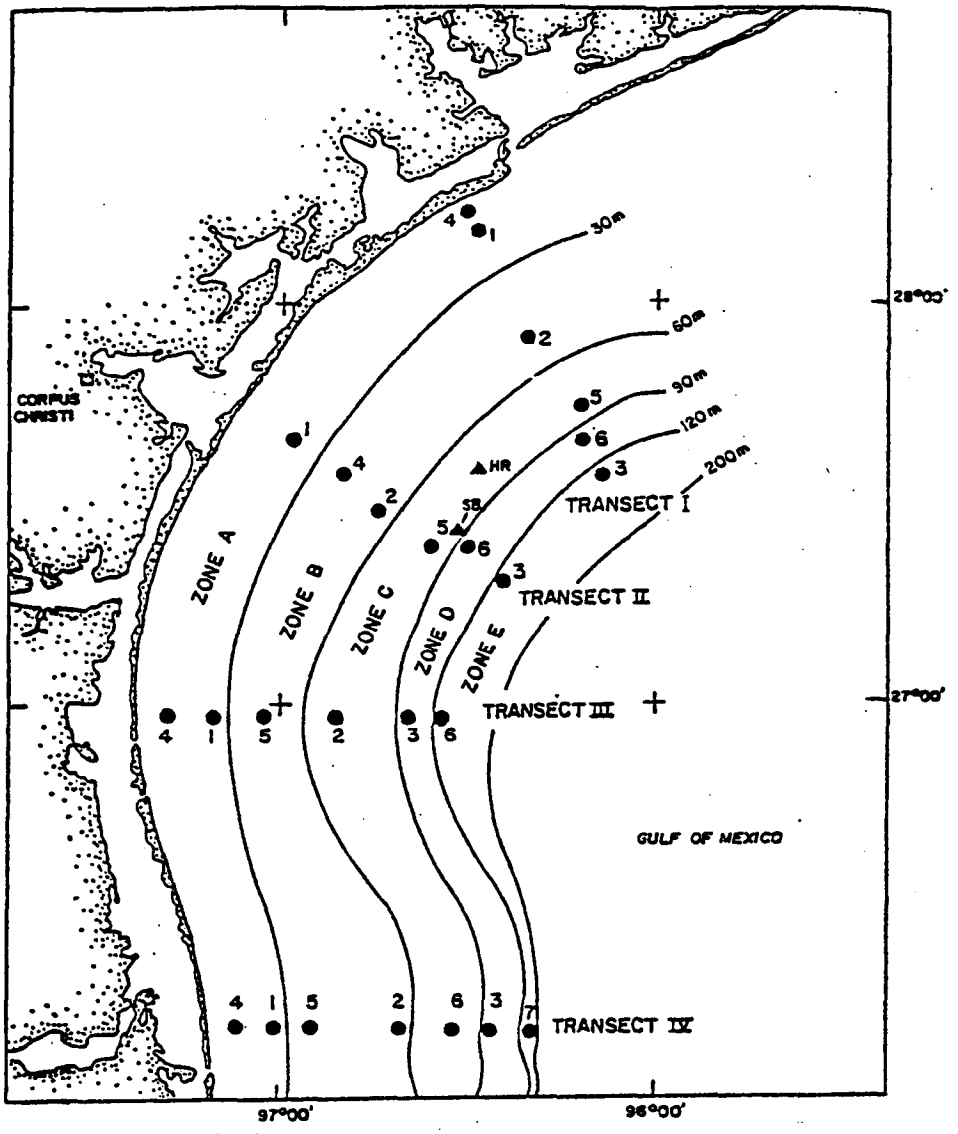
Two replicates were taken at each station sampled in 1976 whereas four replicates per station were taken in 1977. We, therefore, use the means of the replicates in comparing the data from the two years.

Sample Processing

Details of the sample processing procedure can be found in the annual reports for 1976 and 1977. In short, samples were taken by means of a core tube (internal area = 9.187 cm^2) to a depth of 5 cm. Samples were preserved and stained in the field and then brought back to the lab for sieving (using nested 500 µm and 62 µm sieves) and sorting to major taxa. Two replicates were taken for sorting in 1976 and four in 1977.

Treatment of the Data

In both the 1976 and 1977 studies, we regarded as meiofauna those animals in or on the sediment which could be passed through a 500 µm sieve but retained on a 63 µm sieve. The animals were regarded as belonging to one of two groups. One was the True Meiofauna, defined as those metazoans which spend their entire life cycle as members of the meiofauna, including Nematoda, Harpacticoida, Kinorhyncha, Halacaridae, Ostracoda, and Turbellaria. The other group was composed of the Temporary Meiofauna (those metazoans spending only their juvenile life stages in the meiofauna)



LOCATION OF TRANSECTS, SAMPLING STATIONS, AND ZONES

Figure 12.1 Location of South Texas OCS Baseline Study Transects (Roman) and Stations (Arabic). Note also the Location of Southern Bank (SB) and Hospital Rock (HR) Topographic Highs in Zone C.

TABLE 12.1

SOURCE AND TIME OF COLLECTION OF THE
294 MEIOFAUNA SAMPLES COLLECTED AND ANALYZED IN 1976

SAMPLING PERIOD	TRANSECTS				HARD BANK	
1976	I	II	III	IV	SOUTHERN BANK	HOSPITAL ROCK
Winter (Feb. 13-20)	12	12	12	14	4	4
March (25-27)		12			4	4
April (9-10)		12			4	4
Spring (June 13-25)	12	12	12	14	4	4
July (17-18)		12			4	4
August (16-27)		12			4	4
Fall (Oct. 8-9)	12	12	12	14	4	4
November (16-19)		12			4	4
December (9-10)	—	12	—	—	4	4
SUB TOTALS	36	108	36	42 = 222	36	36 = 72
GRAND TOTAL	294 samples analyzed					

TABLE 12.2

SOURCE AND TIME OF COLLECTION OF THE
492 MEIOFAUNA SAMPLES COLLECTED AND ANALYZED IN 1977

SAMPLING PERIOD	TRANSECTS				HARD BANK	
1976	I	II	III	IV	SOUTHERN BANK	HOSPITAL ROCK
Winter (Jan. 28-Feb. 14)	24	24	24	28	8	8
March (14-15)		24				
April (17-18)		24				
Spring (May 24-June 3)	24	24	24	28	8	8
July (8-9)		24				
August (6-7)		24				
Fall (Sept. 26-Oct. 7)	24	24	24	28	8	8
November (21)		24				
December (16-18)	—	24	—	—	—	—
SUB TOTALS	72	216	72	84 = 444	24	24 = 48
GRAND TOTAL	492 samples analyzed					

and the Protozoa, including the Foraminiferida. For this synthesis effort, Foraminiferida and other Protozoa are excluded from analysis, as are Turbellaria. Soft forms such as Protozoa and Turbellaria are very difficult to distinguish after treatment with formalin. The numbers reported for the STOCS study area are, therefore, not reliable. The Foraminiferida data are not analyzed because the rose bengal stain used in the STOCS study may have stained more than the living foraminiferans (Gettleson and Pequegnat, 1976) leading to systematic overestimates not quantifiable in retrospect.

Our earlier work revealed that not all systematic groups of the meiofauna were highly correlated with grain size of the sediment (Pequegnat and Sikora, 1977). However, the nematodes were; and because they are the numerical and biomass dominants on the continental shelf, the meiofauna as a whole appeared to be so correlated. Harpacticoid copepods did not vary predictably with grain size. For this synthesis, we concentrated, therefore, on the groups who were most abundant and whose counts were most reliable, in particular the True Meiofauna, the Nematoda and the Harpacticoida.

RESULTS AND DISCUSSION

Total Numbers of True Meiofauna

Spatial and Temporal Variability

During both 1976 and 1977 meiofaunal populations diminished with increasing depth (Figures 12.2 - 12.5). Consistently Transect IV supported the highest populations inshore and Transect II the lowest (Table 12.3). Populations of the deepest station of Transect II were almost as great as those of the shallowest station. In contrast, for the other three transects, populations of the deepest stations were only a small percentage

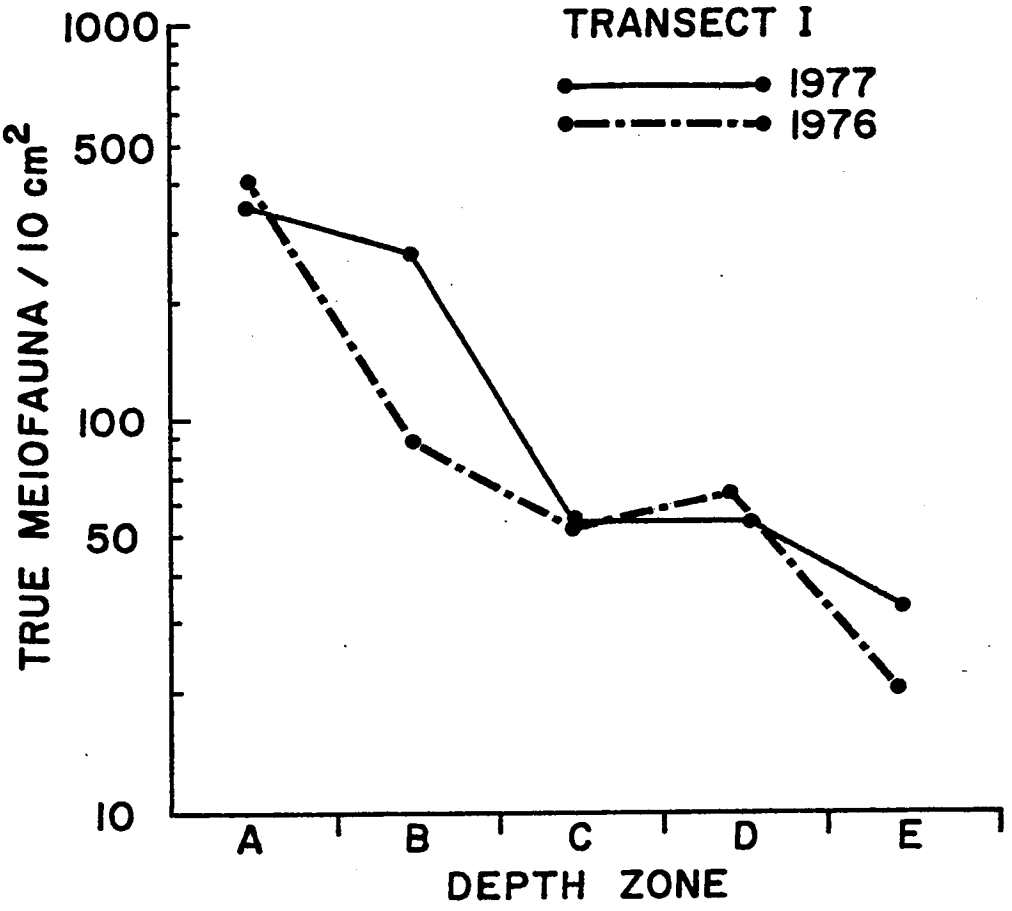


Figure 12.2 Distribution of True Meiofauna on Transect I during the Winter, Spring and Fall Sampling Periods by Depth Zone for 1976 and 1977. Points are means of populations for three seasonal sampling periods plotted logarithmically. Depth Zones are: A (0-30 m), B (30-60 m), C (60-90 m), D (90-120 m), E (>120 m)

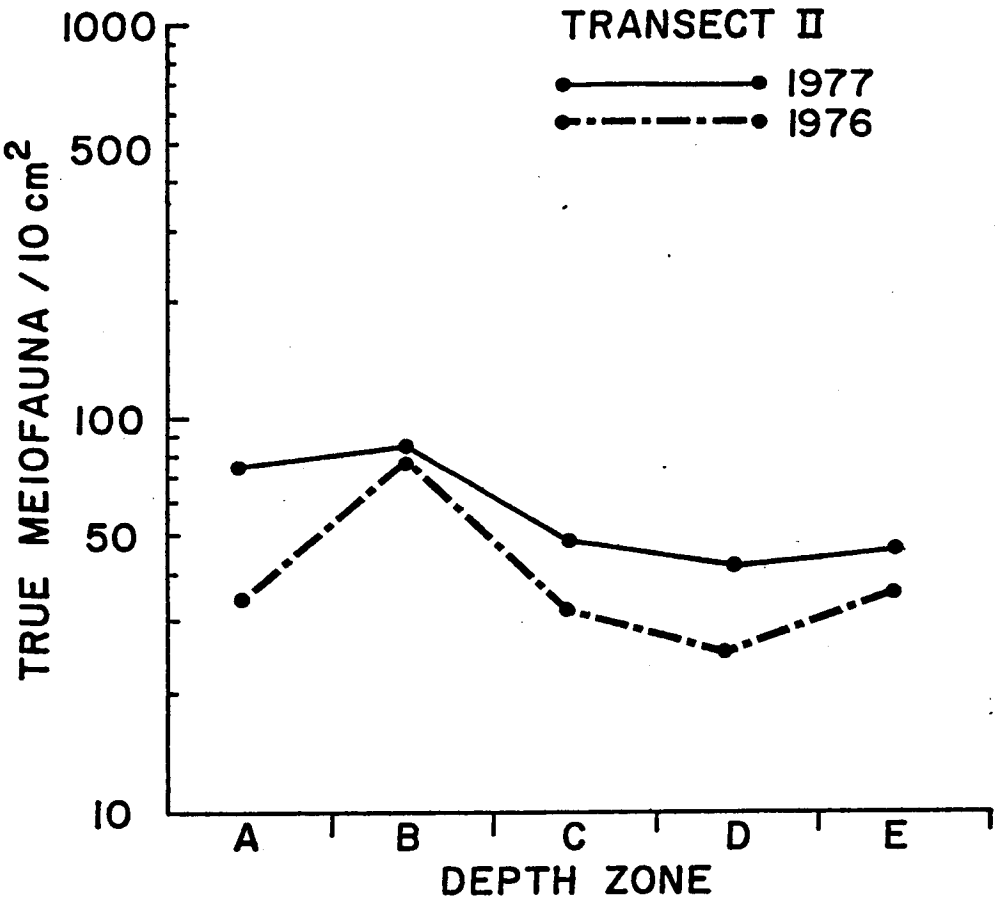


Figure 12.3 Distribution of True Meiofauna on Transect II during the Winter, Spring and Fall Sampling Periods by Depth Zone for 1976 and 1977. Points are means of populations for three seasonal sampling periods plotted logarithmically. Depth Zones are: A (0-30 m), B (30-60 m), C (60-90 m), D (90-120 m), E (>120 m).

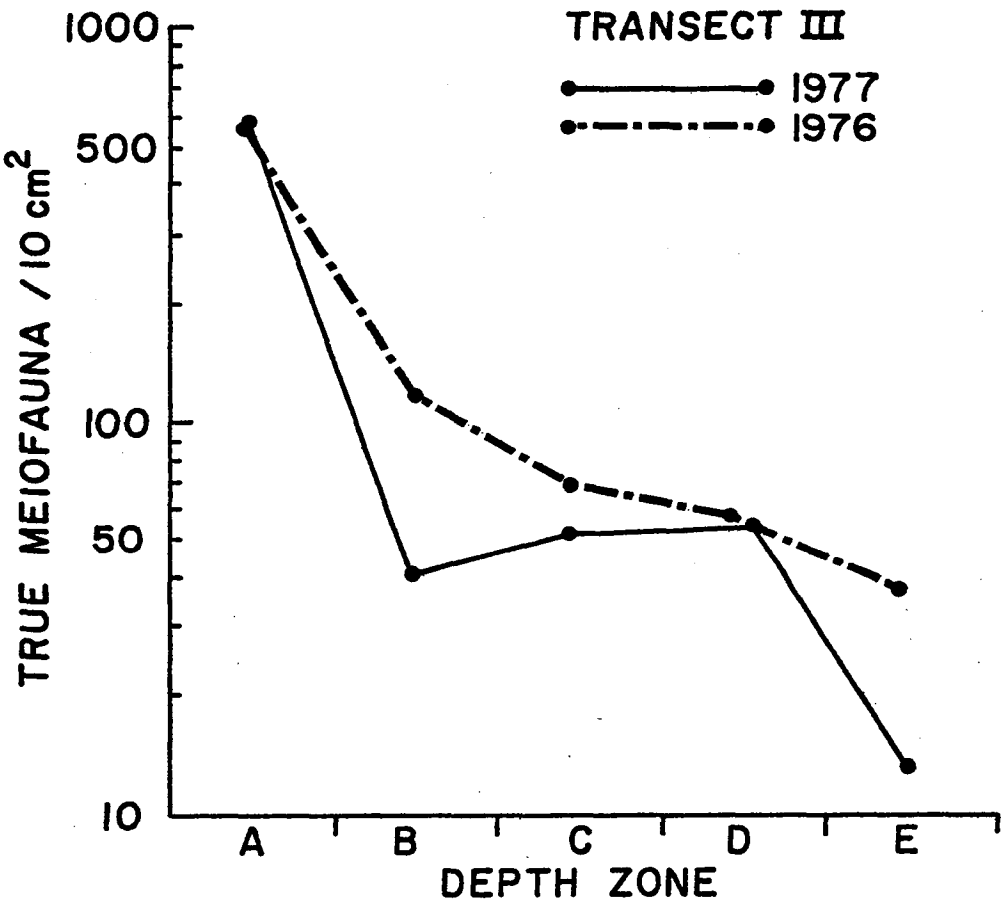


Figure 12.4 Distribution of True Meiofauna on Transect III during the Winter, Spring and Fall Sampling Periods by Depth Zone for 1976 and 1977. Points are means of populations for three seasonal sampling periods plotted logarithmically. Depth Zones are: A (0-30 m), B (30-60 m), C (60-90 m), D (90-120 m), E (>120 m).

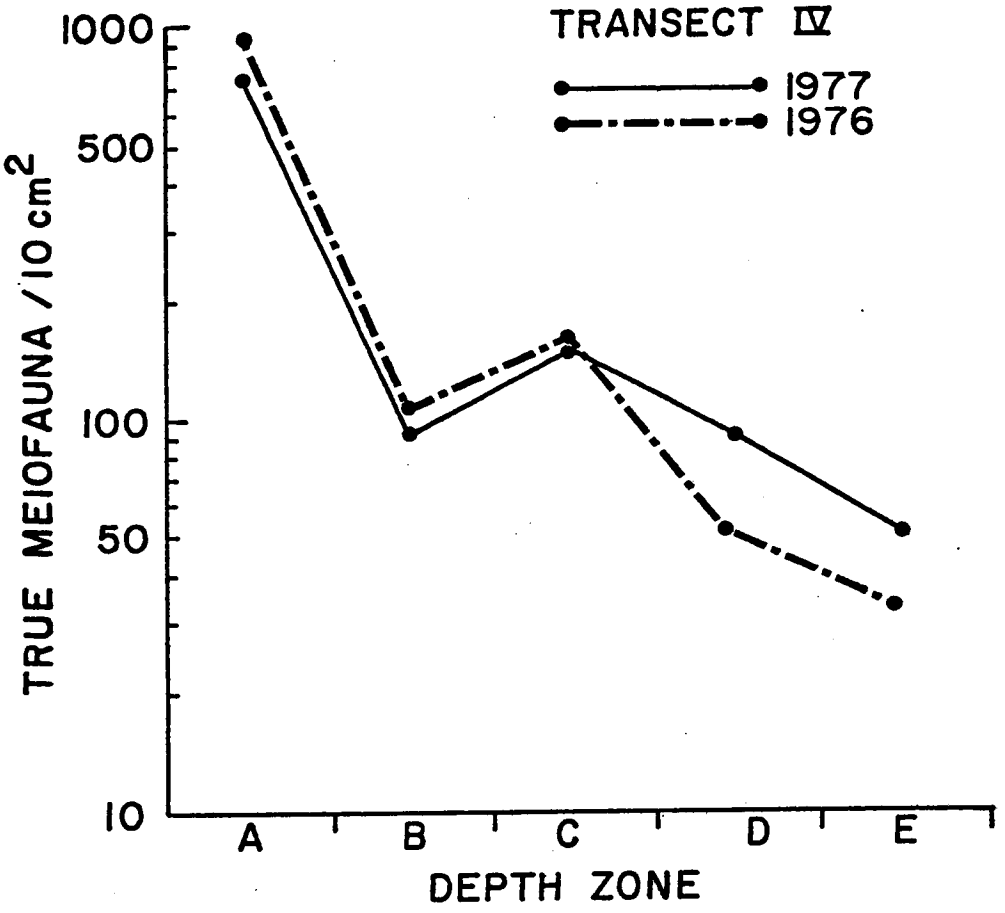


Figure 12.5 Distribution of True Meiofauna on Transect IV during the Winter, Spring and Fall Sampling Periods by Depth Zone for 1976 and 1977. Points are means of populations for the three seasonal sampling periods plotted logarithmically. Depth Zones are: A (0-30 m), B (30-60 m), C (60-90 m), D (90-120 m), E (>120 m).

TABLE 12.3

MEAN ($\bar{X}$) ± STANDARD DEVIATION(S) OF TRUE MEIOFAUNA BY DEPTH ZONE AND TRANSECT STATIONS WITHIN A DEPTH ZONE ARE NOTED BENEATH EACH TRANSECT, WITH THE DEPTH IN METERS UNDER EACH IN PARENTHESES, AND ARE LISTED IN ORDER OF DISTANCE FROM SHORE. NUMBERS ARE MEANS OF REPLICATES FOUND AT EACH STATION (TWO REPLICATES IN 1976 AND FOUR REPLICATES IN 1977) OVER ALL TIME PERIODS

Zone A (0-30 m)	1976 (2 reps)	1977 (4 reps)	Zone B (30-60 m)	1976 (2 reps)	1977 (4 reps)	Zone C (60-90 m)	1976 (2 reps)	1977 (4 reps)	Zone D (90-120 m)	1976 (2 reps)	1977 (4 reps)	Zone E (>120 m)	1976 (2 reps)	1977 (4 reps)
TRANSECT I (3 sampling periods per year)														
Sta. 4 (10 m)	424.7 ± 288.2	256.4 ± 168.2 $\bar{x}$ = 312.5 s = 222.3	Sta. 2 (42 m)	82.7 ± 54.2	240.9 ± 291.2 $\bar{x}$ = 188.2 s = 248.2	Sta. 5 (82 m)	50.3 ± 21.3	46.3 ± 41.8 $\bar{x}$ = 47.7 s = 35.6	Sta. 6 (100 m)	60.0 ± 50.7	48.8 ± 43.9 $\bar{x}$ = 52.5 s = 45.1	Sta. 3 (134 m)	19.0 ± 8.5	35.8 ± 25.8 $\bar{x}$ = 30.2 s = 22.7
Sta. 1 (18 m)	347.5 ± 282.7	376.4 ± 359.0 $\bar{x}$ = 366.8 s = 327.5												
TRANSECT II (9 sampling periods per year)														
Sta. 1 (22 m)	125.7 ± 188.3	148.6 ± 149.2 $\bar{x}$ = 150.0 s = 161.8	Sta. 4 (34 m)	123.2 ± 140.2	82.3 ± 104.7 $\bar{x}$ = 95.9 x = 118.0	Sta. 5 (78 m)	31.8 ± 20.4	36.5 ± 23.2 $\bar{x}$ = 34.9 s = 22.2	Sta. 6 (98 m)	46.1 ± 39.5 $\bar{x}$ = 45.7 s = 37.0	45.6 ± 36.3	Sta. 3 (131 m)	36.9 ± 25.9	23.4 ± 18.8 $\bar{x}$ = 27.9 s = 22.1
			Sta. 2	88.7 ± 56.4	50.5 ± 36.9 $\bar{x}$ = 63.6 s = 47.0									
TRANSECT II (3 sampling periods per year)														
Sta. 1 (22 m)	34.3 ± 13.2	68.6 ± 64.1 $\bar{x}$ = 57.2 s = 54.7	Sta. 4 (34 m)	60.7 ± 65.3	109.3 ± 131.4 $\bar{x}$ = 93.1 s = 114.0	Sta. 5 (78 m)	30.8 ± 21.8	44.6 ± 25.0 $\bar{x}$ = 40.0 s = 24.2	Sta. 6 (98 m)	23.2 ± 10.8	37.8 ± 26.9 $\bar{x}$ = 32.9 s = 23.5	Sta. 3 (131 m)	32.3 ± 28.4	28.3 ± 22.3 $\bar{x}$ = 29.7 s = 23.7
			Sta. 2 (49 m)	84.2 ± 47.3	45.0 ± 30.0 $\bar{x}$ = 58.1 s = 39.9									
TRANSECT III (3 sampling periods per year)														
Sta. 4 (15 m)	872.7 ± 326.7	1020.2 ± 395.6 $\bar{x}$ = 971.0 s = 371.2	Sta. 5 (40 m)	107.2 ± 152.3	37.6 ± 38.5 $\bar{x}$ = 60.8 s = 94.4	Sta. 2 (65 m)	62.7 ± 39.6	45.6 ± 33.7 $\bar{x}$ = 51.3 s = 35.6	Sta. 3 (106 m)	48.7 ± 44.2	48.8 ± 52.9 $\bar{x}$ = 48.7 s = 48.8	Sta. 6 (125 m)	33.8 ± 16.5	11.8 ± 7.0 $\bar{x}$ = 19.1 s = 15.0
Sta. 1 (25 m)	120.7 ± 66.5	59.8 ± 71.8 $\bar{x}$ = 80.1 s = 74.2												
TRANSECT IV (3 sampling periods per year)														
Sta. 4 (15 m)	843.0 ± 101.7	774.6 ± 488.0 $\bar{x}$ = 797.4 s = 397.8	Sta. 5 (37 m)	94.5 ± 59.7	134.6 ± 187.5 $\bar{x}$ = 121.2 s = 155.4	Sta. 6 (65 m)	149.7 ± 74.7	141.2 ± 99.3 $\bar{x}$ = 144.0 s = 89.6	Sta. 3 (91 m)	49.5 ± 14.8	80.9 ± 65.2 $\bar{x}$ = 70.4 s = 55.2	Sta. 7 (130 m)	32.3 ± 23.9	45.5 ± 47.7 $\bar{x}$ = 41.1 s = 41.0
Sta. 1 (27 m)	869.0 ± 468.1	539.6 ± 293.8 $\bar{x}$ = 694.4 s = 381.9	Sta. 2 (47 m)	101.3 ± 26.4	56.0 ± 22.6 $\bar{x}$ = 71.1 s = 31.9									
HOSPITAL ROCK (9 Sampling Periods 1976; 3 Sampling Periods 1977)														
							65.8 ± 54.6	84.5 ± 63.2 $\bar{x}$ = 73.3 s = 58.4						
SOUTHERN BANK (9 Sampling Periods in 1976; 3 in 1977)														
							55.4 ± 40.7	44.9 ± 39.5 $\bar{x}$ = 51.2 s = 40.2						

of those of the shallowest stations. These observations suggest that some unknown environmental factors were impinging on the populations of the innermost station of Transect II.

A three-way analysis of variance with interactions was run on the replicate counts of true meiofauna at each station against the parameters of depth zone, time (sampling period) and transect to determine which of the above might be important to True Meiofauna abundance. The data were first log transformed to better satisfy the assumption of normal distribution necessary for the analysis. As shown in Table 12.4, the three-way interaction of depth x time x transect was significant ($p < 0.005$); therefore, we could not state statistically from the analysis how True Meiofauna varies along any one of the three parameters tested. However, the fact that time alone was not significant ($.05 < p < .1$) indicated that depth and transect were probably the more important of the three parameters.

Figure 12.6 illustrates the mean and 95% confidence limits of the log-transformed true meiofauna abundance for each depth - time - transect combination. The data were placed arbitrarily into the following three groups:

Group 1: High abundance - those whose lower limit is greater than 1.8

Group 2: Low abundance - those whose upper limit is less than 2.1

Group 3: Moderate abundance - those whose lower limit is less than 1.8 and whose upper limit is greater than 2.1.

As shown in the figure, Group 1 contained almost exclusively the zone A stations for Transects I, III and IV. By contrast, Group 2 contained many

TABLE 12.4

p VALUES FOR 3-WAY ANOVA WITH INTERACTIONS

PARAMETER	p
Depth	$p < .005$
Time	$0.5 < p < .1$
Transect	$p < .005$
Depth x Transect	$p < .005$
Depth x Time	$.1 < p$
Time x Transect	$p < .005$
Depth x Time x Transect	$p < .005$

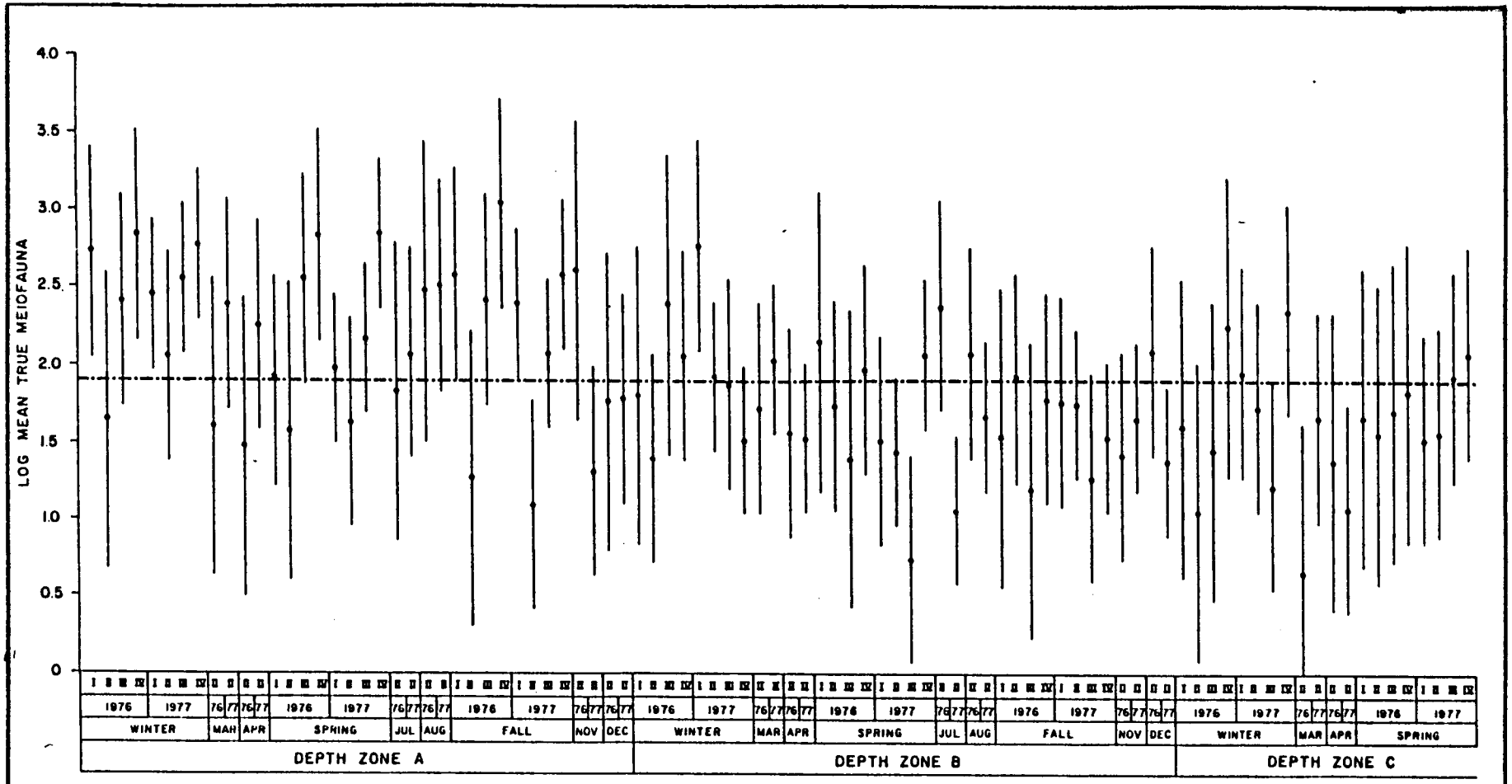


Figure 12.6 Tukey's Q Intervals for Each Station of the STOCS Meiofauna Project, grouped by Depth Zone. Ordinate is the log of the Mean True Meiofauna per core. Dotted line represents the approximate mid-point between Group 1 and Group 2 (see text). (Continued on following page.)

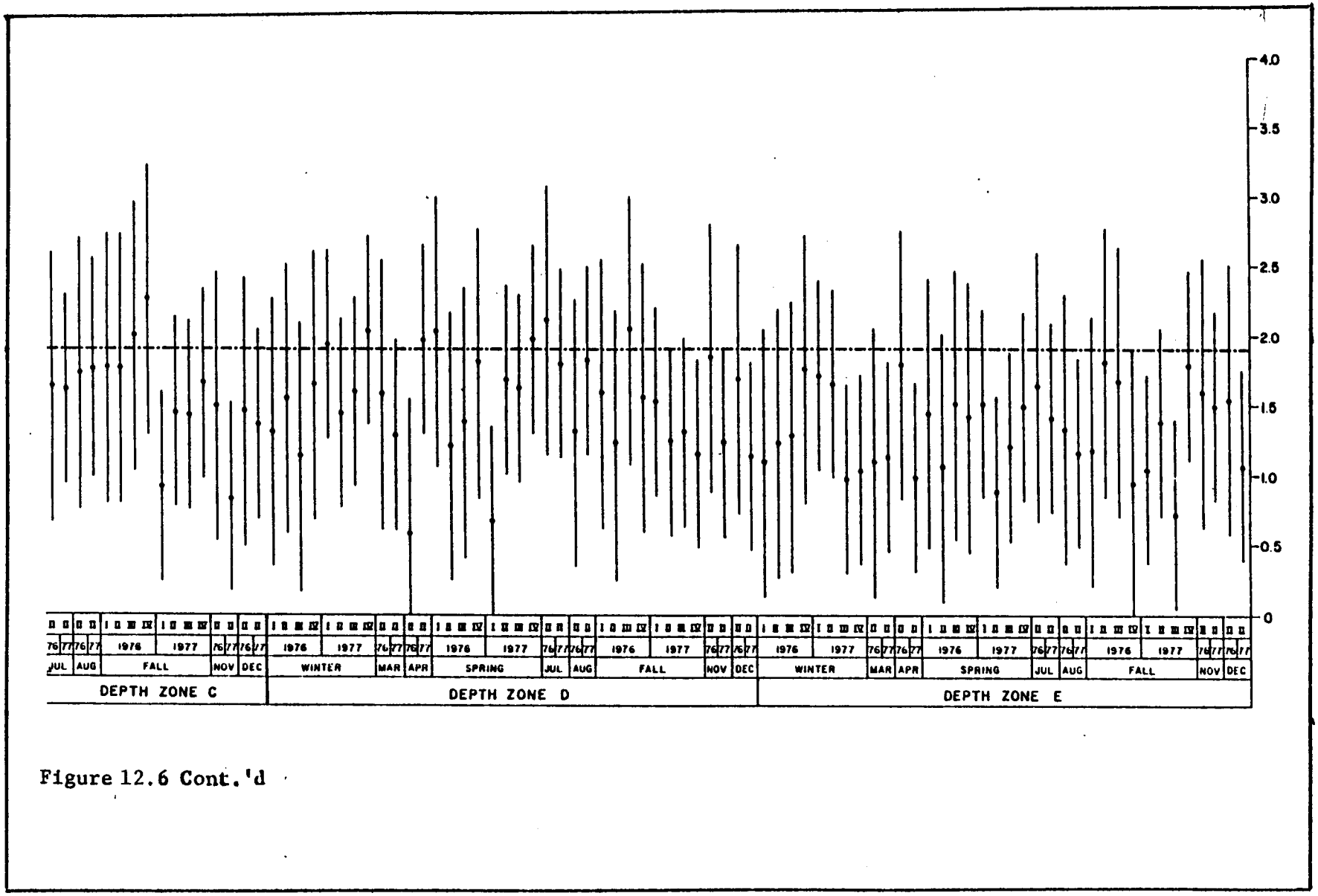


Figure 12.6 Cont.'d

of the deeper stations (Zones C, D, and E) from all four transects, and in addition, the shallower stations (Zones A and B) of Transect II. Qualitatively, therefore, Transect II was anomalous to the other transects with respect to its shallow stations, the entire transect grouping with the deeper stations of the other transects.

Population Changes with Season

Pequegnat and Sikora (1977) reported that sampling on a monthly basis was necessary to reveal seasonality of meiofaunal populations. This was best shown by the Nematoda on Transect II, which was the only transect sampled more than three times during the year (Figures 12.7 and 12.8). There were population peaks in March, July-August, and November. Some within-year differences in population size were worthy of mention. First, the population peaks were much greater inshore than offshore. The between-year differences showed that March or July-August populations may be the larger in the inshore stations, but July-August populations are larger in the offshore stations. Note in Figure 12.7 that the March 1976 inshore population is very small and November is large. This was followed by a very large March 1977 population and a reduced November population (Figure 12.8).

