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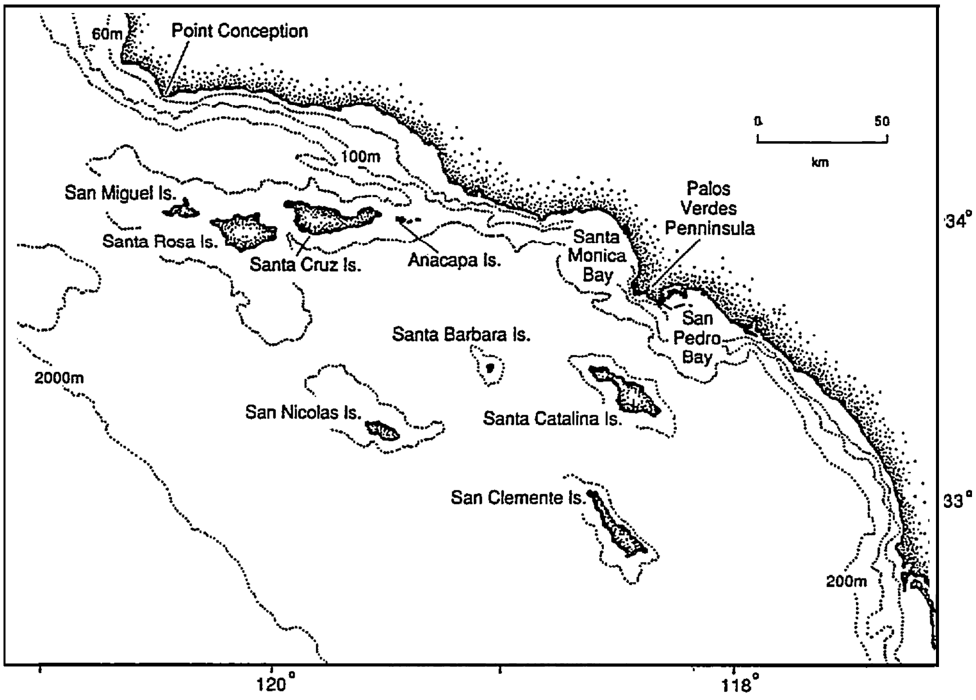
ECOLOGY OF THE SOUTHERN CALIFORNIA BIGHT:

A SYNTHESIS AND INTERPRETATION

FINAL REPORT

VOLUME I: Preliminaries, Chapters 1 through 6



U. S. Department of the Interior
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1990

DISCLAIMER

ECOLOGY OF THE SOUTHERN CALIFORNIA BIGHT:

A SYNTHESIS AND INTERPRETATION

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FOREWORD

Today's student of marine ecology is faced with an almost overwhelming burden of information. The rapid expansion of knowledge in the marine sciences and the increasingly specialized nature of academic pursuits is a challenge to the scientist's ability to look beyond his or her own specialized field and not lose the ability to perceive and encompass the proverbial "forest through the trees." Understanding the relationships between and among the various biotic and abiotic elements in the sea has become increasingly important as escalating demands of recreation, fishing, minerals extraction, shipping, and waste discharge compete for limited ocean space. Resource agencies struggle with an imperfect view of ecological processes ("big picture") in attempting to achieve some balance among potentially conflicting uses of the ocean and the seabed.

It is important that we, as marine scientists and managers, pause occasionally from the rush to acquire new, specialized information and, instead, make an effort to summarize, evaluate, and re-interpret information collected in the past--to look for links in our knowledge of interacting physical, chemical, and biological components of environment, links that may have been previously overlooked.

In preparing this book, we collected a large base of published and unpublished information and assembled a multidisciplinary team to review and synthesize the information. The authors were encouraged to read and discuss each other's material, across disciplines, and, by collective insight, extend each other's understanding of how the marine environment off southern California functions, both naturally and as Influenced by the activities of man. A series of meetings and periods of writing and rewriting occurred over a period of two years, finally culminating with a book that we believe fulfills our plan for an integrated synthesis and interpretations of the ecology of the Southern California Bight.

We hope this book is useful to a wide audience, including the advanced undergraduate or graduate student, just discovering the fascinating world of marine life lying at our front door; the marine scientist, trying to differentiate between potential anthropogenic effects and an inherently variable ecosystem; and the resource manager, making decisions that may weigh economic considerations against environmental protection.

Gary Brewer
Fred Piltz

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PREFACE

The Southern California Bight (SCB) is that body of water which lies between Point Conception on the Santa Barbara County coast and a point just south of the United States-Mexico border. The mild Mediterranean climate, the broad sandy beaches, and rocky shores provide an ideal environment for a water oriented playground for the millions of people who inhabit the shores of the SCB. However, the recreational and commercial fishing elements in the SCB are often in conflict with other elements that include the onshore industrial complex, offshore oil production, operations of one of the world's busiest seaports (Los Angles-Long Beach Harbors), and its use as receiving waters for municipal wastes.

Prior to World War II, oceanographic research in the SCB was largely exploratory and descriptive in nature. It was not until the mid-1950s that integrated studies in oceanography in the SCB were undertaken. The first of these large-scale studies was funded by the California Water Pollution Control Board (now the California Water Quality Control Board) during the period 1956-1961. This study focused on those areas of the SCB which were polluted, those which were expected to become polluted, and those which were expected to remain unpolluted. Two later studies were funded by the Bureau of Land Management (now the Minerals Management Service, or MMS,): The Baseline Study (1975-1976) and the Benchmark Study (1976-1977). These two studies were primarily concerned with obtaining background data from areas where offshore drilling for oil may occur in the future as well as areas which served as reference sites. The data generated from these studies constituted an important source of information for this book.

Synthesis of the accumulated oceanographic data of the SCB is a monumental task, and, until publication of this compendium, only two other such works had been completed. In 1960 K. O. Emery wrote *The Sea Off Southern California*, which integrated the physical, chemical, and geological knowledge of the SCB. The staff of the Southern California Coastal Water Research Project (SCCWRP) wrote the second synthesis, *Ecology of the Southern California Bight: Implication for Water Quality Management*. This synthesis focused on waste disposal, especially municipal wastes, in the SCB.

The impetus for this compendium grew out of public workshops sponsored by MMS in 1982. A report. issued by MMS on the workshops stressed the need for a comprehensive review of the oceanography of the SCB and recommended that the study should emphasize the ecology of the area. *Ecology of the Southern California Bight* is the result of that recommendation.

The primary goal of this work can best be summarized by a statement in the contract between MMS and the Ocean Studies Institute:

> "To produce a comprehensive hard-cover text that will make a significant contribution to the understanding of marine ecological processes within the SCB. By supporting the publication of a book written by a team of recognized experts in marine ecology and oceanography MMS hopes to obtain a highly credible reference that will benefit all scientists as well as the environmental staff of MMS."
>
> The contract specified that the text was to be "a synthesis and interpretation of existing data on the ecology of the SCB" and that "historical data and recent findings need to be thoroughly reviewed and then applied to new descriptions of how the marine ecosystem functions, both naturally and under the influence of human activities."

This book is written with both the advanced undergraduate and graduate student in mind as well as the professional in need of a reference source.

The editors could not have completed this volume without the assistance and cooperation of many people. We appreciate the time and effort that each of the contributing authors has given to this project. We especially thank Dr. Donald W. Hood, author of the chapter, "Ecosystem Interrelationships of the SCB." He brought to the task not only his years of experience but also the expertise he acquired as co-editor of two similar volumes: The Eastern Bering Sea Shelf: Oceanography and Resources, published in 1981 and The Gulf of Alaska, published in 1987.

Many scientists served as reviewers, providing an invaluable service to the editors and authors throughout the writing of this book. A Quality Review Board was selected to advise and assist in producing the compendium. The board met with the authors at the outset to discuss the overall coverage of the book to be written. Then, after completion of the initial draft, the board members met again with the authors to offer suggestions for improvement. After reading the final draft, they met for the last time with the editors to give additional suggestions before the manuscript was submitted to MMS. We, the editors, wish to thank these board members for their help and encouragement:

Dr. Donald Boesch, Director, Louisiana Universities Marine Consortium, Chauvin, Louisiana

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Other scientists acted as peer reviewers for chapters in their areas of expertise. They are:

Dr. Alice Alldredge, Department of Biological Sciences, University of California, Santa Barbara (zooplankton)

Dr. Farooq Azam, Marine Research Biology Department, University of California, San Diego (microbiology)

Dr. Kenneth T. Briggs, University of California, Davis (birds)

Dr. Roy Carpenter, School of Oceanography, University of Washington, Seattle (chemical oceanography)

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Dr. John Stephens, Department of Biology, Occidental College, Los Angeles (fish)

Dr. Peter M. Williams, Research Chemist, University of California at San Diego and Scripps Institution of Oceanography (chemical oceanography)

We are pleased to acknowledge the contributions of the staff of the Ocean Studies Institute, Linda Ennis and Dorothy ("Dee Dee") Rypka, who participated in all phases of this project. Assistance in the preparation of the companion bibliography of published and unpublished literature pertaining to the SCB was provided by Paul Dworian, Patricia Donohue, Sherry McLaughlin, Richard Santangelo, and William Schew. The art work was done by William Dunton, Carol Lyon, Ann Salness, and Marsha Schindler.

We also thank Dr. Gary Brewer, who represented MMS as project manager, for his help and encouragement, and Dr. Fred Piltz of MMS for his interest in this project since its inception.

CHAPTER 1 INTRODUCTION TO THE SOUTHERN CALIFORNIA BIGHT

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INTRODUCTION

This work represents a major new effort by experts in the many disciplines to contribute to better understanding of the Southern California Bight (SCB) ecosystem. No other book has attempted to encompass the available literature on the SCB in all the areas of expertise represented in this text. Toward this goal, each chapter in the work stands alone as a thorough and valuable update on pertinent findings in the field as well as on contributions made toward our understanding of the SCB ecosystem.

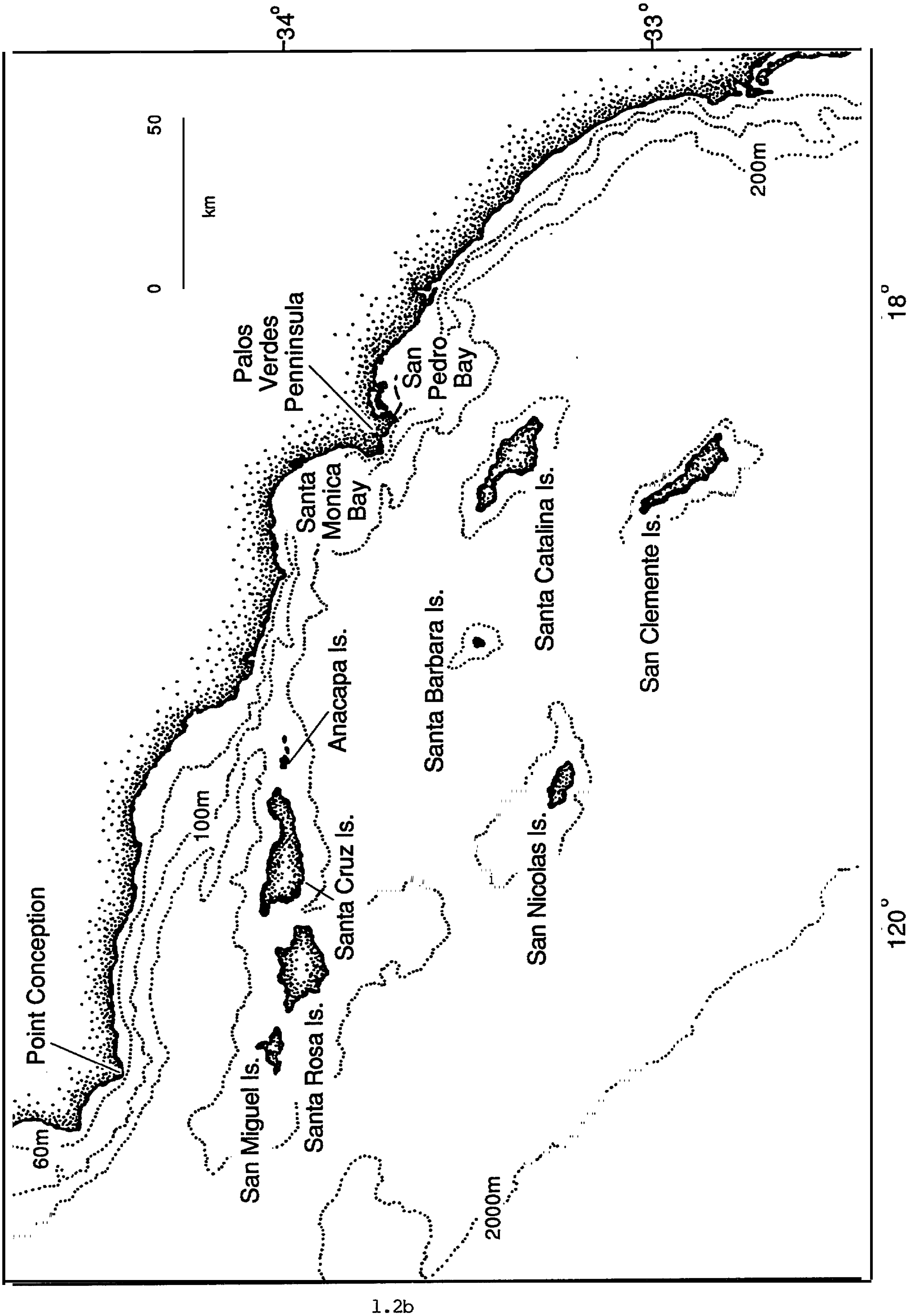
This book endeavors to provide marine scientists of all disciplines a basic review of recent information gathered in their fields of study from the SCB. Further, the authors of each chapter were challenged to furnish a combined summary and prospectus that serves two valuable purposes. First, it identifies study areas within the field that require further investigation, thus leading the next generation of researchers toward productive and essential study topics; and second, in the final chapter, it supplies the reader with the information needed to understand the synthesis of ecosystem interactions at work in the SCB. We also try to present the material so that those responsible for environmental management within the region will also find the information a useful tool in future decision making concerning growth and development of the SCB.

The SCB is one of the most studied areas of the United States. Although the name "Southern California Bight" is a regional name that has not been defined in geologic terms ("bight" Is defined as a "loop" or "curve" in the coastline), it is used in this book to describe the California continental borderland. The SCB includes an area of about 78,000 km^2 of the California borderland. It encompasses that body of water stretching from Point Conception, north of the Santa Barbara Channel, to a point just south of the border between the United States and Mexico (Figure 1.1). The SCB measures about 1000 km in length, and it has a maximum width from shore to the base of the Patton Escarpment of about 300 km (Figure 1.2). The basin floor depths range from 600 m to over 3000 m. Basin sills deepen progressively south and west to the area of the Santo Thomas Fault, where they then shoal to the south (Doyle and Gorsline 1977).

EXPLORATION AND EARLY HUMAN INHABITANTS OF THE SCB

The body of water making up the SCB, the Pacific Ocean, was first seen by Balboa in 1513. He defined the shoreline for the most heavily populated part of the North American continent: California. During that period, the

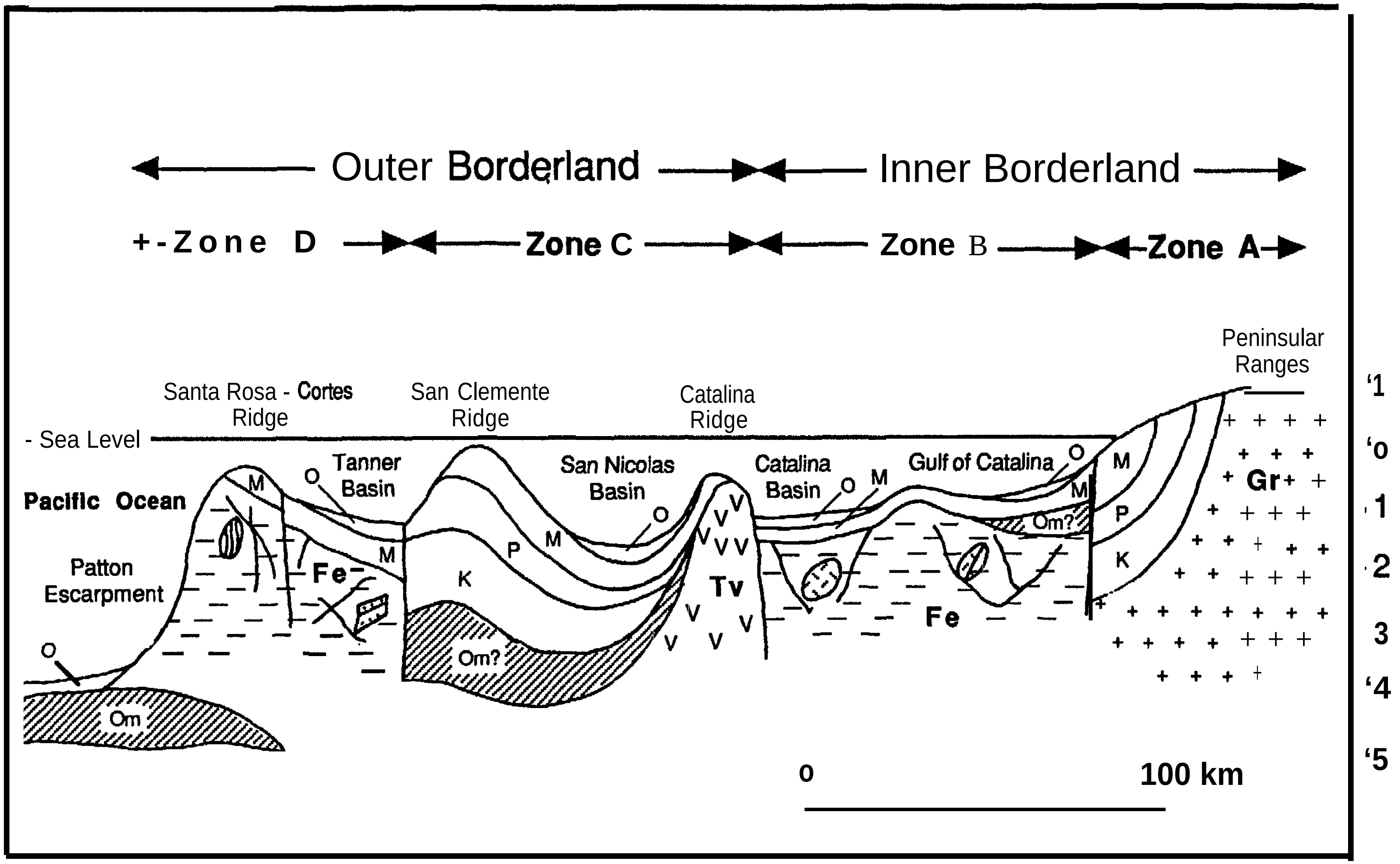
Figure 1.1. The Southern California Bight.


34°
33°
0
50
km
Palos
Verdes
Penninsula
San
Pedro
Bay
Santa
Monica
Bay
Point Conception
60m
100m
200m
2000m
San Miguel Is.
Santa Rosa Is.
Santa Cruz Is.
Anacapa Is.
Santa Barbara Is.
San Nicolas Is.
Santa Catalina Is.
San Clemente Is.
120°
18°

1.2b

Figure 1.2. Cross-section of the Southern California Borderland from the mainland shore to the Patton Escarpment.

1.2d


Outer Borderland
Inner Borderland
+-Zone D
Zone C
Zone B
Zone A
Peninsular Ranges
Santa Rosa - Cortes Ridge
San Clemente Ridge
Catalina Ridge
- Sea Level
Pacific Ocean
Patton Escarpment
Tanner Basin
San Nicolas Basin
Catalina Basin
Gulf of Catalina
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early 1500s, an estimated 700,000 Indians were thought to be living within the boundaries of the present state. Most of the native Southern Californians were organized as loose family units, not as tribes. Those inhabiting the Channel Islands and southern coastal areas lived in "wikiups ," small grass-covered huts, grouped in settlements called "rancheria." Their diet consisted primarily of seafood such as fish, abalone, and sea mammals, supplemented with acorn meal and small terrestrial animals such as, birds, reptiles, and insects (Narlon 1913).

The last known Indian inhabitant of the Channel Islands was Juana Maria, called the "Lone Woman" of San Nicolas (Figure 1.3). Reported to have jumped overboard while being evacuated from San Nicolas by priests in 1835, she was discovered by otter hunters nearly 20 years later (1853). She was taken to Santa Barbara where she died a few weeks after her rescue (Smull 1989).

EARLY SPANISH EXPLORERS

The first European explorers to set foot in what is now Southern California were a small company of Spanish adventurers commanded by Juan Rodriguez Cabrillo. Cabrillo and his men landed at what is now San Diego Bay on 28 September 1542 (Hartman 1968). When Cabrillo first encountered the San Pedro Bay coastline on 8 October 1542, it offered little or no positive features potential for future use. In the words of Richard Henry Dana, who visited the same area nearly 300 years later (in 1835), "The land was of a clayey quality and as far as the eye could reach, entirely bare of trees, not even a house to be seen. What brought us to such a place one could not conceive. We lay exposed to every wind that could blow, except the northerly ones. We found at the low tide rocks and stones, covered with kelp and seaweed, lying bare for the distance of nearly an eighth of a mile.

Figure 1.3. The “Lone Woman” of **San Nicolas** (photo courtesy of the Southwest Museum, Los Angeles).

1.3b

We all agreed that it was the worst place of all we had seen." (Queenan 1983). (How could **Cabrillo** or Dana have imagined that one day this desolate site would become one of the largest and most successful man-made harbors in the world?)

It was not until May of ***1602*** that Don Sebastian **Vizcaino** set sail from Acapulco to search the coast of California for suitable harbors in support of Spanish vessels trading with the Philippines (the Manila Galleon trade). However, **Vizcaino's** voyage was of more permanent value than **Cabrillo's** journey because he kept a careful and detailed record of the voyage. He touched at San Diego, **Avalon,** San Pedro, and Monterey. Don **Vizcaino** named the Coronado Islands as well as Santa Catalina and San **Clemente (Guinn** 1902).

More than 160 years passed before the next recorded vessel arrived at the Bay of San Diego. In 1769 the San Antonio, under the command of Juan Perez, brought the first European settlers who came to make a permanent home in the SCB area. This was the first of a threefold "occupation" to be carried out by the Spanish government. This occupation incorporated a religious, military, **and** civil approach which was intended to stem the Russian occupation of **Alta** California, then encroaching from the north. The execution of this plan was entrusted to Jose de Galvez, the Royal Visitador of Mexico. The plan called for four military divisions, two to arrive by land and two by sea. Gaspar de **Portola** was placed in command as military and **civil** governor, and **Junipero** Serra, as Father-President of the Franciscans, would oversee the religious mission (Lavender 1976). On Sunday, 16 July 1769, the first mission in California was founded by Father Serra in what is now known as Old Town in San Diego. Here Mission San Diego de **Alcala** was formally dedicated.

During **Serra's** lifetime there would be nine missions established; by the end of the eighteenth century there would be 18, and, with the founding of San Francisco **Solano** in 1823, the total number reached 21. All 21 missions and their surrounding lands had been established in the Southern California area under Spanish rule without expense to the royal treasury. The entire cost had been borne by private parties through what became known as the "Pious Fund." The Pious Fund consisted of money and property given by devout Catholics to the cause of proselytizing the California Indians. By 1768, the Fund had reached over $1,273,000 and yielded an income of $50,000 per year to be invested almost entirely in land (**Hartman** 1968).

SPANISH COLONIZATION

At this time Spain was attempting to colonize the area bordering what is presently considered to be the SCB. Eleven families recruited from the Mexican provinces of Sonora and **Sinaloa** followed the trail northward for seven months to become the first settlers in El Pueblo de Nuestra **Senora** La Reina de **Los.Angeles** de **Porciuncula.** The new town was founded on 4 September 1781, at a spot near the Indian village of **Yang-na,** later to become known as Pueblo de Los Angeles (**Hartman** 1968).