Populations Around Hospital Rock and Southern Bank

The meiofaunal populations of Southern Bank and Hospital Rock were similar in 1976 and 1977. In both instances Hospital Rock populations were larger than those of Southern Bank. Although the bank populations were similar to those of the corresponding depths on the transects, the downstream stations of the banks consistently yielded higher harpacticoid and lower nematode population percentages. Considering them together, bank samples ranged from 53.2% to 100% nematodes in 1976 and from 40.9%

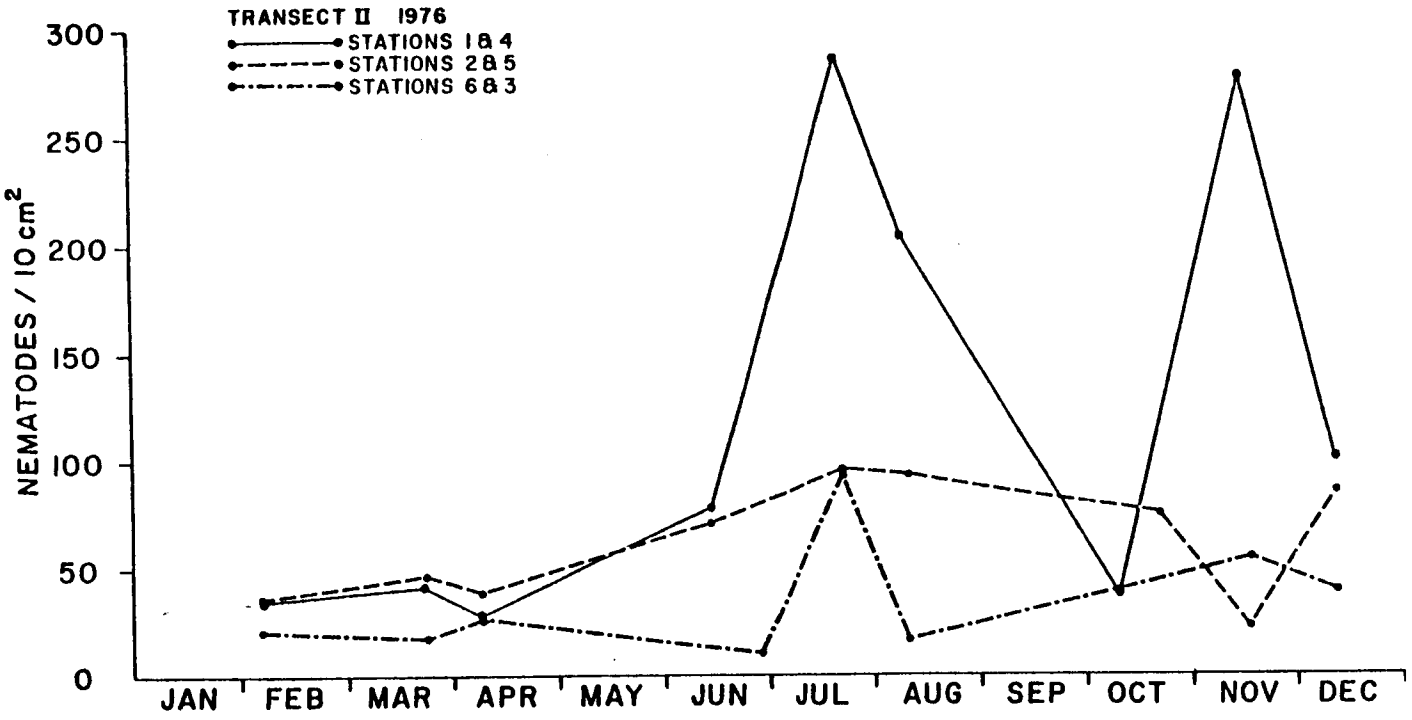


Figure 12.7 Monthly Distribution of Nematoda at Inshore Stations (1 and 4), Mid-Depth Stations (2 and 5) and Offshore Stations (6 and 3) of Transect II During 1976.

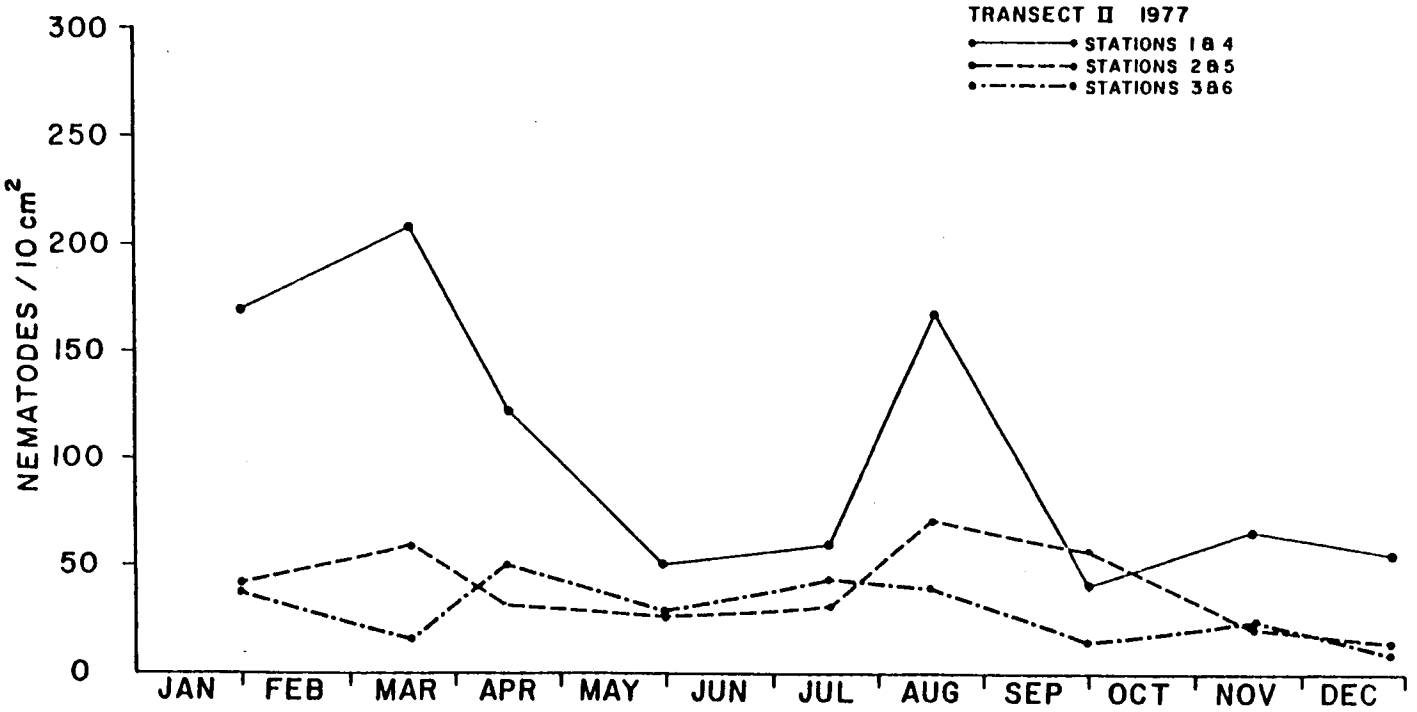


Figure 12.8 Monthly Distribution of Nematoda at Inshore Stations (1 and 4), Mid-Depth Stations (2 and 5) and Offshore Stations (6 and 3) of Transect II During 1977.

to 75.9% nematodes in 1977 and averaged 86.9% and 75.9% in each respective year.

These two banks are in the closest proximity to Transect II, the most depauperate of the four transects. The sediments of both Hospital Rock and Southern Bank are similar in texture to those of Transect II, much finer than those of most of the other topographic highs studied by the senior author in 1977.

For instance, the meiofaunal populations of 28 Fathom Bank, 28 Fathom Southwest Bank, Stetson Bank, and East Flower Garden Bank were much higher than those of the present study. The percentage of the total True Meiofaunal population contributed by the nematodes on the above four banks varied widely, from 28.4 to 96.4. It was found, however, that the low percentages were from southern stations. It was postulated, therefore, that these were downcurrent stations and that they received higher inputs of organic matter favoring development of harpacticoids and thus lowering the nematode percentage, as discussed in a later section dealing with Harpacticoida.

Nematoda

Abundance

The Nematoda were by far the most abundant taxon in the meiofauna of the STOCS area, averaging about 92% of the total abundance of True Meiofauna, and ranging from 48.5% to 100% at the transect stations. They far exceeded in numbers the next three taxocenes, as noted in Table 12.5.

Only 8.8% of the period samples from the transects contained less than 80% nematodes; Transect II for the year 1976 averaged 86.9% nematodes and was the only case of a transect averaging less than 90% in the two years.

TABLE 12.5

MAJOR TAXA OF THE MEIOBENTHOS - NUMBERS SHOWN ARE MEAN % OF TRUE MEIOFAUNA AT ALL STATIONS EXCEPT FOR THE POLYCHAETA, WHERE THE PERCENTAGE SHOWN IS OF TOTAL MEIOFAUNA. PERCENTAGES AND RANGES FOR BOTH BANKS ARE FOR 1976 AND 1977 COMBINED. GENERA ARE LISTED IN ORDER OF NUMERICAL ABUNDANCE.

	NEMATODA	HARPACTICOIDA	KINORHYNCHA	POLYCHAETA*
Transects				
1976 - Mean (%)	94.5	3.1	0.4	4.6
Range (%)	100.0 - 61.6	25.7 - 0.0	3.1 - 0.0	25.0 - 0.0
1977 - Mean (%)	90.7	4.1	0.6	4.1
Range (%)	100.0 - 55.9	15.4 - 0.0	7.3 - 0.0	16.3 - 0.0
Both Years				
Mean (%)	92.6	3.6	0.5	4.3
Principal Genera or Species	Sabatieria	Haloschizopera	Echinoderes	Paraonis gracilis
	Theristus	Enhydrosoma	Pycnophyes	Tharyx setigera
	Halalaimus	Pseudobradya	Semnoderes	Mediomastus californiensis
	Dorylaimopsis	Ameira	Trachydemus	Aedicira belgicae
	Neotonchus	Ectinosoma	Centroderes	Protodorvillea sp. A
	Terschellingia	Typhlamphiascus		[illegible] delta
	Synonchiella	Robertgurneyia		Aricidea cerruti
	Viscosia	Halectinosoma		Ampharete tentaculata
	Laimella	Thompsonula		Prionospio cristata
	Ptycholaimellus	Apodopsyllus		
		Leptopsyllus		
		Stenhelia		
Banks (Both Years)				
Mean (%)	84.1	8.5	0.6	5.4
Range (%)	100.0 - 40.9	36.0 - 0.0	3.3 - 0.0	16.7 - 0.0

*Percentages are of Total Meiofauna excluding Foraminiferida and Protozoa

The high percentage of nematodes in the samples was comparable to that found in muddy continental shelf areas in the Kerguelen Islands (de Bovée and Soyer, 1977) and off Massachusetts (Wigley and McIntyre, 1964) and also to Wieser's (1960) 18 m mud station in Buzzard's Bay, Massachusetts. Guille and Soyer (1968), however, found low nematode percentages (48 to 64%) in their sandy silt stations off Banyuls-Sur-Mer in the Mediterranean Sea. Our work demonstrated a marked increase in Nematoda when the sand content of the sediment is 60% or more by weight.

Taxonomic Composition

The ten most abundant nematode genera found in the STOCS area are listed in Table 12.5. *Sabatieria* occurred very commonly in sandy silts and muds, seemingly regardless of depth. This genus together with *Monhystera* were the most abundant nematode genera at both the 600 m and 800 m stations of Tietjen's (1976) Cape Lookout transect, and *Sabatieria* alone was the most abundant nematode genus of the adjacent Cape Fear transect of the same study. Wieser (1960) also found *Sabatieria* to be the dominant genus in the soft bottom of his deeper water stations. Not always found in deep water, species belonging to *Sabatieria* were found to comprise over 14% of the nematode fauna at the Niantic River North Shoals station and to be fairly common at the other three stations of Tietjen's (1969) study on the meiofauna of two estuaries on the northeast coast of the United States. Another of the ten most abundant genera of the STOCS area, *Laimella*, was found by Wieser to be characteristic of sandy substrates in Buzzard's Bay.

Harpacticoida

Abundance

The second most abundant taxon in the STOCS study was Harpacticoida.

Harpacticoid populations were proportionately much smaller than those of the nematodes, as shown in Table 12.5. Inversely to that of the nematodes, the proportion of harpacticoids was somewhat higher at Hospital Rock and Southern Bank, averaging 8.5% of the True Meiofauna for both banks together over 1976 and 1977, with a range extending from 0 to 36%. The high percentage of harpacticoids could have been more a result of having very reduced total meiofauna populations at these stations, thereby increasing the proportional effect of an occasional occurrence, rather than a true indication of increased harpacticoid abundance. Other studies of topographic highs in the Gulf of Mexico (Gettleson and Pequegnat, 1976; Pequegnat and Sikora, 1978), however, have indicated that there was increased abundance both of total meiofauna and proportion of harpacticoids at many stations of these banks, apparently due to organic enrichment of the sediments of downcurrent stations by the organisms concentrated on the bank proper.

Numbers of harpacticoids taken at the transect stations ranged from 0 to 97.4 individuals per 10 cm^2 in 1977. The sums of the means for all stations were 662 individuals in 1976 and 458.7 individuals in 1977. In 1976 harpacticoids were not sampled at 29 of the 111 stations, whereas they were totally absent from all replicates of 5 of the 111 stations in 1977. This was probably due to the doubling of the number of replicates to 4 in 1977, since in the 1977 data harpacticoids occur in 1 of the 4 replicates at 16 stations and in 2 of the 4 replicates at 21 stations.

Harpacticoid abundance in both numbers and proportionality to the total meiofauna in the STOCS area was comparable to that found in other continental shelf studies, especially those of de Bovée and Soyer (1977) and Dinet (1976). Studies differed in their explanations of harpacticoid abundance. Tietjen (1969) found harpacticoids to be more abundant in the coarser sediments of two estuaries, in contrast to Wieser (1960) and

McIntyre (1964) who found higher numbers of harpacticoids in the finer sediments of Buzzard's Bay and Loch Nevis on the Scottish west coast. Coull (1970) attributed higher abundance of harpacticoids to the presence of coarse carbonate sand, whereas Noodt (1957) found grain size to be less significant to harpacticoid dominance than the amount of organic carbon available.

Labile (readily available) organic carbon was not measured in the STOCS study. It would appear, however, from the upcurrent-downcurrent abundances of harpacticoids at studied topographic highs in the Gulf of Mexico (Pequegnat and Sikora, 1978) and from the much higher abundances of harpacticoids in the shallower, more productive inshore stations of the transects of the STOCS area than in the less productive offshore areas (Pequegnat and Sikora, 1977, 1979), that available organic carbon could be a major controlling factor on harpacticoid populations in the fine sediments of the northwestern Gulf of Mexico.

Taxonomic Composition

Most genera found in taxonomic analysis of Transect I and IV are listed in Table 12.5. Four of these genera, *Enhydrosoma, Typhlamphiascus, Haloschizopera* and *Stenhelia* were included in the sublittoral and isocommunity established by Por (1964) for the Harpacticoida. Por stated that the sublittoral muds extend "to a depth of some 150 meters, down to the edge of the continental slope, and are inhabited by a large number of species. It can be assumed that the leading forms which are present almost everywhere are species of *Bradya, Stenhelia, Haloschizopera, Enhydrosoma,* and *Cletodes*" (Por, 1964). At greater depths, a transitional fauna dominated by *Typhlamphiascus* and *Eurycletodes* was present. Another genus of Harpacticoida that occurred in the STOCS area and belongs to Por's sublit-

toral mud isocommunity (albeit not as abundantly as the four mentioned above) was *Cletodes*. The genera found in the STOCS area were also commonly found on the continental shelf of the Western Mediterranean (Guille and Soyer, 1968).

It appeared that differences in abundance of harpacticoids between Transect I and IV stations of the STOCS area may have been better understood upon analysis of their species composition (Venn, in preparation). It was noted by the junior author that while the major genera summed over both transects fit into Por's sublittoral mud isocommunity, certain genera of this group predominated at Transect I (*Ectinosoma, Enhydrosoma, Stenhelia*) and others at Transect IV (*Typhlamphiascus, Haloschizopera, Robertgurneya, Ameira*).

Kinorhyncha

Abundance

Kinorhyncha were not found to be very abundant in samples from the STOCS area, averaging about 0.5% of the taxa over all transect stations for both years (Table 12.5). They were even less abundant at the two bank stations, a total of 27 kinorhynchs being found from all the stations and sampling periods in 1976 combined, and 24 kinorhynchs in 1977. Wieser (1960) found most taxa of Kinorhyncha to be characteristic of soft bottom and, indeed, he found the Kinorhyncha to be the second most abundant major taxon (after Nematoda) in his study in Buzzard's Bay. Wieser's study was unique in this aspect from other subtidal soft bottom studies, particularly in continental shelf areas. In most studies (de Bovée and Soyer, 1977; Dinet, 1976; Marcotte and Coull, 1974; McIntyre, 1964) for the continental shelf or muddy bottoms, the Kinorhyncha overall made up a fraction of a percent or, at most, a very few percent of the population, far behind the

Harpacticoida.

Taxonomic Composition

Five genera of kinorhynchs were collected from the transect and bank stations of the STOCS study, as noted in Table 12.5. The taxonomy of Kinorhyncha is incompletely known. However, genera found in the STOCS area were similar to those found by McIntyre (1964) and by Wieser (1960).

Polychaeta

Abundance

The Polychaeta was the second most abundant taxon of the Total Meiofauna (excluding the Foraminiferida) of Transects I and IV, totaling 3593 individuals collected over the two years of the study. As with the nematodes and the Mean True Meiofauna, the highest abundances were in the shallow zone (0 to 30 meters), with numbers decreasing in the offshore stations. Abundances ranged from 0 to 115.9 individuals per 10 cm^2 with a mean of 7.0 individuals per 10 cm^2 in 1976, and from 0 to 47.6 individuals per 10 cm^2 with a mean of 5.8 per 10 cm^2 in 1977.

Hospital Rock had a total of 218 polychaetes collected in the two years of sampling, while Southern Bank samples contained only 145 polychaetes totaled over the two years. The mean numbers of polychaetes per station for Hospital Rock and Southern Bank were 3.3 individuals per 10 cm^2 and 4.0 per 10 cm^2, respectively for 1976 and 1.7 polychaetes per 10 cm^2 and 4.0 per 10 cm^2, respectively for 1977. These numbers were low compared with those of other bank studies in the Gulf of Mexico (Gettleson and Pequegnat, 1976; Pequegnat and Sikora, 1978). In yet other studies (Dinet, 1976; Tietjen, 1969, 1971; Guille and Soyer, 1978; McIntyre, 1964; Coull, 1970; Soyer, 1971; de Bovée and Soyer, 1977) the polychaetes usually ranked third in abundance, behind Nematoda and Harpacticoida, and were

numerically larger than those of the STOCS.

Taxonomic Composition

Approximately 65 species of polychaetes occurred in the meiofauna samples of the STOCS area, of which the numerically dominant ones are listed in Table 12.5. *Paraonis gracilis* was the most common polychaete found in the meiofauna of the STOCS area. The same species was also the most common found in McIntyre's (1964) study on similar substrates in Scotland.

Relationship to Environmental Parameters

Abiotic Factors

Meiofauna are controlled by many abiotic factors, the most important usually being temperature, salinity, depth, oxygen concentration, and sediment (McIntyre, 1969; Hulings and Gray, 1971). Pearson correlation coefficients for all of the parameters of the STOCS area vs. one another indicated that meiofaunal density was significantly correlated ($P < 0.05$) to many abiotic factors (Table 12.6).

When making a study in a particular area over time, such as the STOCS study, these factors may have synergistic effects and it is difficult to isolate relationships with particular environmental parameters. For example, both temperature and salinity change with depth, as does oxygen concentration which also varies with current activity and sediment type. Tietjen (1976) has stated that "While substratum *per se* might have a direct influence on the species composition of a particular substratum. . . . sediment type may be regarded mainly as an indicator of a particular suite of environmental conditions at the time of sampling" and that in addition "sediment texture is thought to be a reasonably good indicator of bottom current activity and of organic content of the sediment." With

this in mind, we have chosen to look specifically at certain aspects of the sediment in relation to the meiofauna populations of the STOCS.

Sediment

Increase in Nematode Abundance at 60% Sand

In 1976 a good correlation was found between the abundance of nematodes and the amount of sand in the sediments (Pequegnat and Sikora, 1977). Using linear regression analysis, the observation was refined, and it was shown that the influence of sand was not significant to meiofauna abundance until it reached 60% (Figure 12.9). The dramatic increase in nematodes at 60% sand was repeated in 1977 data (Figure 12.10), although there was more scatter around the line. A higher percentage of sand indicated a more heterogeneous environment with larger and more numerous interstices and deeper penetration of oxygenated water into the sediment, providing more potential niches for different taxa. This resulted in the abundant and diverse populations found on Transect IV (Pequegnat and Sikora, 1977) and also at the East Flower Gardens of the Gulf of Mexico (Pequegnat and Sikora, 1978). We found that the Group 1 (high abundance) stations of the aforementioned three-way ANOVA corresponded to those stations which had higher percentages of sand in the sediments and a larger mean grain size, whereas the Group 2 stations (low abundance) had sediments of finer texture.

As pointed out by Moore (1931), the very fine material in muds is often converted into fecal pellets before or after settling to the bottom. An area where the fine muds are bound up into sand sized or larger fecal pellets would present quite a different habitat to the benthos, particularly the meiobenthos, than one where the fine particles were generally unconsolidated. Therefore, the sediment analysis may not always be reflect-

TABLE 12.6

ENVIRONMENTAL PARAMETERS SIGNIFICANTLY ($p \leq .05$)
CORRELATED WITH MEIOFAUNAL DENSITY

NEGATIVE CORRELATION	POSITIVE CORRELATION
Biotic Factors	**Biotic Factors**
Infauna Equitability	Infauna Species Number
	Infauna Density
	Fish Species Number
	Fish Biomass
	Total Bacteria
	Oil-degrading Bacteria
Abiotic Factors	**Abiotic Factors**
Mean Grain Size (Ø)	Grain Size Skewness
% Silt	Grain Size Kurtosis
% Clay	% Sand
% Ø Greater than 10.6	Sand/Mud Ratio
Bottom Water Salinity	Silt/Clay Ratio
Depth	Bottom Water Temperature
Total Organic Carbon	Bottom Water Temperature Standard Deviation
Bottom Water Nitrogen	Bottom Water Salinity Standard Deviation
Sediment Cadmium	Sediment Delta ^{13}C
Sediment Chromium	Bottom Water Dissolved Oxygen
Sediment Cobalt	Bottom Water Total Pheophytin
Sediment Iron	
Sediment Manganese	
Sediment Nickel	
Sediment Lead	
Sediment Vanadium	
Sediment Zinc	

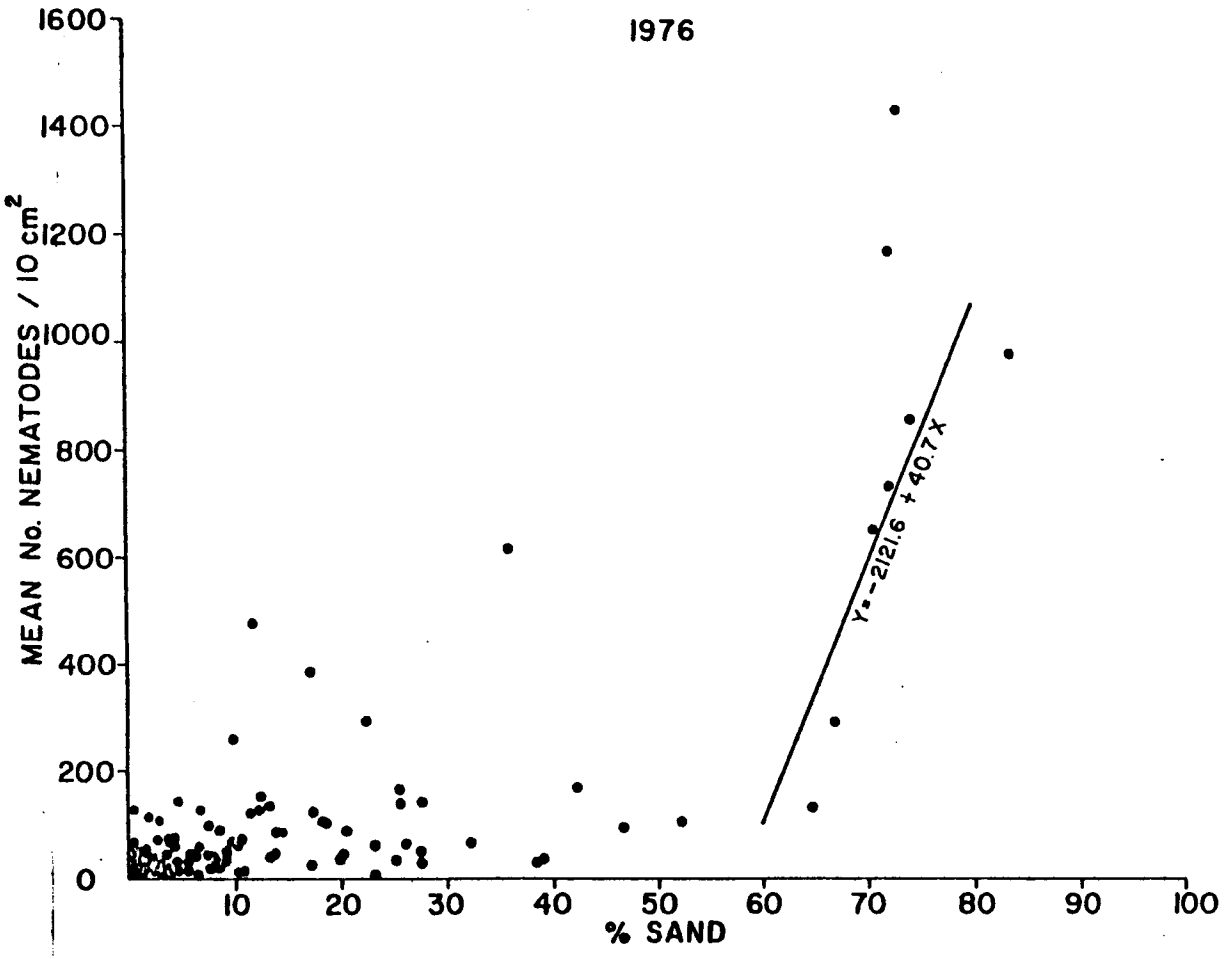


Figure 12.9 Plot of Mean Numbers of Nematodes vs. the Percent of Sand Found at Individual Stations for 1976. (Stations from Winter not Considered due to Differing Sediment Analysis.) $r^2 = .315$, $n = 7$.

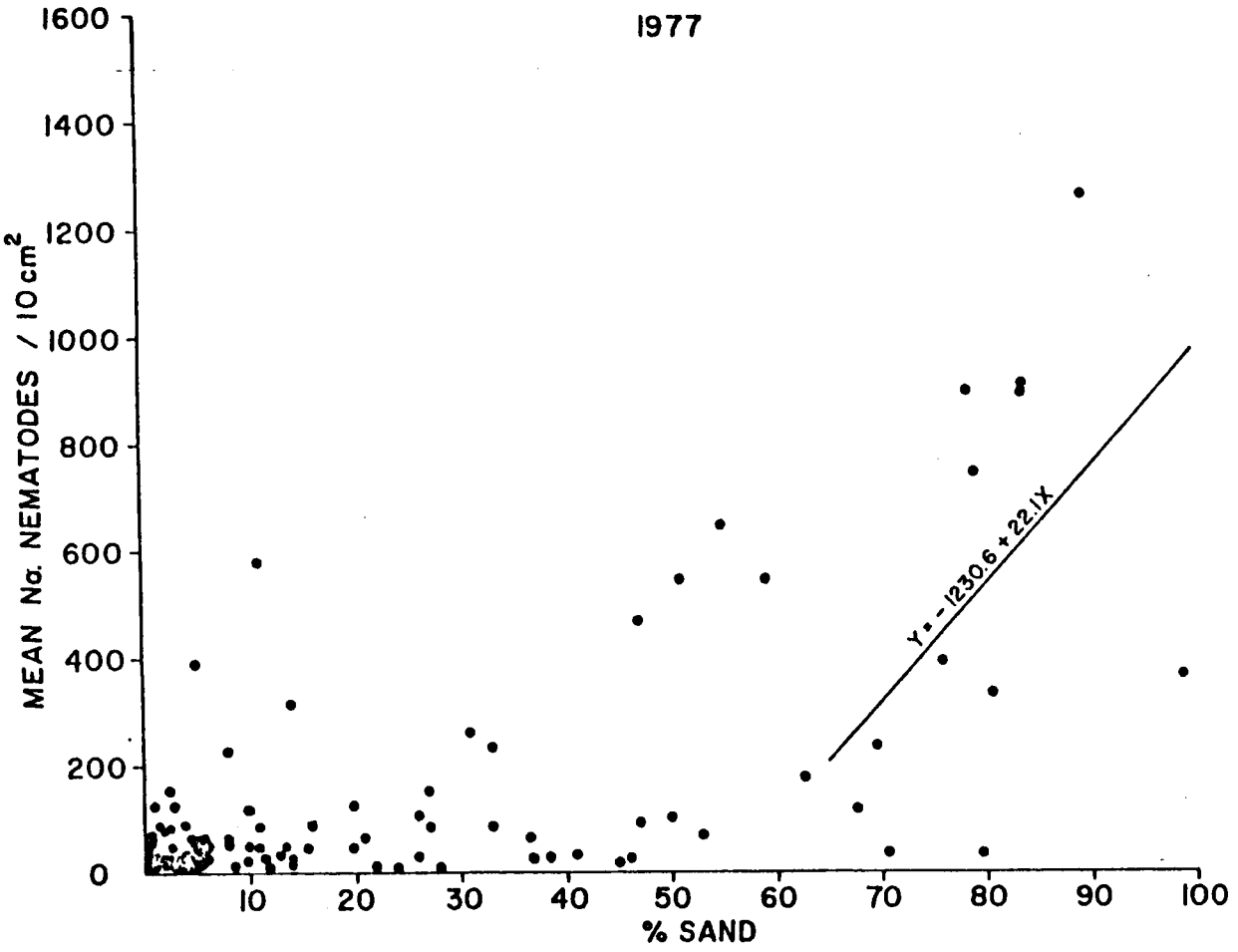


Figure 12.10 Plot of Mean Numbers Vs. the Percent of Sand Found at Individual Stations for 1977. (All Seasonal and Monthly Stations are Considered.) r^2 = .278, n = 13.

ing the true environmental characteristics.

Decrease in Meiofaunal Numbers With Increase in Sediment Trace Metals

Abundance of meiofauna was negatively correlated at the 95% confidence level to all trace metals analyzed in the sediments of the STOCS, excepting barium, meiofaunal density decreasing offshore and trace metal content increasing. The phenomenon, however, is most likely only an incidental relationship, since the sediment generally increases in clay content with distance offshore (Berryhill, 1976, 1977). The adsorption of trace metals into clays is a well-documented occurrence (Riley and Chester, 1971), as is the small meiofaunal abundance found in clay sediments (Moore, 1931; Wieser, 1960; Tietjen, 1971).

Harpacticoid/Nematode Ratio-Is It Useful as an Environmental Indicator?

The possibility of using the ratio of benthic copepods (harpacticoids) to nematodes as an index of pollution as proposed by Parker (1975) or as an indicator of any environmental perturbation has been proposed in previous studies (Gettleson and Pequegnat, 1976; Pequegnat and Sikora, 1977, 1978, 1979). Nematodes and harpacticoids are the two most abundant meiofaunal components in the Gulf of Mexico subtidal studies to date, and therefore, the most reliable to use here. The concept in using a ratio between two taxa is much the same as that associated with percentages of fauna represented, with the exception that in a ratio of two components one might be able to more readily decipher the cause of a perturbation. In previous Gulf of Mexico studies, nematodes were consistently found to be correlated with the sediment, whereas harpacticoids were not (Gettleson and Pequegnat, 1976; Rogers and Darnell, 1973; Pequegnat and Sikora, 1977, 1979). However, in the present study using Pearson correlation coefficients, both nematodes and harpacticoids were significantly correlated

with the same sediment parameters (mean grain size, skewness, kurtosis, percent sand, percent silt, percent clay, percent Ø greater than 10.6, sand/mud ratio, silt/clay ratio), with the exception that harpacticoids were also significantly correlated with sediment grain size standard deviation whereas nematodes were not. Any activity bringing about a change in the appropriate sediment parameters at a station will affect the harpacticoid:nematode ratio. Conversely, if those parameters remain constant and the ratio changes, one could look for another kind of environmental perturbation. Using data from Tietjen (1969) for a single station over time, we found that sediment changes did correspond to changes in the harpacticoid:nematode ratio.

In order for a ratio such as the harpacticoid:nematode ratio to be meaningful, strict conditions must be met. Proper sampling and extraction methods must be used and the type of sediments taken into account. One can say generally that soft bottoms have a fairly low ratio, sandy sediments somewhat higher and coarse carbonate sediments even higher (Coull, 1970). To be more specific than that with inter-area comparisons, however, is probably not valid. Studies by different investigators have shown quite a lack of uniformity with respect to types of samples, sieve sizes used, even depth of the sediment which is sampled.

Nematodes are generally found much deeper in the sediment than harpacticoids, which are usually limited to the upper few centimeters where there is higher oxygen availability (Tietjen, 1969), so that even a sample from a single station would show a different ratio with different depths of sediment samples (McLachlan *et al.*, 1977). Therefore, the harpacticoid:nematode ratio should only be used to trace effects on a single station or area over time with uniform sampling and sample treatment. Approached in this way it may allow some insight into environmental per-

turbations affecting the area.

Speculations on Possible Interactions with Recommendations

Usefulness of Available Organic Carbon as a Parameter

Total organic carbon includes many refractory compounds that are not utilizable by animals. Therefore, the negative correlation of sediment carbon with True Meiofauna density was difficult to interpret. Studies which measured available organic carbon (Coull, 1974; Noodt, 1957) showed that the available organic carbon content and meiofaunal density were positively correlated. In order to better understand the biological implications of sediment organic carbon and certainly in order to build a model reflecting accurately the trophic structure of the STOCS, it would be vital to quantify the labile organic compounds.

Trophic Interactions

There are some indications that the meiofauna may contribute more to the matter and energy cycles of the sea than was envisaged by earlier investigators (Perkins, 1958; McIntyre, 1969). Recent caging experiments (Bell and Coull, 1978; Rubright, 1978, Buzas, 1978) have shown that meiofaunal populations, particularly the Nematoda, the Foraminiferida and the Polychaeta, are substantially reduced by predation and, therefore, probably represent an important food source (Buzas, 1978). Since the STOCS study was designed as a baseline survey, and therefore its sampling was not appropriate for delineation of processes and interactions between compartments of the system, we cannot from our data ascertain with certainty the role of the meiofauna in the trophic structure of this marine ecosystem. Comparison of our data with those of other compartments in the STOCS study, however, did indicate some relationships worthy of future investigation.

In a study of some banks in the Gulf of Mexico, sipunculids were negatively correlated with Total Meiofauna, indicating that they were possibly feeding on the meiofauna. Sipunculids and meiofauna in the STOCS did not show this correlation. However, macroinfaunal density and species diversity did show a high correlation with meiofaunal density (Table 12.6).

Pequegnat and Sikora (1977) pictorially represented the 1976 Transect II nematode populations through space and time and hypothesized large populations of predators moving in a pattern through time (Figure 12.11). Recent evidence has indicated that animals termed detritovores may be getting their energy input not from the detritus *per se* but from meiofauna (mainly nematodes) in the sediment with the detritus (McIntyre and Murison, 1973; Sikora, 1977; Bell and Coull, 1978, Sikora *et al.*, 1977). Taking the abundances on Transect II over 1976 of *Penaeus aztecus* and of eight species of benthic fish which we grouped together as "Fish Detritovores" (Table 12.7), we compared them to the aforementioned nematode population abundances. A direct comparison was not feasible since, given that the hypothesis was correct, the nematode abundance would still depend on the amount of time that the predators had been there. However, an examination of the abundance pattern of the predators over time versus that of the reduced abundances of the nematodes might imply a trophic relationship. Figures 12.12 through 12.14 illustrate the abundances over time and transect for *Penaeus aztecus*, Fish Detritovores and both groups combined, respectively. The general pattern of movement inshore during the summer months and then offshore again in the winter is evident, particularly with *Penaeus aztecus*.