In 1784, the first of the vast California ranchos was established in the area around San Pedro Bay by Juan Jose **Dominguez,** a 65-year old bachelor and veteran of the **Portola** expedition. For his devoted service to Spain, Dominguez received a land grant of 74,000 acres, extending from what is now Redondo Beach south to include the entire Pales Verdes Peninsula and some distance eastward. Known as **Rancho** San Pedro, the original grant encompassed present-day Pales Verdes Estates, **Rancho** Pales Verdes, Rolling Hills Estates, San Pedro, Torrance, Gardena, **Compton,** Redondo Beach, Wilmington, **Lomita,** Harbor City, and Carson.

Other large land grants were doled out in the vicinity of the new pueblo of Los Angeles. Among the recipients was Jose Maria Verdugo, who received a large grassland area which covered the present city of Glendale and part of Burbank. Another huge grant, adjoining Rancho San Pedro and inclduing present-day Long Beach and other nearby communities, went to Manuel Perez Nieto. The founding fathers of Los Angeles were given title to their original holdings on the town's fifth anniversary in 1876. Along with the rancheros (those given land grants), these were the first private landholders in the pioneer province (Queenan 1983) (Figure 1.4).

On 13 May 1846, the United States declared war on Mexico and moved American naval units into every port in California. Not long afterward, an uprising took place in Los Angeles when the pueblo inhabitants pobladores grew tired of petty tyrannies imposed by occupation leader Archibald Gillespie. The pobladores chased Gillespie and his soldiers out of Los Angeles and caused the resistance to spread throughout Southern California. The resistance ended on 6 December 1846, near the Indian town of San Pasqual. By 1847 the pobladores had capitulated to the United States and the war in the West was over, although it would be another year before Mexico yielded and signed the peace treaty of Guadalupe Hidalgo (Hartman 1968) .

PRESENT GEOLOGIC, CLIMATIC AND OCEANOGRAPHIC SETTING

GEOLOGY

The U.S. Pacific Margin, a plate collision boundary, includes the typical narrow shelf (average width 25 km) fronting high-relief, coastal-parallel mountains. The shelf passes seaward to a steep slope and marginal trench. This morphology is characteristic of most of the Pacific Rim except off Southern California and northern Baja California, where a continued

Figure 1.4. Diego Sepulveda of **Rancho** Los Pales Verdes played a prominent role in the early development of San Pedro Harbor (photo courtesy of the Los Angeles Maritime Museum, San Pedro).

1.6b

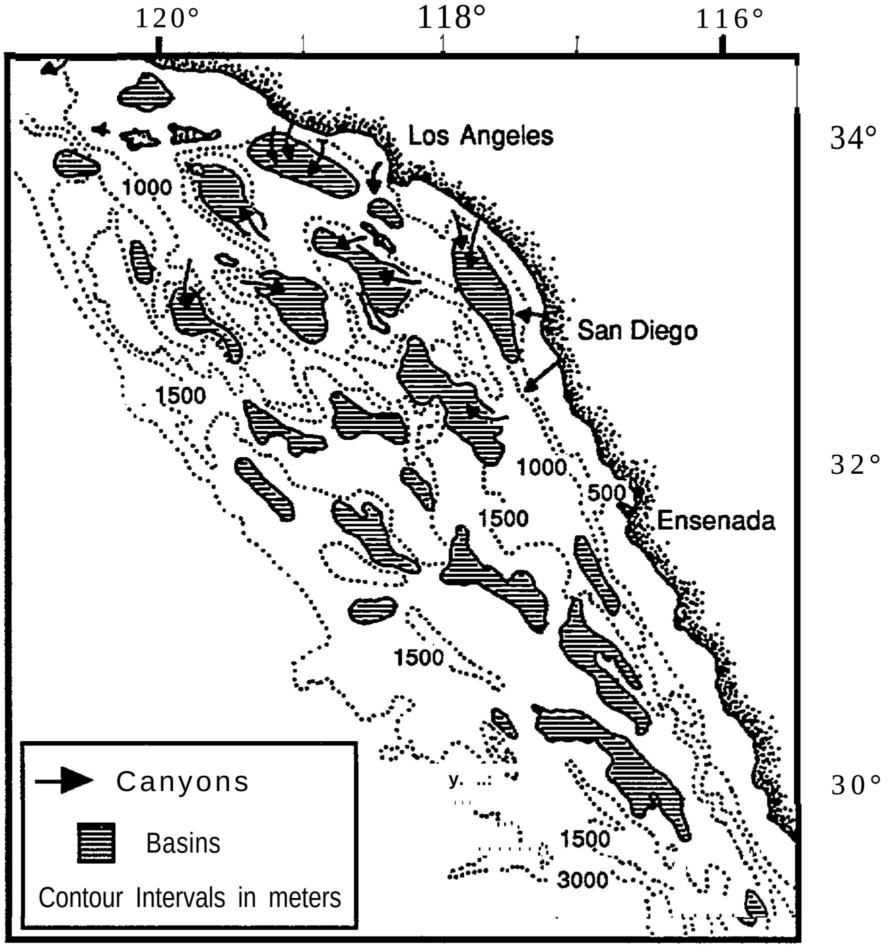
large-scale overriding of the North American Plate by the Pacific Plate has produced movements along a major fault line (San Andreas Fault System) (Teng 1985). The resulting Pacific Margin is wide (up to 300 km), and is composed of a series of laterally shifted blocks that produce roughly a checkerboard pattern (Howell et al. 1980) (Figure 1.5).

This checkerboard pattern is formed by basins that are arranged in rough rows, trending northwest-southeast and converging to the south. off California, the depressions are grouped as inner, central, and outer basins relative to the mainland. For the entire province, 23 depressions have been named (Emery 1960), of which 16 are located in the U.S. portion of the Borderland. The actual continental slope at the seaward margin is the Patton Escarpment (Uchupi and Emery 1963).

The U. S. Pacific Coast rivers typically drain tributary basins which are steep in gradient, small in area, and produce a large amount of sand discharge (Table 1.1). Southern California is noted for mild temperatures, short wet winters and long dry summers. There are only relatively small changes in these conditions between Santa Barbara in the north and San Diego in the south. Mean rainfall at Santa Barbara and Los Angeles is about 38.1 cm per year, while San Diego shows a slightly lower mean of 25.4. The same is true of the mean annual air temperatures. They vary only from 17.8°C in Los Angeles to 15°C and 16.7°C in Santa Barbara and San Diego respectively. The largest recorded discharges occur at about 20-30 year intervals. The major Southern California sediment discharge is delivered by the Santa Clara River in Ventura county, whose sources are in the San Gabriel Mountains at elevations of 2000 m (Table 1.1).

This discharge is first sorted by wave action at the coast into coarser particles, usually sands and gravels, which move in traction or in short-term, near-bottom suspension. The coarse fraction travels along the shore

Figure 1.5. Canyons and basins of the SCB.


120°
118°
116°
34°
32°
30°
Los Angeles
San Diego
Ensenada
1000
1500
1000
500
1500
1500
1500
3000
Canyons
Basins
Contour Intervals in meters

1.7b

Table 1.1. Discharges for Southern California and Baja California streams. Average annual rates in tons per year (**Brownlie** and Taylor 1981; **Schwalbach** and **Gorsline** 1985). Estimates for southern streams are subject to error because of limited data on discharge. Natural discharge is based on estimates of controlled drainage of present streams and corrections for delivery from those areas in a natural, uncontrolled state (**Brownlie** and Taylor 1981).

Drainage	**Sediment Discharge** $x10^6$ tons yr^{-1}	Suspension **Discharge** $X10^6$ tons yr^{-1}
Santa Ynez Mountains	0.70	0.52
Ventura River	0.93	0.58
Ventura area	0.02	0.01
Santa Clara River	3.72	2.44
Oxnard area	0.01	0.01
Calleguas Creek	0.26	0.16
Santa Monica Mountains	0.33	0.24
Los Angeles River	1.20	0.62
Long Beach area	0.01	0.01
San Gabriel River	1.20	0.62
Oceanside-San Diego area	3.s0	?
Baja Coastal streams	1.00 ?	?
Total Natural Discharge	**13.18**	5-6 **?**

within the beach and inshore zone, and offshore to the inner and central shelf at times of strong storm surging. Where canyons cut into the nearshore, as at the ends of each coastal cell, they intercept much of this transport (Inman and Frautschy 1966). Silts and clays are transported as suspension load and follow the water circulation during their slow fall. The influx of fine sediment particulate is generally low except for the times of winter runoff, and the multi-year cycle of major flooding. Therefore, during much of the year and during dry years, the predominant suspension particulate are of biological origin (biogenic).

Biogenic components undergo extensive recycling before they reach the ocean bottom. Much of this material is probably aggregated in the form of pellets and aggregates of planktonic origin and may be degraded by bacterial action as they sink. Additional aggregation occurs from ingestion by benthic organisms and infaunal reworking. This component reaches the bottom principally by particle or aggregate settling. The process is continuous, but it occurs at varying rates related to the cycle of seasonal blooms. Biogenic particulate contribute about 20$ of the total borderland sediment, which also includes carbonate, opaline silica, and other organic matter. During floods or wet seasons the flux of terrigenous material dominates the deposited sediments.

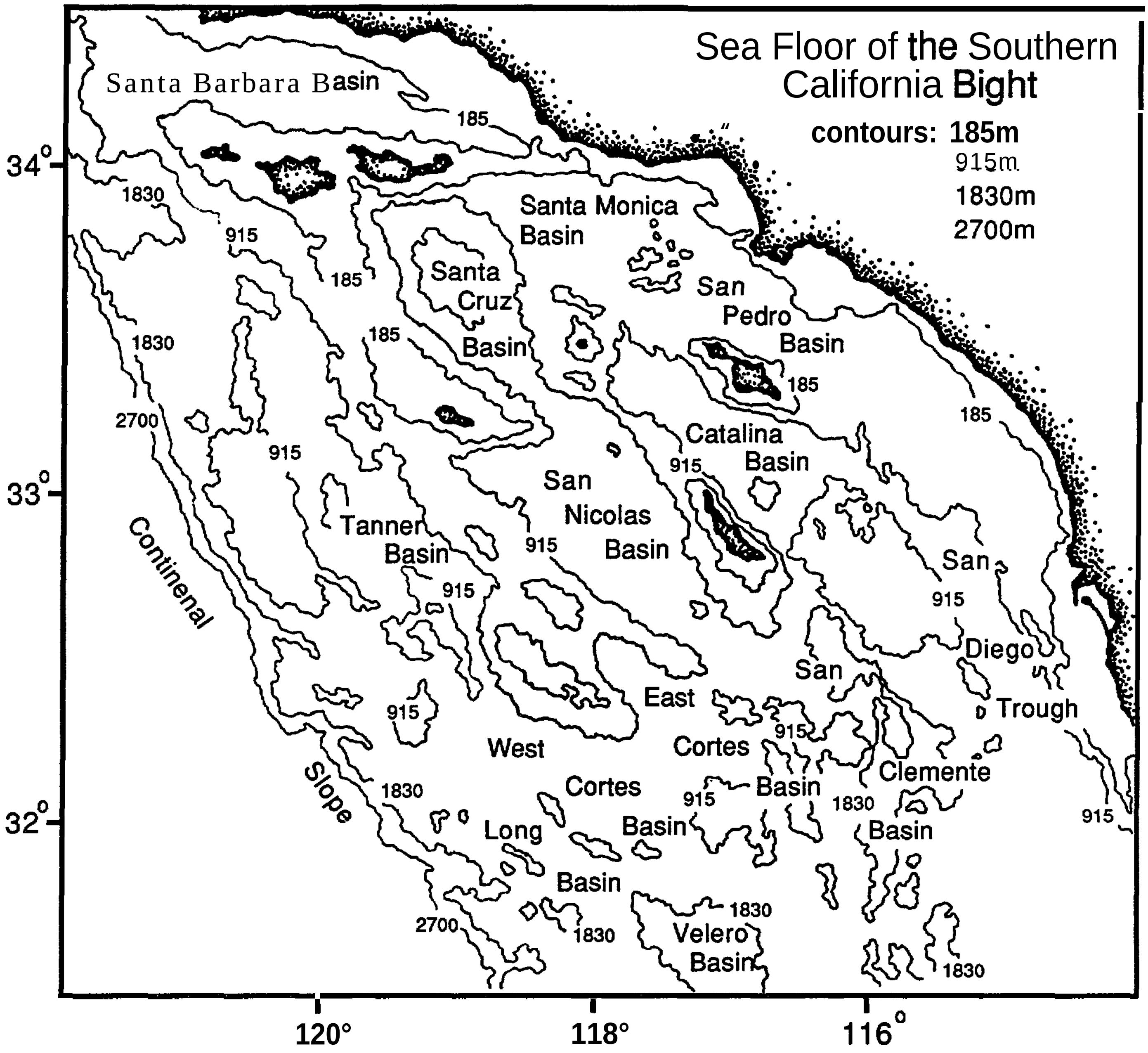
We can simplify description of the physical characteristics of the submarine canyons by considering them in relation to the three environments that they cross: shelf, slope, and basin (trough floor). Emery (1960) states that there are 13 large named canyons and 19 smaller unnamed canyons in Southern California. Of this total of 32 submarine canyons, 20 border the mainland, 10 border islands, and 2 are located off submarine banks. The canyons exert an influence on shelf-water circulation because of the pumping of water by tide-driven flows up and down the canyon axis. This action draws some of the suspension load to the canyon circulation systems (Drake and **Gorsline** 1973; Shepard et al. 1979). Much also passes over the shelves in complex circulations and is ultimately concentrated in **nepheloid** plumes (Karl 1976). These are found in surface waters, in the water column, and as near-bottom turbid layers.

Sand sediments initially deposited in nearshore canyon heads are progressively transferred **downslope** by mass movement processes and sediment gravity flows **(Nardin** et al. 1979). Fine sediments also initially accumulate in canyon walls and deeper canyon floors, where they are incorporated and carried out of the canyons to the fans and basin floors **(Shepard** and Dill 1966) (Figure 1.6).

The surface water circulation of the **SCB** tends to move fine suspended sediment into the Santa Barbara Basin from the California Current system to the west and through the **Anacapa** Passage from the southeast (Thornton **1981a,b).** These conditions produce high rates of fine clay-silt sedimentation in Santa Barbara Basin. As clay content increases, organic carbon content increases. Oxygen demand for the decay of this material utilizes oxygen faster than the rate of recharge. This high oxygen demand is superimposed on an already low oxygen-content. bottom water that enters the basin over the western sill at about the depth of the core of the Pacific Intermediate Water (Reid 1965). This low-oxygen deep-basin water can rapidly become **dysaerobic** (less than 0.3 ml 1^{-1} dissolved oxygen), and, where demand is increased, can become anaerobic **(anoxic;** oxygen absent or below 0.1 ml l-l). This factor is the major control on the basin floor **benthic** communities. In true **anoxic** environments, only anaerobic bacteria can flourish.

Since the central-basin bottom waters of Santa Barbara Basin are

Figure 1.6. Seafloor of the SCB.


Sea Floor of the Southern California Bight
contours: 185m
915m
1830m
2700m
Santa Barbara Basin
185
34°
1830
915
185
Santa Monica Basin
Santa Cruz Basin
San Pedro Basin
1830
185
185
185
2700
915
Catalina Basin
915
33°
San Nicolas Basin
Tanner Basin
915
915
San
915
Continenal
Diego
San
East
Trough
915
915
West
Cortes
Clemente
Slope
1830
Cortes
915
Basin
1830
915
32°
Long
Basin
Basin
Basin
1830
2700
1830
Velero Basin
1830
120°
118°
116°

1.9b

presently anoxic, the seasonal sediment arrangement's are preserved in the fine deposits. As shown by Emery and Hulsemann (1962) and Soutar and Crill (1977), these sediments preserve detailed annual records of biological and climatic events. These anoxic environments are widely viewed as the principal source conditions for petroleum generation (DeMaison and Moore 1980). Similar environments in the past produced the black shale facies found extensively in both deep-ocean floor and continental stratigraphies.

In the recent past (about 15,000 years ago), during low sea-level stands , which are typically periods of increased sedimentation rate and faster ocean circulation (and upwelling), other borderland basins have become anoxic. These include Santa Monica and San Pedro Basins, parts of Santa Catalina Basin, and possibly the San Diego Trough. In the past 200 years, the low-oxygen bottom water of Santa Monica Basin has spread, possibly because of increasing anthropogenic influxes, and has formed a near-anoxic non-bioturbated bottom sediment layer. San Pedro Basin is presently dysaerobic, approaching anaerobic, and all other basins are in the low aerobic or dysaerobic state. These conditions permit bioturbation of bottom sediments to occur (Savrda et al. 19S4).

WINDS

A subtropical high-pressure system stationed offshore of the SCB produces a net weak southerly and onshore flow within the area (Dorman 1982). In general, the wind speeds can be classified as moderate-typical in the offshore region and are on the order of 10 km hr^{-1}. The strength of the winds diminishes with proximity to the coast, averaging about half the speeds found offshore. Speeds are approximately one-half those found off Central and Northern California (Hickey 1979). However, strong winds may occasionally accompany the passage of winter storm systems or, more rarely, the northward penetration of a tropical storm into the southern region of the SCB. Within 10-40 km of the coast, the diurnal land-breeze becomes increasingly important, particularly during the summer, when a thermal low forms over the deserts to the east of the SCB.

On occasion, a high-pressure area can develop over the Great Basin area (flat desert area to the east of the SCB), reversing the surface pressure gradient and generating strong, dry, gusty offshore winds in the coastal area. These Santa Ana ("Santana") winds are most common in the late summer, but can occur during any time of the year.

The coastal mountain ranges and islands modify the strength and direction of the winds on a local and regional scale. San Miguel Island, for example, frequently blocks a portion of the wind flowing southeastward from Point Arguello, producing a zone of strong onshore flow along the north side of the northern Channel Islands. Strong Santa Ana winds can also produce strong flows below coastal canyons and valleys.

CURRENTS AND WATER PROPERTIES

The primary surface current in this region is the California Current. This current flows southeastward off the Central California coast with a maximum speed of about 10-15 cm s^{-1} (Pavlova 1966; Hickey 1979). Although the current is relatively slow moving, its broad width (approximately 300 km) results in a volume transport on the order of 1 x 10^{7} m^{3} s^{-1}. This rate, however, varies from year to year, with profound consequences for the properties of the water and the abundance and composition of the biota within the SCB.

Near Points Arguello and Conception, the coast bends sharply to the east, forming the SCB. The outer edge of the continental borderland, however, continues southeastward before bending to the east near the border with Mexico. The inner edge of the California Current tends to flow along the edge of the borderland (except during spring), swinging inward toward the coast between San Diego, California, and Punta Colnett, 210 km downcoast in Baja California, Mexico (Figure 1.7).

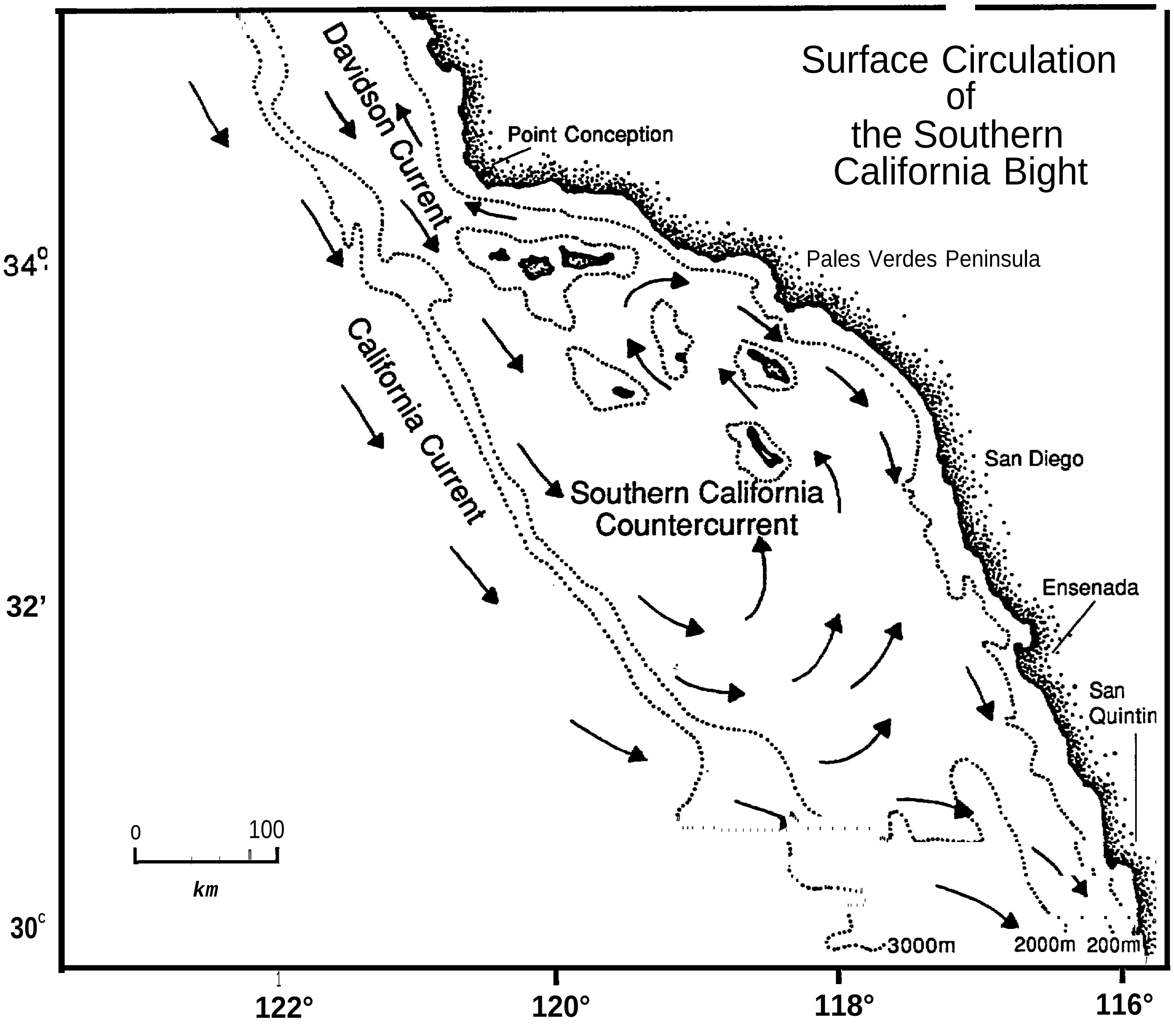
Over the central portion of the borderland, the average surface flow is upcoast, and is called the "Southern California Countercurrent." This upcoast flow is substantially blocked by the northern Channel Islands and the bulk of it is diverted to the west and merges with the California Current. This results in the formation of a counterclockwise-rotating gyre within the SCB, except during the spring. The remaining portion of the Countercurrent flows into the Santa Barbara Channel. Large variations are observed in the strength of these currents, with time-scales ranging from hours to months. Hickey (1990) has suggested that, on occasion, such as during extreme fluctuations, the SCB might be flushed within a few weeks.

The net flow beneath the California Current and the Countercurrent is poleward and is called the "California Undercurrent." Typical speeds are on the order of 10-20 cm s^{-1}, with maximum speeds occuring over slope areas (Hickey 1990). Like the surface currents, substantial variations, frequently in excess of the net flow, occur over time-scales of hours to weeks.

Flow over the shelves is generally weaker than over the basins and slopes. Also, equatorward mean flow is more common, especially in the very near surface layers. Although shelf flows may be driven in part by the local wind field, they may also be related to larger-scale basin flows.

The properties of the water in the SCB represent a mixture of subarctic water carried equatorward into the region by the California Current, and equatorial waters carried poleward by the California Undercurrent.

Figure 1.7. Circulation of the SCB.