An Ecosystem Model

One of the glaring weaknesses of many quantitative models of benthic

TABLE 12.7

FISH DETRITOVORES

Micropogon undulatus
Stenotomus caprinus
Sphaeroides parvus
Diplectrum bivittatum
Porichtys porossissimus
Symphurus plagiusa
Synodus poerji
Halieutichthys aculeatus

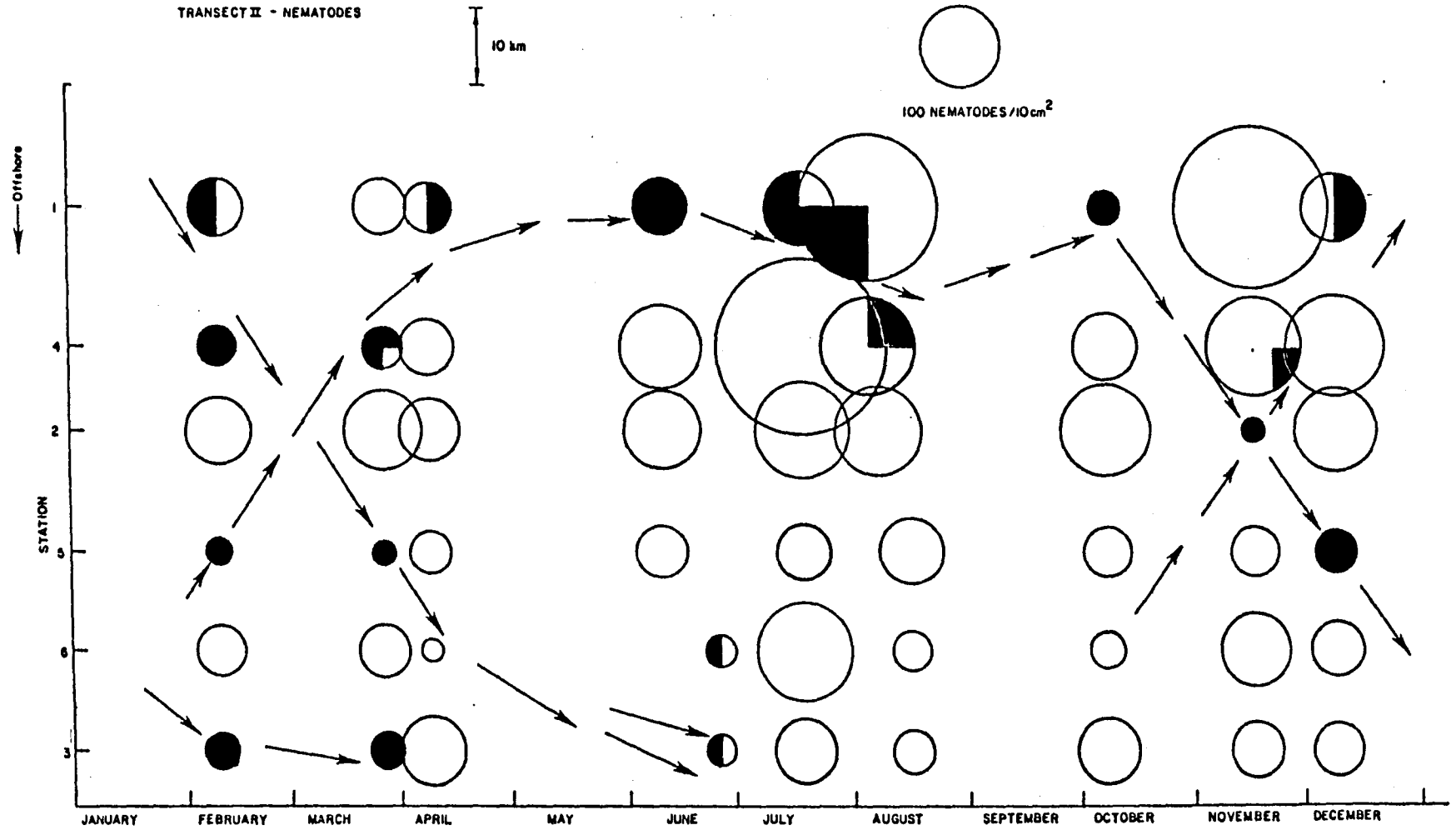


Figure 12.11 Transect II through time (abscissa) and space (ordinate), indicating population densities of nematodes. Shaded areas indicate nematode population values lower than expected. Arrows indicate pattern of movement of large populations of hypothetical predators which could be responsible for lowered nematode numbers. Data are from 1976.

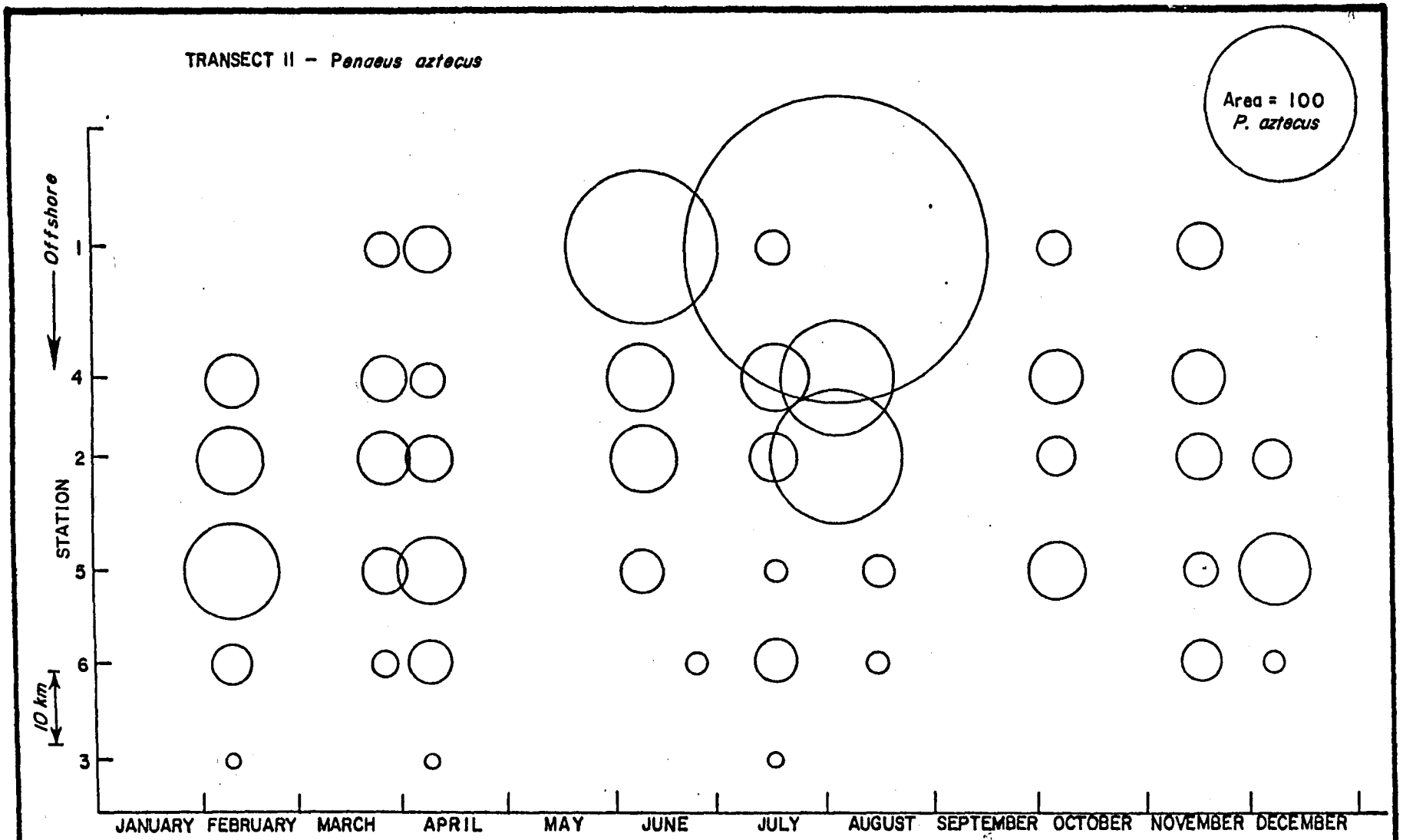


Figure 12.12 Transect II through time (abscissa) and space (ordinate), indicating population densities of Penaeus aztecus. Data are from 1976.

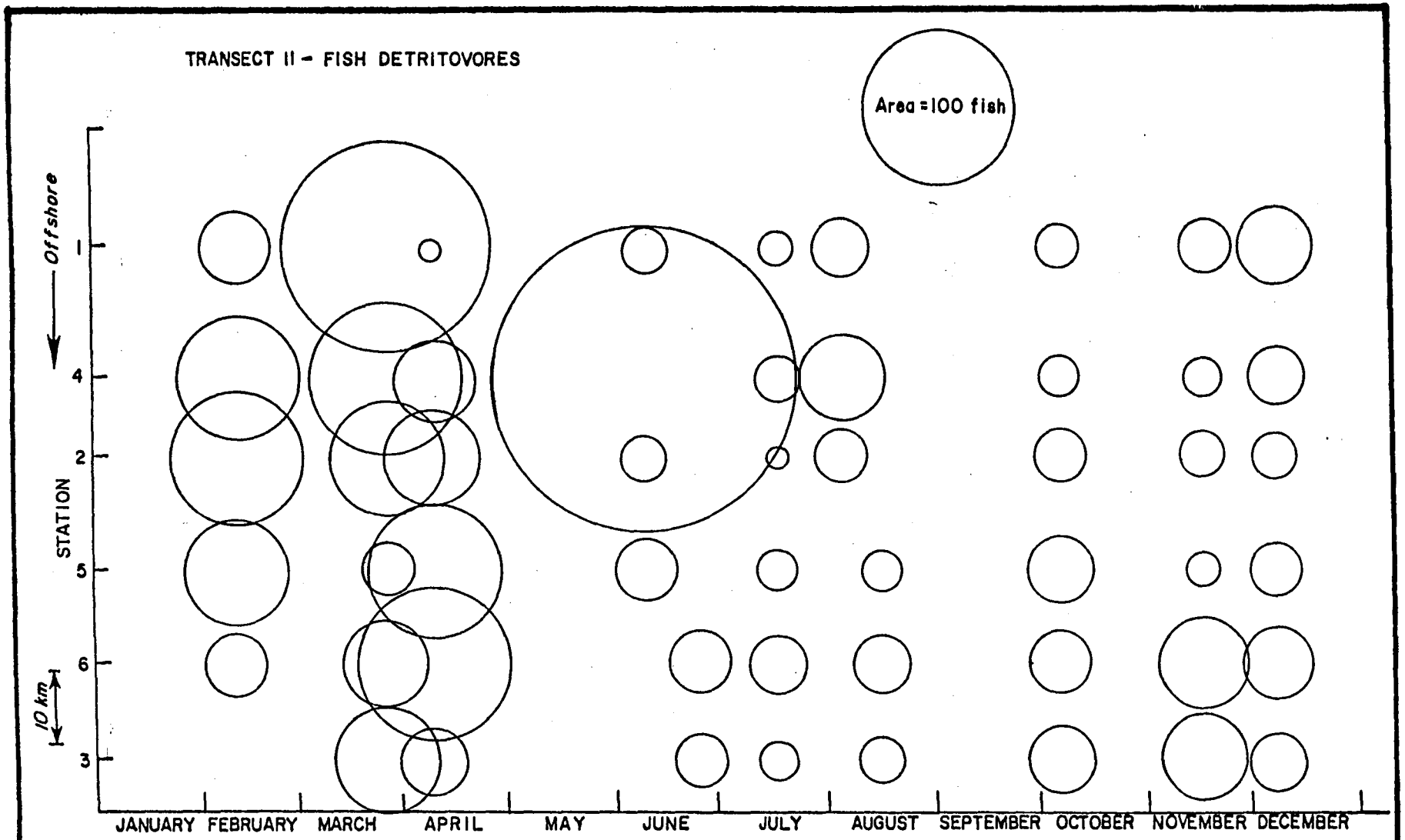


Figure 12.13 Transect II through time (abscissa) and space (ordinate), indicating population densities of Fish Detritovores (see text). Data are from 1976.

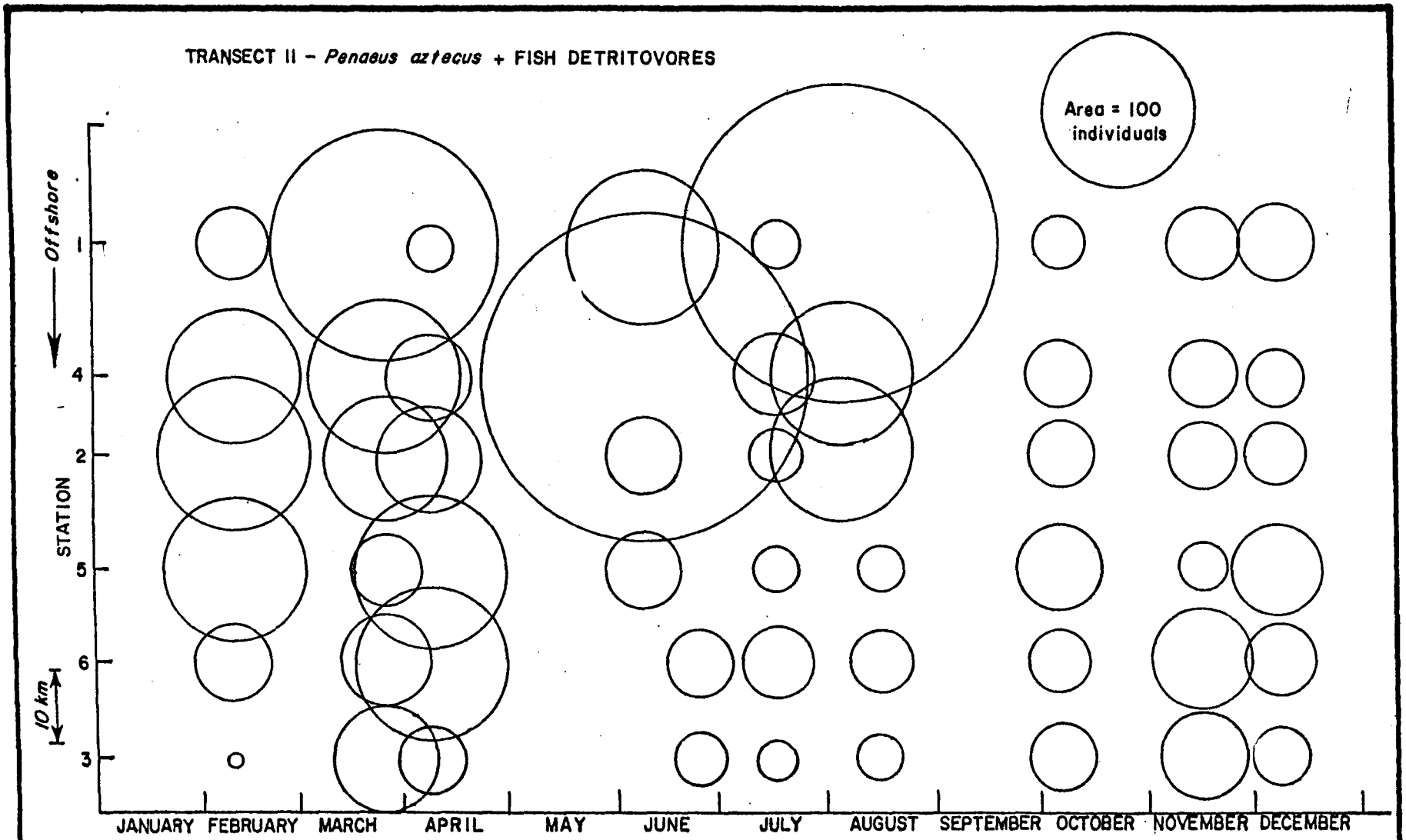


Figure 12.14 Transect II through time (abscissa) and space (ordinate), indicating combined population densities of Penaeus aztecus and Fish Detritovores.

marine ecosystems is that they are based upon too little truly quantitative data and lack any consideration of the links between nonliving organic detritus and the macrofauna, particularly the meiofauna. This is lamentable in view of the fact that the meiofauna can be quantified and its role as food can be demonstrated by antibody responses of the predator. On the one hand then, it should be possible to relate the dropping of meiofaunal populations on the shelf with the appearance there of juvenile shrimp. After an appropriate short interval it should then be possible to ascertain by immune responses whether or not the shrimp have been consuming the meiofauna. The latter is far from conjecture. Rubright (1978) has shown that developing shrimp in mariculture ponds at Angleton, Texas do indeed consume the meiofauna. The link on the other side of the chain would relate the growing meiofaunal populations in July-August with reduction in the microflora by determining trend changes of biomass, using the ATP method (Sikora *et al.*, 1977).

CONCLUSIONS

1. Meiofaunal populations of the STOCS area were remarkably similar in size and predominant taxa during the years 1976 and 1977.

2. The STOCS meiofauna exhibit population peaks in March, July-August, and November. The seasonal peaks are highest at inshore stations.

3. Populations of the STOCS meiofauna decrease with increasing depth of water.

4. Consistent with the findings of other investigators, the Nematoda are by far the most abundant taxon in the STOCS meiofauna, averaging about 92% of the total of True Meiofauna.

5. The Harpacticoida are the second most abundant taxon of the True Meiofauna. This finding is consistent with other studies.

6. Nematode abundance increases markedly in sediments having 60% or more sand.

7. The harpacticoid:nematode ratio of abundance is a potential indicator of environmental disturbance when applied on a station-by-station basis.

8. Space-time abundances of certain demersal fish, the brown shrimp, and nematodes vary in such manner as to support the conclusion that the nematodes are a food source of the fish and shrimp.

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CHAPTER THIRTEEN

BENTHIC INVERTEBRATES
MACROINFAUNA AND EPIFAUNA

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ABSTRACT

Benthic infaunal and epifaunal invertebrate communities of the STOCS were assayed on a monthly and/or seasonal basis for a three year period (1975-1977). Invertebrates of the STOCS were described taxonomically by phylum and by community. Temporal and spatial variations in community structure and taxonomic composition were discussed. Relative stability of infaunal communities appeared greater than epifaunal communities. Both infaunal and epifaunal communities were distributed primarily by depth or depth-related factors. Sediment parameters, particularly grain size, apparently were the major factors, other than depth, affecting infaunal distribution. Both infaunal and epifaunal communities were distributed in bands parallel to the curving Texas coast. Infaunal and epifaunal communities found at various depths were composed of varying numbers of groups of organisms. Some groups were ubiquitous or nearly so while others were limited primarily by depth and/or sediment. Many shallow stations had highly unique communities, usually dominated by a small number of species. Most intermediate and deep stations had relatively homogenous communities within their respective depth zones. Infaunal biomass (standing crop) is thought to be very small (*e.g.* 4 grams/m^2 wet weight). Interactions between invertebrate fauna and a suite of physical, chemical and biological parameters were examined.

INTRODUCTION

The wide-ranging continental shelf studies funded by the Bureau of Land Management (BLM) as well as other multidisciplinary marine ecosystem studies (Prutar and Alverson, 1972; Pararas-Carayannis, 1973) have heavily stressed the need to assess benthic invertebrate fauna. As stated by a sub-committee of the International Council for the Exploration of the Sea (ICES Cooperative Research Report #75, 1978), "a large number of field studies are documented that have as their basis the identification and enumeration of the species occurring in a community, many of which are concerned with the relatively sedentary benthos on the basis that these species will be unable to avoid adverse conditions. Thus, the status of such populations at any point in time is likely to reflect the conditions that prevailed over a relatively long preceding period. These benthic populations may also be important components of the marine food webs". The benthic invertebrate fauna was one of the most rigorously studied, in terms of time span, spatial scale and sample number, aspects of the south Texas outer continental shelf.

Goals for the benthic invertebrate portion of the STOCS study were stated (Holland *et al.*, 1979) as: 1) the identification and quantification of macroinfauna and epifauna inhabiting the STOCS region; 2) the delineation of faunistically similar geographical regions within the study area and concommitant identification of faunal assemblages characteristic of these areas; and 3) the correlation of observed distributions of invertebrate populations with biological, chemical and physical factors assayed in the area. This paper integrates the results of three years of data, (Holland *et al.*, 1976, 1977, 1979) so that a coherent statement concerning each of the stated goals can be made.

Literature Review

Historical information concerning benthic invertebrates of the Texas coastal waters and the Gulf of Mexico, in general, is relatively scarce, with some groups of organisms and geographical areas better represented than others. Any statement concerning the historical study of benthic invertebrates in the Gulf of Mexico should express the greater emphasis on the larger, often commercially important epifauna and the relative paucity of of studies of the northwestern Gulf when compared to the southeastern Gulf. Several studies stand out in historical significance including biological investigations, under the supervision of A. Agassiz, from the U.S. Steamer *Blake* (1877-1879) reported variously in the first 50 volumes of the Bulletin of Comparative Zoology, Harvard University. Historical reports of various major taxa include those by Ehlers (1878, 1887), and McIntosh (1885) for annelids and Dall (1889, 1903), Roemer (1849), Singely (1893), Mitchell (1894) for molluscs. More recent surveys of general interest to the Texas gulf coast include Hildebrand (1954), Springer (1951), Springer and Bullis (1956), Compton and Bradley (1964), and Defenbaugh (1976). Galtsoff's (1954) general treatise was of great benefits.

METHODS

The benthic invertebrate facet of the multidisciplinary STOCS study was, in fact, two studies, utilizing different collecting techniques, sample numbers, etc., for assessing the macroinfauna and epifauna of this region. By definition, the macroinfauna included these organisms collected in our bottom sampler (Smith-McIntyre) while the epifauna were those organisms collected in the box otter trawls. Data from each group were temporally and spatially analogous, but analyzed separately. As such, it will be reported

separately herein.

Collection methods were essentially similar over the three year span of the study. Numbers of samples taken and their temporal and spatial distribution changed somewhat annually (Table 13.1).

Infaunal samples were collected with a Smith-McIntyre bottom sampler (0.1 m^2; 0.0125 m^3) consistently through the three year study. They were sieved through a 0.5 mm mesh sieve on board the R/V LONGHORN. Standard techniques (Holme and McIntyre, 1971) were utilized for treating and sorting samples. Biomass measures were made on total infaunal samples and selected species during the latter part of the study.

Epifaunal samples were collected with a standard (10.7 m width) Texas box otter trawl (Table 13.1). During the first year and the winter collection of the second year, the trawl had a liner (4.8 mm stretched mesh). Due to fouling problems the liner was removed before the spring collection of the second year of the study. Each trawl was of 15 minutes duration at minimal speed required to maintain headway, usually less than two knots. Invertebrates from the trawl samples were treated using standard techniques (Holme and McIntyre, 1971). Biomass measures of wet weight, dry weight and ash-free dry weight were made on selected species during the latter part of the study.

Benthic community structure parameters of species richness, density, species diversity (Pielou, 1966), and equitability (Lloyd and Ghelardi, 1964) were assayed during the study. By combining a diversity index with measures of species richness (number of species) and evenness (distribution of relative abundance of species) a reasonable comparison between communities can be accomplished. Comparisons of structural parameters were made on spatial and temporal basis by visual trend analyses of annual parameter plots

TABLE 13.1

BENTHIC INVERTEBRATE SAMPLING - TRANSECT STATIONS

INFAUNA

	Seasonal (3)		Monthly (6)		
	Stations	Replicates	Stations*	Replicates	Total
1975	12	4	0	0	144
1976	25	6	6	6	666
1977	25	6	0	0	450

EPIFAUNA

	Seasonal (3)			Monthly (6)		
	Stations	Replicates	D/N**	Stations*	Replicates	Total
1975	12	2	1/1	0	0	72
1976	25	2	1/1	6	4	294
1977	25	2(4*)	1/1(1/3*)	6	3	294

* Transect II Stations
** D/N = day/night

(Holland *et al.*, 1976, 1977, 1979) and standard statistical procedures (ANOVA) on multi-year data. These analyses were utilized primarily to achieve the first goal of the benthic studies as previously stated. To achieve the second goal of this project several analysis techniques including cluster, ordination, and discriminant analyses were utilized. Detailed descriptions of these techniques are provided by Holland *et al.* (1976, 1977). The integrative effort of assessing correlations between benthic data and that of other facets of the program utilized basic linear collection techniques (Downie and Heath, 1965), multicurvilinear techniques for some epifaunal species and discriminant analyses.

RESULTS

Taxonomy

Nine hundred and seventy three (973) taxa of benthic invertebrates representing 14 phyla were delineated during this study. Of the 14 phyla collected, six accounted for 98.85% of the taxa delineated and included: Mollusca, Annelida, Arthropoda, Echinodermata, Nemertinea, and Sipuncula. The remaining eight phyla accounted for 1.15% of the total taxon and included: Porifera, Cnidaria, Platyhelminthes, Ectoprocta, Phoronida, Brachiopoda, Echiuridea, and Chordata. Based on current taxonomic breakdown of 973 taxa, the polychaetous annelids accounted for over 40% of the total species richness of benthic invertebrates of the STOCS. The crustaceans and molluscs comprised approximately 34% and 18% of the total number of taxa, respectively.

Of the 837 infaunal species collected during the study (129,081 individuals), 122 species comprised better than 90% of the total individuals. Polychaetous annelids (69 species) made up over 56% of these numerically dominant taxa. Crustaceans (28 species) and molluscs (20 species) comprised

approximately 23% and 16% respectively. An examination of only transect data from 1976 and 1977 showed similar trends for polychaetes, crustaceans and molluscs. They each represented 59%, 17%, and 18% of the numerically dominant taxa respectively. The 10 most numerically dominant infauna are presented in Table 13.2.

Of 163 epifaunal species (67,694 individuals) collected during this study, 12 species (7.98%) comprised better than 90% of the individuals. Ten decapod species, a mollusc and an echinoderm represented the vast majority of the individuals collected. The 10 most numerically dominant epifauna are presented in Table 13.2.

The number of infaunal taxa and individuals collected increased due to increased sampling during the second year of the study and remained at similar levels during the third year. Epifaunal collections produced similar numbers of taxa and individuals in all three years.

Community Structure

Decided differences in the basic pattern of aggregation were observed between infaunal and epifaunal collections. Infauna had much greater species richness and density. The dominant infaunal species group (comprising 90% of the total individuals) contained twice as many species on a percentage basis than did the dominant species group of epifauna. The epifaunal group showed far more temporal and spatial variability in the basic structure parameters.

Structural patterns of both infaunal and epifaunal communities showed variations in both time and space. Statistical analyses of data from the seasonal collections of 1976 and 1977 were employed with visual inspection of community structural parameters presented graphically by year in annual

TABLE 13.2

THE TEN MOST ABUNDANT INFAUNAL AND EPIFAUNA TAXA COLLECTED FROM THE STOCS STUDY AREA IN DECREASING ORDER OF ABUNDANCE

Infaunal	Epifaunal
Magelona phyllisae	*Trachypenaeus similis*
Paraprionospio pinnata	*Sicyonia dorsalis*
Lumbrinereis parvapedata	*Penaeus aztecus*
Mediomastus californiensis	*Acetes americana*
Sipunculida	*Callinectes similis*
Nemerteanea	*Solenocera vioscai*
Ampelisca agassizi	*Portunus spinicarpus*
Paraonis gracilis	*Amusium papyraceus*
Tellina versicolor	*Squilla empusa*
Abra aequalis	*Squilla chydaea*

reports (Holland *et al.*, 1976, 1977, 1979). Statistical treatment of seasonal and monthly data from 1976 for Transect II stations was also utilized to assess community and population variability.

There was a high degree of similarity in basic infaunal community patterns from year to year. There was, of course, some variation among the various parameters. Data from two groups of stations, representing inshore and offshore communities, are presented in Tables 13.3 and 13.4. Inspection of these data indicate less temporal variation than spatial for most parameters, particularly in the inshore stations (Table 13.3). A randomized block analysis of variance of the seasonal infaunal data showed significant ($P < 0.05$) variability between all inshore community parameters spatially and only the number of individuals temporally (Table 13.3). Offshore, infaunal community structure showed significant temporal and spatial differences in most parameters (Table 13.4). Results of significant differences between means (Duncan's New Multiple Range Test) for various infaunal parameters, are presented in Table 13.5. Nine collections during 1976 were made at each station on Transect II. No significant ($P < 0.05$) differences with collection (time) were found for species richness, density or diversity. Five stations (omitting Station 6 due to program limitations) were analyzed for spatial variations and all three community parameters were seen to have significant variations along Transect II.

Six infaunal populations at the innermost stations (1, 4 and 2) on Transect II were analyzed (ANOVA) for significant variations in distribution through the nine collections in 1976 and across the five replicates (omitting the sixth replicate due to program limitations) collected at each site and time. Four species, *Paraprionospio pinnata, Ampelisca abdita, Cossura delta* and *Nephtys incisa* were found to have significant variations between

TABLE 13.3

STRUCTURAL PARAMETERS OF INFAUNAL COMMUNITIES FROM INSHORE STATIONS*
(<49 m WATER DEPTH) 1976-1977

SPECIES

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	88	33	104	114	84.8	36.1
Spring 1976	152	40	209	229	157.5	84.9
Fall 1976	113	39	188	201	135.3	75.0
Winter 1977	95	45	164	187	122.8	64.9
Spring 1977	129	43	165	186	130.8	63.1
Fall 1977	75	65	204	206	137.5	78.1
$\bar{X}$	108.7	44.5	172.3	187.2		
S	28.5	11.0	38.4	39.1		

INDIVIDUALS

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	2037	442	2095	1439	1503	767
Spring 1976	4292	884	6772	3691	3909	2418
Fall 1976	1865	454	6023	2875	2804	2364
Winter 1977	2283	454	4634	3084	2613	1739
Spring 1977	3167	526	5675	2278	2911	2144
Fall 1977	2143	434	4475	2947	2589	1471
$\bar{X}$	2631	532	4946	2719		
S	932	175	1641	773		

DIVERSITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	4.15	3.45	3.51	4.99	4.03	.72
Spring 1976	4.77	2.60	4.94	6.05	4.59	1.40
Fall 1976	4.01	3.38	5.05	5.44	4.47	.94
Winter 1977	4.03	4.00	4.90	5.22	4.61	.59
Spring 1977	4.07	3.58	4.81	5.86	4.58	.99
Fall 1977	3.52	4.55	5.64	5.85	4.89	1.10
$\bar{X}$	4.09	3.59	4.81	5.57		
S	.40	.65	.71	.42		

EQUITABILITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	.3068	.4848	.1635	.4211	.3441	.1411
Spring 1976	.2697	.2250	.2249	.4410	.2902	.1028
Fall 1976	.2124	.4103	.2660	.3284	.3043	.0851
Winter 1977	.2632	.5333	.2744	.3048	.3439	.1275
Spring 1977	.2016	.4186	.2606	.4731	.3385	.1282
Fall 1977	.2267	.5538	.3725	.4272	.3951	.1355
$\bar{X}$	.2467	.4376	.2603	.3993		
S	.0401	.1193	.0685	.0669		

*Stations 4/I, 1/I, 2/I, 1/II, 4/II, 2/II, 4/III, 1/III, 5/III, 4/IV, 1/IV and 5/IV.

TABLE 13.4

STRUCTURAL PARAMETERS OF INFAUNAL COMMUNITIES FROM OFFSHORE STATIONS*
(> 49 m WATER DEPTH) 1976–1977

SPECIES

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	54	27	30	73	46.0	21.7
Spring 1976	51	53	45	85	58.5	18.0
Fall 1976	63	53	67	135	79.5	37.5
Winter 1977	91	58	60	133	85.5	35.1
Spring 1977	91	83	55	121	87.5	27.2
Fall 1977	66	61	50	128	76.3	35.1
$\bar{X}$	69.3	55.8	51.2	112.5		
S	17.7	18.0	12.9	26.7		

INDIVIDUALS

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	102	37	66	290	124	114
Spring 1976	155	135	112	269	168	70
Fall 1976	135	130	261	529	264	187
Winter 1977	324	155	173	479	283	151
Spring 1977	303	217	194	460	294	121
Fall 1977	237	204	138	511	241	128
$\bar{X}$	209	146	157	423		
S	92	64	68	114		

DIVERSITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	5.40	4.56	4.54	5.19	4.92	.44
Spring 1976	4.91	5.17	4.99	5.58	5.16	.30
Fall 1976	5.43	5.28	5.25	6.01	5.49	.35
Winter 1977	5.86	5.28	5.27	6.10	5.63	.41
Spring 1977	5.89	5.78	5.27	5.99	5.73	.32
Fall 1977	5.36	5.17	5.05	5.77	5.34	.32
$\bar{X}$	5.48	5.21	5.06	5.78		
S	.36	.39	.28	.34		

EQUITABILITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	1.1200	1.2500	1.1000	.7671	1.0593	.2058
Spring 1976	.9020	1.0000	1.0222	.8588	.9458	.0780
Fall 1976	1.0000	1.0755	.8657	.7259	.9168	.1540
Winter 1977	.9670	1.0000	.9833	.7820	.9331	.1016
Spring 1977	1.0000	1.0000	1.0162	.8017	.9454	.1021
Fall 1977	.9545	.9016	1.0000	.6484	.8761	.1571
$\bar{X}$	.9906	1.0379	.9979	.7640		
S	.0730	.1177	.0762	.0715		

*Stations 5/I, 6/I, 3/I,5/II, 3/II, 6/II,2/III, 3/III, 6/III, 3/IV, 6/IV, 2/IV, 7/IV

TABLE 13.5

SIGNIFICANT TEMPORAL AND SPATIAL VARIATION BETWEEN INFAUNAL COMMUNITIES AS SHOWN BY DUNCAN'S NEW MULTIPLE RANGE TEST
COMPARISON OF PARAMETER MEANS

Inshore-Spatial

Species Richness	II I III IV
Individuals (Density)	II I IV III
Diversity	I II III IV
Equitability	I III IV II

Temporal

Individuals (Density)	W76 S76 F76 F77 W77 S77

Offshore-Spatial

Species Richness	III II I IV
Individuals (Density)	II III I IV
Diversity	III II I IV
Equitability	IV I III II

Temporal

Species	W76 S76 F77 F76 W77 S77
Individuals (Density)	W76 S76 F76 F77 W77 S77
Diversity	W76 S76 F77 F76 W77 S77

monthly collections. Two, *Ampelisca agassizi* and *Sigambra tentaculata*, showed no significant temporal variations and no significant variations between replicates at a given collection time.

Similarly, three infaunal populations were analyzed at Station 3/II, the most offshore station on this transect. One, *Sigambra tentaculata*, indicated a significant temporal variation. An examination of monthly means by T-test for sample mean differences (Snedecor and Cochran, 1967) indicated significant variation between the collections from November and December. No *S. tentaculata* were found in November at this site, while it was found at its maximal density (21 per 0.6 m^2) in December. The significant variation then must be due to sampling error rather than true seasonal variation. The other two organisms showed no significant differences through time or replication.

The annual epifaunal community structural parameters showed less similarity in basic patterns than seen for infaunal data. There appeared to be more variation through time and space than in analogous infaunal data. Again, several suites of stations, representing shallow communities (Table 13.6) and deep communities (Table 13.7) were tested (ANOVA) for spatial and temporal variation in epifaunal community structural parameters. Results were initially surprising in that far fewer significant variations were seen with epifaunal data than with infaunal data. With inshore epifauna, number of individuals showed a significant ($P < 0.05$) temporal and spatial variation and equitability showed a significant temporal variation. Offshore populations showed significant variations only with temporal changes in species richness and diversity. Table 13.8 shows distinct differences with inshore individual temporal variation. Winter and spring, 1976, had decidedly greater numbers of individuals at the inshore sites. Similarly

TABLE 13.6

STRUCTURAL PARAMETERS OF EPIFAUNAL COMMUNITIES FROM INSHORE STATIONS*
(< 49 m WATER DEPTH) 1976-1977

SPECIES

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	22	10	8	10	12.5	6.4
Spring 1976	23	10	5	10	12.0	7.7
Fall 1976	4	1	8	12	6.3	4.8
Winter 1977	5	7	8	6	6.5	1.3
Spring 1977	11	7	4	7	7.3	2.9
Fall 1977	11	11	6	2	7.5	4.4
$\bar{X}$	12.67	7.7	6.5	7.8		
S	8.16	3.7	1.8	3.6		

INDIVIDUALS

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	817	397	328	179	430.3	273.4
Spring 1976	708	785	52	443	497	330.9
Fall 1976	6	1	37	61	26	28.4
Winter 1977	160	29	46	10	61.3	67.5
Spring 1977	303	153	6	12	118.5	140.5
Fall 1977	241	359	14	3	154.3	175.1
$\bar{X}$	372	287	80	118		
S	320	294	123	173		

DIVERSITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	2.50	1.42	.78	2.36	1.76	.81
Spring 1976	2.84	1.51	1.63	2.50	2.12	.65
Fall 1976	1.93	0	2.33	2.76	1.76	1.21
Winter 1977	1.61	1.91	2.47	2.45	2.11	.42
Spring 1977	2.69	1.75	1.80	2.69	2.23	.53
Fall 1977	2.47	2.91	2.13	1.00	2.13	.82
$\bar{X}$	2.34	1.59	1.86	2.29		
S	.47	.94	.62	.65		

EQUITABILITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	.3636	.3000	.2500	.7000	.4034	.2031
Spring 1976	.4783	.4000	.8000	.8000	.6196	.2108
Fall 1976	1.2500	0	.8750	.8333	.7471	.5275
Winter 1977	.8000	.7143	1.0000	1.1667	.9203	.2033
Spring 1977	.8142	.7143	1.0000	1.1423	.9179	.1911
Fall 1977	.7273	1.0000	1.0000	1.0000	.9318	.1363
$\bar{X}$	.7389	.5231	.8208	.9405		
S	.3097	.3575	.2917	.1922		

*Stations 4/I, 1/I, 2/I, 1/II, 4/II, 2/II, 4/III, 1/III, 5/III, 4/IV, 1/IV, 5/IV.