Surface Circulation
of
the Southern
California Bight
Davidson Current
Point Conception
Pales Verdes Peninsula
California Current
Southern California
Countercurrent
San Diego
Ensenada
San
Quintin
0
100
km
3000m
2000m
200m
34°
32'
30°
122°
120°
118°
116°

Differences between the two water masses have been used to estimate the relative percentages of each type of water within the SCB, For comparable densities, the equatorial waters have higher temperatures, salinities, phosphate concentrations, and lower dissolved oxygen. Between 200 m and 400 m deep, more than half of the water inshore of the Cortes Ridge is of southern origin (60-80%); offshore from the ridge, only about 20-30% of the water is of equatorial origin (Sverdrup et al. 1942).

The upper layer of the water column (40 m inshore, 100 m offshore) is relatively isosaline. Nearshore, salinities peak in the July at about 33.6 ppt, decreasing to between 33.4 and 33.5 ppt in the late winter and early spring. Near the Cortes Ridge, salinities are 33.3 to 33.4 ppt. The upper portion of the water column is strongly thermally stratified from about May to October, reaching an average maximum surface temperature of approximately 19°C from July to September. During this period, the temperature changes by about 5°C over the upper 20 m of the water column. The minimum temperature (approximately 14.5°C) occurs in the late winter. Average concentrations of dissolved oxygen at the surface range from about 5.5-6.0 ml l^{-1} nearshore, and slightly less at the outer edge of the SCB. Close to shore there are upward shifts in the isopleths of temperature, salinity, density, and dissolved oxygen for the period from April through July. These displacements occur to a depth of at least 400 m, average about 50-100 m, and are associated with a wind-driven coastal upwelling. A similar displacement occurs offshore later in the year (June-August) and is associated with the large-scale California current. Localized nearshore upwelling can also occur throughout the year in the vicinity of bathymetric features like points of land.

EL NINO

The phenomenon known as El Nino occurs yearly off the coast of Peru. The term "El Nine", or **"The Child," was** apparently coined by the **Peruvian** fishermen because of its appearance around **Christmastime.** During the summer months the Peruvian Current extends northward into the Northern Hemisphere and the Equatorial Countercurrent is displaced to the south. These waters are warmer and lower in salinity, and this current converges with the Peruvian Current. The combined currents move southward and the peak of this yearly event is reached in February and March.

In some years physical events occur which cause the Equatorial Countercurrent to extend farther south into the Southern Hemisphere. This change from the typical pattern can result in profound biological changes. Generally the northwest winds of the South Pacific Ocean induce strong **upwelling** water movements along the coasts of Peru and Chile. However, in years of severe El Nine, physical changes occur which cause modifications in the environment. These include: (1) a decrease in the strength of the upper westerly winds in the Pacific; (2) a difference in the sea level between the two sides of the Pacific Ocean at the equator; and (3) differences in the transport of the Equatorial Countercurrent **(Cushing** and Dickson 1976).

These physical changes result in many alterations in the biological environment off the Peruvian coast, such as (1) a decrease in **phytoplankton** productivity, especially by diatoms; (2) movement into deeper, colder waters by the anchovy **Engraulis ringens** or migration into Chilean waters; (3) a decrease in the recruitment of the anchovies resulting from either the failure to reach sexual maturity or the lack of sufficient food for the larvae; (4) migration of whole populations of sea birds to Chilean waters--especially the Peruvian cormorant **(Phalacrocorax bougainvillii),** the brown pelican **(Pelecanus** occidentals **thagus),** and the Peruvian booby **(Sula** nebouxi); and (5) the killing of fish and other marine organisms as a result of the warmer waters (7°C higher) (Cushing and Dickson 1976; Schott 1913).

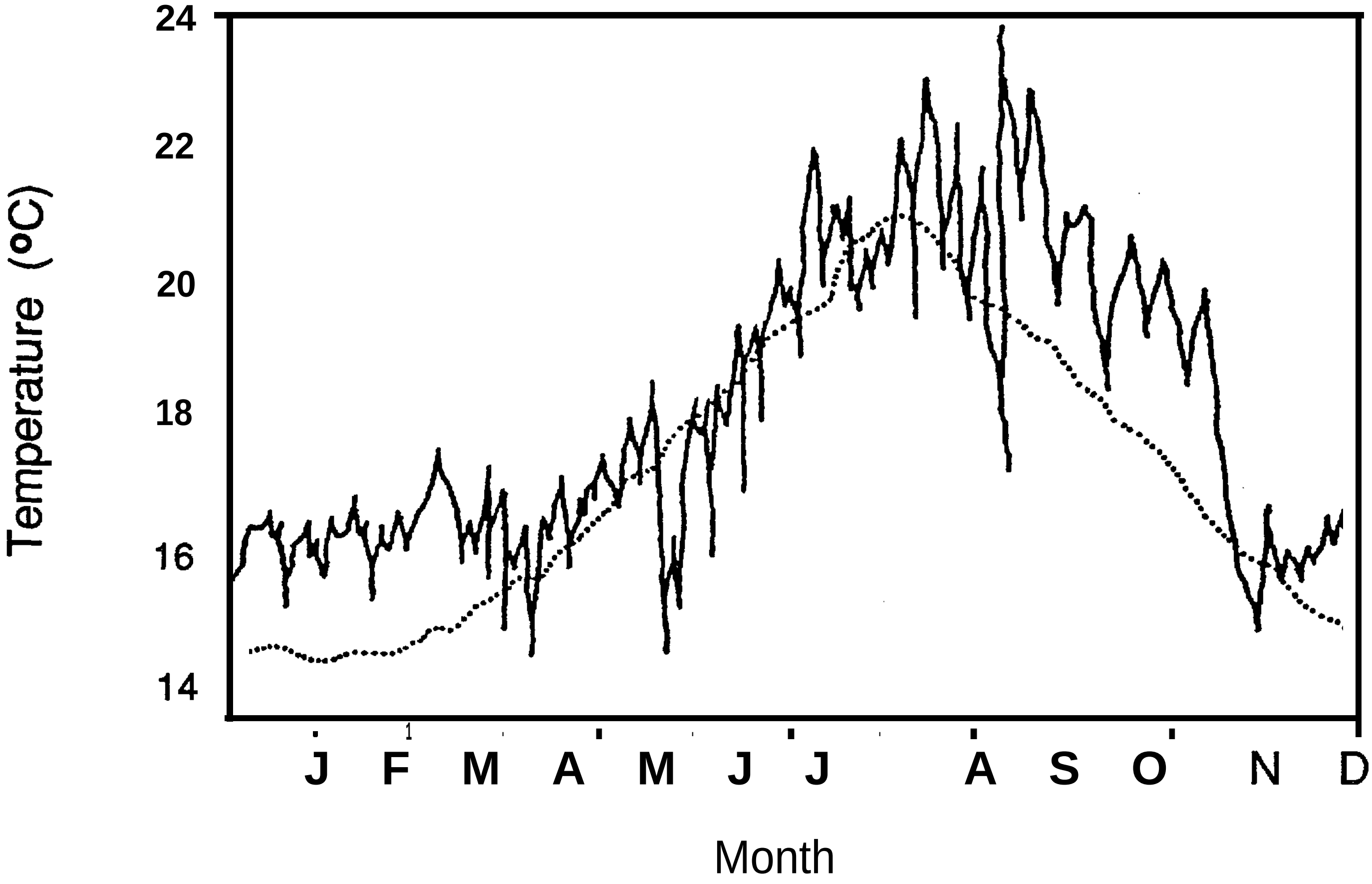
The decomposition of dead organisms leads to build-up of hydrogen sulfide which can blacken the paint of boats. Peruvian fishermen call this discoloration of their boats "Aguaje" or "Callao Painter" (Sverdrup et al. 1942).

In some years the southern-moving California Current is weakened, resulting in an anomalous northern polarward movement of water. As a result of the change in current strength, some of the warmer Equatorial Countercurrent flows northward into the North Pacific Ocean. The marine waters off the SCB are elevated several degrees above normal. This condition in the Northern Hemisphere, also referred to as El Nine, does not occur yearly. It has been reported in the literature in 1911-1912, 1917, 1925, 1932, 1939-1942, 1953, 1957-1958, 1965, 1976-1977, and 1982-1983 (Vildosa 1974; Kerr 1988). Comparisons of the daily water temperatures recorded in 1983 to the 63-year mean (Figure 1.8) indicated warmer waters than usual in the winter and fall months (Kerr 1988). The 1982-1983 El Nino brought to the SCB not only increases In water temperature, but also severe storms along the coastline that winter, causing damage to marine structures and erosion to the beaches (Kerr 1988).

Quinn (1974) has developed a predictive technique for occurrences of El Nino in the Northern Hemisphere. He took into consideration the strength of the southeastern trade winds, basing his calculations on the differences in the sea level atmospheric pressure between Easter Island and Darwin, Australia. This difference results in an increased transport of warmer water to the east along the equator.

A contrasting phenomenon called "La Nina" ("The Girl") has been

Figure 1.8. Annual water temperature profile for the SCB.



D′

observed. "La Nina" is characterized by colder waters than normal for the SCB (Kerr 1988). Such events recur about every 4 years in the SCB, but the interval may be as great as 10 years.

The unique coastline of the SCB and the changing strengths of the California Current and the Equatorial Countercurrent result in a fluctuation in water temperatures. Elevation of 7-10°C results in an alteration in the composition of the flora and fauna in the SCB. Species fluctuations are readily apparent in the plankton and shallow-water biota, but it is not known if either El Nino or La Nina affects the deeper water fauna. The measurable effects of El Nino on specific groups of plants and animals are addressed in later chapters.

Biological Setting

Its many habitats encourage a rich and varied marine life in the SCB. The mainland consists of a series of rocky shores, sandy beaches, and embayments of different types. Dredging and construction of harbors, marinas, jetties, and piers have increased the diversity of habitats. Eight major offshore islands, the Channel Islands, which are distributed along the edge of the continental borderland of the SCB, provide additional habitats for marine organisms; they also serve as breeding grounds for marine birds and as protected shores for marine mammals. Since the Channel Islands are located some distance from the heavily populated mainland of the SCB, they represent the best examples of pristine marine environments in the Southern California area. Distributed between the mainland and the Channel Islands (and beyond) are a series of submarine canyons, ridges, basins, and submarine sea mounts which provide unique habitats in the SCB.

The SCB is subject to short-term or long-term temperature fluctuations, depending upon the strength or weakness of the ocean current system. The interplay of the physiography, current systems, and anthropogenic inputs also influences the richness of the marine life in the SCB.

Primary production in the SCB depends upon the source of the nutrients from storm runoff, aerial fallout, seasonal upwelling, and anthropogenic inputs coupled with long periods of sunshine. Emery (1960) calculated the phytoplankton productivity to be about 500 g dry wt m^{-2} yr^{-1} over the 7S,000 km^2 area of the SCB. Productivity measurements over a 10-year period by Eppley and Helm-Hansen (1986) In the southern region of the SCB were 0.39 g C m^{-2} d-l or 4.3 x 10^6 t of carbon per year for this 30,000 km^2 area.

Zooplankton displacement volumes were measured from 1949-1969 under the auspices of the California Cooperative Oceanic Fisheries Investigation (CalCOFI) project which encompassed the SCB and adjacent areas to the north, south, and west of the SCB (Bernal 1979). The mean zooplankton volume in the SCB for this period was 243.7 ml/1000 m^3. This figure was about 60$ of the volume measured for the area north of Point Conception, but was greater than those for Baja California and the open ocean. Monthly means ranged from a low of 101.2 in December to a high of 239.0 ml m^{-3} in February. The seasonal highs over the CalCOFI study area varied from year to year as to the month (spring, summer, or fall), but the lowest values were measured in the November-January period (Chapter 6).

Seventy percent of the known algal species from California occur in the SCB (Chapter 7). This high percentage is attributed to the extensive mainland shoreline of diverse habitats and the offshore Channel Islands. In the final analysis, this figure may be high, since many areas of the Central California coast are difficult to reach and have not been studied extensively. Kelp beds form a unique shallow water community which is not only important economically and recreationally, but also provides a haven for a complex array of additional algal species, invertebrates, and fish.

Productivity of individual algal species ranges from less than 0.1 to 11.2 mg C g dry wt^{-1} h-i with the sheet species (for example, *Ulva*) having the highest values and the crustose species (such as *Lithothamnium*) the lowest values.