TABLE 13.7

STRUCTURAL PARAMETERS OF EPIFAUNAL COMMUNITIES FROM OFFSHORE STATIONS*
(> 49 m WATER DEPTH) 1976-1977

SPECIES

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	14	23	14	24	18.8	5.5
Spring 1976	8	5	4	10	4.8	4.1
Fall 1976	7	11	9	12	9.8	2.2
Winter 1977	8	3	12	2	6.3	4.7
Spring 1977	10	3	1	9	5.8	4.4
Fall 1977	9	3	6	10	7.5	2.4
$\bar{X}$	9.3	8.3	7.7	11.2		
S	2.5	7.8	4.9	7.2		

INDIVIDUALS

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	19	52	76	246	98	101
Spring 1976	16	7	9	54	22	22
Fall 1976	9	31	28	61	32	23
Winter 1977	15	3	28	4	13	12
Spring 1977	46	24	11	28	27	15
Fall 1977	59	61	28	101	62	30
$\bar{X}$	27	30	30	82		
S	20	23	24	87		

DIVERSITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	3.62	4.11	2.87	3.06	3.42	.56
Spring 1976	2.61	2.13	1.66	2.76	2.28	.50
Fall 1976	2.73	2.62	2.53	2.76	2.7	.11
Winter 1977	2.61	1.59	3.14	1.00	2.1	.97
Spring 1977	2.14	1.15	0	2.68	1.5	1.18
Fall 1977	1.67	.88	1.57	2.71	1.7	.75
$\bar{X}$	2.56	2.08	1.96	2.50		
S	.65	1.18	1.15	.75		

EQUITABILITY

Transect	I	II	III	IV	$\bar{X}$	S
Winter 1976	1.2100	1.0435	.7857	.5000	.8848	.3103
Spring 1976	1.0000	1.0000	1.0000	1.0000	1.0000	0
Fall 1976	1.2857	.8182	.8889	.8373	.9565	.2215
Winter 1977	1.0000	1.3333	1.0000	1.0000	1.0833	.1666
Spring 1977	.6000	1.0000	0	1.0000	.6525	.4680
Fall 1977	.4444	.4000	.6667	1.0000	.6278	.2742
$\bar{X}$	.9234	.9320	.7236	.8889		
S	.3344	.3086	.3770	.2018		

*Stations 5/I, 6/I, 3/I, 5/II, 3/II, 6/II, 2/III, 3/III, 6/III, 3/IV, 6/IV, 2/IV, 7/IV

TABLE 13.8

SIGNIFICANT VARIATIONS BETWEEN EPIFAUNAL COMMUNITIES
SPATIALLY AND TEMPORALLY AS SHOWN BY DUNCAN'S NEW MULTIPLE RANGE TEST

Inshore-Spatial		
	Individuals	III IV II I
	Temporal	
	Individuals	F76 W77 S77 F77 W76 S76
	Equitability	W76 S76 F76 S77 W77 F77
Offshore-Temporal		
	Species	S76 S77 W77 F77 F76 W76
	Diversity	S77 F77 W77 S76 F76 W76

distinct differentiation was obtained with temporal variation of species richness offshore. The winter, 1976, collection was far richer in species than other seasonal collections. Other differences, though statistically significant ($P < 0.05$), were less distinct (Table 13.8).

The question of relative stability of infaunal and epifaunal populations, raised when apparent differences were not corroborated by ANOVA, was assessed comparing the coefficient of variation ($S.D./\overline{X} \times 100\%$) for inshore and offshore communities (Tables 13.9 and 13.10). Using this technique, communities that are less stable, *i.e.* have greater standard deviations, will have a higher $S.D./\overline{X}$ ratio and these ratios can be compared directly. It is apparent (Tables 13.9 and 13.10) that $S.D./\overline{X}$ ratios associated with spatial variations for both inshore and offshore populations are much smaller for infaunal populations than for epifauna. Although a similar trend may be evident for the seasonal data, no significant differences were seen (ANOVA) for seasonal data while spatial variations except inshore equitability showed significant ($P < 0.05$) differences between the $S.D./\overline{X}$ ratios for infaunal and epifaunal communities. There appears to be a true difference in relative stability. The lack of significant differences in the ANOVA data for epifauna are due to the large standard deviations encountered. This does not mean that populations of infaunal organisms did not wax and wane. Several were observed from the nine collections on Transect II in 1976 that had significant variations and several did not. Sampling error is though to be the source of variation in some species. No true seasonality among species was observed.

Thus, temporally, the structural parameters of infaunal communities varied relatively little. Also, individual populations, particularly some of the numerically important species, generally showed small range of -

TABLE 13.9

THE RELATIVE STABILITY OF INFAUNAL AND EPIFAUNAL COMMUNITIES. FROM THE INSHORE STATIONS (SEE TABLE 13.3). VARIANCE EXPRESSED AS THE PERCENT OF THE MEAN REPRESENTED BY THE STANDARD DEVIATION (S/X • 100)

		TRANSECTS			
		I	II	III	IV
Species	Infauna	26.2	25.0	22.3	20.1
	Epifauna	64.5	47.9	27.1	45.9
Individuals	Infauna	35.4	32.9	53.2	28.4
	Epifauna	86.0	102.3	152.3	146.2
Diversity	Infauna	9.8	18.1	14.8	7.5
	Epifauna	20.2	59.3	32.1	28.4
Equitability	Infauna	16.3	27.3	26.3	16.8
	Epifauna	41.9	67.8	35.5	20.4

		SEASONS					
		W76	S76	F76	W77	S77	F77
Species	Infauna	42.6	53.9	55.4	52.9	48.2	56.8
	Epifauna	51.2	64.2	76.6	19.9	39.6	58.1
Individuals	Infauna	51.0	61.8	84.3	66.6	73.7	56.8
	Epifauna	102.9	102.4	66.6	93.6	53.1	48.2
Diversity	Infauna	17.8	31.4	21.1	12.1	21.7	22.0
	Epifauna	46.1	30.8	69.0	20.0	23.7	38.4
Equitability	Infauna	41.0	35.4	28.0	37.1	37.9	34.3
	Epifauna	50.4	34.0	70.5	22.1	20.8	14.6

TABLE 13.10

THE RELATIVE STABILITY OF INFAUNAL AND EPIFAUNAL COMMUNITIES FROM THE OFFSHORE STATION (SEE TABLE 13.4). VARIANCE EXPRESSED AS THE MEAN REPRESENTED BY THE STANDARD DEVIATION

		TRANSECTS			
		I	II	III	IV
Species	Infauna	25.5	32.3	25.2	23.7
	Epifauna	26.8	94.0	63.6	64.3
Individuals	Infauna	44.1	44.0	43.2	26.9
	Epifauna	73.9	78.8	80.7	105.2
Diversity	Infauna	7.3	7.7	5.9	5.2
	Epifauna	25.4	56.7	58.5	29.9
Equitability	Infauna	7.4	11.3	7.6	9.4
	Epifauna	36.2	33.1	52.1	22.7

		SEASONS					
		W76	S76	F76	W77	S77	F77
Species	Infauna	47.1	30.8	47.1	41.0	31.0	46.1
	Epifauna	29.3	85.4	22.5	74.6	75.9	32.0
Individuals	Infauna	92.1	41.6	70.9	53.5	41.1	53.1
	Epifauna	102.9	102.4	66.6	93.6	53.1	48.2
Diversity	Infauna	8.9	5.8	6.4	7.4	5.6	5.9
	Epifauna	16.4	21.8	4.1	46.2	78.7	44.1
Equitability	Infauna	19.4	8.25	16.8	10.9	10.7	17.9
	Epifauna	35.1	0.0	23.1	15.4	71.7	43.7

variation in density. Other studies have shown varying degrees of seasonality in communities of estuaries (Field, 1971; Boesch *et al.*, 1976). The small range of temperature and salinity variation within our study area, normally without the limiting lower extremes found in shallow estuaries and higher latitude shelf areas, may preclude seasonality in the benthic infauna. The generally small individual size and apparent year-round reproduction of many infaunal species adds credence to the lack of seasonality. The relatively warm waters and concommitant early maturation could result in small individual size at maturation, multiple annual generations and low biomass, all of which were observed or hypothesized during this study.

As shown in Tables 13.5 and 13.8, some very distinct variation in community structural parameters are present. Transect II apparently has a relatively depauperate infaunal community inshore. Water depth at the shallower stations on Transect II is greater than the inshore stations on all other transects. Diversity apparently increases among the inshore stations on all other transects with a decrease in latitude. Winter and spring (1976) collections of infauna were relatively depauperate; apparently increasing over the last two years of the study, both inshore and offshore, in a similar pattern. Infaunal equitability was highest inshore, on Transect II and offshore on Transect IV. With the foregoing as major variations in infaunal community structural parameters, basic trends were observed to include: species richness generally peaked inshore, except on Transect II, with mild depression at mid-depths, increasing slowly offshore; individual abundance peaked inshore decreasing with depth; and diversity and equitability generally increased with depth.

Some epifaunal community structural variations (Table 13.8) were in direct contrast to their infaunal counterparts. Winter and spring (1976) collections of epifauna showed significantly greater numbers of individuals

inshore and species offshore. These collections of infauna were significantly more depauperate than other collections (Table 13.5).

Infaunal Geographical Regions

The study area of the STOCS study is on a broad, gently sloping section of the continental shelf. Its bottom topography is relatively monotonous, broken primarily by a few mid-shelf carbonate reefs. Sediment ranged from sand at the innermost stations to muddy clay at the deepest stations. Results from benthic data were utilized to partition this area into regions that differed physically, thus affecting the benthic aggregations that inhabited them.

Benthic infaunal communities differed in a cross-shelf direction. Cluster analysis of each annual set of data indicated at least three biological provinces (areas represented by distinct faunal communities) in bands roughly parallel to the shore. The number of biological provinces and their exact placement varied slightly between years. Cluster analysis of the combined 1976-1977 data showed the same basic pattern. Three major regions were established with subdivisions of the mid-depth and deepest station groups (Figure 13.1). Stations in the shallowest group (Group A) showed the most individuality and consistency observed. All four stations of this group clustered such that all six seasonal collections at each station (winter, spring and fall, 1976 and 1977) grouped together prior to the stations clustering to form this geographic region. Thus, each of these stations had benthic populations that were both highly stable and essentially separate from all other stations within this group. This set of stations (biotic province) ranged from 10 to 27 meters in depth and from approximately 2 to 9 miles offshore.

The second major province included eight stations (Figure 13.1) ranging

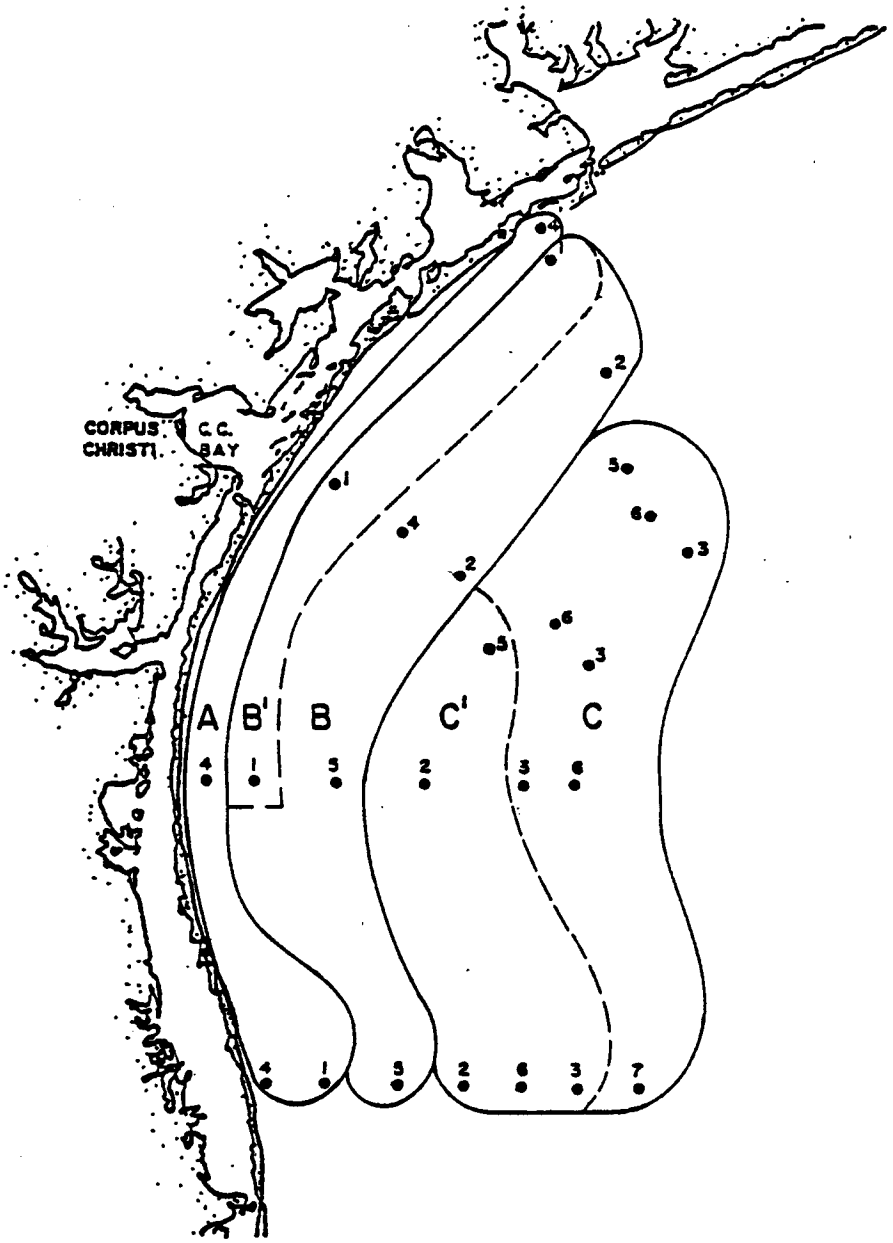

Figure 13.1 Infaunal station groups from combined 1976-1977 normal cluster analysis.

in depth from 18 to 49 meters. This shallow to mid-depth group can be separated into sub groups of B and B', with B' stations overlapping in depth (18 to 25 m) with the four stations of the A group and sharing with them the almost unique situation of having all collections from each of these stations (1/I, 1/II, and 1/III) cluster together prior to grouping with any other site. The five remaining stations of this inner to mid-shelf province ranged from 34 to 49 meters depth. The stability of this group of stations is very high in that only two stations ever clustered outside this group. Station 5/IV clustered with the A group in the 1976 spring collection and Station 2/II appeared in Group C' in the 1976 fall collection.

The last major group of stations defined a mid-depth to deep province that can be divided into subclusters. These 13 stations ranged in depth from 47 to 134 meters. Five stations form a sub-cluster (C') ranging in depth from 47 to 91 meters. C' stations appear to dominate the southern mid-depth region. C stations included all the deepest sites and the northern mid-depth areas. Of the 78 possible station collections, there were five which switched from the C group to C' group in the 1976 winter collection. No other lapses in fidelity to group were observed in the 1976-1977 data. A single station within this group was observed to react to the clustering program as did all stations in A and B'. All collections at 6/IV clustered together, prior to further clustering with collections from other stations.

All the normal cluster analyses separated station groups based upon benthic populations characteristic of the various groups. A discriminant analysis of 1977 data showed four basic groups of stations defining geographic regions of the STOCS study area (Holland *et al.* 1979, pg. 17-25).

The first three groups delineated in the discriminant analysis were essentially the same as the three major groups described for the 1976-1977 combined cluster analysis with the exception that Stations 3/IV and 6/IV (1976-1977 combined C' group) were separated as a fourth group. There is reason to believe that this may be a valid separation as these two stations clustered together at a low dissimilarity level (along with three collections from 2/IV) and clustered with the remaining C' stations at a relatively high dissimilarity level in the cluster analysis. The discriminant analysis provided a spatial separation of station groups based on both infaunal aggregations and station physical characteristics. Major variables in the discriminant analysis included the first infaunal principal coordinate (from an ordination technique), mean grain size, percent sand and clay, and number of species. These variables helped to explain approximately 93% of the observed variation between stations in 1977. It appeared from a plot of the first discriminant function on the second Discriminant Function that the Group A stations (of 1976-1977 combined cluster analysis) were well separated primarily by the high sand component. The discriminant Group A was shown to be separated more by sediment than by infaunal composition (Holland *et al.*, 1979; pg 17-25). Three major geographic provinces were indicated in the STOCS study area; each, with the exception of the innermost, having one or more minor subdivisions based on faunal similarity or physical characteristics.

Infaunal Biotic Assemblages

The infaunal biotic assemblages that are characteristic of various provinces on the STOCS, like the provinces themselves, have proven to be very stable. There is, of course, greater variability with the larger number of entities involved in the biotic assemblages analyses but the major groups

delineated have been shown to be very similar between years (1976-1977) and although clustering was not done with the 1975 data, major portions of some of the most recognizable groups (*e.g.* common and dominant species) were observed to be similar to those of subsequent years. Inverse cluster analysis of 1976 data was interpreted as showing six basic species groups when data were analyzed on a seasonal basis. The 1977 data, with a somewhat different set of species for inclusion in the cluster analysis and with analysis of a full year's data, showed nine separate species groups. The 1976-1977 benthic infaunal cluster analysis, using essentially the same criteria for inclusion as the 1977 analyses, may be interpreted as showing 11 species groups, several with a great deal of overlap and similarity, within four major divisions (Table 13.11).

Species Group I included 21 species of which 6 were ostracods, 3 molluscs, 4 amphipods, and 8 polychaetes. This group is perhaps the most stable, unvarying group observed. It is predominantly and, for some of its component species, exclusively a deep water group in our study area. Several taxa (*e.g. Paralacydonia paradoxa* and *Sternaspis scutata*) are indicated to be deep-water indicators. Adopting Boesch's (1973) use of a fidelity value less than one to indicate an aversion of the group to a specific area, Species Group I (Figure 13.2) shows an aversion to provinces A, B' and B; a very low fidelity at C' and moderate fidelity at C. Constancy measures indicating the number of times a species or groups of species occurs in a station group, increased with water depth (Figure 13.3). This single group comprised all of the first major division of benthic infauna which may be called the deep-water infauna.

The second major cluster division was composed of four separate groups. Member groups were characterized by relatively low occurrence and abundance

TABLE 13.11

INFAUNAL SPECIES GROUPS FROM INVERSE CLUSTER ANALYSIS
OF 1976-1977 COMBINED DATA

SPECIES GROUP 1

Alternochelata sp. A
Dentalium sowerbyi
Thyasira pygmaea
Paralacydonia paradoxa
Sternaspis scutata
Ampelisca sp. A
Byblis cf. *affinis*
Scutopus sp. A
Glycera tesselata
Spiophanes longicirrus
Heterophoxus cf. *oculatus*
Onuphis sp. B
Rutiderma sp. A
Ostracod sp. D
Sarsiella cf. *greyi*
Syllis sp. C
Poecilochaetus johnsoni
Eriopisa incisa
Philomedes sp. A
Ostracod sp. AA
Sanguilonaria sanguinolenta

SPECIES GROUP 2

Clymenella torquata
Isolda pulchella
Caeceum pulchellum
Ampharete americana
Aricidea cf. *fragilis*
Nereis sp. A
Prionospio steenstrupi
Ceratonereis irritabilis
Chaetozone gayheadia

SPECIES GROUP 3

Notomastus americanus
Nereid sp. B
Philine sagra
Pilargis berkelyae
Spiophanes wigleyi
Ampharete parvidentata
Minuspio longibranchiata
Sigambra bassi
Kalliapseudes sp. B

SPECIES GROUP 4

Pseudophilomedes sp. A
Sphaerosyllis cf. *sublevis*
Apanthura magnifica
Spiophanes sp. A
Onuphis sp. F
Glottidia pyramidata

SPECIES GROUP 5

Onuphis sp. A
Phyllodoce mucosa
Unciola serrata
Laonice cirrata
Nuculana acuta
Harbansus paucichelatus
Lumbrineris albidentata
Xenanthura brevitelson
Rutiderma sp. B
Aglaophamus circinata
Terebellides stroemii
Spiochaetopterus costarum

SPECIES GROUP 6

Aedicira belgicae
Aricidea wassi
Lumbrineris tenuis
Diopatra cuprea
Aricidea jeffreysii
Minuspio cirrifera
Ceratocephale oculata
Ampharete acutifrons
Sthenelais boa
Gyptis vittata
Paleanotus heteroseta
Listriella barnardi
Natica canrena

SPECIES GROUP 7

Paraonides lyra
Polychaete sp. A
Corbula swiftiana
Tharyx annulosus
Magelona pettigoneae

TABLE 13.11 CONT.'D

SPECIES GROUP 7 (cont.'d)

Aricidea taylori
Prionospio cristata
Spiophanes bombyx
Owenia fusiformis
Anadara transversa
Abra aequalis
Tellina versicolor

SPECIES GROUP 8

Lumbrineris parvapedata
Mediomastus californiensis
Magelona phyllisae
Paraprionospio pinnata
Cossura delta
Sigambra tentaculata
Paraonis gracilis
Tharyx marioni
Nephtys incisa
Magelona longicornis
Paraonis sp. A
Thyasira sp. A
Paramphinome pulchella
Pitar cordatus

SPECIES GROUP 9

Nereid (Nicon) sp. A
Magelona rosea
Ampelisca verrilli
Notomastus cf. *latericeus*
Ampelisca abdita
Ampelisca agassizi
Apseudes sp. A

SPECIES GROUP 10

Cirrophorus lyriformis
Drilonereis magna
Notomastus latericeus
Vitrinella floridana
Ninoe nigripes
Armandia maculata
Automate evermanni
Eudorella monodon
Volvulella texasiana

SPECIES GROUP 11

Hyala sp. A
Asychis elongata
Asychis carolinae
Corophium ascherusicum

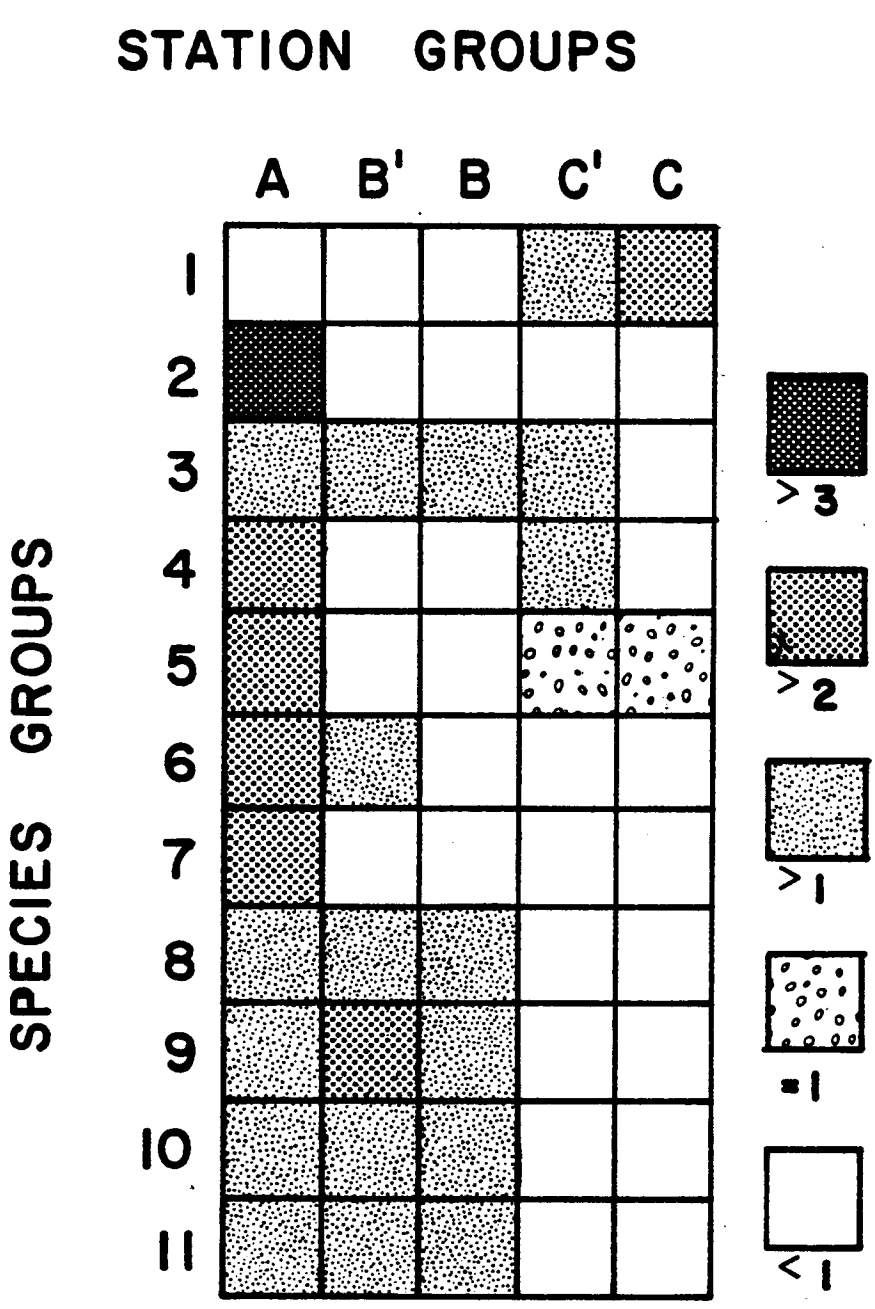

Figure 13.2 Results of benthic infauna two-year cluster analysis presented as a two-way table of fidelity of species groups within a station group.

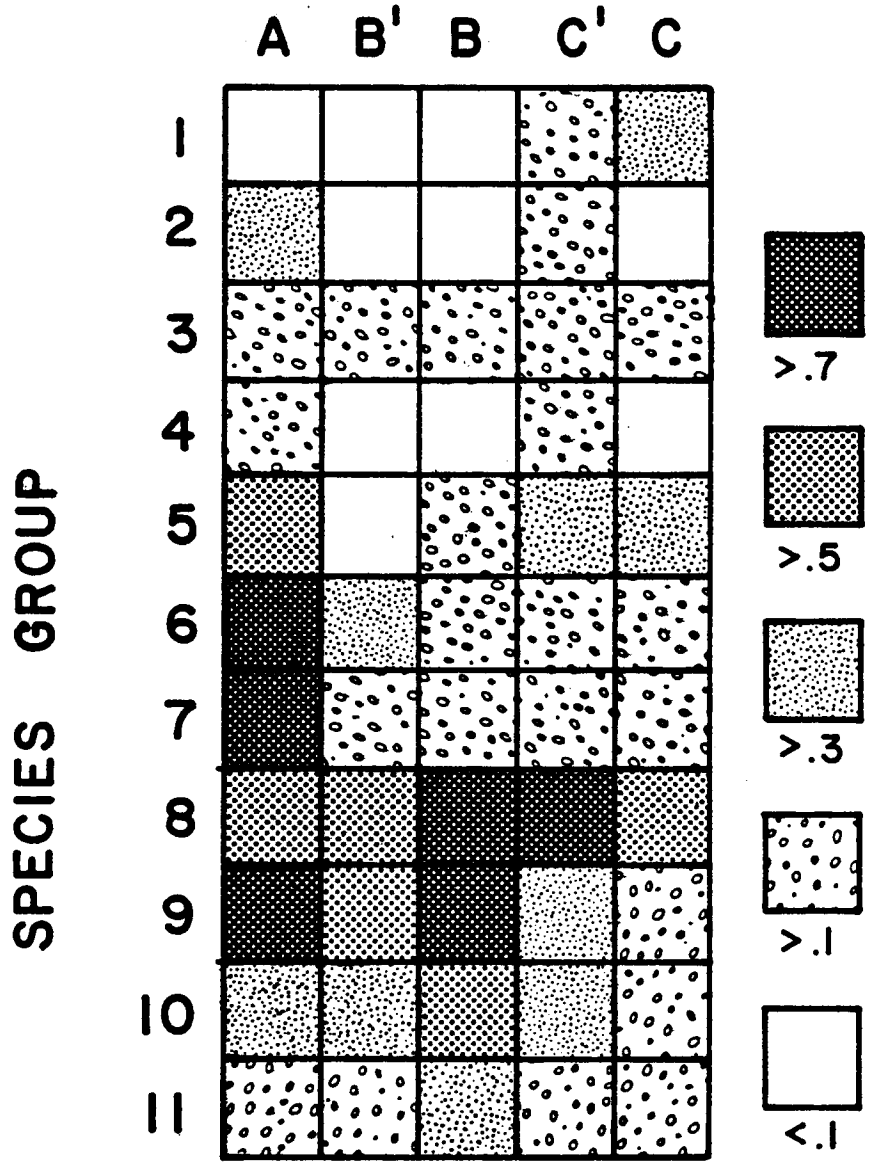

Figure 13.3 Results of benthic infauna two-year cluster analysis presented as a two-way table of constancy of species groups in a station group.

of most species. Distribution varied from shallow to moderate depths. This second division is thought to be composed of groups with varying degrees of similarity to the truly shallow water and deep water species groups and therefore somewhat intermediate to these groups.

Species Group 2 (Table 13.11) was composed of nine species, eight polychaetes and a mollusc. This group, although in the intermediate depths division of the cluster analysis, showed moderate constancy (Figure 13.3) and high fidelity (Figure 13.2) to the A province group with very low constancy and fidelity to all intermediate and deep station groups. Several species of this group, *Clymenella torquata*, *Caecum pulchellum* and *Prionospio steenstrupi*, were collected periodically in moderate numbers (100 - 500 individuals/0.6 m^2).

Species Group 3 (Table 13.11) was composed of nine species including seven polychaetes, one mollusc and one tanaidacean. Again, the distribution pattern was intermedaite in that low constancy and low fidelity were exhibited to all station groups except the deepest (C) where "negative" fidelity was seen. Members of this group were found fairly consistently across the shelf in low abundances and occurrence, absent only from the deepest stations.

Species Group 4 (Table 13.11) contained six species; three polychaetes, one ostracod, one isopod, and a brachiopod. This group had relatively low occurrence and abundance and appeared to have moderate fidelity (Figure 13.2) to the Station Group A, low fidelity at C' and negative fidelity at all other groups. Constancy of this species group (Figure 13.3) followed a similar pattern in that it showed moderate and low constancy to Station Groups A and C', respectively, and very low constancy to all other station groups (provinces). This group then was characterized by low occurrence, a shallow to intermediate distribution. It was observed that the majority of occurrences

of species of this group at intermediate depths were of Stations 6/IV and 3/IV.

Species Group 5 (Table 13.11) contained 12 species, 7 polychaetes, 2 ostracods, and 1 each, amphipod, isopod and mollusc. This group is generally quite similar to the preceding species group and is separated only because of the relatively high occurrence and abundance of some component species at Station Groups A and C'. Distribution, fidelity and constancy patterns were similar except that high fidelity and constancy were seen at Station Group A due to the increased number of occurrences exhibited by this species group. Moderate constancy was seen at C and C'. Fidelity was low at C and C' and negative at B and B' stations.

The third major division of the 1976-1977 combined cluster analysis was comprised of two species groups. These groups were basically limited to the shallow water sites of our study area.

Species Group 6 (Table 13.11) contained 13 species, 11 polychaetes, an amphipod and a mollusc. It showed very high constancy at Station Group A, moderate at B', and low constancy to all other provinces (Figure 13.3). It had high occurrences and abundance at many sites in Station Group A. This group showed high fidelity to Station Group A, low fidelity at B', and "negative" fidelity at all other provinces (Figure 13.2). This group was then essentially limited to Station Groups A and B', the most shallow regions of our study area.

Station Group 7 (Table 13.11) contained 12 species, 8 polychaetes, and 4 molluscs. It showed high constancy for Station Group A and low constancy for all other station groups (Figure 13.3). It had high fidelity at Station Group A and negative fidelity for all other station groups (Figure 13.2). It had relatively high occurrence and abundance at Station Group A. This

group was the most limited to shallow areas.

The fourth major division of the 1976-1977 cluster analysis was composed of four groups primarily separated by degrees of ubiquity. Species Group 8 (Table 13.11) consisted of 14 species, 12 polychaetes, and 2 molluscs. This group contained the numerically dominant, distributionally ubiquitous species. It showed high constancy at Station Groups A, B' and C and very high constancy at B and C' (Figure 13.3). It had relatively high occurrences and abundances across the shelf. It showed low fidelity to A, B, and B' provinces and negative fidelity to C' and C (Figure 13.2).

Species Group 9 (Table 13.11) contained seven species, three polychaetes, three amphipods, and one tanaidacean. This group was almost as ubiquitous as the preceding group but had greater decrease in abundance and occurrence at the deepest sites. It showed very high constancy at Station Group A and B, moderate at C' and low at C (Figure 13.8). It showed low fidelity at A, B, and B' and negative fidelity at C and C' (Figure 13.2).

Species Group 10 (Table 13.11) contained nine species, five polychaetes, two molluscs, one cumacean and one alpheid shrimp. It showed high constancy at Station Group B, moderate constancy at Station Groups A, B' and C', with low constancy at C (Figure 13.3). Fidelity was low at A, B' and B, negative at C' and C. This group showed moderate to low occurrence and abundance and was most prevalent at mid-depth stations decreasing slightly at both depth extremes.

Species Group 11 (Table 13.11) was composed of four species, two polychaetes, one mollusc and one amphipod. It was separated from the preceding group primarily due to lower numbers of occurrences and abundance. Its distribution is essentially similar in that it had moderate constancy at Station Group B and low constancy at all other stations (Figure 13.3). It

had low fidelity at A, B' and B and negative fidelity at C and C' (Figure 13.2).

It was apparent through all three years of this study that major divisions of infaunal species could be delineated and within these major divisions, groups having slightly varied distributions could be observed. A qualitative examination of the various divisions and groups showed that the basic characteristic species of each remained essentially the same through time. The least varying major division appeared to be the deep species group. Within each of the other divisions, there was some interchange between groups and infrequently between major divisions. In all, the infaunal species showed a great deal of stability in their temporal and spatial distribution.

Epifaunal Geographical Regions

Analyses of the 1976 seasonal epifaunal data by normal cluster analysis indicated four major geographic provinces in which stations clustered at least twice in the three seasons. Fidelity to station groups increased with depth. Analysis of 1977 data indicated six basic clusters or biotic provinces arranged again with increasing depth with several small outlying clusters inshore on Transect I and mid-depth on Transect IV.

A combined cluster analysis of 1976 and 1977 data utilizing 50 epifaunal species and 150 station/season collections provided the same basic pattern of separation of epifaunal biotic provinces along a depth gradient. This combined analysis showed greater station variability since each station was occupied six times over the two year period. Six major cluster divisions were inspected for seasonal or latitudinal trends. Although a given season or transect seemed to dominate in some of the clusters, no effects of season or latitude were seen. The major physical factor common to the separate clusters is depth.

An inspection of the variability of stations clustering in the combined analysis indicated that most of the stations were best represented by one of the clusters, most having only one or two collections of the six possible in an adjacent cluster. By placing all stations in clusters to which they seemed most similar, five major geographic regions were delineated (Figure 13.4). The sixth cluster had no stations that appeared to fit primarily into it.

Station Group A is a relatively constant group of seven shallow-intermediate stations which were very similar to the shallow-intermediate groups from 1976 and 1977 clusters. Station Group B was a cluster of three shallow southern (Transects III and IV) stations. Again it was very similar to the 1977 data. Station Group C was comprised of three stations, shallow and northern (Transects I and II). These two station groups combined were similar to the 1976 shallow station cluster. Station Group D was a set of five deep-intermediate stations while Station Group E was comprised of six deep stations. One station (2/III) was difficult to place in a station group due to its wide fluctuation through time, clustering with four to six major cluster divisions. It fit most closely with the Station Group D cluster. Although a Station Group F was delineated by the cluster analysis, it had no major dominance and was a minor component in some stations of the deep-intermediate and deep groups.

Epifaunal Biotic Assemblages

As with the geographic distribution of epifaunal organisms, their assemblages were less stable than infaunal assemblages of the same area. Epifaunal assemblages from the 1976 and 1977 collections numbered 13 and 8, respectively. Seventy-eight (78) species were utilized in the 1976 clustering program while 38 were used in 1977. Comparisons between the years show

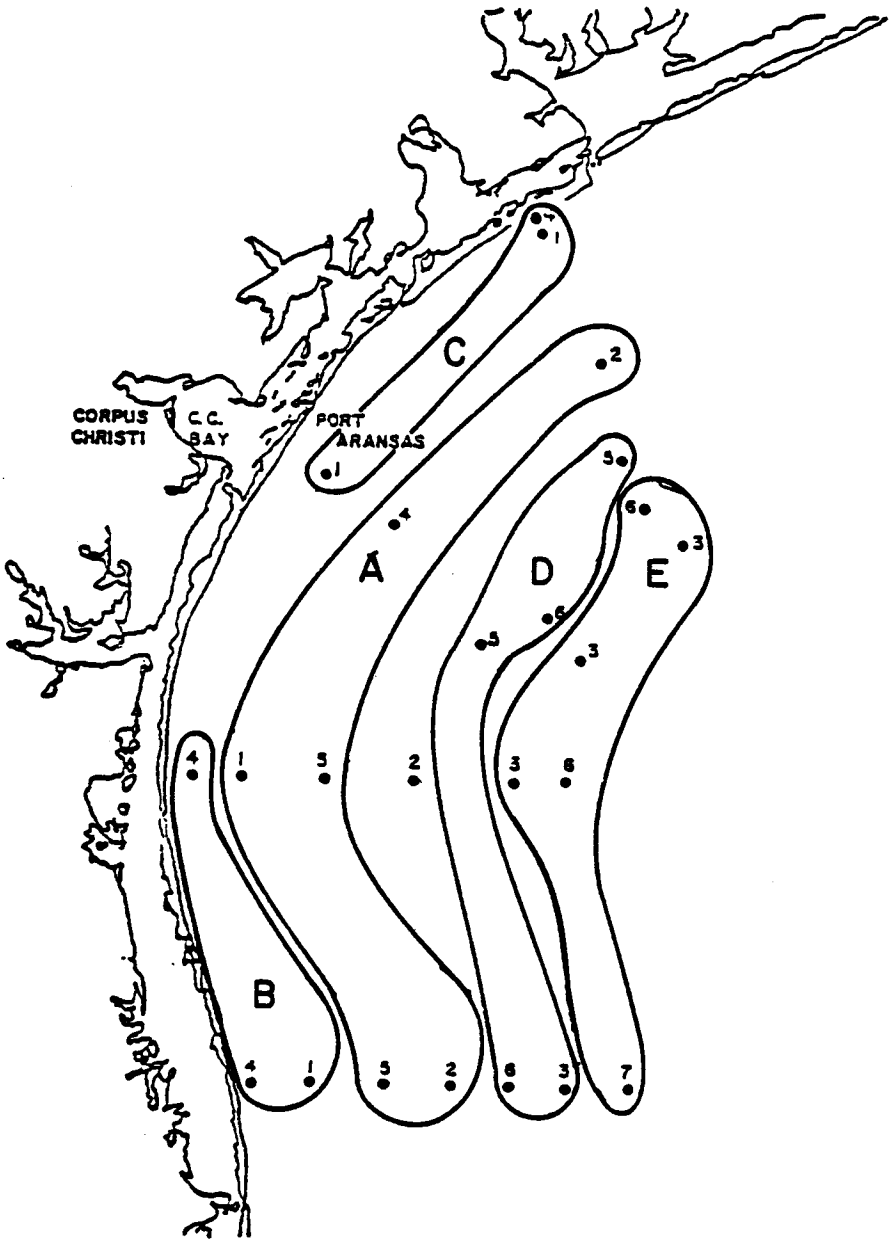

Figure 13.4 Epifaunal biotic provinces from combined 1976-1977 normal cluster analysis.

disparities based on the differences between the data analyzed. The basic groups (shallow, shallow-intermediate, deep-intermediate and deep) had similar core species within both data sets. An inverse cluster analysis of the combined 1976-1977 seasonal epifaunal data using 50 species and 150 station collections provided nine aggregations of species that in various groupings were typical of the various biotic provinces (Table 13.12).