Over 5000 species of benthic marine invertebrates exist in the SCB. They inhabit all areas of the sea floor, from the high intertidal splash zone to the bottoms of the offshore basins (over 2500 m deep). The benthic fauna are so diverse because the region is an area of overlap between the northern Oregonian and southern Panamic biotic provinces and because of the wide range of habitats provided in the region (Chapter 8). Benthic invertebrates occur in rather discrete assemblages of species that also differ in diversity and biomass depending on water depth and substrate type. The ecology of shallow subtidal and intertidal assemblages has received considerable investigation, but there has been very little study of deep-water assemblages (Chapter 8).

The SCB supports a diverse and dynamic ichthyofauna. Of the 144 families and 554 species of California coastal marine fishes, 129 families and 481 species occur in the SCB. The SCB is the southern terminus of the ranges of many northern species and the northern terminus of the ranges of many southern species. Point Conception, a widely recognized faunal boundary, is more important as a barrier to southern species than to northern ones. Northern species cross Point Conception by moving into deeper water off Southern California, and by occupying upwelling areas on the southern side of headlands, especially off Baja California. Northward incursions of tropical fishes into the SCB during abnormally warm water years associated with El Nino demonstrate the dynamic nature of the Southern California ichthyofauna. Less well known are the southerly incursions of northern fishes during cool years. Warm-water and cool-water events in the SCB affect fish recruitment, and can alter the composition of fish assemblages for several years thereafter.

The complex bathymetry of the SCB offers a variety of habitats for fishes that live on (or are associated with) the bottom as well as fishes that live in the water column. The basins provide habitat for a significant number of midwater and benthic deep-sea fishes very near the coast. The nearshore waters contain a variety of habitats. Soft substrates, such as bays and estuaries, man-made harbors, exposed sandy beaches, shelves, and slopes, are abundant along the mainland and the offshore islands. Hard substrates, such as the rocky intertidal, shallow subtidal reefs, deep rock reefs, and kelp beds, are common along the mainland and abundant at the offshore islands (Chapter 9).

The SCB is the residence at least part of the "year for over 195 species of coastal and offshore birds. Resident species constitute the greatest percentage of the bird population. The large population of birds in the SCB is attributed to the fact that this area is the northern and southern limits of the breeding range of many species. Mainland wetlands and the Channel Islands are the principal breeding sites in the SCB. The conversion of two-thirds of the wetlands of California for other uses has destroyed valuable habitats, feeding areas, and breeding sites for many species of birds (see Chapter 10). The establishment of marine sanctuaries in the SCB in recent years will preserve at least some of these wetlands for birds and other species (Chapter 13).

Thirty-nine species of marine mammals have been sighted, some only rarely, in the SCB. Eleven species are year-round residents, 22 are occasional or possible visitors, and 6 are migratory species. While accurate numbers of marine mammals are difficult to obtain, as many as three hundred thousand individuals are believed to reside in, or pass through, the SCB within a year. The large population of mammals in the SCB is, in part, the result of a rich supply of food resources. **Pinnipeds,** of which many are year-round residents, are estimated to consume nearly 50$ of the food eaten by all marine mammals. The migratory baleen whales account for nearly 20$ of the food consumed by this group (Chapter 11).

GROWTH OF THE SCB AND DEVELOPMENT OF MARINE SCIENCE

The earliest documented maps of the Southern California Bight were made by the Spaniards. However, Captain George Vancouver is credited with the first known oceanographic work, performed during his first visit to the area in 1793. Between Vancouver's visit and California statehood in 1850 virtually nothing was added to the existing oceanographic information.

In 1960, approximately 100 years later, the state's population had grown to more than 15 million. The population of Los Angeles County alone had grown to more than 6 million.

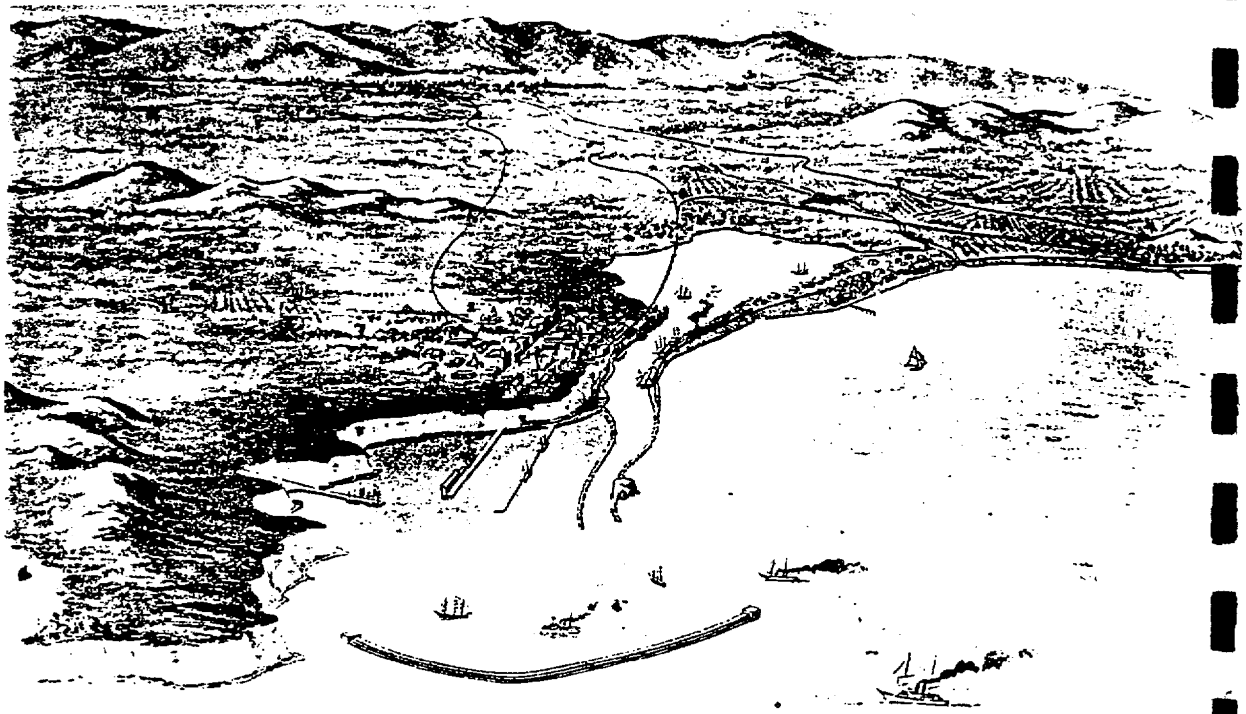
The growth of the SCB port cities was very rapid. Los Angeles, a hamlet of 4385 people in 1860, possessed none of the natural advantages that enabled San Francisco to *grow* into one of the nation's urban centers between 1847 and 1859. The southern city had no **navigable** rivers for opening easy transportation routes to inland mines or farming areas. Even San Diego's superlative harbor provided its citizens little, for the mountains **and** deserts behind the bay remained too undeveloped to support commerce.

However, after the completion of the Southern Pacific Railroad from the East in 1876, the Los Angeles and San Diego area populations grew rapidly. San Diego's population jumped from 5000 in 1884 to an estimated 32,000 in three years. Real-estate promoters tried to hasten the growth of Los Angeles westward toward Santa Monica rather than south to San Pedro, but eventually the victory went to San Pedro (Figures 1.9 and 1.10). **Los** Angeles, in 1906, annexed a 20 mile strip of land that directly connected the city to the port. This allowed the municipal government, working with neighboring Long Beach, to turn their man-made harbor into one of the world's busiest ports. Within a few decades Los Angeles-Long Beach Harbors were able to monetarily surpass the San Francisco harbor (Queenan 1983).

The growth of Santa Barbara, Ventura, Los Angeles, Orange, and San Diego counties ranked the area number two in growth in the nation during the 1950s and 1960s and number one during the 1970s and 1980s (U.S. Department of Commerce). The combined population of the area increased from 6 million to 12 million during the 20-year period between 1960-1980. Between 1980 and 1985 the area grew by another 1.2 **million** people. This represents an increase of more than 100$ during those 24 years. In the Los Angeles-Long Beach area there are 1837 people per square mile of land (U.S. Department of Commerce). According to a recent government report, it is projected that more than 300 thousand new homes will be needed in Los Angeles County over the next 22 years to house the growing population (Independent Press-Telegrsm April 29, 1988). This prediction was made in the Regional Housing Needs Assessment from the Southern California Association of Governments; **it** is based on a forecast that 5.5 million more people will live in the Southern California counties by the year 2010. This continued growth of an already impacted area will continue to exacerbate the already delicate balance found in the ecology of the SCB offshore and tideland waters.

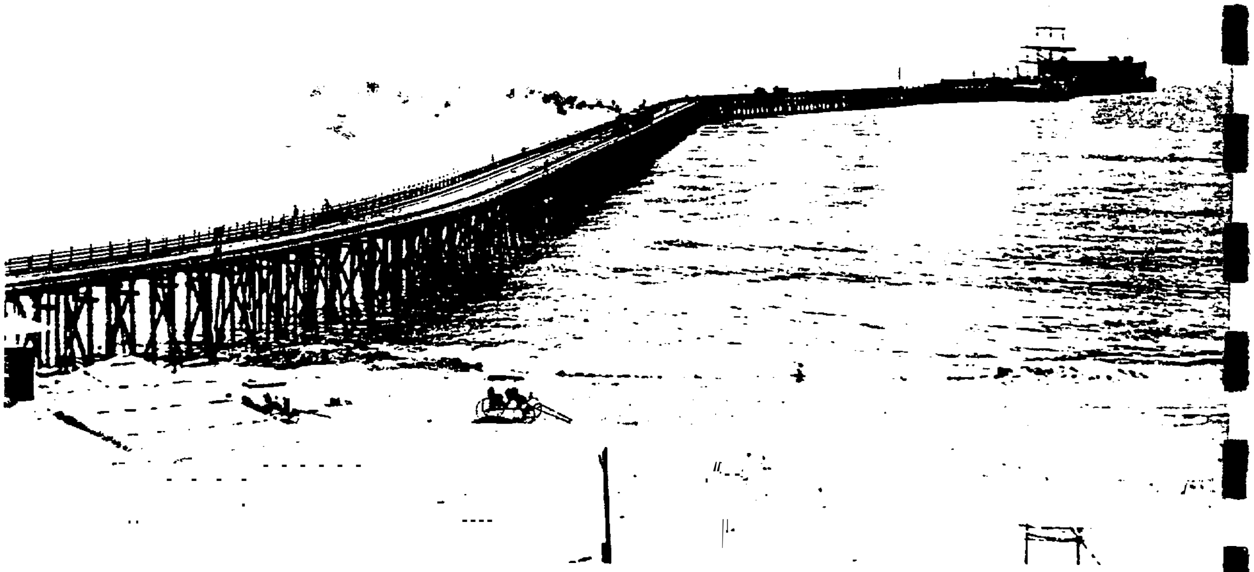
The history of oceanographic research in the SCB can be divided into three general periods: the exploratory, descriptive, and the **experimental-analytical**. These are not precise periods of time, since exploratory

Figure 1.9. Diagrammatic representation of early San Pedro Harbor (photo courtesy of Los Angeles Maritime Museum, San Pedro).



1.21b

Figure 1.10. Early cargo wharf at San Pedro Harbor used for unloading coal and lumber (approximately 1883) (photo courtesy of Los Angeles Maritime Museum, San Pedro).



oceanographic research is still being conducted today. Rather, it indicates, as is characteristic of scientific research in general, the developmental process which has taken place in oceanography.

The early oceanographic explorations in the North Pacific Ocean were summarized by Hood (1986), beginning with the voyage of the St. Peter in 1741. This and subsequent early expeditions were concerned with physical measurements, such as water temperature and salinity, which assisted scientists in the initial mapping of ocean currents. Biological investigations focused on vertebrate species which had potential for economic importance and could be easily exploited.

The descriptive phase of marine biology began elsewhere in the late eighteenth century, but did not begin in the SCB until the subtidal collections were made from the U.S. Fish Commissioner's steamer, the Albatross, in 1904. In the early part of the twentieth century, faculty and students from the San Francisco Bay area universities began studying marine life in Southern California. W.E. Ritter (who played a significant role in the formation of Scripps Institution of Oceanography) and others conducted investigations and instruction at several locales in Southern California before establishing a permanent station at La Jolla. W.A. Setchell and N.L. Gardner published extensively on the algae of Southern California as well as elsewhere. D.S. Jordan and C.H. Gilbert contributed in a similar way to the knowledge of the fishes of the SCB. While much of the intertidal marine life of the SCB has been described, the subtidal collections made under the auspices of the Bureau of Land Management (now Minerals Management Service) and other public agencies concerned with the environmental condition of the SCB have yielded hundreds of species of organisms which remain undescribed. The purely descriptive phase of marine biology in the SCB will continue well into the next century.

As the frontier of marine science advanced from the descriptive phase to a more experimental-analytical type of research, questions were directed to answer both academic and practical problems. The California Cooperative Oceanic Fisheries Investigations (CalCOFI) was established to investigate fishery productivity in the SCB and nearby areas. As part of its charge, CalCOFI has amassed one of the world's most extensive databases on the occurrence, distribution, and productivity of planktonic communities.

The rapid population growth of Southern California has created many environmental problems. Since the ocean is the only accessible receptacle for municipal waste water, the sanitation districts in the SCB are required to monitor both their discharges and the receiving oceanic waters. The staffs of these agencies, with the assistance of personnel of the Southern California Coastal Water Research Project, have been collecting and analyzing vast amounts of chemical, physical, and biological data since the 1970s. Not only do these data assist public officials in evaluating environmental conditions, they also provide basic scientific information on the spatial and temporal variations of contaminants and organisms in the SCB .

Seashore-based laboratories make it possible to pursue studies that are otherwise difficult or impossible to conduct in a university setting, especially with living organisms. Scripps Institution of Oceanography was the first such station to be established in the SCB and is now recognized as one of the paramount oceanographic centers of the world. **W.E. Ritter,** a professor at the University of California, Berkeley, who (as noted earlier) had conducted summer marine biological programs in Southern California, became acquainted with E.W. and Ellen Scripps in 1903. With their financial backing, and that of others, the forerunner of the present Scripps was founded in La Jolla (Raitt and Moulton 1967). Later two marine biological stations, neither in existence today, were administered by Pomona College in Laguna Beach and by the University of Southern California at Venice. The California Institute of Technology developed a small laboratory, initially under the direction of Professor G.E. MacGinitie, near the mouth of Newport Bay.

More recently, the University of Southern California built an instructional and research facility at Santa Catalina Island and a research laboratory in Los Angeles Harbor. The California State University system and Occidental College currently operate marine research vessels for the collection of samples and basic instruction in the SCB. Many universities without shoreside facilities transport sea water to their campuses to provide limited opportunities to conduct marine research. Currently there are plans to construct a mainland marine facility in the San Pedro area which would suffice to meet the needs of Los Angeles County. These facilities are expected to be operational in the early to mid-1990s.

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CHAPTER 2 PHYSICAL OCEANOGRAPHY

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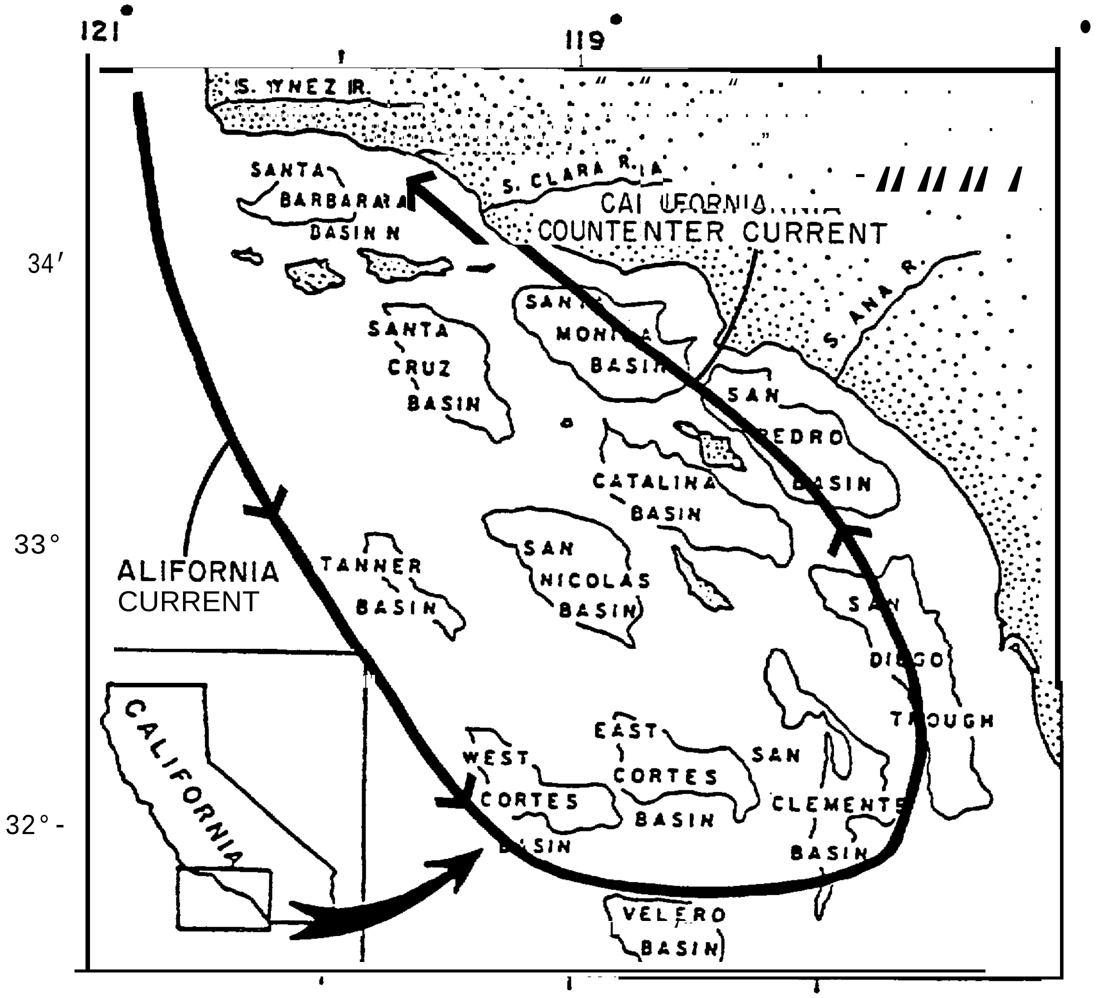
- I. Introduction
- II. Data Sources and Analyses
- III. Seasonal Patterns
  - A. Currents
  - B. Water Properties
- IV. Subtidal Fluctuations
  - A. Currents
  - B. Water Properties
- V. Tidal Fluctuations
- VI. Interannual Fluctuations
- VII. Basin Water Renewal
- VIII. Wave Climate
- IX. Summary and Prospectus for Future Research
- X. Literature Cited

INTRODUCTION

The Southern California Bight (SCB) constitutes a unique physical environment within a major eastern boundary current system. A dramatic change in the angle of the coastline, coupled with the morphology of the Southern California offshore coastal area (Figure 2.1), results in circulation patterns and forcing mechanisms that differ significantly from other locations on the west coast of the United States. In particular, because of the bend in the coastline, the coastal wind stress decreases by almost an order of magnitude between the Central California coast and the SCB (Hickey 1979). Thus, we can expect the effects of local wind-stress forcing which predominate within approximately 40 km of the coast north of Point Conception to be much reduced in the SCB.

The morphology of the SCB includes 12 major offshore basins (Figure 2.1). All of the basins are completely enclosed at some depth (for example, 740 m for the Santa Monica Basin) and semi-enclosed at shallower depths. Thus, the region includes time-variable circulations characteristic of enclosed basins as well as fluctuating flows over sills between the basins.

Figure 2.1. Schematic representation of coastal basins off Southern California, showing the path of the large-scale California Current over the region.


121°
119°
34'
33°
32°-
S. YNEZ R.
S. CLARA R.
S. ANA R.
CALIFORNIA
COUNTENTER CURRENT
SANTA BARBARA BASIN
SANTA CRUZ BASIN
SANTA MONICA BASIN
SAN PEDRO BASIN
CATALINA BASIN
SAN NICOLAS BASIN
TANNER BASIN
ALIFORNIA CURRENT
SAN DIEGO TROUGH
WEST CORTES BASIN
EAST CORTES BASIN
SAN CLEMENTE BASIN
VELERO BASIN
CALIFORNIA

2.1b

Submarine canyons are also common in the area and may affect sediment movement as well as local water properties.

The SCB includes both narrow shelf regions (<5 km) as well as broader (approximately 20-40 km) shelves (Santa Monica and San Pedro). In contrast to coastal regions outside the SCB, the sections of shelf are virtually disconnected by coastal promontories such as headlands and capes. Even the relatively long uninterrupted shelf from Newport to San Diego is an order of magnitude shorter than the shelf north of Point Conception (100 km vs. 1000 km).

The mean circulation in the SCB is dominated by the poleward flowing California Countercurrent, which may be thought of as a very large-scale eddy in the California Current (**Hickey** 1979; **Tsuchiya** 1980) (Figure 2.1). The California Current is a broad-scale, rather sluggish equatorward flow that occurs off the west coast of the United States, with a seasonal mean speed maximum (about 10 cm s^{-1}) that occurs a few hundred kilometers offshore (**Hickey** 1979). The California Current has a seasonal speed maximum in late summer, as does the California Countercurrent.

A poleward flowing current, the California Undercurrent, occurs on the shoreward side and beneath the California Current all along the west coast. Flow in the undercurrent is concentrated over the continental slope. In the SCB, the undercurrent is concentrated over the near-shore continental slope (rather than the slope that occurs on the seaward side of the SCB) so that the California Current and Undercurrent are spatially separated. Also, in the SCB, where both the surface flow (the California Countercurrent) and the subsurface flow (the California Undercurrent) are directed poleward, the presence of the undercurrent is demonstrated by a subsurface maximum in the current speed. The California Undercurrent, like the California Current, has a seasonal speed maximum in late summer.

Monthly mean winds blow equatorward off the Southern California coast. There is no seasonal wind reversal, although there is a variation in amplitude, with maximum equatorward winds occurring during early summer (Hickey 1979).

Emery (1960) was the first to address the physical oceanography of the SCB as a system. Emery's description was improved significantly by Jackson (1986), who included results from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program (see below) as well as other then-available data. Several comprehensive data sets have recently become available. This chapter incorporates the results of these data sets to provide a further updated description of the currents and water properties of the region. The following section describes the principal data sets and their limitations. For simplicity the discussion is organized according to the frequency band of the dominant fluctuations: seasonal, subtidal (approximately 2-30 days), high frequency (tidal and supra-tidal) and interannual bands. Discussion of basin-to-basin exchange and of the local wave climate follows the discussion of the several frequency bands. Last, the information is summarized.

DATA SOURCES AND ANALYSES

Several spatially and temporally comprehensive data sets are available for the SCB. These include CalCOFI hydrographic data and direct current measurements over the Santa Barbara Basin and shelf, the Santa Monica Basin and the San Pedro Basin, adjacent shelves and sills, including the San Pedro and Newport shelves, the shelf between Newport and the entrance to San Diego harbor, and the bight south of San Diego. Extensive conductivity and temperature versus depth (CTD) data are also available for the Santa Barbara

Channel and the Santa Monica and San Pedro basins and shelves.

The CalCOFI data set consists of water property information available on a fixed station grid at roughly seasonal intervals since 1950 (Lynn and Simpson 1987) (Figure 2.2). Data coverage extends as far north as San Francisco and as far south as lower Baja California, although not on every cruise. These data provide important information on the large-scale current system and its seasonal and interannual variability. Data from over 16,000 stations are available for the period 1950-1978. The sampling grid consists of parallel lines oriented roughly normal to the coast, spaced at approximately 74 km intervals along the coast. Stations are also separated along the lines by approximately 74 km, except near the coast, where the spacing is half or less. All stations are restricted to the upper water column ($\leq$500 m). Until 1964, data consisted of 18-bottle Nansen casts; subsequent data were obtained with a CTD. Seventeen standard stations are located within the SCB.