Species Group 1 (Table 13.12) consisted of four species that were numerical dominants in the shallow and shallow-intermediate Station Groups A, B and C. This group of decapod crustaceans had high constancy (Figure 13.5) and moderate fidelity to the shallow-to-mid-depth regions (Figure 13.6) with declining constancy and fidelity in the deeper waters.

Species Group 2 (Table 13.2) consisted of three species, two decapods, and a stomatopod. This group was similar to Species Group 1 but showed higher constancy to the inshore shallow stations, particularly Station Group C (Figure 13.5) than the preceding group which had greatest constancy at the shallow-intermediate stations of Station Group A. This group also showed a much more complete dissociation from the deeper areas in that practically no individuals were found deeper than the Group A stations.

Species Group 3 (Table 13.12) consisted of eight species, six decapods, an asteroid, and a mollusc. This low abundance, low occurrence group was almost limited to the innermost stations on Transects I and II (Station Group C). It showed moderate constancy at this station group (Figure 13.5) and very high fidelity (Figure 13.6).

Species Group 4 (Table 13.12) consisted of two species, an actinarian (Cnidaria) and a decapod. This group may be only a less abundant offshoot from the preceding group. It is again strictly limited to the Station Group C area and was apparently limited temporally to the spring and fall

TABLE 13.12

EPIFAUNA SPECIES GROUPS FROM INVERSE CLUSTER ANALYSIS
OF 1976-1977 COMBINED DATA

SPECIES GROUP 1

Trachypenaeus similis
Sicyonia dorsalis
Callinectes similis
Penaeus aztecus

SPECIES GROUP 2

Portunus gibbesii
Penaeus setiferus
Squilla empusa

SPECIES GROUP 3

Trachypenaeus constrictus
Luidia clathrata
Acetes americana
Cantharus cancellaria
Persephona crinata
Hepatus epheliticus
Calliactis tricolor
Porcellana sayana

SPECIES GROUP 4

Pagurus pollicaris
Xiphopenaeus kroyeri

SPECIES GROUP 5

Portunus spinimanus
Callinectes sapidus
Sicyonia brevirostris
Penaeus duorarum
Renilla mulleri
Ovalipes floridanus

SPECIES GROUP 6

Portunus spinicarpus
Amusium papyraceus
Anasimus latus
Solenocera vioscai
Squilla chydaea
Astropecten duplicatus

SPECIES GROUP 7

Acanthocarpus alexandri
Collodes leptocheles
Brissiopsis alta
Astropecten cingulatus
Raninoides louisianensis
Pagurus bullisi

SPECIES GROUP 8

Parapenaeus longirostris
Parapandalus cf. *longicauda*
Anadara baughmani
Pitar cordatus
Sicyonia stimpsoni
Pseudorhombila quadridenta
Euphrosynoplax clausi
Leiolambrus nitidus

SPECIES GROUP 9

Porcellana sigsbeiana
Clypeaster ravenellii
Parthenope serrata
Polystira albida
Calappa sulcata
Tethyaster vestitus
Paguristes cf. *moorei*

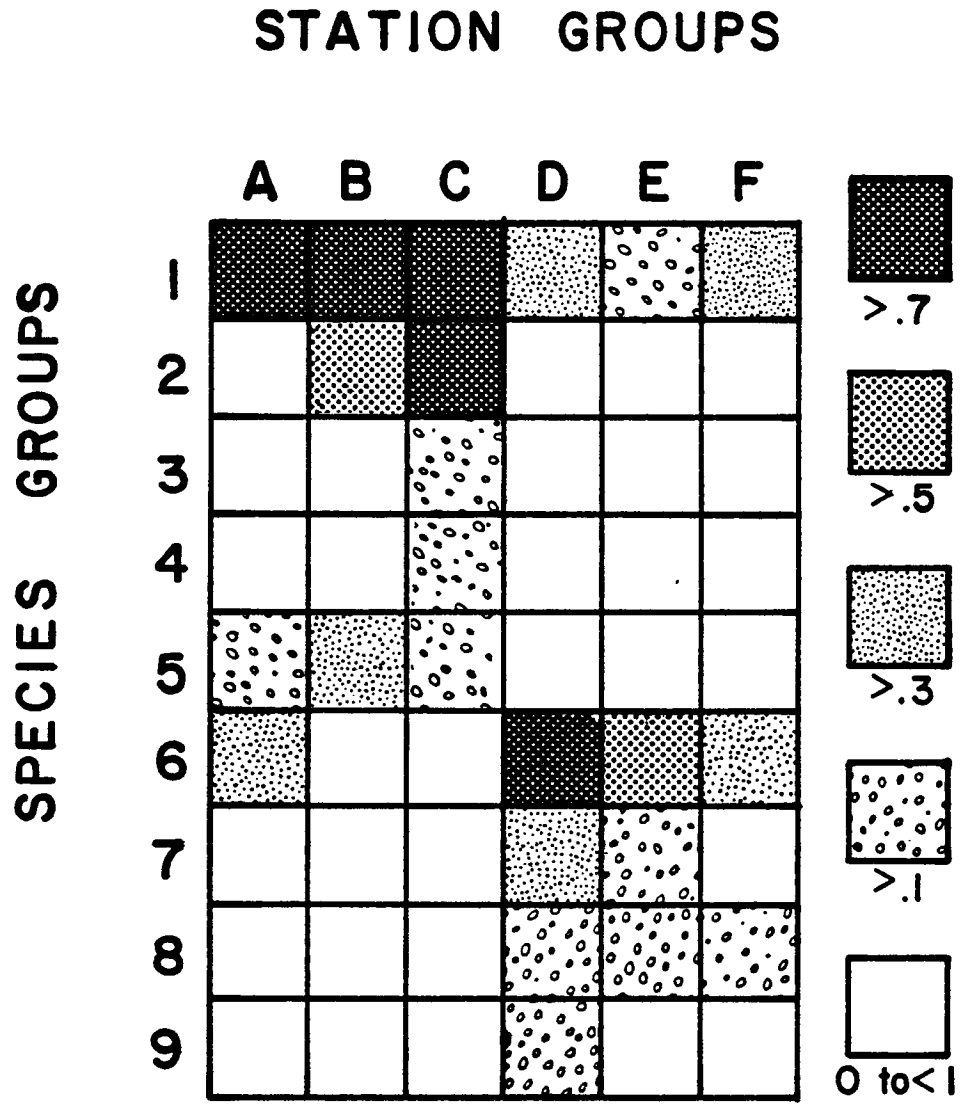

Figure 13.5 Results of benthic epifauna two-year cluster analysis presented as a two-way table of constancy of species groups in a station group.

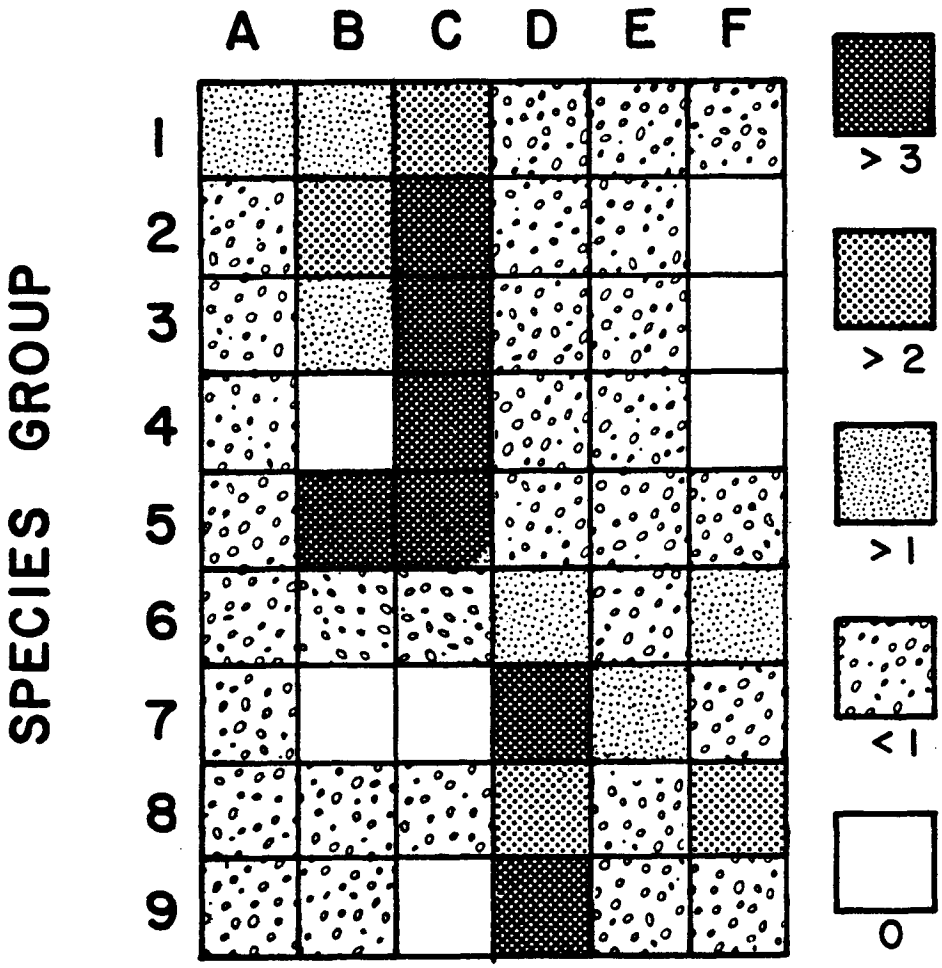

Figure 13.6 Results of benthic epifauna two-year cluster analysis presented as a two-way table of fidelity of species groups in a station group.

collections of 1977. This group exhibited very low constancy at all areas (Figure 13.5) but had very high fidelity at Station Group C (Figure 13.6).

Species Group 5 (Table 13.12) consisted of six species, five decapods, and an anthozoan. This groups' distribution pattern was basically similar to that of Species Group I but was far less abundant. It was broadly scattered with limited occurrence over the shallow and shallow-intermediate areas, with very limited occurrence in the deeper zones. Its low constancy at all station groups (Figure 13.5) attest its relatively low occurrence. It had high fidelity only to the inner stations of the southern transects (Figure 31.6).

Species Group 6 (Table 13.12), composed of six species (three decapods, a mollusc, an asteroid and a stomatopod), was the most numerous group at the deep and intermediate-deep stations. It was present with moderate frequency at the shallow-intermediate stations as well. It appears to be the most nearly ubiquitous epifaunal group assessed, apparently limited only in the shallow areas. It showed moderate to high constancy at all station groups excepting B and C, the shallowest areas (Figure 13.5). Its fidelity was basically low everywhere but peaked at Station Group D (Figure 13.6).

Species Group 7 (Table 13.12) consisted of six species, four decapods, an echinoid and an asteroid. This group showed low to moderate occurrence and low abundance and was strictly limited to the deepest half of the study area. It showed moderate to low constancy in the deep waters (Figure 13.5) and high fidelity only at Station Group D, the intermediate-deep stations (Figure 13.6).

Species Group 8 (Table 13.12) contained eight species, six decapods and two molluscs. Its distribution pattern was similar to the preceding group but had lower occurrence and abundance and a smaller representation at the

shallow-intermediate stations, Station Group A. Its constancy was low at the deeper stations (Figure 13.5) and fidelity was moderate at Station Groups D and F (Figure 13.6).

Species Group 9 (Table 13.12) consisted of seven species, four decapods, a mollusc, an asteroid and an echinoid. This was a low frequency, low density group found primarily at the intermediate-deep stations with scattered occurrence in the deep area and shallow zones. It had very low constancy with a peak at Station Group D (Figure 13.5) and high fidelity only at that Station Group (Figure 13.6).

Apparently, the epifaunal aggregations of the STOCS can be divided basically into a shallow to moderate depth group and a moderate to deep group with relatively little overlap. Only two species groups (1 and 6) show a decided tendency to occur in both depth realms. Each of these species groups is a numerical dominant of its respective depth range and does show relatively important distribution in the contiguous zones of the alternate depth range.

Infaunal Biomass

Biomass, measured as wet weight for 14 selected infaunal species, was assessed during the monthly collections of 1976. Infaunal biomass for the 14 selected species totaled less than 43 grams for the year, with 22,226 individuals weighed. It was estimated that infaunal biomass comprised only .03% of the combined infaunal and epifaunal biomass, but infauna made up more than 53% of the combined total number of individuals. The three infaunal species having the greatest total biomass during the 1976 collections were *Diopatra cuprea, Paraprionospio pinnata* and *Abra aequalis*. They accounted for 69.91% of the total assayed infaunal biomass.

There was a significant decrease in biomass measured across the shelf. Shallow stations, here defined as the innermost two stations on each transect,

accounted for almost 86% of the total infaunal biomass. Mid-depth stations, the middle two stations on each transect, produced only slightly over 11% of the total infaunal biomass during the year. The deepest two stations on each transect produced only slightly over 3% of the total infaunal biomass.

Seasonal values for total biomass were not significantly ($P < .05$) different (ANOVA). Spring values were highest and fall values the lowest, but statistically significant differences were not seen. Several species showed seasonal changes in biomass and numbers. *Diopatra cuprea* had a much lower biomass in the fall collection although the numbers of individuals was not much lower. *Abra aequalis* showed peak biomass and numbers in the spring collection. Biomass of most species varied relatively little during the various seasonal collections; however, numbers of individuals varied significantly for a few species (*Lumbrineris parvapedata, Magelona phyllisae, Abra aequalis*) but remained relatively unchanged for others (*Armandia maculata, Ampelisca agassizi*).

Wet weights of whole infaunal samples from the fall collections of 1976 were made prior to sorting. Wet weights for 108 samples varied from .0019 g/.1 m^2 to 25.1322 g/.1 m^2, with an average of .9399g/0.1 m^2. A more realistic average, if samples known to contain molluscs or large epifauna are excluded, would be around 0.4 g, indicating a hypothesized macroinfaunal crop of 4 g/m^2.

Epifaunal Biomass

Nineteen (19) epifaunal species were selected for utilization in biomass measurements from the 1977 monthly collections. Wet weights were the basic unit of biomass used, although for a selected group, dry weight and ash-free dry weight were also measured. Biomass decreased cross-shelf in a different pattern than that exhibited by infauna. Epifauna biomass was similar in the

first two depth zones and declined precipitously in the deepest area. Almost 110 kg of biomass from the 19 epifaunal species was measured during the years. The shrimp, *Penaeus aztecus*; the crab, *Callinectes similis*; and the mollusc, *Amusium papyraceus* were the major contributors to the total biomass of the 19 species investigated. These three species contributed almost two-thirds (66.12%) of the total epifaunal biomass measured.

No statistically significant ($P < .05$) variations in total seasonal biomass were elicited. Some fluctuations in species such as *Solenocera vioscai*, *Penaeus aztecus* and *Astropecten cingulata* showed definite trends for seasonal occurrence of smaller individuals. Other species showed several periods in which smaller individuals occurred, interspersed with periods in which only relatively large individuals occurred.

Dry weights and ash-free dry weights of several decapod and stomatopod species were compared from fresh and preserved specimens. The percentage of the wet weight contributed by the dry and ash-free dry weights were somewhat higher for the non-preserved specimens. The dry weight of preserved specimens represented between 18 and 26% of the wet weight. The ash-free dry weight of this group ranged from 12 to 22% of the preserved weight for various species. Ths dry weight of fresh specimens represented from 29-36% of the wet weight while ash-free dry weight ranged from 10-23% of the wet weight.

Integration-Infauna

Infaunal species and abundance were analyzed with data from various facets of the STOCS study as independent variables utilizing Pearson bivariate correlation analysis with a cutoff level of significance of 5% ($P < .05$).

No significant correlations between abundance or species richness of macroinfauna and the same parameters for meiofauna were observed. A significant correlation between infaunal species abundance and transect number was

seen. According to the correlation analyses infaunal species richness was directly related to movement in a southern direction.

Correlation with sediment parameters showed significant correlations with species richness and/or abundance of infauna. Both species and abundance increased significantly with increasing sediment particle size. There appeared to be a tendency for increasing infaunal abundance with decreasing sediment sorting. Both skewness and kurtosis measures of the grain size distribution showed strong positive correlation with species richness and abundance. In our area, both species richness and abundance increased significantly with percent sand in the sediment and decreased with increasing levels of silt and clay. Macroinfaunal species richness and abundance also increased with increasing sand/mud and silt/clay ratios as they also did with water depth.

Hydrographic parameters tested for correlation with macroinfaunal species richness and abundance included bottom temperature, salinity, temperature standard deviation, salinity standard deviation, depth and dissolved oxygen. Species richness and abundance had a tendency to increase with bottom temperature, decrease with increasing bottom salinities, increase with decreasing bottom salinity variability and to decrease with increasing depth. Abundance of infauna was positively correlated with dissolved oxygen.

Infaunal species richness and abundance showed significant correlation with several sediment chemical parameters and bottom water nutrients. They varied positively with Delta ^{13}C and inversely with total sediment carbon. Both species number and abundance showed a slight but significant negative correlation with bottom water silicon. No correlation was observed with bottom water phosphorus. Abundance of benthic infauna showed a negative correlation with bottom water nitrogen.

Infaunal species richness and abundance were tested against a number of biological parameters. There seemed to be a slight positive correlation between abundance of infauna and zooplankton biomass. Both total chlorophyll and total phaeophyton were positively correlated with infaunal abundance. No significant correlations were seen with epifaunal invertebrate species richness, epifaunal invertebrate abundance, fish species richness, or fish biomass. A slight negative correlation between infaunal abundance and fish abundance was observed.

Discriminant analyses of 1977 infaunal data resulted in the recognition that various physical and biological parameters including mean grain size, percent sand and clay and number of species, explained the majority of the variation between station groups. Thus, relations between these parameters and infaunal species groups representative of the various station groups could be hypothesized, *i.e.* species groups characteristic of station groups characterized by large mean grain size require or may be influenced by large particle size sediments.

Integration-Epifauna

Epifaunal species richness and abundance were analyzed with various physical, chemical and biological parameters utilizing correlation analysis.

There was no significant correlation with latitude. Neither species richness nor abundance seemed to increase or decrease significnatly with transect number.

No significant correlation was observed with either infaunal species richness or abundance. There was a slight, but significant, negative correlation between epifaunal abundance and infaunal diversity. Epifauna was apparently denser where infaunal diversity was low.

Apparently epifaunal species richness and abundance have less relation to the sediment parameters measured than do the infauna. Epifaunal species richness was not correlated significantly with any of the 10 sediment parameters measured. Significant correlations between epifaunal abundance and the sediment parameters always had very small correlation coefficients. These correlations included positive sediment grain size, positive percent sand, negative percent clay and positive silt/clay ratio. No significant correlation was found with sorting, skewness, kurtosis, silt or sand/mud ratio.

Hydrographic parameters measured also seemed to have less correlation with epifaunal species richness and abundance than with similar infaunal parameters. There was no significant correlation with temperature or dissolved oxygen. Epifaunal species richness apparently was not affected significantly by any of the measured hydrographic parameters. Epifaunal density showed a slight propensity for increasing with decreasing salinity, with increasing temperature variability, with increasing salinity variability, and with decreasing depth. Again all significant correlation values were low.

No significant correlation between epifaunal parameters and Delta ^{13}C, total carbon, silicon or phosphorus were observed. A slight negative correlation between epifaunal density and nitrogen occurred.

Biological parameters utilized indicated a positive correlation between epifaunal density and total chlorophyll, negative correlation between epifaunal species richness and total phaeophyton, and positive correlations between both species richness and density and fish species, fish density and fish biomass.

Correlation of abundance of selected individual species of epifauna with various benthic physical variables was obtained from the 1977 data. The most significant correlations were with depth and particularly with those

species designated as shallow or deep organisms. Those of intermediate depth or ubiquitous distribution showed less significant relationship with depth. Other parameters including Julian Day, temperature, salinity, mean grain size, percent silt and transect (latitude) showed few significant correlations with the abundance of 15 species assayed.

DISCUSSION

The benthic fauna assayed in the present study is a "soft-bottom" fauna. The STOCS may indeed be among the "softest" of soft-bottom areas in which benthic species have been reported. Sanders (1958), Holme (1953), Lie (1974) report greater percentages of gravel than the negligible amounts found in the STOCS region. Boesch (personal communication) has reported a much greater proportion of gravel on the continental shelf off Virginia. The Texas coast is almost devoid of natural hard bottom, with the exception of a few ancient carbonate reefs basically in the mid-shelf area. So by circumstance and design, our sampling was primarily limited to true soft, level bottom fauna. A few fouling and/or encrusting forms were collected, usually in conjunction with anthropogenic debris.

Many marine and estuarine studies of invertebrate benthos are reported in the literature. They have ranged from listings of species found (Pulley, 1949; Pereyra and Alton, 1972) through slightly more complex studies descriptive of various community functions (Boesch, 1972; Holland *et al.*, 1973; Rowe *et al.*, 1974) to complex analyses of ecosystem functions often made possible only by modern data manipulative techniques (Field, 1971; Lie and Kelly, 1970). It was the purpose of the present study to delve into each of the aforementioned areas.

On a purely descriptive taxonomic basis, almost 1,000 benthic taxa were isoalted. Total species lists, not included herein, were appended to annual reports to the BLM (Holland *et al.*, 1977, 1979). It has become a general pattern of observation in marine benthic assemblages studies elsewhere that there will be a few species with great abundance and a great many species with few individuals (Buchanan and Warwick, 1974; Woodin, 1974; Sanders, 1961). This appeared consistent with both epifaunal and infaunal assemblages of the STOCS. The major (numerically) higher taxa were the polychaetous annelids, crustaceans and molluscs. Wade (1972) listed polychaetes, crustaceans and bivalves as major constituents of a diverse soft-bottom community in Kingston Harbor, Jamaica. Boesch (1973), describing the macrobenthos of the Hampton Roads area of Virginia, found higher taxa with the most species to be Polychaetes, Gastropoda, Amphipoda, and Bivalvia. Pereyra and Alton (1972) found a much greater importance of the echinoderms in their studies off the coast of Oregon. The major difference appears to be the depth regimes in which they worked. They found five assemblages of echinoderms, each apparently related to a depth zone. The echinoderm fauna at the outer sublittoral area of their study (50-75 fathoms, corresponging to our deepest stations) contained few species and few individuals relative to their deeper zones. It appears that within similar depth restrictions, the benthic fauna of the STOCS is similar in taxonomic composition to that of soft level bottoms of other areas.

Benthic invertebrate phyla were classified as major or minor on the basis of their contribution to the total number of species collected. Several of the phyla presently included with the minor group (Rhyncocoela and Phoronida) were placed in this categorization due to taxonomic difficulties. They were, however, equal to, if not more numerous than, several of the phyla

included in the major category. Discussion of distribution of several phyla is hampered by the low number of individuals collected.

The poriferan fauna of the eastern Gulf of Mexico and the southwestern sector off the Mexican coast is both diverse and abundant (Tierny, 1954; Hartman, 1955; Hopkins, 1956; and De Laubenfels, 1953). Hopkins (1956), in his discussion of boring sponges of the northern Gulf of Mexico, alluded to scarcity of sponges in the bays and estuaries of the northwestern Gulf. This scarcity was noted in the present study by the fact that only one sponge was found in the 1976-1977 seasonal collections. A greater diversity and abundance of sponges occur on the introduced hard substrate such as rock jetties and drilling platforms of our area. Tierny (1954) speaks of sponges being prolific on reefs and rocky outcroppings of the eastern Gulf of Mexico. There are a number of topographic features in the study area which probably support a larger poriferan fauna than indicated in the present collections limited to level, soft-bottom communities.

A less abundant member of the minor group of phyla, the Cnidaria, was well represented in our area both in trawl and grab samples. The hydrozoans and anthozoans were the major benthic groups of this phylum collected with 16 and 14 species, respectively. Deevy (1950) stated "few parts of the world offer a more absolute blank to the zoogeography of marine hydroids than the Gulf coast of Texas" and proceeded to produce 26 species of hydroids taken from the Texas coastal waters. In a later paper (1954) he presented a check list of 183 hydroid species from the Gulf of Mexico. Defenbaugh and Hopkins (1973) described 62 species of hydroids from the Gulf. Anthozoans observed on the STOCS included gorgonians, pennatulids, zoantharians and ceriantherians. This group was infrequently encountered. More abundant anthozoans included the sea pansy, *Renilla mulleri*, and a group of eight-

actinarian species. Hedgpeth (1954a) presented a synposis of the anemones from the Gulf of Mexico. Carlgren and Hedgpeth (1951) discussed the actinaria, zoantharia and ceriantheria of the shallow regions of the northwestern Gulf of Mexico.

Representatives of the phylum Platyhelminthes included in our samples were all free-living turbellarians. No attempt was made to determine the parasitic forms of this phylum. Hyman (1954) stated that little was known of the free living flatworms of the Gulf of Mexico and that which was known concerned the macroscopic polyclad tubellarians. Specimens collected in this study were generally very small (< 3 mm preserved). Some 28 individuals were collected during the normal seasonal collections during 1976 and 1977. Others were collected from around topographic features. At the present, all our specimens are taxonomically designated Platyhelminthes but many are though to be of the genus *Stylochus*. Hyman (1954) included this genus as among the most common forms of littoral polyclad turbellarians along the Gulf coast. Members of this phylum were not found on Transect II during the 1976 sampling periods but appeared as frequently on that transect as any other transect in 1977.

Osburn (1954) in his short treatise on the bryozoans of the Gulf of Mexico stated that little knowledge exists in the Gulf relative to knowledge of bryozoans. As bryozoans are basically hard-substrate fauna, they were not common in our collections. They were recorded from only 23 samples during the seasonal collections of 1976 and 1977. Shier (1964) listed 62 species of bryozoans from the northwestern coast of Florida and stated that bryozoans are common in coastal waters wherever firm substrate is present. Due to scarcity and to relative difficulty in their taxonomic assessment, we have left them at phylum level, awaiting further work. Lagaaij (1963) dealt

with 34 species of bryozoans not previously reported from the Gulf of Mexico and stated that this brought the total known bryozoan fauna in the Gulf of Mexico to 216 species.

Seventy-four (74) *Glottidia pyramidata* comprised the total collection of brachiopods from our study area during 1976-1977. For the most part, brachiopods were found in the southern portion of the south Texas study area. Cooper (1954) recorded 12 species of brachiopods from the Gulf, including *G. pyramidata*.

Phoronids, after the nemerteans and sipunculids, were the most abundant of the eight "minor" phyla represented in the STOCS collections. Hedgpeth (1954b) stated that no records for adult phoronids in the Gulf of Mexico existed at that time. We collected a total of 397 phoronids at 33 stations during the 1976-1977 seasonal sampling periods. Hedgpeth (1954b) mentioned *Phoronis architecta* from the Beaufort area and *P. ovalis* from the coast of Brazil. The present author has collected specimens identified as *P. architecta* from the bays and estuaries of south Texas. It is probable that many of the present collection of phoronids belong to the genus *Phoronis*.

Phoronids were collected at the innermost two stations on Transects I, II and IV during 1976. The 1977 collections had a similar pattern but included a few individuals from deep stations on Transect II.

Numerically, sipunculids were the most abundant of the eight "minor" phyla. A total of 4,491 individuals were collected during the seasonal collections of 1976-1977. Sipunculids were collected at 121 of the possible 150 stations during the two-year period. Hedgpeth (1954c) noted that a total of 11 species of sipunculids were known from Gulf waters, several of these, *Phascolion strombi* and *Dendrostoma alutaceum*, being recorded from northern Gulf waters and from the south Atlantic coast. Preliminary work on our

specimens indicated several genera including *Golfingia, Aspidosiphon* and *Phascolion* may be present. Again much further taxonomic work is needed.

Sipunculid distribution showed similar patterns both spatially and temporally from the collections of 1976-1977. Spatially, the shallow stations and the southernmost transect had greatest abundance of sipunculids both years. There seemed to be a relatively minor secondary peak of abundance at the deepest stations leaving a depauperate mid-depth region. This may indicate several different species segregating by depth or depth-influenced factors. Temporal patterns were not obvious from the two year's data.

Hedgpeth's (1954c) brief description of the echiurids of the Gulf of Mexico listed a total of four records of this phylum. A single specimen of *Thallassema philostracum* Fisher was reported from near Port Aransas, Texas (Fisher, 1947). Echiurids were found only in 1976 at two sites (3/I and 4/III in fall and winter, respectively.

Nemerteans (Phylum Rhynchocoela) were well represented numerically in our 1976-1977 seasonal samples. They were the most ubiquitous of the eight minor phyla being collected in 145 of 150 possible station collections. When taxonomic work-up of the rynchocoels, sipunculids, and perhaps phoronids is complete, these phyla will undoubtedly represent a greater contribution to the total number of taxa. Cursory examination of nemertean samples revealed several different morphotypes, with perhaps a decided dominance of individuals fitting the external morphological description of *Cerebratulus lacteus*, which is very commonly observed in the Gulf of Mexico.

Distribution of nemerteans followed an already familiar pattern in that they were decidely more abundant at the shallowest stations on Transects I, II and IV and generally showed slightly increased abundance along the northern and southernmost transects (I and IV). No significant change in abundance

was noted seasonally.

The molluscs are the most studied benthic invertebrates of the Texas Gulf coast. Numerous surveys and taxonomic treatises of this phylum have been recorded from the Gulf of Mexico. Those of general Gulf distribution include: Dall (1889, 1903), Maury (1920, 1922), Johnson (1934), Galtsoff (1954), and Perry and Schwengel (1955). Molluscan studies of specific interest to Texas coastal waters include: Roemer (1849), Singley (1893), Mitchell (1894), Strecker (1935), Pulley (1949, 1952), and Andrews (1971, 1977).

Molluscs are generally found to be the second or third most diverse major taxa of benthic invertebrates of the Texas coastal zone (Holland *et al.*, 1973, 1974, 1975; Matthews and Marcin, 1973). While most Texas coastal molluscan species are rarely numerically dominants, some have periodic large numerical increases (Holland, unpublished data).

Gastropods and pelecypods were the most predominant molluscan fauna observed during this study in terms of both species richness and abundance. Several taxonomic classes observed during this study (Caudofoveata and Solenogastres) have not previously been reported from the Gulf of Mexico (Salvini-Plawen, 1968).

Molluscs, with 174 taxa delineated, comprised 17.88% of the benthic invertebrate species richness of the south Texas outer continental shelf. Gastropods and pelecypods were almost equal with 81 and 75 taxa, respectively. Amphineurans, scaphapods and cephalopods were present usually in low numbers of taxa and individuals (possibly due to collection gear used), although squid were often numerically dominant in diurnal trawl samples. Of prime taxonomic interest was the discovery of aplacophorans previously unreported from the Gulf of Mexico. Treece and Holland (accepted for publication) report the finding of four genera of this worm-like class of molluscs from the north-

western Gulf of Mexico.

Distribution of molluscs on the Texas continental shelf followed patterns of the invertebrate fauna in general. There was a general decline in numbers of species and individuals across the shelf. The mollusca were more often of relative numerical "importance" in the deeper waters.

The dominant trawl-collected mollusc was *Amusium papryaceus*. Of 116 infaunal (bottom sampler-collected) species selected from 1976-1977 collections for inclusion in cluster analysis, 13 were molluscs. *Amusium papyraceus* was distributed primarily in the deeper areas off the Texas coast. *Corbula swiftiana* was broadly distributed, almost ubiquitous, in small numbers. Several molluscs including *Anadara transversa, Abra aequalis, Tellina versicolor, Natica canrena* and *Caecum pulchellum* were basically limited to shallow areas. *Volvulella texasiana* was found primarily in the mid-depth range while others including *Dentalium sowerbyi, Pitar cordatus* and *Sanguinolaria sanguinolenta* were consistently in intermediate-deep to deep regions of the study area.

Of 826 species of infauna collected at the seasonal transect sites in 1976-1977, 109 species (13%) comprised 90% of the total abundance. Of these, 21 species were molluscs. Molluscs accounted for 19.27% of the species in the numerically dominant group and for 11.58% of the abundance.

Marine annelids of the class Polychaeta were the numerically dominant benthic invertebrates both in species richness and density of the south Texas outer continental shelf. Many, if not most, of the general surveys of marine benthos in the Gulf of Mexico have concentrated on the larger epifaunal forms. The annelids from our region of the Gulf are generally very small and have received relatively little attention. Early studies of the Gulf of Mexico annelids include those by Ehlers (1878, 1887) and McIntosh

(1885). Hartman (1951, 1954) made significant contributions to the knowledge of littoral polychaetes of the Gulf of Mexico. Most recent, surveys in Texas bays and estuaries by Holland *et al.* (1974, 1975) and Matthews and Marcin (1973) have reported polychaetous annelids from Texas coastal waters.

Three hundred ninety-one (391) taxa of polychaetes have been delineated in the present study. This accounts for 40.18% of the total number of benthic invertebrate taxa collected. Of the 109 species of numerically dominant organisms (those in the group comprising 90% of the total abundance) from the seasonal transect collections, 64 (58.72%) were polychaetes. They accounted for 70.12% of the abundance of the numerically dominant group.

One polychaete, *Magelona phyllisae*, with 13,423 individuals made up 11.81% of the total number of individuals collected from the seasonal transect collections of 1976-1977. Representatives from 47 families were found in the three-year study.

Distribution of polychaetes, in general, showed diminishing numbers of both species and individuals with increasing depth. Various groups of polychaetes had specific distributional patterns. A large group of numerically dominant species were practically ubiquitous. Other groups were limited to various zones primarily by depth or sediment characteristics.

The remaining class of annelids, oligochaetes, was practically nonexistent, represented by only three taxa. The oligochaetes were primarily of the genus *Peloscolex*. Only three individuals were found during the 1976-1977 seasonal collections.

The phylum Arthropoda was represented by the classes Arachnida, Pycnogonida and Crustacea. The former two were each represented by only one taxon while the crustaceans were second only to the polychaetes in species richness with 331 taxa delineated. Unlike the other numerically important phyla, the

arthropods were heavily collected in the trawl samples. This was true particularly for the decapod crustaceans. This phylum was also well represented in the infaunal samples.

The crustaceans found included 51 ostracods, 6 copepods, 2 barnacles, 1 leptostracan, 10 mysids, 22 cumaceans, 20 tanaidaceans, 21 isopods, 4 stomatopods, 58 amphipods, and 136 decapods. Those crustaceans primarily collected in the sediment sampler (infauna) comprised 16.51% of the species richness of the abundant infaunal taxa from the 1976-1977 seasonal collections, accounting for 8.32% of the total number of individuals in this group. Larger decapod crustaceans were frequently the numerically dominant organism in the trawl samples (epifauna).

Distribution of the crustaceans showed several patterns. Those generally included in the infauna showed typical infaunal distribution patterns as a group. They were most abundant in the nearshore regions, with the amphipods, particularly the ampeliscids, often being numerical dominants in the shallower regions. As with other infauna, numbers of individuals generally decreased with depth. Generally, little or no seasonal variation was observed. The epifaunal crustaceans showed varying patterns of abundance both spatially and temporally. Several, such as the penaeid shrimp, move across the shelf with maturation, entering bays and estuaries as larval forms and migrating to deep water with maturity. They often show distinct patterns of distribution with season.

In the treatise on echinoderms of the Gulf of Mexico, Clark (1954) gave a brief history of the study of echinoderms in the Gulf of Mexico, noting that although the echinoderms collected until that time had been studied, the majority of collections had been from the extreme southeastern Gulf and that the majority of the Gulf echinoderm fauna was unknown, particularly in

the zone between the shoreline and 150 fathoms. Downey (1973), in her excellent contribution to the starfish of the Caribbean and Gulf of Mexico, presented a similar pattern with historical study of the starfish.

Pereyra and Alton (1972) found that the echinoderms were the most important single phylum of animals encountered in their study area. Echinoderms were of relatively minor importance in that only 25 taxa (2.57% of species) were collected and that, of the numerically dominant infaunal species (accounting for 90% of the abundance), only one echinoderm taxon was included. The echinoderms were of great importance in the trawl samples but were still overshadowed by the numbers of crustaceans and molluscs in most areas. The distribution in deeper zones may be a major factor in the difference between the observed relative importance of echinoderms in our study and that of Pereyra and Alton (1972). Their study, generally done at much greater depths than the present study, indicated the relative "importance" of echinoderms increasing with depth.

The echinoderm fauna in the present study was composed of 8 asteroids, 6 ophiuroids, 6 echinoids and 5 holothuroids. No crinoids were observed. Distribution, as previously noted, seemed depth dependent with the majority of species preferring greater depths. An exception to this pattern was the sea star, *Luidia clathrata*, which was found primarily in the shallow zones of our study area. Others, including *Astropecten duplicatus*, were distributed primarily in deeper waters. *Brissiopsis alta, Clypeaster ravenelli* and *Tethyaster vestitus* were essentially limited to the deeper zones of the study area. Distribution of echinoderms showed no seasonal pattern.

Marine Chordates of the Gulf of Mexico are discussed by Van Name (1954) and Hedgpeth (1954d). Van Name stated that sessile benthic tunicates of the class Ascidiacea are the most well-known urochordates from the Gulf of Mexico.

Hedgpeth (1954d), in a very brief discussion of the branchiostomids of the Gulf of Mexico, cited several records of the lancelots, *Branchiostoma caribbaeum* and *B. floridae*, from the Gulf.

Only nine taxa of chordates, seven urochordates and two hemichordates, were found in the present study. They comprised a small part (<1%) of the taxa enumerated from the south Texas outer continental shelf and were far less important in terms of total abundance of organisms collected.

Community Structure

While it is not the purpose of this particular paper to delve into ecological theory and semantics, a short aside concerning our usage of the terms community, assemblages and species group may be in order. Anyone familiar with the marine benthic field will realize that there has been a great number of words published concerning the use of these words. Differing schools of thought have held one of two views concerning benthic communities: either that while communities may not be the tight entities described by Petersen, they are nonetheless discrete entities; or that benthic organisms are distributed along one or more continua of physical or chemical variables and have no discrete grouping. The present author's feeling is that the truth lies somewhere in between. In the very diverse assortment of organisms described as benthos, some probably form communities in the classic sense of the word. Others may react only to a limiting physical or chemical factor and have little or no relation to other organisms found proximally. The groups of organisms delineated in the present study are not, for the most part, felt to be of the Petersen-Thorson (Thorson, 1957) conceptualization. A definition of the term "community" by Mills (1969) may be useful. Thus, a benthic community is herein defined as "a group of organisms occurring in a

particular environment, and separable by means of an ecological survey from other groups". "Assemblage" and "species group" normally do not have the same conceptualization of interaction between populations of organisms. Analysis of structural parameters of both infaunal and epifaunal communities indicated that structural attributes, including stability, varied with type of fauna, time and space.

Infauna

Infaunal communities had significant variations in structural parameters spatially, both with depth and transect. Cluster analysis indicated that major differences in communities were primarily related to depth. It should be remembered that the quantitative community structural parameters, species richness and density, utilized all species; while cluster analysis was limited to the numerically dominant species.

Statistically significant ($P < 0.05$) variation of inshore infaunal species richness and density (Table 13.5) between transects is indicated to be related to depth and sediment. In the STOCS study areas, depth and sediment coarseness are generally inversely related. A significant decrease in both species richness and density were apparent at the innermost station on Transect II as contrasted to other shallow stations on the other transects. This station was at least seven meters deeper than the shallowest stations on the other transects. It has, as expected, a lower percentage of sand, *i.e.* a finer sediment, than others in the shallow station group. Species richness and density varied significantly between transects in the offshore infaunal communities also (Table 13.2). The offshore station on Transect IV (3/IV) had significantly greater density and species richness. It was shallower than the other offshore stations but depth is not thought to be the primary factor in this case. Other stations of similar depth had much lower species richness

and density. The major factor other than depth was the much higher sand/mud ratio of greater than 1.0, while the other stations of the deep group averaged less than 0.1.

It appears that depth and depth-related factors, particularly coarseness of sediment are of major importance in the distribution of infauna in the study area. Benthic community distribution of continental shelves and deeper zones are apparently determined by depth in most areas (Carey, 1972; Wigley and McIntyre, 1964; Lie and Kelly, 1970). Several benthic infaunal studies (Sanders, 1958; Boesch, 1973) have shown the importance of sediment type to infaunal distribution in shallow estuarine areas. It is logical to assume that interactions between depth (depth-related factors) and sediment may determine the distribution of infaunal communities in areas where both are variable. There was a significant positive correlation between both species richness and density to particle size and an inverse relation to water depth. However, at several sites (3/IV and 6/IV) where the particle size was greater than that of areas of similar depth on other transects, species richness and density are increased. This may indicate a greater importance of sediment coarseness.

Thus, significant variations between infaunal community structure on transects are due to station depth and sediment. Cluster analysis does not indicate this spatial difference since many species are not included in the cluster analysis.

While significant temporal variations were indicated by the statistical (ANOVA) treatment of the infaunal community structure data, no seasonality in the infaunal data was suggested by the analyses. The only significant temporal variation in nearshore infaunal communities was in numbers of individuals (Table 13.5). This difference is not distinct as is seen from the

results of the Duncan's New Multiple Range Test. Fewer individuals were collected in the winter of 1976. The same temporal variability pattern was seen with individuals from the offshore communities. A distincly lowered species richness was observed for this same collection period. That this pattern is not a seasonal attribute is indicated by the data from the 1977 winter collection. Several possibilities exist which might explain the low number of individuals of the first collection of 1976. First, taxonomic error is a possibility, in that we had a suite of new people working on the increased sampling program. Unfortunately, the general increasing mean number of species and individuals (Table 13.5) may seem to also indicate this possibility. There may have been an actual decrease in infaunal populations for some unknown reason. Water temperature was much colder (mean 11.4°C, bottom, inshore) suggesting the possibility of a winter kill in 1976. A third possibility is that of navigational error. The data (Table 13.3) seem to indicate major differences to be limited to Transect III and IV inshore data, indicating sampling error.

Although significant temporal variations in both inshore and offshore infaunal communities existed, the lack of true seasonal fluctuations was also apparent from the cluster analysis. No seasonal trends within clusters were observed.

Epifauna

Statistical treatment of epifaunal data indicated fewer significant variations in structural parameters of inshore and offshore communities than with analogous infaunal communities. Significant inshore spatial variations were limited to individuals (density) and no distinct variation was produced (Table 13.8). This variation, though significant statistically, is not felt to have biological relevance. Temporally, numbers of inshore individuals and

species richness offshore varied significantly. Contrary to infaunal findings, the winter (1976) collection of epifauna was significantly greater than that of other seasonal collections. Again, there appear to be no real seasonal variations in basic community structural parameters for epifauna as with the infauna. The numbers of inshore epifauna were definitely greatest in the winter and spring collections of 1976. The shrimp, *Trachypenaeus similis*, was abundant in the winter and most 1976 collections, accounting for the large numbers encountered. It was found only in very small numbers at the inshore stations during the remainder of the study. No reason for the winter-spring increase can be given. The winter (1976) offshore epifaunal community had a significantly greater number of species than that of other collections.

It was felt that the variability of epifaunal samples through both time and space was far greater than that observed for infauna. The ANOVA found fewer significant variations which would be expected with greater sample standard deviation. Comparison of the coefficient of variation ratio showed that inshore infaunal communities were far more stable than corresponding epifaunal communities. Comparisons between offshore communities indicated higher, but not statistically significant, stability for infaunal populations.

The greater variability observed in epifaunal populations was due to several factors including greater motility of individuals, fewer sample replications, apparent migrations of some species across the study areas and recruitment.

The biotic provinces, geographic areas with similar biotic composition, for both infauna and epifauna were assessed primarily by normal cluster analysis. Comparative efforts utilizing other classificatory analyses, such as ordination and discriminant, for infauna generally corroborated provinces

delineated by cluster analysis.

Three of the eight shallow to mid-depth stations representing the second biotic province showed similar clustering strategy (B'). The remaining stations, group B, had a mixture of seasonal collections' clustering, indicating a general lack of uniqueness among these mid-depth stations. The B' stations each were represented by several uniquely common species while the B stations had no truly representative species.

The 13 stations at the deep water province were separated into two groups (C and C') primarily on the basis of relative abundance of species from the deep-water species group (Species Group 1).

The infauna of the shallowest and deepest zones have distinct elements plus the various ubiquitous groups. The mid-depth zone appears to lack groups of species unique to it, being composed of the ubiquitous species and remnants of both shallow and deep populations. Species included in the cluster analysis formed 11 clusters which are thought to represent four major groups. There was a distinct deep-water group (Species Group 1), a shallow-water group (Species Groups 6 and 7), a ubiquitous group (Species Groups 8, 9, 10 and 11) and a rather non-descript group (Species Groups 2, 3, 4, and 5) which were found in shallow, mid-depths and, to a limited extent, in deeper zones in small numbers.

It may be of some value to try to categorize infaunal communities as physically controlled or biologically accommodated as defined by Sanders (1968). The high density, high diversity infaunal communities of the shallow zones may have a small physically controlled component or, more accurately, be closer to the physically controlled extreme of the community continuum than the deeper stations; but it is doubtful that any physical factor plays a limiting role in the STOCS infaunal communities. It is more likely that

the majority of the STOCS region should be considered to have biologically accommodated infaunal communities or to be closer to that end of the ecological spectrum. Because of the uniformity of the physical and chemical variables over the period of study plus the evident stability in benthic community structure, one would have to assume that these communities are structured primarily by biological accommodated processes. This description does not agree with that of Hill (1975) but follows that of Sanders (1968) in that he specifies tropical shallow-water marine regions as typical, of biologically accommodated communities. The STOCS study area is most assuredly sub-tropical, shallow and marine.

Epifaunal biotic provinces were apparently also based on depth or depth-related factors. Five major epifaunal provinces were delineated from a multi-year analysis (Figure 13.4). Epifaunal species were basically limited to shallow and deep groups. Only two of the nine clusters observed showed much overlap. All the other species clusters were basically shallow to shallow-intermediate or deep to deep-intermediate. As observed in the structural parameter analysis, the communities of epifauna were not as stable as the infaunal communities. Cluster groups in annual data analyses did not display trends as well with epifaunal data as with infaunal data, again showing the lack of stability in these former fauna. It is believed that, although a portion of this lack of stability is undoubtedly due to the lack of replications, the motility of many epifaunal species, as well as varying patterns of reproduction and recruitment, produce a less stable community both in structural patterns and qualitative composition than is found in the infauna.

Biomass was assessed from a limited number of samples from the 1976 data. Infaunal organisms of the STOCS region were extremely small, some 22,000 individuals weighed only 43 g. Visiting investigators have remarked about

the small size at maturity of many of the STOCS species. Predicted biomass from 16 infaunal species was less than one gram per square meter. Weights of individuals were invariably low due to fragmentation. Actual average wet weight biomass of whole infaunal samples was about 4 g/m^2, a very low standing crop. Buchanan and Warwick (1974) reported macroinfaunal biomass as almost 4 g/m^2 ash-free dry weight. Rowe *et al.* (1974) reported deep benthic fauna biomass to be 27 g/m^2 wet weight. No productivity measures to predict annual production of benthic biomass in our area have been attempted. If benthic infauna are playing a role in the transferral of energy through the ecosystem, the turnover rate must be very high. The standing crop of various species was observed during the year and generally little variation was seen. This, with the small individual size, leads again to the conclusion that many of the STOCS infaunal invertebrate populations are maturing rapidly, reproducing throughout the year and maintaining a fairly well balanced predation-recruitment cycle. This would, of cource, be expected in a well-balanced biologically accommodating community. A point of interest concerning the relative distribution of biomass across the shelf between epifaunal and infaunal communities was that the infauna produce almost 90% of the total infaunal biomass measured in the very shallow zone consisting of the first two stations on each transect. The epifauna, however, have slightly over 90% in the shallow and intermediate depths with the two depth zones approximately equal in biomass. This disparity in distribution raises questions of the importance of the infauna to the epifaunal invertebrates. If they are not an important food item for the epifaunal invertebrates, are they important to bottom-dwelling fish? If not, are they an important link in the ecosystem?

In an attempt to integrate benthic infaunal and epifaunal data with other facets of the STOCS study, an assessment of what data sets (physical,

chemical, or biological) might be expected to affect the benthos, was made. Several of the parameters studied were not indicated to significantly affect benthic distributions. However, some 30 to 40 parameters including hydrological, sedimentary, chemical, trace metal, and biological parameters were tested for correlations against both species richness and abundance of infauna and epifauna. The correlation analysis, even if significant, does not imply cause and effect relations. Many of the significant correlations were very low which questioned the value of the correlation, as to how much of the variation was actually explained.

Significant correlations between infaunal numbers and species richness to a number of parameters are thought to exist. The correlation between species richness to transect is thought to present a valid relationship. Correlation analyses and ANOVA indicated a greater species richness on southern transects particularly on Transect IV. The major factor involved is thought to be sediment texture rather than true latitudinal differences. Correlations between infaunal numbers and species richness to hydrographic parameters such as temperature and salinity indicated a decrease in numbers and diversity with water depth. The lack of significant correlations between infauna to meiofauna and epifauna to demersal fish is not felt to exclude interactions between the infauna and the other biotic groups. Either the interaction is not based on numbers and species richness or sampling was unable to detect it. The slight positive correlation between infauna to both phytoplankton and zooplankton indicates a similar distribution pattern, *i.e.* inshore to offshore gradation, but does not necessarily imply a direct relationship. The inverse relation between total carbon to infaunal species richness and abundance indicated a lowered carbon component in the inshore sandy sediments where richest infaunal communities were. This may indicate either a lack of

utilization by infauna of the carbon measured or inadequate measurement of carbon that is biologically unavailable. It may indicate that carbon is not a limiting resource on the STOCS for benthic infauna and that communities are responding to other factors, *e.g.* sediment particle size.

A similar set of correlation analyses was calculated for epifaunal density and species richness to various physical, chemical, hydrological and biological parameters. As might be expected from these analyses, far fewer significant relations were observed than with infauna. Apparently the more mobile, less structured communities of epifauna either do not have the same degree of relationship to most environmental parameters or the sampling was unable to detect it. The relation of individual populations of epifaunal organisms to certain environmental parameters did show some significance.

CONCLUSIONS

1. The STOCS region is characterized by a relatively sparse benthic invertebrate fauna, particularly the infauna. It is a moderately diverse fauna with moderate density and low biomass.

2. The basic infaunal distribution patterns are depth-related, primarily modified by sediment. Epifaunal distribution seems only depth-oriented.

3. A stable suite of species groups defines readily identifiable biotic provinces for both infauna and epifauna. The infauna show greater spatial and temporal stability.

4. Present distribution patterns can be accounted for by natural physical, chemical, hydrological, and biological interactions. No evidence for oil and gas exploration and production related perturbations was observed.

5. Given time, place and sediment type, a reasonable benthic infaunal community could be hypothesized for any of the STOCS study area. Epifaunal

predictions would be far less accurate.

6. Infaunal communities are basically biologically accommodating, and non-physically limited. Evidence for low biomass and high turnover with small individuals and short life spans is strong.

7. No significant seasonal variations were observed in benthic invertebrate communities of the STOCS.

RECOMMENDATIONS

1. Utilization of present study.

a. Infaunal communities of inshore stations appear to be the most stable communities assayed. Any future comparative work should involve these communities.

b. Epifaunal communities of the STOCS have been shown to be highly variable, temporally and spatially, and should not be utilized in monitoring studies due to this variability.

c. Individual species have been shown to have distributional characteristics, *i.e.* ubiquitous and common; ubiquitous and uncommon; restricted to shallow water; restricted to deep water, etc. These characteristics should be taken into consideration in future planning.

2. Further study.

a. A great deal of information resides in samples already collected and analyzed. In-depth studies of individual species should be attempted.

b. Life history information on the majority of species shown to be numerically of distributionally important on the STOCS is lacking. The information should be obtained and integrated into the existing distributional knowledge.

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CHAPTER FOURTEEN

DEMERSAL FISHES

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ABSTRACT

Results from a three-year trawl survey of benthic fishes and supporting data on benthic macroinvertebrate and physical parameters were used to characterize the south Texas outer continental shelf (STOCS) ecosystem. Numerical classification indicated general similarity in the ichthyofauna at sampling stations of similar depths, but also definite change in character of the ichthyofauna with increasing depth. There were some differences in this depthwise grouping of stations between seasons, years, and day/night periods. Differences between time periods were also evident in the associations of species defined by the numerical classification.

Discriminant analysis was used to further describe differences among sampling stations at different depths with respect to the most abundant benthic fish and macroinvertebrate species. Among the fishes which most distinguished the depth zones from one another were *Cynoscion nothus*, *Pristipomoides aquilonaris*, *Sphoeroides parvus*, *Syacium gunteri*, and *Trichopsetta ventralis*. Macroinvertebrates were also examined in this study because of their potential as a food source to demersal fish. Among macroinvertebrates which most distinguished depth zones were *Squilla empusa*, *Penaeus duorarum*, *Penaeus setiferus*, *Trachypenaeus constrictus* and *Renilla mulleri*. Discriminant analysis using physical parameters indicated greatest differences between depth zones primarily with respect to a combination of sediment mean grain size, percent silt composition and bottom salinity.

Multiple regressions of abundances of individual species on selected physical and biotic variables yielded equations which explained 4 to 41% of the variation in abundance of the fishes. Regressions were considered effective only for *Pontinus longispinis* (31% of variation explained) and *Anchoa hepsetus* (41%). Although the multiple regressions could be interpreted to suggest possible causal relationships between fish abundances and environmental variables, the main value of such regressions would be in prediction in broad terms of the abundance levels of species, given information on their environment.

INTRODUCTION

Patterns of distribution and abundance of outer continental shelf fishes off the Texas coast have been examined by a number of workers (*e.g.* Hildebrand, 1954; Chittenden and McEachran, 1976; Chittenden and Moore, 1977), but ecological aspects of this ichthyofauna (particularly regarding factors which affect these patterns) remain poorly understood. Although distributions of certain species off Texas and in other parts of the Gulf of Mexico have been related in a broad manner to a few obvious factors such as depth, sediment and temperature (Dawson, 1964; Chittenden and McEachran, 1976; Lewis and Yerger, 1976), a more detailed exposition of the relationship between fish populations and the ecological factors which affect them is desirable. The need for statistical evaluations of these fish-environment relationships has been specifically pointed out (Chittenden and Moore, 1977).

A multifaceted environmental survey of the south Texas outer continental shelf (STOCS) conducted from 1974 to 1977 (Parker, 1976; Groover, 1977; Flint and Griffin, 1979) has generated substantial amounts of information appropriate for statistical evaluation of relationships between biotic and abiotic components of this system. The following material draws from this data base to broadly describe the benthic ichthyofauna of this region, and integrates data on benthic epifauna (fishes and invertebrates) and environmental factors to indicate possible significant relationships between certain species and features of their environment.

MATERIALS AND METHODS

Data on fishes and macroinvertebrate epifauna were derived from 15-minute (bottom time) drags with an otter trawl, conducted during 1974-1977. Specifics on sampling protocol and gear are given in Wohlschlag *et al*

(1976). Sampling of invertebrate infauna is described by Holland *et al.* (1977), and methods of collection of hydrographic and geological data are found in Parker (1976), Groover (1977) and Flint and Griffin (1979).

A total of 569 trawls for fishes and invertebrates were made, with one to three trawls taken during a given sampling episode (defined as all trawls taken at a single station during a given time period; *e.g.* station 1/I-day-winter). Sampling effort varied between years (258 trawls in 1977; 239 in 1976; 72 in 1975), but sampling effort within each year was distributed over all (4) transects (latitudes) and major depth zones. Trawls were made over the entire range of the sampling area during winter, spring and fall of each year, with additional trawls taken between seasons (limited to Transect II) in 1976 and 1977.

Sampling stations were divided among three station groups on the basis of depth for summarization and analytical purposes (Figure 14.1). Depths defining station groups were arbitrarily chosen, although that separating station groups 1 and 2 (30 m) corresponded roughly with the boundary between the so-called white (shallow) and brown shrimp grounds (Chittenden and Moore, 1977). These station groups were employed in discriminant analysis and analysis of variance (described below). The division of sampling effort over the station groups are shown in Table 14.1.

Analysis of data utilized multivariate numerical and statistical techniques. Cluster analysis (numerical classification) was employed to determine overall patterns of distribution and abundance of benthic fishes. This analysis grouped together sampling stations which were similar in composition and abundances of fishes and grouped together species which were similar in distribution over sampling stations. Discriminant analysis was then performed on data for physical variables and abundances of invertebrate epifauna and benthic fishes to provide further

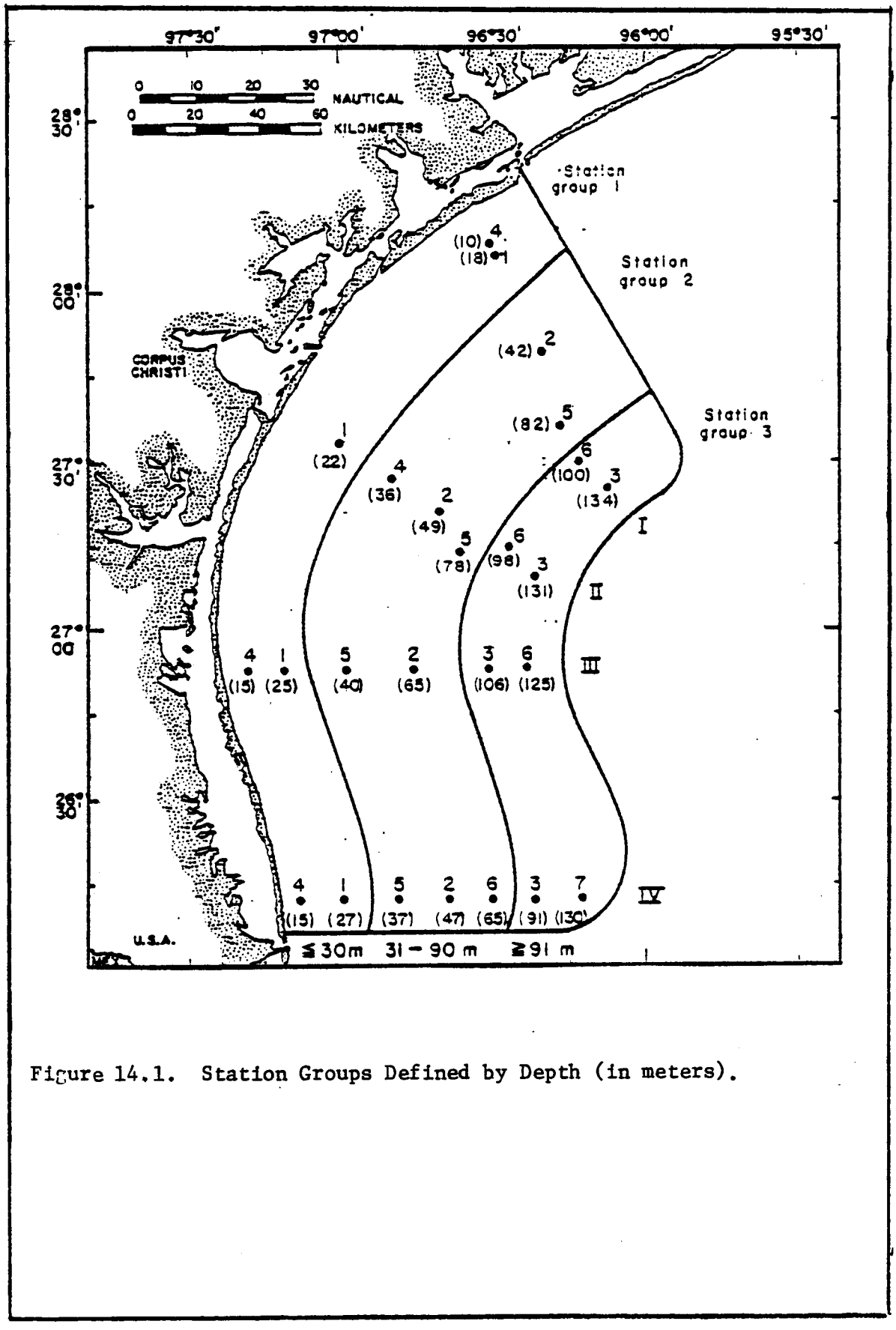

Figure 14.1. Station Groups Defined by Depth (in meters).

TABLE 14.1

SAMPLING EFFORT OVER THE DEFINED STATION GROUPS
DURING 1974-1977

	Number of Trawls		
	Station Group 1	Station Group 2	Station Group 3
1974-1975	24	24	24
1976	66	104	70
1977	69	105	84

description of spatial trends in these variables. Finally, multiple regressions of abundances of the most common fishes were carried out using selected physical factors and information on invertebrate infauna as predictor (independent) variables. Multiple regression provided a quantitative description of the association between fish abundances and predictor variables, and also an assessment of the ability of this method to predict fish abundances from data on predictor variables.

Cluster Analysis

Cluster analysis was carried out by a computer program derived and modified from those developed by Dr. R. W. Smith of the University of Southern California and Anderberg (1972). The protocol of analysis largely followed that employed by Holland *et al.* (1977) and Wohlschlag *et al.* (1977).

For the present study, the Canberra-Metric measure of Lance and Williams (1967a) was employed to measure dissimilarity between two entities (entities here being either individual species or stations, or groups thereof). The Canberra-Metric (C.M.) measure applied to two entities j and k has the form:

$$C.M._{jk} \equiv \frac{1}{n} \sum_{i}^{n} \frac{|X_{ij} - X_{ik}|}{(X_{ij} - X_{ik})}$$

where n is the number of attributes considered in measuring similarity and X_{ij} and X_{ik} are the values of attributes X_i for entities j and k, respectively. With stations taken as entities, attributes were numerical abundances of species and n was the number of species present at either or both of the stations j, k with abundance $\geq$ 1 individual. X_{ij} and X_{ik} then represented the abundance of species i at stations j and k, respectively. An unattractive feature of this measure is that if the attribute

value for one of the entities equals zero, then the measure takes the maximum value one (1) regardless of the attribute value for the other entity. This was remedied in the present study by substituting a very small value (1/5 the value of the smallest nonzero data entry) for all the zero values (following Stephensen and Cook, 1972).

The clustering strategy employed was the "flexible clustering" of Lance and Williams (1967b), with the constraint parameter β set at -.25 by the convention of other workers (Clifford and Stephenson, 1975).

Cluster analysis was applied separately to the catch data for benthic fishes for each season (winter, spring, fall) within each of the years 1976 and 1977. Furthermore, separate analyses were done for day and night periods within each season, so a total of 12 cluster analyses were performed.

Each cluster analysis yielded two dendrograms--one displaying the sampling stations arranged in the standard hierarchical format, and the other displaying the species. These dendrograms allowed major groups of stations or groups of species to be defined on the basis of the dissimilarity values between groups. Two-way tables were also provided by the computer program. These tables are basically matrices containing the original data on abundances, with rows corresponding to species and columns corresponding to stations, but with the species and stations arrayed in the order generated by the cluster analysis. The two-way tables were used to pick out species which, on the basis of their abundance and distribution patterns, appeared to be misclassified. These "misclassified" species were moved to other species groups, based on subjective decisions on the appropriateness of such moves.

Discriminant Analysis

Discriminant analysis was applied to selected physical variables measured at sampling stations with groups of stations defined as Figure 14.1. The goal was to determine the relative importance of each of these physical variables in differentiating between the station groups. Relative importance was assessed by examining the values for the standardized weights (standardized discriminant function coefficient) assigned to each of the original physical ("discriminating") variables by discriminant analysis.

Discriminant analysis of physical variables also represented a means of characterizing the station groups with respect to these variables. Specifically, the analysis allowed us to examine the differences between station groups relative to each discriminant function (*i.e.* each transformed axis achieved through discriminant analysis), and to interpret these differences with respect to the original physical variables which dominated that discriminant function. Again, the identification of variables which dominated each discriminant function was based on values of the standardized weights corresponding to that discriminant function.

Finally, discriminant analysis provided a means of obtaining quantitative measures of the "strength" or validity of the station groups with respect to physical variables. The motivation for defining station groups as we did (by depth) was that cluster analysis indicated differences in the species compositions and patterns of abundance of demersal fishes between sampling stations in different depth zones. We wished to see if these differences were also reflected by physical variables. The strength of the station groupings could be measured by the square of the canonical correlation for each discriminant function; each was interpreted as the proportion of variance in the corresponding discriminant function accounted

for by the groups (Klecka, 1975). A second measure of the strength of station groupings was Wilk's Lambda criterion, which was used to test the significance of the overall difference among station group centroids (Tatsuoka, 1971; Klecka, 1975). A third indirect measure of the strength of groups utilized the classification capabilities of discriminant analysis, with the proportion of stations assigned to the correct station groups by the classification procedure taken as the measure.

Discriminant analysis was also carried out on sampling stations using the abundances of selected fishes and (separately) benthic macroinvertebrates as discriminating variables. The purpose was to characterize the station groups with respect to the predominant fish or invertebrate species captured during the study. Fishes selected were those which occurred with abundance of at least 100 individuals in each year 1975-1977 while the invertebrates used had total abundance exceeding 90 individuals over the combined years 1976-1977. Data from all three years (1975-1977) were used for these analyses. For 1976 and 1977 data, we used averages of replicate trawls within a sampling episode. No replicate trawls were taken within sampling episodes in 1975. The procedures used in the discriminant analyses based on fish and invertebrate abundances were identical to those used for the analysis based on physical variables.

Discriminant analysis was carried out using the Statistical Package for the Social Sciences (SPSS) (Nie *et al.*, 1975), which provided standardized weights corresponding to each discriminant function, values for all measures used to assess the strength of station groupings (including classification of data cases), and the necessary statistical tests. SPSS also provided values for the discriminant criteria associated with the dis-

criminant functions, which were used to gauge the relative importance of each discriminant function in differentiating between station groups. Specifically, the proportionate contribution of each discriminant criterion to the sum of all discriminant criteria represented the relative importance of its corresponding discriminant function in separating the station groups. Furthermore, the sum of the discriminant criteria is a measure of the total variance in the discriminating variables (Klecka, 1975), so the proportionate contribution of each discriminant criterion to the sum also represented the relative importance of the associated discriminant function in accounting for the total variance. The proportionate contributions of the discriminant criteria were used in conjunction with the standardized weights for the physical variables in assessing the relative importance of the variables.

Pairwise comparisons of station group centroids, using F-values based on the Mahalonobis distance between groups were performed by SPSS. As with the overall test of difference among groups using Wilk's Lambda, these F-tests could be viewed as a test of the distinctiveness of the defined station groups with respect to discriminating variables.

Tests of equality of station group means and variances were also performed using SPSS for each discriminating variable. An arcsine transformation was performed on values for percent silt prior to all statistical analyses and other transformations to avoid difficulties inherent in data expressed as percentages (Sokal and Rohlf, 1969). Homogeneity of variances among station groups was tested with Bartlett's test (Sokal and Rohlf, 1969) or Cochran's C statistic. If a station group had zero variance for a variable, it was omitted and Cochran's C was used in place

of Bartlett's test to compare the two remaining groups. Analysis of variance (ANOVA) was performed for each variable to test for differences among station groups means. If either a square root or natural log transformation yielded greater equality of variances among groups (indicated by a less significant Bartlett's or Cochran's statistic), that transformation was performed on the variable prior to performing ANOVA. Zero abundances of species were replaced by the value 1 prior to transformation [to avoid values of ln(0) = -00]. A posteriori comparisons among group means were made using the Student-Newman-Keuls (SNK) procedure (Sokal and Rohlf, 1969).

Multiple Regression

The final phase of analysis consisted of multiple regression of abundances of common fishes on selected predictor (independent) variables. The predictor variables were depth, day or night (coded 1 and 2, respectively), Julian Day, bottom temperature, percent silt in the sediment, percent sand, sediment mean grain size (Ø units), depth (in meters), skewness and standard deviation of sediment grain sizes, percent of sediment (by weight) comprised by organic carbon, invertebrate infauna abundance (total no. of individuals) and Shannon-Wiener diversity of invertebrate infauna. Data from 1976 and 1977 only were available for predictor variables. Polynomial regression with linear, quadratic and cubic terms of all predictor variables was conducted using a stepwise procedure. The "tolerance level" for entry of variables into the regression was set to .05. Thus predictor variables with more than 95% (=100-5%) of their variability explained by variables already entered into the regression were not included in the regression. Stepwise regression was also terminated when none of the predictor variables remaining out of the regression had F-values $\geq$ 1.0.

Regressions were carried out using SPSS, which provided values for all parameters in the regression model, the standard error of residuals about the regression, the mutiple correlation coefficient (multiple-R) and analysis of variance for determining significance of the regression in explaining variability in fish abundances. The underlying polynomial regression model was:

$$\hat{Y} = B_0 + B_1X_1 + B_2X_1^2 + B_3X_1^3 + B_4X_2 + B_5X_2^2 + B_6X_2^2 + \cdots +$$

$$B_{3p+1}X_p + B_{3p+2}X_p^2 + B_{3p+3}X_p^3 + e_o$$

where $\hat{Y}$ is predicted abundance, $X_1 \cdots X_p$ are the predictor variables, $B_1 \cdots B_{3p+3}$ are partial regression coefficients, B_0 is the constant term, and e_o an error term assumed to be independently distributed as Normal (0, σ^2; σ^2, unknown). Multiple-R was the correlation between actual fish abundance and predicted abundance from the regression equation. The squared multiple-R represented the proportion of variability in fish abundance explained by the regression (Klecka, 1975; Affifi and Azen, 1972), and was used to assess the effectiveness of the regression model for each species. Prediction accuracy of the regression model is also related to the standard error of residuals about the regression, also known as the standard error of estimate (Klecka, 1975). These standard errors were useful for showing the variation in numbers of individuals about the regression hyperplane, but since fish abundances could vary widely about the regression and still have a significant proportion of variation explained by this regression, the standard errors of residuals were not used to assess the accuracy of the regression model.

RESULTS

Over 160 fish species were captured during the three years of sampling, but only 57 species were captured in excess of 100 individuals and 22 species in excess of 1000. The most common species are listed in Table 14.2, and their frequencies of occurrence among the ten most abundant species for each season and station group given in Tables 14.3 and 14.4 (data from Wohlschlag *et al.*, 1977, 1978). Most of the common species were dominant elements (*i.e.* among the top ten species) of the ichthyofauna in only one or two station groups (*e.g. Syacium gunteri, Diplectrum bivittatum* in Station Groups 1 and 2; *Serranus atrobranchus* in Station Groups 2 and 3), reflecting the spatial (depthwise) differences in the fish assemblages found over the study area. The notable exception was *Trachurus lathami*, which was dominant at roughly equal frequencies in all three station groups. Seasonal changes in the extent to which species dominated the ichthyofauna also occurred (*e.g. Syacium gunteri* was predominant mainly in winter and fall), although a number of species showed no variation (*e.g. Stenotomus caprinus, Serranus atrobranchus;* Table 14.3). More detailed and extensive descriptions of the ichthyofauna of the study area can be found in Wohlschlag *et al.* (1976, 1977, 1978).

Cluster Analysis

Major station groups, derived from the cluster analysis, were defined as all groups of stations which differed from other groups by a dissimilarity level of at least .50. If no major divisions occurred at dissimilarity levels of at least .50, then the major division which occurred with the highest dissimilarity value was taken to define the major station groups. Examples of these major station groups are charted in

TABLE 14.2

TOTAL ABUNDANCE AND NUMBER OF OCCURRENCES
(NUMBER OF TRAWLS IN WHICH TAKEN)
OF THE MOST ABUNDANT FISHES CAPTURED DURING THE
SAMPLING PROGRAM, 1974-1977

Species	Number of Individuals	Number of Occurrences
Trachurus lathami	8612	243
Serranus atrobranchus	8406	365
Micropogon undulatus	7767	140
Peprilus burti	6656	169
Cynoscion nothus	5952	123
Syacium gunteri	4465	263
Stenotomus caprinus	3905	327
Pristipomoides aquilonaris	3534	312
Prionotus paralatus	2608	235
Polydactylus octonemus	2392	65
Saurida brasiliensis	2162	194
Anchoa hepsetus	1987	59
Chloroscombrus chrysurus	1945	65
Sphoeroides parvus	1724	163
Upeneus parvus	1724	217
Centropristis philadelphica	1705	297
Prionotus stearnsi	1635	187
Cynoscion arenarius	1431	130
Prionotus rubio	1429	217
Trichopsetta ventralis	1390	193
Synodus foetens	1186	308
Diplectrum bivittatum	1072	133
Porichthys porosissimus	957	189
Pontinus longispinis	548	73
Synodus poeyi	512	112
Bollmannia communis	507	112
Lepophidium graellsi	455	149

TABLE 14.3

FREQUENCY OF OCCURRENCE OF COMMON FISHES AMONG THE TEN MOST ABUNDANT SPECIES DURING EACH SEASON. EACH OCCURRENCE CORRESPONDED TO A SINGLE SAMPLING SERIES (E.G. STATION GROUP 1-DAY-1977). A TOTAL OF 12 OCCURRENCES (SAMPLING SERIES) PER SEASON WAS POSSIBLE. SAMPLING SERIES INCLUDED: STATION GROUPS 1, 2, 3/DAY,NIGHT/1976, 1977 (DATA FROM WOHLSCHLAG 1977, 1978).

Species	Number of Occurrence Among Top Ten Species		
	WINTER	SPRING	FALL
Anchoa hepsetus	2	3	1
Cynoscion nothus	3	3	3
Micropogon undulatus	3	4	6
Peprilus burti	3	6	3
Syacium gunteri	8	3	7
Cynoscion arenarius	4	3	1
Sphoeroides parvus	4	3	4
Trachurus lathami	2	8	6
Polydactylus octonemus	-	4	6
Chloroscombrus chrysurus	-	3	3
Upeneus parvus	4	7	4
Stenotomus caprinus	8	8	9
Diplectrum bivittatum	2	1	6
Saurida brasiliensis	3	2	2
Serranus atrobranchus	8	8	8
Synodus foetens	2	3	1
Prionotus stearnsi	2	3	5
Pristipomoides aquilonaris	6	7	6
Prionotus paralatus	4	5	5
Trichopsetta ventralis	5	3	4
Halieutichthys aculeatus	2	1	3
Pontinus longispinis	1	2	4
Prionotus rubio	4	1	3
Centropristis philadelphica	3	3	3

TABLE 14.4

FREQUENCY OF OCCURRENCE OF COMMON FISHES AMONG THE TEN MOST ABUNDANT SPECIES IN EACH DEFINED STATION GROUP.
EACH OCCURRENCE CORRESPONDED TO A SINGLE SAMPLING PERIOD (E.G. WINTER-DAY 1977). A TOTAL OF 12 OCCURRENCES (SAMPLING PERIODS) PER STATION GROUP WAS POSSIBLE.
SAMPLING PERIODS INCLUDED: WINTER, SPRING, FALL/DAY, NIGHT/1976, 1977
(DATA FROM WOHLSCHLAG 1977, 1978)

Species	Number of Occurrences Among Top Ten Species		
	Station Group 1	Station Group 2	Station Group 3
Anchoa hepsetus	6	-	-
Cynoscion nothus	8	1	-
Micropogon undulatus	11	2	-
Peprilus burti	7	4	1
Syacium gunteri	9	8	1
Cynoscion arenarius	7	1	-
Sphoeroides parvus	7	4	-
Trachurus lathami	5	6	5
Polydactylus octonemus	7	3	-
Chloroscombrus chrysurus	5	1	-
Upeneus parvus	2	5	8
Stenotomus caprinus	2	12	11
Diplectrum bivittatum	4	5	-
Saurida brasiliensis	-	5	2
Serranus atrobranchus	-	12	12
Synodus foetens	-	5	1
Prionotus stearnsi	-	8	2
Pristipomoides aquilonaris	-	7	12
Prionotus paralatus	-	2	12
Trichopsetta ventralis	-	2	10
Halieutichthys aculeatus	-	1	5
Pontinus longispinis	-	-	7
Prionotus rubio	4	2	2
Centropristis philadelphica	2	7	-

Figures 14.2 through 14.7. Also mapped on these figures are subgroups within major station groups. Only subgroups with dissimilarity values ≥ .40 are included.

The major station groups were generally delimited from each other by depth. Subgroups within major station groups also tended to show depth-wise divisions. The indication, therefore, is that stations of similar depth tend to have fish assemblages of similar composition. However, the demarcation between the major groupings varied from season to season, and also between day and night periods within a given season (Figures 14.2 through 14.7). The extent of the difference between day and night periods ranged from slight (Spring 1976) to substantial (Spring 1977). Differences in the composition of major station groups generally also varied between years. Although major station groups for the fall-day period were identical for 1976 and 1977, the other time periods for 1976 showed various degrees of difference with the corresponding time periods in 1977.

Examples of species groups obtained from cluster analyses are shown in slightly modified form in Tables 14.5 through 14.9. Species groups were defined as all groups which differed from one another by a dissimilarity level of at least .50. If no groups emerged at dissimilarity levels of at least .50, then the major division with the highest dissimilarity value (in the species dendrogram) was taken to define the major species groups. The modifications of the species groups consisted of moving a few species from one species group to another whenever such moves appeared, on the basis of these species' abundance and distribution patterns, to improve the internal consistency of the species groups. Also included in the tables are alphabetic codes representing the levels of constancy and fidelity (*sensu* Stephenson *et al.*, 1970) the species

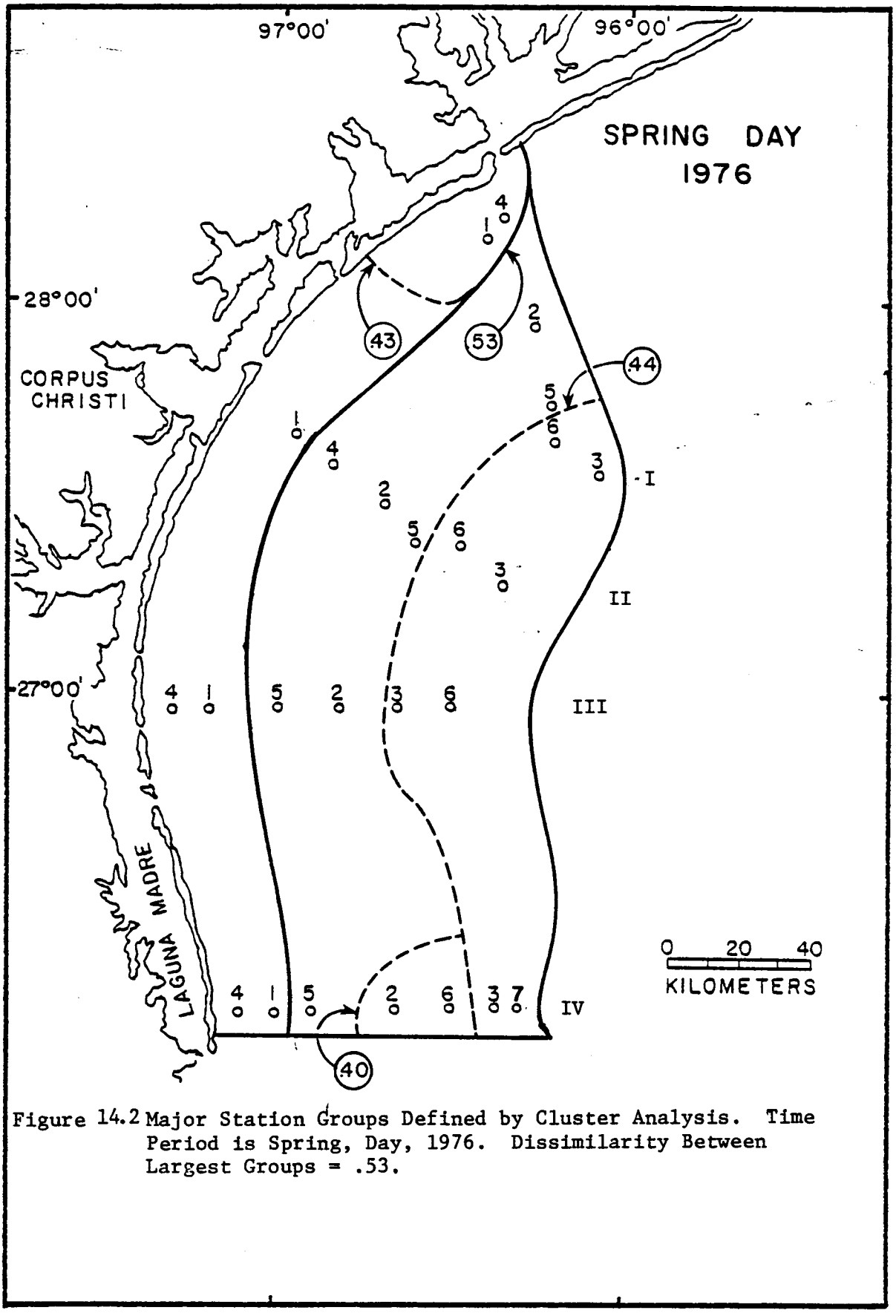

Figure 14.2 Major Station Groups Defined by Cluster Analysis. Time Period is Spring, Day, 1976. Dissimilarity Between Largest Groups = .53.

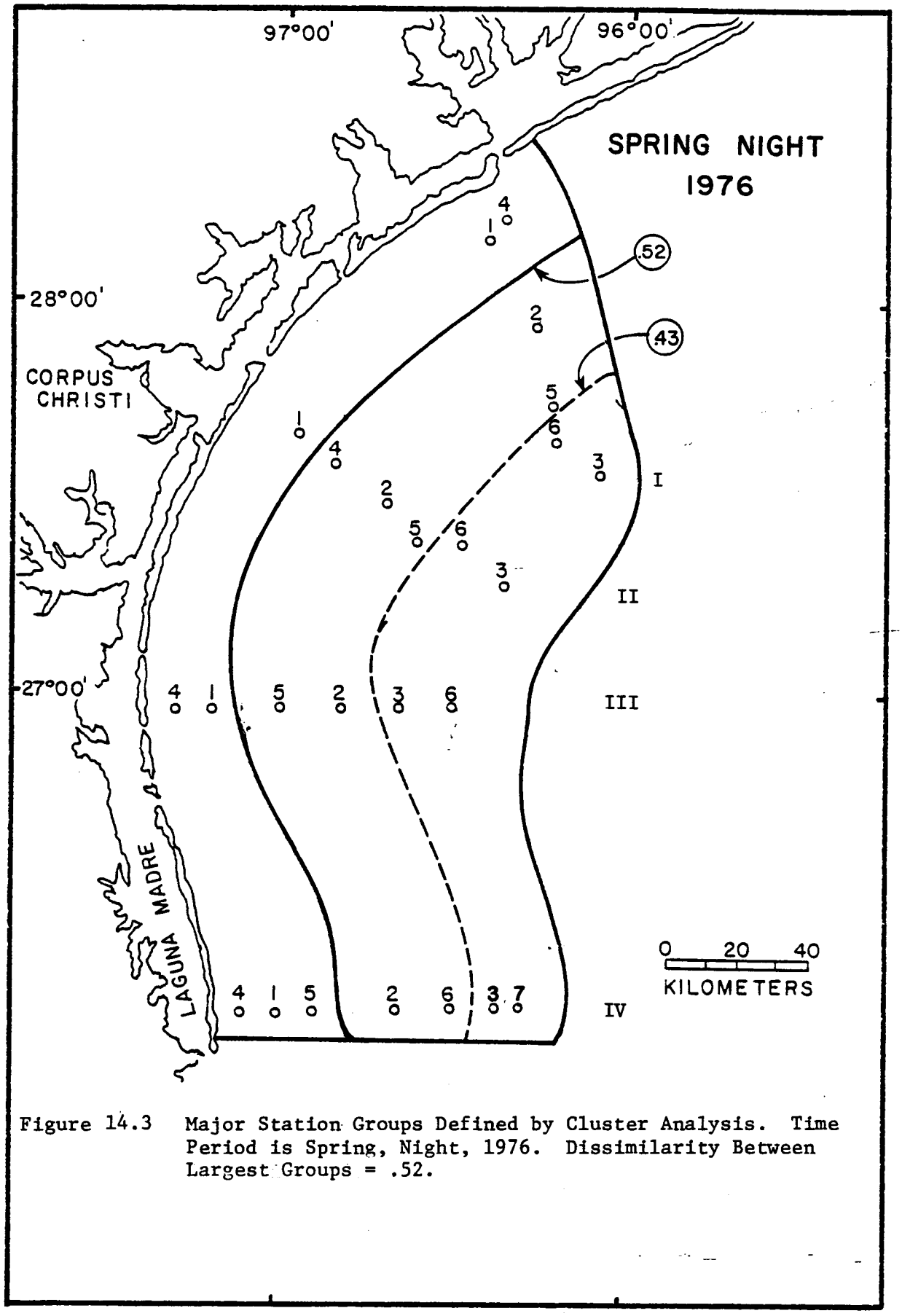

Figure 14.3 Major Station Groups Defined by Cluster Analysis. Time Period is Spring, Night, 1976. Dissimilarity Between Largest Groups = .52.

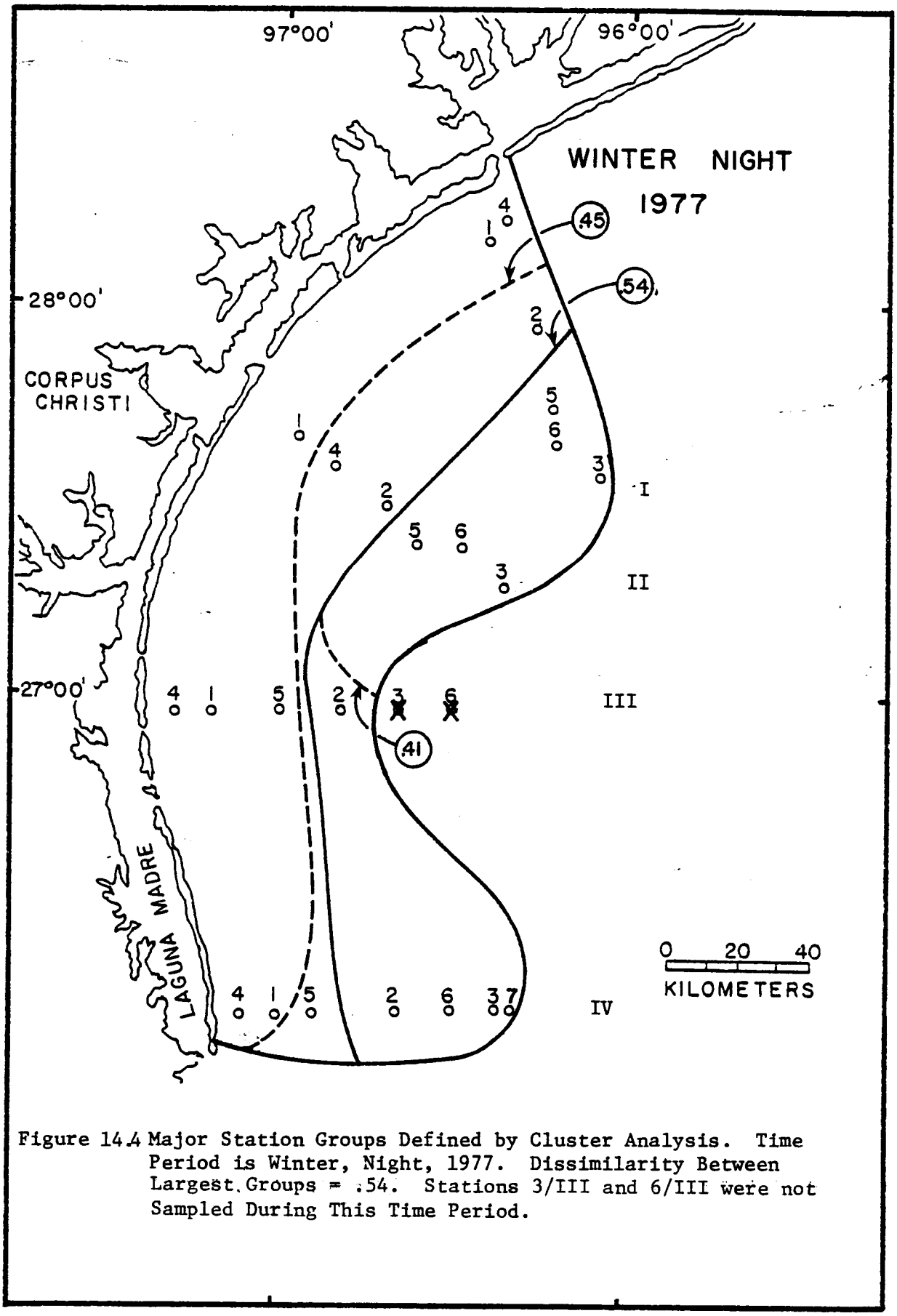

Figure 14.4 Major Station Groups Defined by Cluster Analysis. Time Period is Winter, Night, 1977. Dissimilarity Between Largest Groups = .54. Stations 3/III and 6/III were not Sampled During This Time Period.

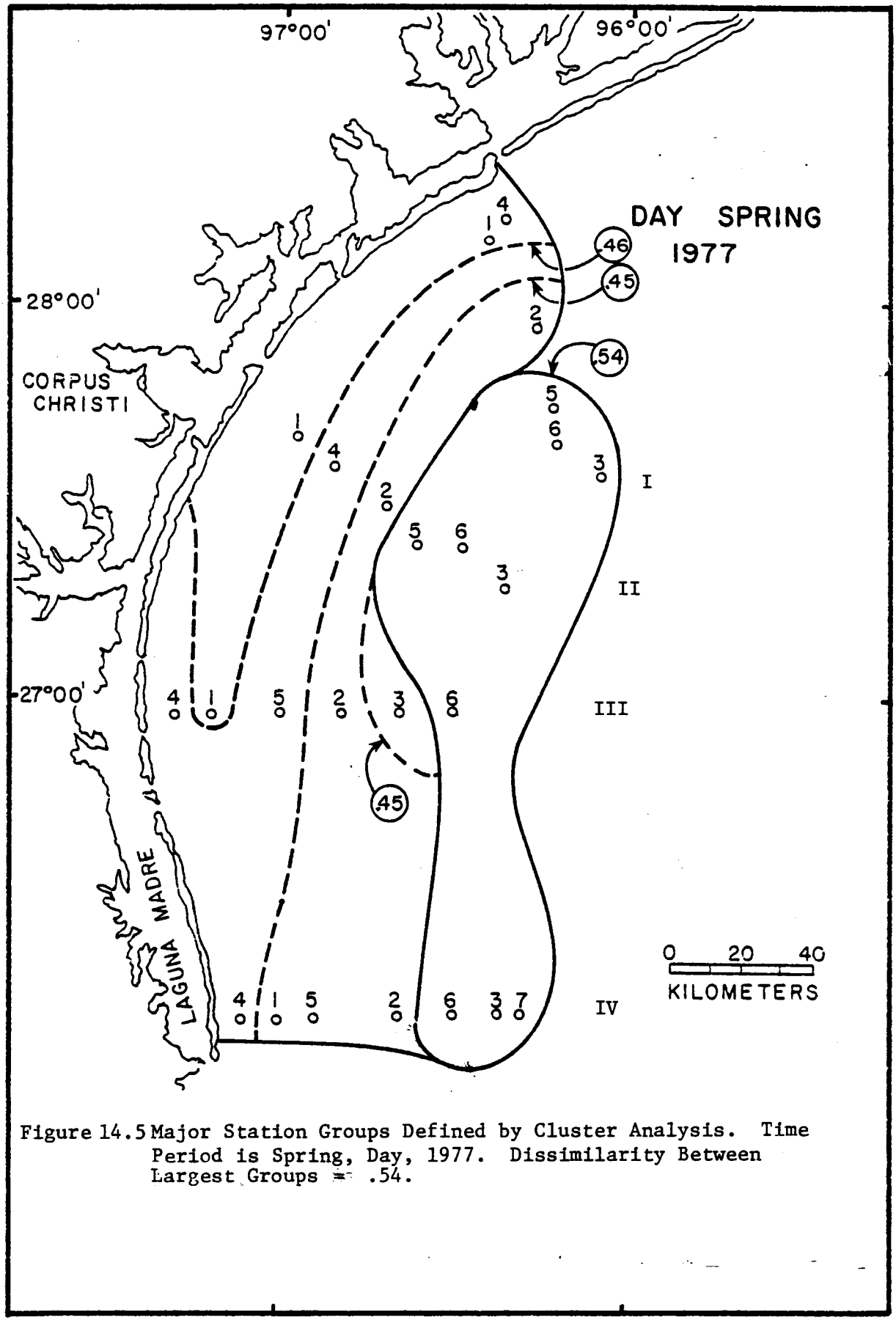

Figure 14.5 Major Station Groups Defined by Cluster Analysis. Time Period is Spring, Day, 1977. Dissimilarity Between Largest Groups = .54.

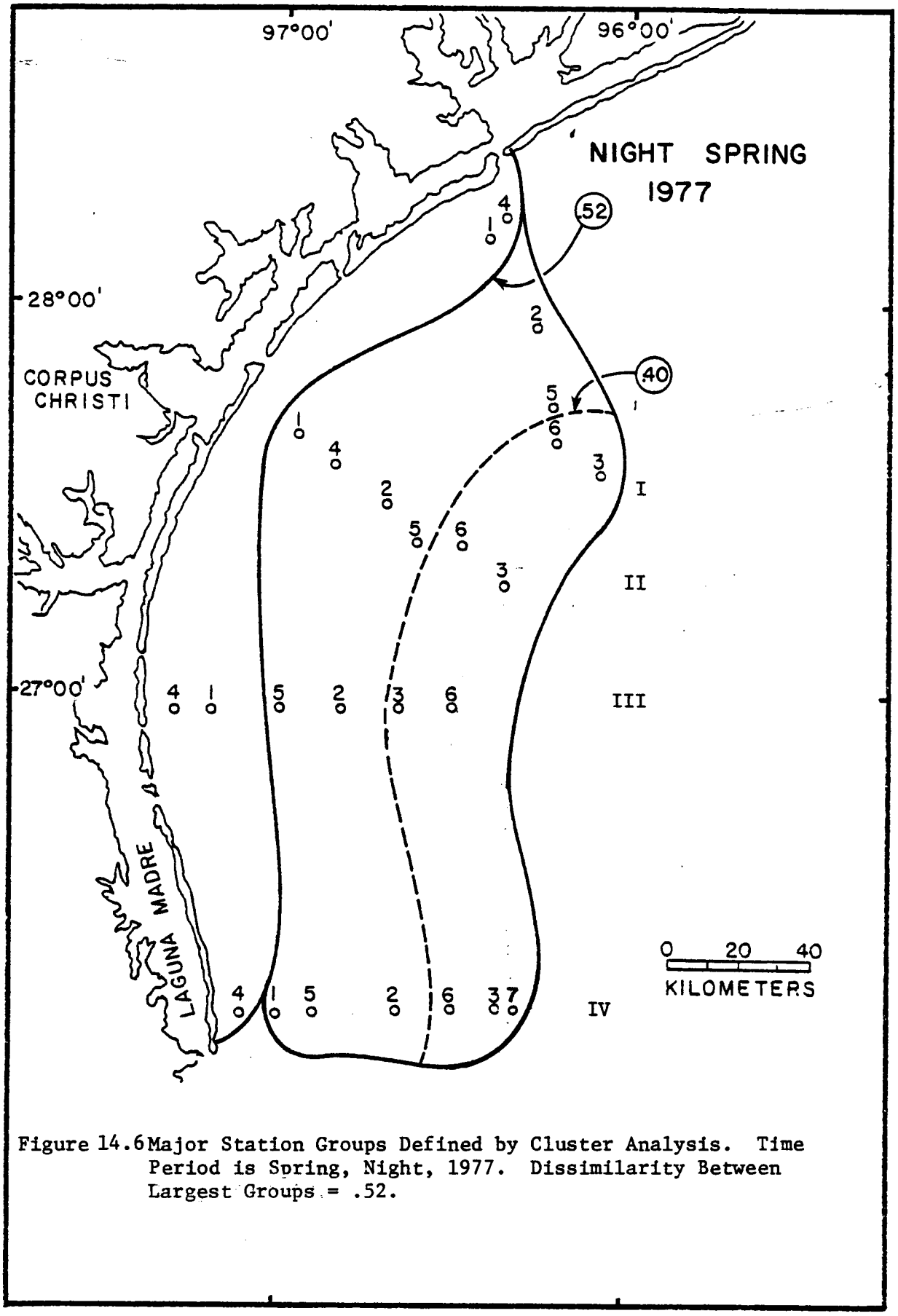

Figure 14.6 Major Station Groups Defined by Cluster Analysis. Time Period is Spring, Night, 1977. Dissimilarity Between Largest Groups = .52.

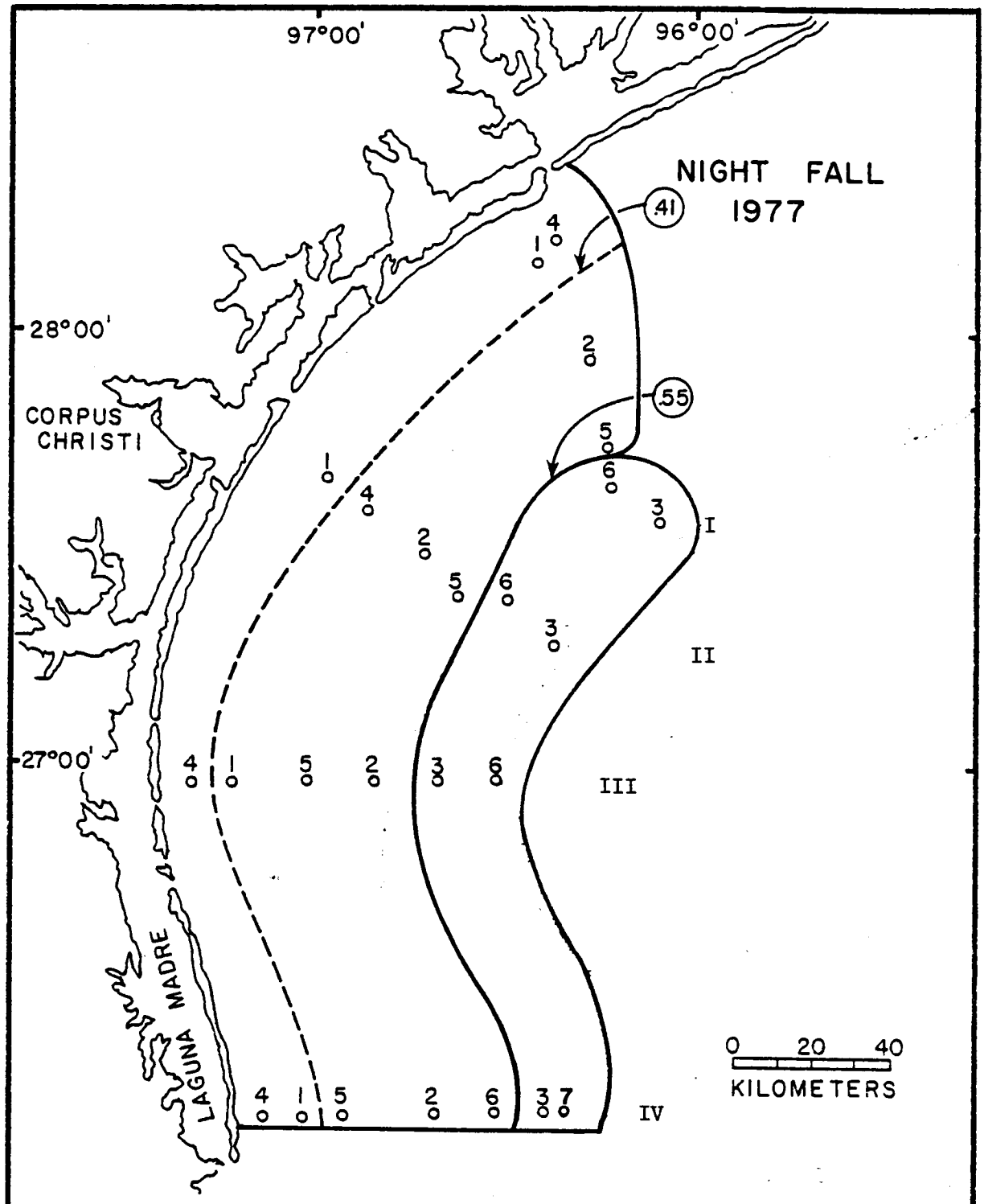

Figure 14.7 Major Station Groups Defined by Cluster Analysis. Time Period is Fall, Night, 1977. Dissimilarity Between the Largest Groups = .55.

TABLE 14.5

CONSTANCY AND FIDELITY LEVELS FOR SPECIES ARRANGED BY SPECIES GROUP, BASED ON CLUSTER ANALYSIS FOR SPRING-DAY 1976 SAMPLES. ONLY SPECIES CAUGHT AT ABUNDANCE ≥ 30 INDIVIDUALS ARE INCLUDED

Species	Number of Occurrences	Total Number	Major Station Group 1		2	
			Constancy	Fidelity	Constancy	Fidelity
Anchoa mitchilli	2	33			L	VH
Larimus fasciatus	1	74			L	VH
Anchoa hepsetus	7	450	L	L	H	VH
Chloroscombrus chrysurus	5	449			H	VH
Polydactylus octonemus	3	1012			M	VH
Cynoscion arenarius	4	577			M	VH
Micropogon undulatus	5	1218	L	L	M	VH
Cynoscion nothus	3	465			M	VH
Trichiurus lepturus	4	170			M	VH
Trachurus lathami	16	1989	H	M	M	M
Upeneus parvus	12	135	M	M	M	M
Serranus atrobranchus	12	54	M	VH	L	L
Saurida brasiliensis	10	41	M	H	L	L
Pristipomoides aquilonaris	12	90	H	VH		
Synodus foetens	10	34	M	VH	L	L
Stenotomus caprinus	12	58	M	M	L	M
Lagocephalus laevigatus	15	95	M	H	VH	L
Peprilus burti	12	164	M	M	H	M

TABLE 14.6

CONSTANCY AND FIDELITY LEVELS FOR SPECIES ARRANGED BY SPECIES GROUP.
BASED ON CLUSTER ANALYSIS FOR SPRING-NIGHT 1976 SAMPLES.
ONLY SPECIES CAUGHT AT ABUNDANCE ≥ 30 INDIVIDUALS ARE INCLUDED

Species	Number of Occurrences	Total Number	Major Station Group 1		2	
			Constancy	Fidelity	Constancy	Fidelity
Cynoscion nothus	5	86			M	VH
Lagocephalus laevigatus	7	98	L	L	H	VH
Micropogon undulatus	3	776			M	VH
Larimus fasciatus	3	284			M	VH
Polydactylus octonemus	4	433	L	L	M	VH
Anchoa mitchilli	2	120			L	VH
Pristipomoides aquilonarus	15	92	H	VH	L	L
Prionotus paralatus	15	78	H	H	L	L
Stenotomus caprinus	18	952	H	M	M	M
Serranus atrobranchus	18	423	H	VH	L	L
Upeneus parvus	11	67	M	L	M	H
Synodus foetens	13	30	M	M	M	M
Saurida brasiliensis	9	60	L	M	M	M
Porichthys porosissimus	11	38	M	H	L	L
Prionotus stearnsi	7	111	M	VH		
Synodus poeyi	8	42	M	VH	L	L
Bollmannia communis	6	55	L	H	L	L
Bregmaceros atlanticus	7	41	L	H	L	L
Sphoeroides parvus	10	419	L	L	VH	L
Syacium gunteri	12	292	L	M	H	M
Prionotus rubio	14	541	M	L	H	H
Centropristis philadelphica	19	258	H	L	H	H
Cynoscion arenarius	6	190	L	L	M	H
Trichopsetts ventralis	10	52	M	VH		

TABLE 14.6 CONT.'D

Species	Number of Occurrences	Total Number	Major Station Group 1		2	
			Constancy	Fidelity	Constancy	Fidelity
Lepophidium graellsi	14	34	M	M	M	M
Symphurus plagiusa	7	32			H	VH
Ophidion welshi	5	31			M	VH
Anchoa hepsetus	3	256			M	VH
Conodon nobilis	2	191			L	VH
Chloroscombrus chrysurus	1	144			L	VH
Stellifer lanceolatus	2	44	L	L	L	VH
Trachurus lathami	10	141	M	L	M	H

TABLE 14.7

CONSTANCY AND FIDELITY LEVELS FOR SPECIES ARRANGED BY SPECIES GROUP.
BASED ON CLUSTER ANALYSIS FOR SPRING-DAY 1977 SAMPLES.
ONLY SPECIES CAUGHT AT ABUNDANCE ≥ 30 INDIVIDUALS ARE INCLUDED

Species	Number of Occurrences	Total Number	Major Station Group 1		2	
			Constancy	Fidelity	Constancy	Fidelity
Pristipomoides aquilonaris	17	178	VH	H	M	L
Stenotomus caprinus	8	80	H	VH		
Serranus atrobranchus	14	89	H	H	M	
Synodus foetens	14	52	H	M	M	M
Peprilus burti	11	4109	L	L	H	VH
Trachurus lathami	22	3095	H	L	H	H
Etrumeus teres	2	136			L	VH
Scomber japonicus	6	52	L	L	M	VH
Chloroscombrus chrysurus	5	603			M	VH
Cynoscion nothus	5	445			M	VH
Harengula pensacolae	5	82			M	VH
Micropogon undulatus	3	750			L	VH
Brevoortia patronus	2	181			L	VH
Anchoa hepsetus	4	68			L	VH
Polydactylus octonemus	3	46			L	VH

TABLE 14.8

CONSTANCY AND FIDELITY LEVELS FOR SPECIES ARRANGED BY SPECIES GROUP.
BASED ON CLUSTER ANALYSIS FOR SPRING-NIGHT 1977 SAMPLES.
ONLY SPECIES CAUGHT AT ABUNDANCE ≥ 30 INDIVIDUALS ARE INCLUDED

Species	Number of Occurrences	Total Number	Major Station Group 1		2	
			Constancy	Fidelity	Constancy	Fidelity
Polydactylus octonemus	6	154	L	L	VH	VH
Cynoscion nothus	6	68	L	H	H	L
Micropogon undulatus	4	79	L	L	M	VH
Prionotus rubio	9	30	M	H	M	L
Pontinus longispinis	6	31	L	VH		
Syacium gunteri	13	74	M	H	M	L
Prionotus stearnsi	9	69	M	VH		
Upeneus parvus	11	42	M	H	L	L
Pristipomoides aquilonaris	19	182	H	VH	L	L
Stenotomus caprinus	15	129	H	VH		
Serranus atrobranchus	17	277	H	VH		
Centropristis philadelphica	13	49	M	VH		
Trachurus lathami	14	48	H	VH		
Urophycis cirratus	14	42	H	VH		
Prionotus paralatus	11	62	M	VH		
Trichopsetta ventralis	9	35	M	VH		

TABLE 14.9

CONSTANCY AND FIDELITY LEVELS FOR SPECIES ARRANGED BY SPECIES GROUP BASED ON CLUSTER ANALYSIS FOR FALL-NIGHT 1977 SAMPLES. ONLY SPECIES CAUGHT AT ABUNDANCE ≥ 30 INDIVIDUALS ARE INCLUDED

Species	Number of Occurrences	Total Number	Major Station Group 1		2	
			Constancy	Fidelity	Constancy	Fidelity
Pristipomoides aquilonaris	15	135	VH	H	M	L
Trichopsetta ventralis	12	58	VH	H	L	L
Serranus atrobranchus	16	650	VH	H	M	L
Prionotus paralatus	13	533	VH	H	L	L
Stenotomus caprinus	15	272	H	M	M	M
Trachurus lathami	11	119	M	H	M	L
Upeneus parvus	10	60	H	H	L	L
Lutjanus campechanus	7	149	L	L	M	VH
Orthopristis chrysoptera	3	67			L	VH
Arius felis	4	130			L	VH
Syacium gunteri	14	145			H	VH
Cynoscion nothus	7	67			M	VH
Micropogon undulatus	17	346	L	L	H	VH
Polydactylus octonemus	10	106			M	VH
Diplectrum bivittatum	9	129			M	VH
Sphoeroides parvus	11	55			M	VH
Prionotus stearnsi	9	84	L	L	M	VH
Synodus foetens	12	35	L	L	M	H
Prionotus rubio	12	31	M	L	M	H
Centropristis philadelphica	18	91	M	L	H	H
Pontinus longispinis	4	39	M	VH		
Halieutichthys aculeatus	8	42	H	H	L	L

showed for each station group. The codes and the value ranges they represent were adopted from Cole (1977), and are as follows: very high (VH) 1.00-.95; high (H) .94-.66; medium (M) .65-.33; and low (L) .32-0.00.

The numbers of species groups which were obtained differed between seasons and between day and night periods, as did the composition of these species groups. Some differences between the corresponding time periods for 1976 and 1977 were also evident. A few species showed strong tendency to occur in the same species groups (*e.g. Stenotomus caprinus, Pristipomoides aquilonaris,* and *Serranus atrobranchus;* or *Cynoscion nothus, Polydactylus octonemus* and *Micropogon undulatus*). Most species, however, showed weaker degrees of association with each other, undoubtedly reflecting sampling error and spatial patchiness of fish distributions but probably also due to seasonal fluctuations in abundance and movements of some species between depth zones.

Thus the major result which emerged from the cluster analysis was that temporal variation occurred in assemblages of fishes found in different depth zones. This was reflected by the general lack of consistency in station and species groups between seasons, years and between day and night periods. These shifts in the boundaries separating major station groups derived from cluster analysis indicated that no single station grouping was superior to the station groups defined in Figure 14.1, and in a sense provided justification for the use of the defined grouping scheme.

Discriminant analysis (using the defined station groups; Figure 14.1) was applied to data on physical variables associated with 186 data cases (stations at specified time periods). Physical variables used were bottom water temperature (°C) and salinity (‰), mean grain size (Ø units)

of the sediment, standard deviation and skewness of the sediment grain size distribution (Ø) and percent silt composition of the sediment.

The analysis yielded two discriminant functions (the maximum number possible for three station groups; Table 14.10). Values for the discriminant criteria revealed that the first discriminant function was substantially more important (by roughly four times) than the second in differentiating between station groups. Values for the standardized weights indicated that mean grain size, salinity and percent silt were the most important variables on the first discriminant function. That is, these three variables served most to discriminate between station groups with respect to the first discriminant function. Mean grain size, skewness and standard deviation of the grain size distribution served most to separate station groups with respect to the second discriminant function. The overall importance of the skewness and standard deviation of the grain size distribution, however, was less than that of the other variables since they figured importantly only in the second (less important) discriminant function.

Centroids of the station groups and discriminant scores for data cases are plotted with respect to the first and second discriminant functions in Figure 14.8. Interpreting the patterns in terms of the original physical variables, station group 1 was characterized (relatively) by a combination of large mean grain size, low salinity and high percent silt composition. Station group 3 had the opposite characteristics, while station group 2 could be characterized as intermediate between station groups 1 and 3. Station groups 3 and 2 had the highest and lowest mean values, respectively, on the second discriminant function. In terms of the physical variables, station group 3 thus had, in combination, a relatively small mean sediment grain size, low variation

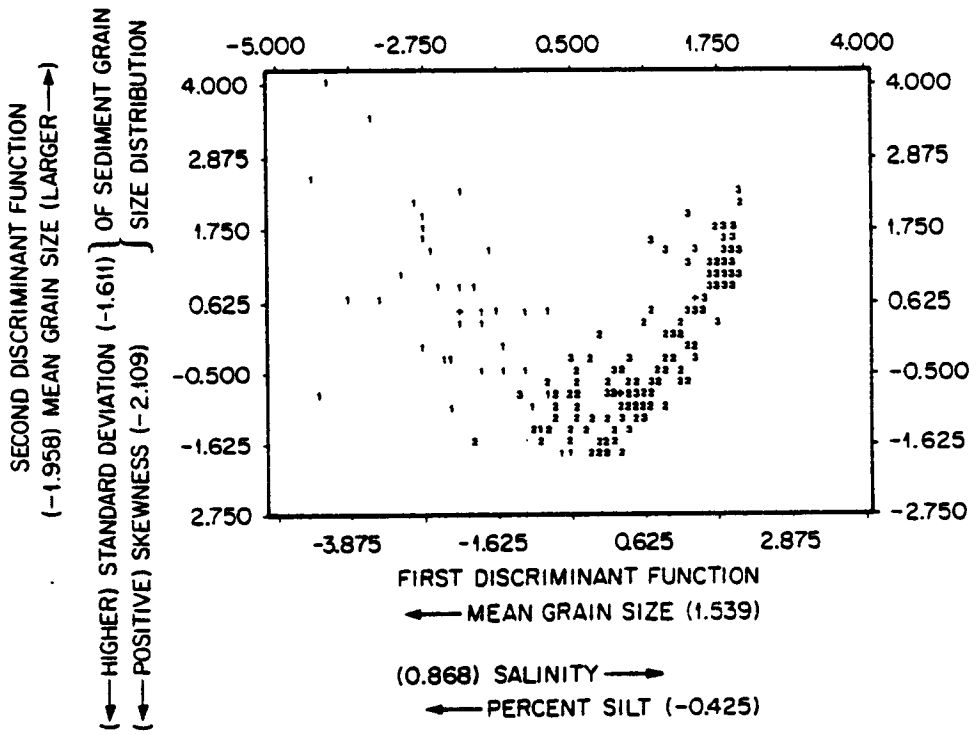

Figure 14.8 Discriminant Space Based on Analysis of Physical Variables. Each Number Represents a Sampling Episode (Sampling station for a Given Time Period; *e.g.* Station 1/I, Day-Winter) with Value Equal to Station Group Identification. Symbol (+) Denotes a Group Centroid. Values in Parentheses by Discriminating Variables are Standardized Discriminant Function Coefficients (Weights).

(standard deviation) in the sediment grain size distribution, and a negative skewness in this distribution. Station Group 2 had the opposite characteristics, and Station Group 1 was intermediate between the other two groups.

It is emphasized that these descriptions of the station groups with respect to combinations of discriminating variables are valid only when all discriminating variables are considered simultaneously. Thus, for example, station group 1 had relatively large mean grain size when it also had low salinity and high percent composition of the sediment (on the first discriminant function), or large mean grain size when it also had low percent silt and negative skewness and low variation in the sediment grain size distribution (on the second discriminant function). It would not be correct to simply say, on the basis of the discriminant scores, that station group 1 was characterized by large mean grain sizes alone. Such a statement requires the examination of means (over station groups) and tests such as analysis of variance.

Pairwise differences between station group centroids were tested for significance using F-values based on the Mahalonobis distance between groups. Each station group showed significant differences from the two other groups ($p < .001$).

Values for the squared canonical correlation (Table 14.10) showed that the station groups accounted for roughly 81% of the variation among the sampling stations (with stations from all sampling time periods considered together) with respect to the first discriminant function and roughly 56% with respect to the second discriminant function. Thus, the influence of the station groups was substantial.

Values for Wilk's Lambda (Table 14.10) indicated that a statistically

TABLE 14.10

RESULTS OF DISCRIMINANT ANALYSIS APPLIED TO DATA ON SIX PHYSICAL VARIABLES.
WILK'S LAMBDA MEASURES THE DIFFERENCE BETWEEN STATION GROUPS.
NUMBER OF CASES (STATIONS SAMPLED IN A CERTAIN TIME PERIOD) = 186

Discriminant Function	Discriminant Criterion	Proportion of Total (1.12681)	Canonical Correlation Squared	Wilk's Lambda (Level of Significance)
1	1.97048	.809	.81447	.22955
2	.46656	.191	.56403	(P ≈ 0)
TOTAL	1.12681			

significant difference existed among station groups with respect to the physical variables considered, further supporting the validity of the groupings. In addition, the moderately high proportion (.812) of correct assignments of stations to station groups by the classification phase of the analysis indicated satisfactory discrimination between station groups.

Tests for equality of variances among station groups showed significant heterogeneity for all physical variables except standard deviation of grain sizes, which had a marginally significant test statistic (Table 14.11). Skewness in grain sizes showed less heterogeneity in variances after natural log transformation than when square root or not transformed, and so ANOVA was performed on ln-transformed skewness values. All other physical variables had lowest heterogeneity in variances when not transformed, but heterogeneity was still significant ($p \leq .05$) for all variables (including ln-skewness). ANOVA's indicated significant differences among group means for all physical variables ($p \approx 0$). A posteriori tests revealed that all groups differed from one another with respect to mean grain size, standard deviation of grain size distribution and percent silt composition of the sediment, group 3 differed from groups 1 and 2 with respect to bottom temperature, group 1 differed from groups 2 and 3 in salinity, and group 2 differed from groups 1 and 3 in skewness of grain sizes.

Analysis of variance assumes equality of variances among groups. Since this assumption was violated for almost all physical variables, the results of ANOVA must be viewed for the most part as approximations. The marginally significant test statistic shown by the standard deviation of grain sizes ($p = .05$) indicated, however, that the ANOVA and a posteriori tests gave exact results for this variable.

Since none of the station groups derived from the cluster analysis corresponded closely with the three station groups in the defined grouping

TABLE 14.11

COMPARISON OF STATION GROUP MEANS WITH RESPECT TO PHYSICAL VARIABLES, USING A POSTERIORI TESTS (STUDENT-NEWMAN-KEULS PROCEDURE). MEANS CONNECTED BY LINES WERE NOT SIGNIFICANTLY DIFFERENT (P > .05)

Variable ln=natural log	a posteriori comparisons Group 1 n = 48	 Group 2 n = 78	 Group 3 n = 60
Temperature (°C)			
Mean	22.1033	21.3138	18.6543
Standard Deviation	5.6480	3.1145	2.1750
Salinity (‰)			
Mean	34.3044	36.0026	36.2620
Standard Deviation	1.6717	.5371	.4158
Mean Grain Size (Ø)			
Mean	5.8948	7.8583	8.9483
Standard Deviation	1.6040	1.1069	1.1647
Standard Deviation of Grain Sizes			
Mean	3.2573	3.4212	3.0442
Standard Deviation	.4807	.3537	.3795
Arcsin (Percent Silt x 100)			
Mean	.2421	.3555	.3067
Standard Deviation	.1430	.0987	.0589
ln (Skewness of Grain Size)			
Mean	-.1911	-1.0406	-.2063
Standard Deviation	1.0541	1.1133	.5102

scheme (Figure 14.1), the fish species groups obtained from cluster analysis were not valid for describing any of the defined station groups. Lacking such a description for the three defined station groups prompted us to derive one (using fish abundance data) via discriminant analysis. Discriminant analysis was also applied to abundance data on selected macroinvertebrates with the same purpose.

Discriminant analysis using fish abundances (from all sampling episodes over three years) as discriminating variables yielded two discriminant functions (Table 14.12), with the first roughly twice as important as the second in separating station groups. Standardized weights showed the following species to contribute most to the first discriminant function: *Cynoscion nothus, Pristipomoides aquilonaris, Sphoeroides parvus, Syacium gunteri, Trichopsetta ventralis,* and to a lesser degree, *Chloroscombrus chrysurus, Micropogon undulatus, Peprilus burti,* and *Prionotus paralatus. Bollmannia communis, Syacium gunteri, Synodus foetens, Synodus poeyi* and *Trichopsetta ventralis* were the most important species for the second discriminant function.

Centroids of the station groups (Figure 14.9) showed group 1 to generally have the highest scores and group 3 the lowest on the first discriminant function. Group 1 could therefore be viewed as having, in combination, relatively high abundances of *Cynoscion nothus, Sphoeroides* and *Syacium* and low abundances of *Pristipomoides* and *Trichopsetta*, while group 3 had the opposite characteristics. Groups 1 and 3 had roughly equal mean scores (with group 1 slightly higher) and group 2 had the lowest on the second discriminant function. Groups 1 and 3 thus could be characterized as having a combination of relatively high abundances of *Syacium* and *Trichopsetta* and low abundances of *Bollmannia* and the two

TABLE 14.12

RESULTS OF DISCRIMINANT ANALYSIS APPLIED TO DATA ON THE 27 MOST COMMON FISH SPECIES ENCOUNTERED FROM 1975-1977. NUMBER OF CASES (STATIONS SAMPLED IN A CERTAIN TIME PERIOD) = 459

Discriminant Function	Discriminant Criterion	Proportion of Total (1.18082)	Canonical Correlation Squared	Wilk's Lambda (Level of Significance)
1	.77013	.652	.43507	.40047
2	.41069	.348	.29112	(P ≈ 0)
TOTAL	1.18082			

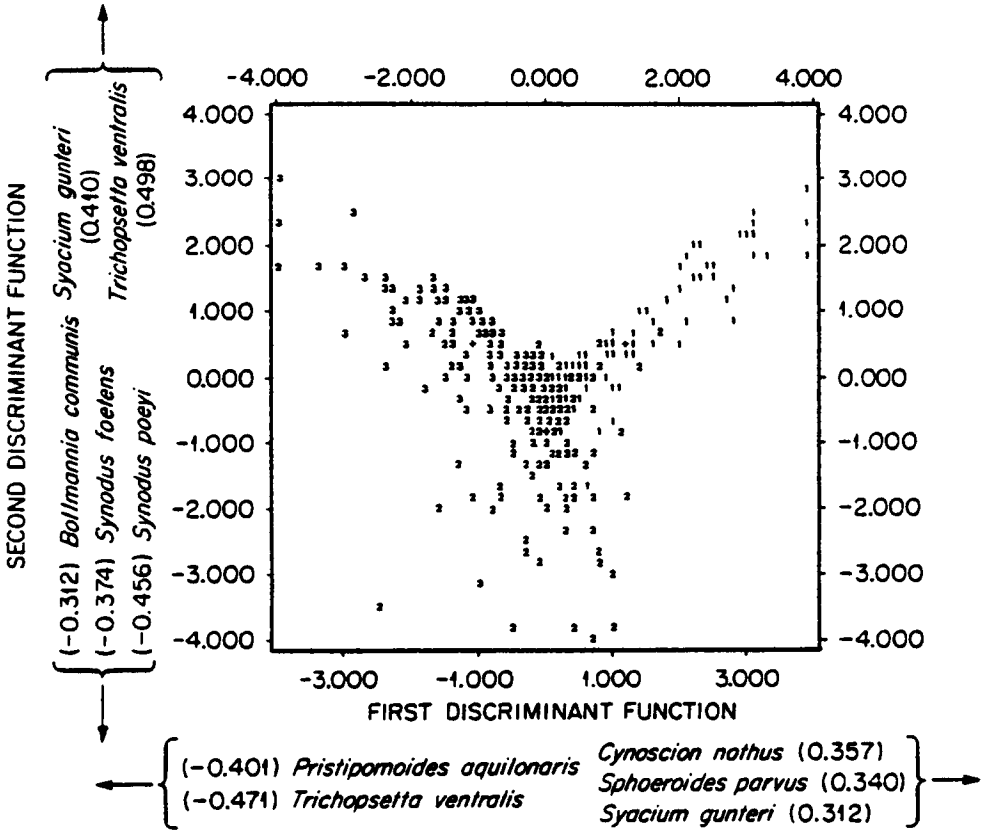

Figure 14.9 Discriminant Space Based on Analysis of Fish Abundance. Each Number Represents a Sampling Episode (Sampling Station for a Given Time Period; *e.g.* Station 1/II, Day-Winter) with Value Equal to Station Group Identification. Symbol (+) Denotes a Group Centroid. Values in Parentheses by Discriminating Variables are Standardized Discriminant Function Coefficient (Weights).

Synodus species. Group 2 has converse features. Pairwise statistical comparisons of the group centroids (using F-values based on Mahalonobis distances between groups) revealed significant differences between all groups ($p < .001$).

Although the discriminant analysis using fish abundance data was aimed primarily toward obtaining descriptions of the defined station groups with respect to the common fishes, it also provided a test of the strength of the groupings (as did the analysis using physical variables). Values for the squared canonical correlation (Table 14.12) showed that the station groups accounted for approximately 44% of the variation among stations on the first discriminant function and about 29% on the second discriminant function, indicating that the fish abundance data were substantially less effective in separating station groups than were physical variables. However, the statistically significant value for Wilk's Lambda criterion (.40047) and the moderate-high proportion (.758) of data cases correctly classified by the classification procedure indicated that the defined station groups could be satisfactorily differentiated on the basis of abundances of common fishes.

Discriminant analysis using invertebrate abundance data (Table 14.13) gave two discriminant functions with the first function approximately twice as important as the second in separating groups, as in the analysis using fish abundances. Standardized weights showed *Squilla empusa, Penaeus duorarum, Penaeus setiferus, Trachypenaeus constrictus, Renilla mulleri, Solenocera vioscai, Anasimus latus* and *Penaeus aztecus* to be the most important species on the first discriminant function. *Squilla chydaea, Anasimus, Brissopsis alta, Solenocera, Acetes americana* and *Astropecten duplicatus* contributed most to the second discriminant function.

Station group 3 had the highest group centroid and station group 1

TABLE 14.13

RESULTS OF DISCRIMINANT ANALYSIS APPLIED TO DATA ON THE 24 MOST COMMON INVERTEBRATE SPECIES ENCOUNTERED FROM 1975-1977. NUMBER OF CASES = 425.

Discriminant Function	Discriminant Criterion	Proportion of Total (.85100)	Canonical Correlation Squared	Wilk's Lambda (Level of Significance)
1	.57676	.678	.36578	.49772
2	.27424	.322	.21522	(P ≈ 0)
TOTAL	.85100			

the lowest with respect to the first discriminant function (Figure 14.10). Station group 3 was thus characterized by a combination of relatively high abundances of *Trachypenaeus constrictus*, *Solenocera* and *Anasimus* and relatively low abundances of *Squilla empusa*, *Penaeus duorarum*, *P. setiferus*, *P. aztecus*, and *Renilla*, while station group 1 had the opposite features. Station group 3 also had the highest centroid on the second discriminant function and was characterized by relatively high abundances of *Anasimus*, *Brissopsis* and *Acetes* together with low abundances of *Squilla chydaea*, *Astropecten*, and *Solenocera*. Station group 2, with the lowest centroid on the second discriminant function, showed the opposite characteristics. Pairwise comparisons of group centroids (based on Mahalonobis distances) yielded significant F-values for all pairs ($p < .001$).

Squared canonical correlation values (Table 14.13) showed that station groups accounted for 37% of the variation among stations on the first discriminant function and 22% on the second, indicating somewhat poorer separation of station groups than achieved using fish abundance data and substantially less separation than by physical variables. However, significant overall differences among station groups existed, shown by Wilk's Lambda criterion (.49772) and by the F-values from pairwise comparisons (above). This, together with the moderate-high proportion (.72) of data cases correctly classified pointed to satisfactory discrimination between station groups by invertebrate abundance data.

Means and variances of abundances of common fishes and invertebrates are given in Table 14.14. Analysis of variance showed that only *Lepophidium graellsi*, *Trachurus lathami* (among fishes), *Polystira albida*, *Trachypenaeus constrictus*, *Sicyonia brevirostris*, and *Tethyaster vestitus* (among invertebrates) showed no difference in abundances among station groups (Table 14.15). Tests for homogeneity of variances showed all

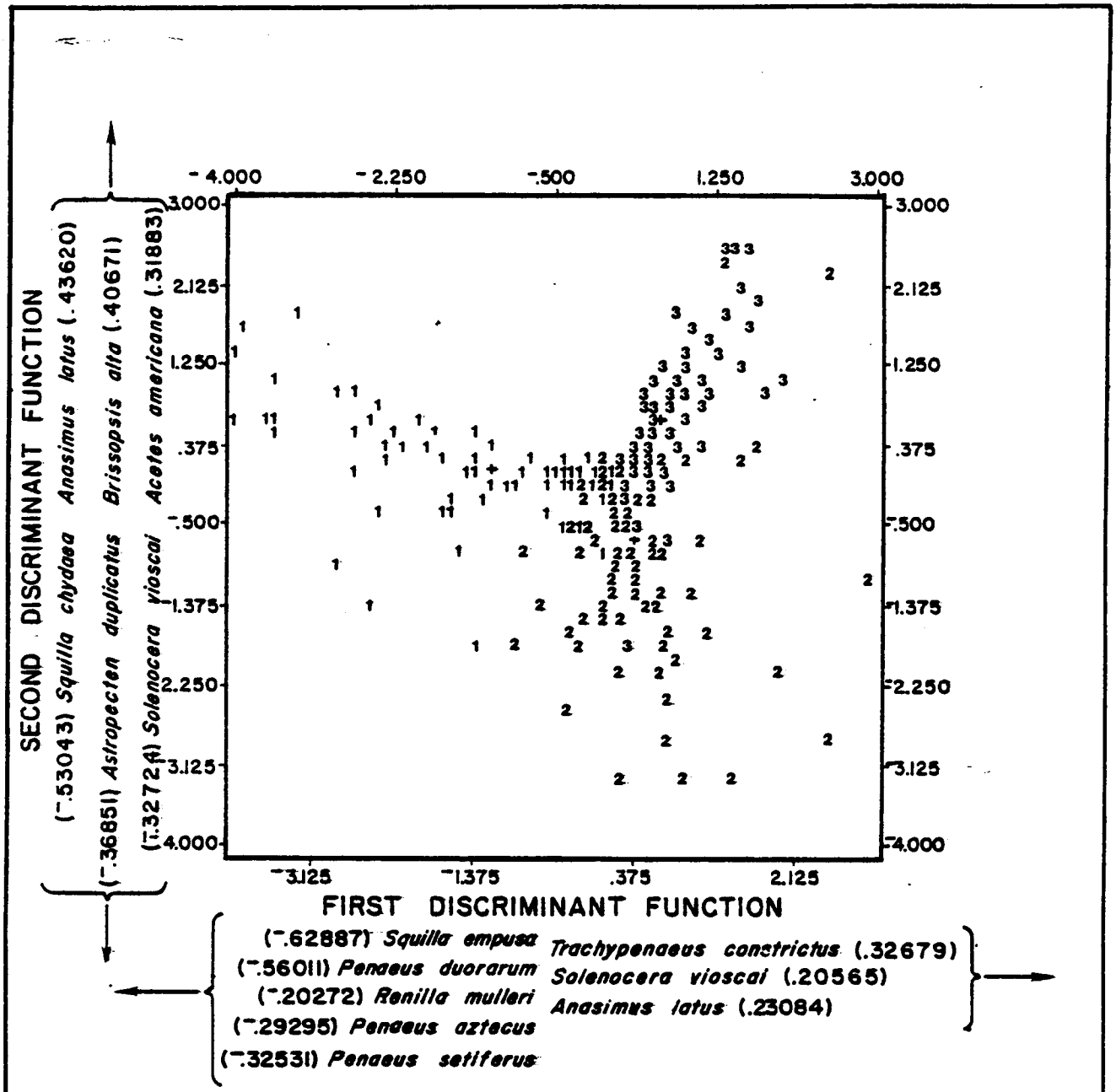

Figure 14.10 Discriminant Space Based on Analysis of Abundance of Epifaunal Invertebrates. Each Number Represents a Sampling Episode (Sampling Station for a Given Time Period; *e.g.* Station 1/I, Day-Winter) with Value Equal to Station Group Identification. Symbol (+) Denotes a Group Centroid. Values in Parentheses by Discriminant Variables are Standardized Discriminant Function Coefficients (Weights).

TABLE 14.14

MEANS AND STANDARD DEVIATIONS OF ABUNDANCES OF COMMON FISHES AND MACROINVERTEBRATES IN THE DEFINED STATION GROUPS (1, 2, 3)

FISHES	Mean			Standard Deviation		
	1	2	3	1	2	3
Anchoa hepsetus	15.33	.09	.01	74.66	.55	.16
Bollmannia communis	.29	1.96	.20	1.00	4.82	2.23
Centropristis philadelphica	4.00	3.96	1.21	15.70	5.20	2.82
Chloroscombrus chrysurus	14.48	.62	.00	58.73	3.79	.00
Cynoscion arenarius	8.36	.89	.16	42.40	4.29	.62
Cynoscion nothus	41.63	.52	.01	94.63	2.54	.16
Diplectrum bivittatum	2.06	2.97	.01	6.15	7.72	.08
Lepophidium graellsi	.83	1.02	.61	1.92	2.48	1.82
Micropogon undulatus	53.34	1.23	.07	154.85	5.03	.43
Peprilus burti	30.57	5.51	.67	147.27	27.95	2.59
Pontinus longispinis	.00	.10	3.12	.00	.96	10.80
Polydactylus octonemus	15.84	.86	.00	69.46	5.04	.00
Porichthys porosissimus	.87	2.78	1.59	2.21	8.26	6.31
Prionotus paralatus	.06	2.42	10.27	.36	6.07	17.63
Prionotus rubio	6.19	2.35	.79	30.18	4.44	2.08
Prionotus stearnsi	.89	6.19	1.59	6.61	23.48	6.82
Pristipomoides aquilonaris	.23	4.64	14.69	1.90	12.90	18.43
Saurida brasiliensis	2.73	7.91	1.45	13.66	27.60	4.95
Serranus atrobranchus	.35	21.18	22.59	1.99	33.79	27.99
Sphoeroides parvus	9.67	1.72	.05	27.87	7.45	.36
Stenotomus caprinus	5.77	6.97	7.47	28.12	30.08	8.88
Syacium gunteri	16.13	9.51	.18	38.79	18.96	.92
Synodus foetens	2.10	3.18	1.21	6.00	4.29	2.72
Synodus poeyi	.03	2.22	.12	.21	5.32	.51
Trachurus lathami	22.95	15.89	11.95	88.46	56.60	47.95
Trichopsetta ventralis	.01	1.27	6.40	.12	3.60	8.63
Upeneus parvus	2.24	3.38	4.57	9.78	11.52	17.19

TABLE 14.14 CONT.'D

INVERTEBRATES	Mean			Standard Deviation		
	1	2	3	1	2	3
Renilla mulleri	3.65	.33	.01	19.53	1.86	.09
Polystira albida	.00	.35	.90	.00	3.46	6.08
Anadara baughmani	.02	.33	.98	.18	1.52	2.54
Amusium papyraceus	.01	5.50	5.36	.09	23.44	9.31
Squilla chydaea	1.38	4.56	.62	5.20	7.88	1.65
Squilla empusa	10.83	.52	.00	16.88	1.56	.00
Solenocera vioscai	.00	12.53	3.28	.03	31.56	6.30
Acetes americana	47.48	.01	.00	355.60	.11	.00
Anasimus latus	.04	.45	2.86	.46	1.80	6.91
Callinectes similis	17.94	11.80	.23	46.80	39.69	1.38
Portunus gibbesii	4.23	.18	.01	14.56	.66	.09
Portunus spinicarpus	.07	1.97	10.44	.64	7.81	37.43
Parapenaeus longirostris	.01	1.13	1.77	.09	7.08	5.19
Penaeus aztecus	23.25	10.86	1.39	74.46	18.42	2.83
Penaeus duorarum	2.79	.03	.00	9.22	.19	.00
Penaeus setiferus	3.24	.04	.00	7.41	.18	.00
Trachypenaeus constrictus	1.26	.01	.00	12.07	.15	.00
Trachypenaeus similis	100.20	17.89	.01	315.38	45.34	.09
Sicyonia brevirostris	.64	.97	.30	2.72	4.23	1.50
Sicyonia dorsalis	33.70	39.31	.05	101.96	126.95	.35
Astropecten cingulatus	.02	.58	1.32	.18	2.20	2.98
Astropecten duplicatus	2.86	2.60	.10	27.01	6.48	.51
Tethyaster vestitus	.00	.35	.35	.00	2.50	1.31
Brissopsis alta	.00	.02	3.08	.00	.24	10.16

TABLE 14.15

TESTS FOR EQUALITY OF MEANS AND VARIANCES AMONG STATION GROUPS WITH RESPECT TO ABUNDANCES OF COMMON FISHES AND INVERTEBRATES.
ANALYSIS OF VARIANCE WAS USED TO TEST MEANS, AND BARTLETT'S TEST OR COCHRAN'S C STATISTIC TO TEST VARIANCES.
INDIVIDUAL MEANS WERE COMPARED USING A POSTERIORI TESTS (STUDENT-NEWMAN-KEULS PROCEDURE).
SYMBOL (*) DENOTES SPECIES WITH HOMOGENOUS VARIANCES AMONG STATION GROUPS (P> .05).
AND FOR WHICH ANOVA AND A POSTERIOR RESULTS WERE EXACT.

No significant overall differences among station groups means (ANOVA ; P > .05)

Fishes:	*Lepophidium graellsi*	Invertebrates: *Polystira albida*	*Sicyonia brevirostris*
	*Trachurus lathami**	*Trachypenaeus constrictus*	*Tethyaster vestitus**

A posteriori comparisons. Station groups connected by lines were not significantly different (p>.05)

All Groups Different	Station Groups 1 2 3	Station Groups 1 2 3	Station Groups 1 2 3
Fishes	Fishes	Fishes	Fishes
Peprilus burti	*Chloroscombrus chrysurus*	*Anchoa hepsetus*	*Bollmannia communis*
Prionotus paralatus	*Diplectrum bivittatum*	*Cynoscion arenarius*	*Centropristis philadelphica*
Pristipomoides aquilonaris	*Pontinus longispinis*	*Cynoscion nothus*	*Porichthys porosissimus*
Serranus atrobranchus	*Prionotus rubio*	*Micropogon undulatus*	*Prionotus stearnsi*
Sphoeroides parvus		*Polydactylus octonemus*	*Saurida brasiliensis*
*Stenotomus caprinus**		*Upeneus parvus*	*Synodus foetens*
Syacium gunteri			*Synodus poeyi*
Trichopsetta ventralis			

TABLE 14.15 CONT.'D

All Groups Different	Station Groups 1 2 3	Station Groups 1 2 3	Station Groups 1 2 3
Invertebrates	Invertebrates	Invertebrates	Invertebrates
*Amusium papyraceus**	*Anadara baughmani*	*Renilla mulleri*	*Squilla chydaea*
Solenocera vioscai	*Anasimus latus*	*Squilla empusa*	*Astropecten duplicatus*
Portunus spinicarpus	*Callinectes similis*	*Acetes americana*	
Trachypenaeus similis	*Penaeus aztecus*	*Portunus gibbesii*	
Astropecten cingulatus	*Sicyonia dorsalis*	*Penaeus duorarum*	
	Brissopsis alta	*Penaeus setiferus*	

-*Parapenaeus longirostris** had significant overall differences (p = .0030;ANOVA), but a posteriori tests did not detect groupwise differences.

except five species to have significant differences in variances among station groups. With the exception of these five species, results of ANOVA and a posteriori comparisons must therefore be viewed as approximations. *Parapenaeus longirostris* showed significant overall difference in abundance over station groups, but the SNK procedure was not powerful enough to detect groupwise differences. In general, abundances of common fishes and invertebrates showed significant differences between station groups, which served to further emphasize the distinctness of the station groups with respect to biological characteristics.

Multiple regression of abundances of common fishes on selected biotic and abiotic predictor variables showed that for all species a statistically significant ($p \leq .01$) amount of variation in fish abundance was explained by the polynomial regression model employed (Table 14.16). The percentage of variation explained by regression (indicated by squared multiple-R) ranged from 4 to 41%. The regression model was relatively ineffective in explaining variation in abundance of *Pristipomoides aquilonaris* (4% explained variation), *Synodus poeyi* (8%), and *Saurida brasiliensis* (9%) and somewhat more satisfactory for most other species (10-27%). The regression could be considered effective only for *Pontinus longispinis* (31%) and *Anchoa hepsetus* (41%). Standard errors of residuals about the regression (S.E. in Table 14.16) also varied widely. *Lepophidium graellsi* varied the least about the regression hyperplane (1 standard error = 1.23 individuals) while *Peprilus burti* varied the most (1 standard error = 94.66 individuals).

DISCUSSION

The multiple regression model employed here was in general only marginally successful in accounting for variation in fish abundances. However, this was to be expected in view of the low level of replication of

TABLE 14.16

SUMMARY OF MULTIPLE REGRESSION OF FISH ABUNDANCES ON SELECTED BIOTIC AND ABIOTIC PREDICTOR VARIABLES. A MULTIPLE POLYNOMIAL REGRESSION MODEL WAS USED WITH STEPWISE INCLUSION OF VARIABLES (BASED ON 298 DATA CASES PER SPECIES). MULTIPLE-R IS THE MULTIPLE CORRELATION COEFFICIENT AND S.E. IS THE STANDARD ERROR OF RESIDUALS ABOUT THE REGRESSION. ALL REGRESSIONS WERE STATISTICALLY SIGNIFICANT (ANOVA; $p \leq .01$). SIGNS PRECEDING PREDICTOR VARIABLES REFLECT SIGNS OF CORRESPONDING PARTIAL REGRESSION COEFFICIENTS, AND ENTRIES IN PARENTHESES ARE PROPORTIONS OF TOTAL VARIATION IN ABUNDANCE OF EACH SPECIES EXPLAINED. ONLY PREDICTOR VARIABLES EXPLAINING $\geq .02$ OF TOTAL VARIATION PER SPECIES ARE LISTED.

SPECIES	Multiple-R	$(\text{Multiple-R})^2$	S.E.	MAJOR PREDICTOR VARIABLES[1]			
Anchoa hepsetus	.64	.41	37.03	+(Grain Size Skewness)^2 (.10)	-(Grain Size Skewness)^3 (.05)	-(Percent Sand)^3 (.11)	-Infauna Abundance (.04)
				+(Grain Size Std. Dev.)^3 (.05)	+Mean Grain Size (.04)		
Bollmannia communis	.39	.15	2.58	+(Percent Silt)^3 (.05)	+(Day/Night)^2 (.04)	-(Depth)^2 (.02)	
Centropristis philadelphica	.42	.18	5.78	+Day/Night (.06)	+(Percent Silt)^3 (.04)	+Temperature (.04)	-(Julian Day)^3 (.02)
Chloroscombrus chrysurus	.39	.16	35.93	-(Salinity)^3 (.06)	+Temperature (.02)	-Infauna Abundance (.02)	+(Percent Sand)^2 (.02)
Cynoscion arenarius	.39	.16	25.93	-Salinity (.11)			

TABLE 14.16 CONT.'D

Species	Multiple-R	(Multiple-R)	S.E.	Major Predictor Variables			
Cynoscion nothus	.48	.23	38.19	-(Salinity)^3 (.10)	-(Temperature)^3 (.02)	+(Depth)^3 (.02)	
Diplectrum bivittatum	.47	.22	8.86	+(Temperature)^3 (.08)	+(Grain Size Skewness)^3 (.04)	+(Percent Silt)^3 (.03)	+(Julian Day)^3 (.03)
Lepophidium graellsi	.44	.19	1.23	+Day/Night (.10)	+(Percent Silt)^3 (.02)	-(Salinity)^3 (.02)	+Temperature (.02)
Micropogon undulatus	.46	.21	83.59	-Salinity (.12)	+Temperature (.02)		
Peprilus burti	.34	.12	94.66	-Day/Night (.02)	-Depth (.02)	+Julian Day (.03)	
Pontinus longispinis	.55	.31	2.17	+(Depth)^3 (.22)	-(Sediment Carbon)^2 (.04)		
Polydactylus octonemus	.49	.24	40.34	-Salinity (.16)	+Temperature (.03)	+Depth (.02)	
Porichthys porosissimus	.37	.14	4.58	+Day/Night (.03)	+(Mean Grain Size)^3 (.04)	+Temperature (.02)	

TABLE 14.16 CONT.'D

Species	Multiple-R	(Multiple-R)^2	S.E.	Major Predictor Variables			
Prionotus paralatus	.43	.19	11.29	+(Depth)^2 (.09)	+(Julian Day)^3 (.05)	+(Day/Night)^3 (.03)	-(Temperature)^3 (.02)
Prionotus rubio	.40	.16	18.15	-Salinity (.09)			
Prionotus stearnsi	.21	.04	17.74	+Infauna Diversity (.02)			
Pristipomoides aquilonaris	.56	.31	7.60	+(Depth)^2 (.30)			
Saurida brasiliensis	.30	.09	16.65	+(Percent Silt)^3 (.02)	-Julian Day (.02)	-(Day/Night)^3 (.02)	
Serranus atrobranchus	.45	.20	22.73	+Percent Sand (.06)	+(Day/Night)^3 (.06)	+Infauna Diversity (.03)	-(Infauna Diversity)^3 (.02)
Sphoeroides parvus	.33	.11	15.60	+(Temperature)^3 (.04)	+Day/Night (.02)	-(Julian Day)^3 (.02)	
Stenotomus caprinus	.32	.10	28.64	+(Percent Silt)^3 (.03)	+(Day/Night)^2 (.02)	-Percent Silt (.02)	

TABLE 14.16 CONT.'D

Species	Multiple-R	(Multiple-R)^2	S.E.	Major Predictor Variables			
Syacium gunteri	.45	.20	12.41	-Depth (.09)	+Day/Night (.05)	-(Percent Sand)^2 (.02)	
Synodus foetens	.39	.15	2.50	-(Day/Night)^2 (.05)	-(Depth)^3 (.03)	-Infauna Abundance (.05)	
Synodus poeyi	.28	.08	3.41	-(Depth)^3 (.03)			
Trachurus lathami	.45	.21	66.23	-(Day/Night)^2 (.06)	-Infauna Diversity (.02)	-(Julian Day)^3 (.03)	+Julian Day (.06)
Trichopsetta ventralis	.52	.27	4.07	+Depth (.16)	+Day/Night (.04)	-Julian Day (.02)	+(Julian Day)^3 (.02)
Upeneus parvus	.34	.11	5.16	+(Infauna Diversity)^3 (.03)	+Salinity (.02)		

[1]Grain size mean, skewness and standard deviation refer to sediment grain size distribution; Day/Night to day/night code; infauna abundance and diversity to macroinvertebrate infauna.

samples employed in data collection. More than 334 (67%) sampling episodes at a given station and time period consisted of a single trawl and the highest replication was three trawls. Thus, a relatively high sampling error (probably due mainly to patchiness in fish distributions and human error during sampling) attended the data, giving rise to the large variation about the regression hyperplanes.

The primary use of the results from multiple regression would be prediction of fish abundances based on predictor variables. Ten species had between 20 and 41% of their variation in abundance explained by regression, and the regression models should yield rough estimates of abundances for these species from information on predictor variables. However, prediction of abundances using the parameter values for regressions derived here would be strictly valid only within the ranges of values for predictor variables upon which the regression were based and legitimate only for the outer continental shelf environment.

Results of regression may also be used to indicate possible causative relationships among fish abundances and predictor variables. For example, the relative importance of sediment skewness and percent sand in the sediment in explaining variation in abundance of *Anchoa hepsetus* (Table 14,16) suggests that these sediment parameters have direct ecological significance to this species. The causative nature of relationships between fish abundance and predictor variables suggested by regression analysis is, however, strictly inferential and direct ecological studies of species would be required to confirm these relationships. It would be safer to regard the relationships as correlative ones, and for practical purposes they may be just as useful as information on the casualty of factors. Thus, certain sediment characteristics may not be directly important to *Anchoa hepsetus*

but could be highly correlated with some other factors (possibly not measured) which affect its abundance.

With foregoing considerations in mind, important predictor variables for common fishes can be identified from Table 14.16. Of those predictor variables which explained at least two percent of the variation in abundances of the fishes, day-night code did so for 14 species, depth for 11 species and temperature for 10 species. Julian day, salinity and percent silt in the sediment explained $\geq$ 2% of the numerical variation in 8, 8 and 7 species, respectively. Standard deviation, mean and skewness of the sediment grain size distribution and percent organic carbon in the sediment were each important for only one or two species.

The lack of detailed information on the biology of most of the species encountered makes it difficult to assess the functional significance of various predictor variables to the fishes. For example, it is unclear exactly why certain sediment characteristics are important in explaining variation in abundance of *Anchoa hepsetus*. Other predictor variables are somewhat more amenable to interpretation, although without data such interpretation is more guesswork than fact. Thus, Julian day may be important for *Prionotus paralatus* because of seasonal trends in abundance of this species (perhaps due to large scale seasonal movements or to recruitment of young); and invertebrate infauna abundance may be important for *Chloroscombrus chrysurus* because it possibly reflects the food supply available to this fish. The elucidation of such relationships is beyond the aims of this study. What is important here is to define statistical relationships which may then be used for predicting the identity and abundance of fishes given information on predictor (or discriminating) variables. To this end, the results of multiple regression analysis

presented here have yielded a reasonable starting point. It is likely that with application of other (nonlinear) regression techniques, a greater degree of predictive capability may be achieved.

Earlier studies (including several extensive surveys) on fishes of the continental shelf off Texas have generally treated relationships of fishes to environmental variables only in broad terms. Depth and temperature appear to have been the primary environmental correlates considered (*e.g.* Miller, 1965; Moore *et al.*, 1970; Chittenden and Moore, 1977), although a few studies have also mentioned sediment characteristics and day-night variability in captures (Caldwell, 1955; Moore *et al.*, 1970; Chittenden and McEachran, 1976). Nonetheless, quantitative aspects of fish-environment relationships for this region are poorly known. In spite of the caveats attending it, the present study hopefully serves to point out some of those relationships which may be important in determining fish abundances and distributions.

At the least, the present work serves to identify major components of the outer continental shelf benthic ichthyofauna and describes the more obvious spatial and temporal patterns in abundance of species. The characterization of major depth zones using common fishes (and macroinvertebrates) by discriminant analysis as well as by straightforward descriptions of the fauna should be particularly useful for the assessment of man-induced impacts on this environment.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.