The Santa Barbara Channel data sets include both a 4-month pilot program and a year-long program (1984) of direct current measurements (Figure 2.3) as well as seasonal CTD measurements (Gunn et al. 1987). Seasonal CTD measurements were also made during 1969 (Kolpack 1971). The comprehensive 1984 measurement program was executed by Science Applications International Corporation (SAIC), under contract to Dynalysis of Princeton, Inc. as part of a Minerals Management Service contract. The current meter array of roughly 40 current meters included several moorings across both the east and west channel entrances as well as in all of the inter-island passages. One mooring, the only mooring with surface current meters, was maintained in mid-basin. The CTD surveys consisted of quarterly surveys of approximately 50 stations along eight roughly north-south sections.

The comprehensive Santa Monica-San Pedro data set consists of four

Figure 2.2a. **CalCOFI** station pattern. The 2000 m **isobath** is shown dotted. **Bathymetry** less than 500 m is hatched (from Simpson et al. 1984). b. Record of station occupation (from Simpson et al. 1984).

2.4b

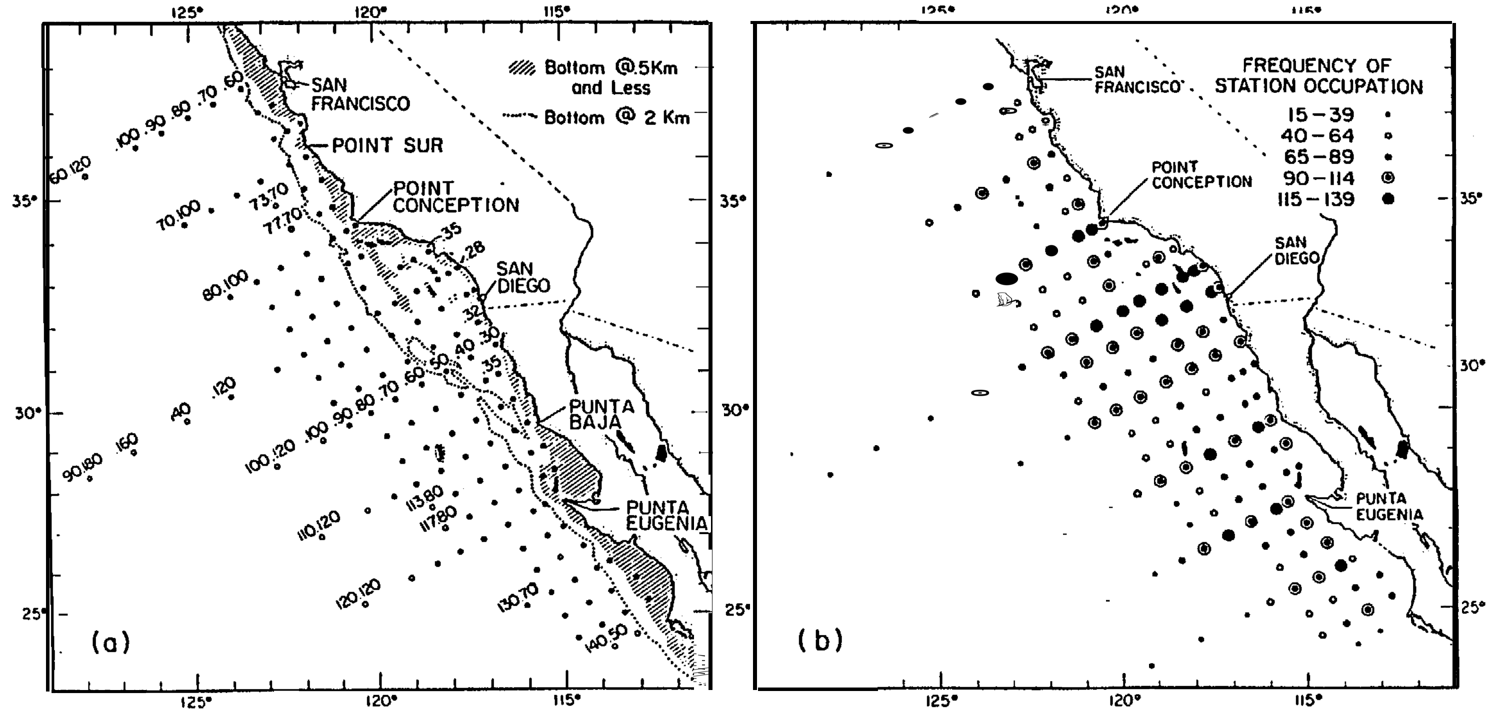
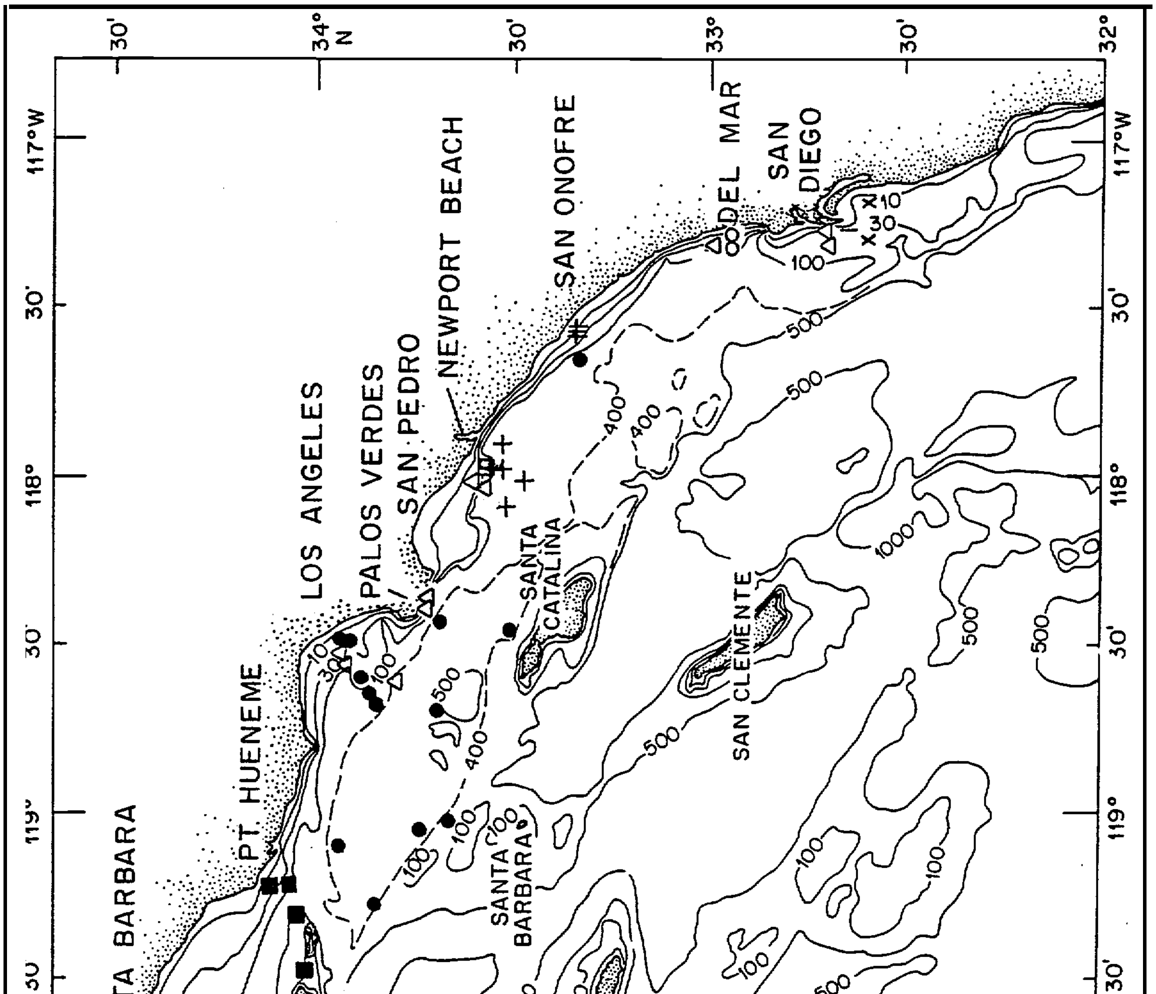

(a)
▨ Bottom @.5Km and Less
Bottom @ 2 Km
SAN FRANCISCO
POINT SUR
POINT CONCEPTION
SAN DIEGO
PUNTA BAJA
PUNTA EUGENIA
60 120
100 90 80 70 60
70 100
73 70
77 70
80 100
35
28
32
30
40
35
50
60
70 80 90 100 120
40 120
90 180 160
100 120
113 80
117 80
110 120
120 120
130 70
140 50
125°
120°
115°
35°
30°
25°
(b)
FREQUENCY OF STATION OCCUPATION
15 – 39 •
40 – 64 ∘
65 – 89 •
90 – 114 ◉
115 – 139 ●
SAN FRANCISCO
POINT CONCEPTION
SAN DIEGO
PUNTA EUGENIA
125°
120°
115°
35°
30°
25°

Figure 2.3. Locations of most comprehensive direct current records in the SCB. The location of offshore and nearshore wave monitoring sites is indicated with the letter “w.” Depth is in fathoms.


POINT CONCEPTION
SANTA BARBARA
PT. HUENEME
LOS ANGELES
PALOS VERDES
SAN PEDRO
NEWPORT BEACH
SAN ONOFRE
DEL MAR
SAN DIEGO
SAN MIGUEL
SANTA ROSA
SANTA CRUZ
SANTA BARBARA
SANTA CATALINA
SAN NICOLAS
SAN CLEMENTE
● Hickey
△ SCCWRP
□ SAIC
■ DYNALYSIS
○ Winant & Bratkovich
x ENG. SCI.
+ MRC
117°W
118°
119°
120°
121°W
30'
34° N
33°
32°
10
30
100
400
500
1000
1500
2000

separate experiments, supported by the Department of Energy (Hickey 1990a) (Figure 2.3). Each experiment included approximately 40 current meters distributed on approximately 10-12 moorings over the basin and shelves in the area as well as intensive CTD surveys 2-3 times per year. Several transects *were* occupied on every CTD cruise. Additional lines were occupied along and across sills and in the vicinity of canyons, depending on the focus of the particular experiment. The first experiment (October 1985-February 1986), which was designed to establish cross-shore coherence scales and basic forcing mechanisms of the currents, consisted of a cross-shelf-slope-basin transect across the Santa Monica region. The second experiment (May-October 1986) was designed to establish slope-parallel and around-the-basin coherence scales and to determine basin circulation patterns below the depth of the deepest sill. The third experiment (April-October 1987) focused on exchange between Santa Monica and San Pedro basins and adjacent basins. The last experiment (February-October 1988) was designed to determine scales and patterns and forcing mechanisms of the shelf circulation in Santa Monica Bay as well as the effect of Redondo Canyon on the circulation.

Only data from the first three experiments have been processed sufficiently to include in this synthesis.

The narrow Southern California Shelf also has been the subject of a focused set of experiments (locations are shown in Figure 2.3). The earliest experiments (Winant and Olson 1976) were performed on the Navy tower near San Diego during summer in a water depth of 18 m. This experiment was designed using very closely spaced current meters to determine vertical scales of variability. The second set of experiments consisted of a cross-shelf array of 12 instruments distributed on moorings on the inner (15 m), mid (30 m), and outer (60 m) shelf at Del Mar, 30 km north of San Diego (Winant and Bratkovich 1981). This array was deployed for roughly 6-week periods in each of the four seasons to determine the cross-shelf structure of the shelf currents (see Figure 2.3). The third and last experiment was designed to determine long-shelf coherence scales for current and temperature fluctuations during the summer season. Current meters were deployed from San Diego to Newport Beach along the 30 m isobath (two per mooring) at intervals as close as 2 km (Winant 1983).

The Southern California Coastal Water Research Project Authority (SCCWRP) has maintained moorings at selected sites near sewage outfalls along the Southern California shelf since 1974 (Hendricks 1974, 1975, 1976, 1980, 1982, 1984), including the San Diego Bight, Point Loma, Mission Beach, La Jolla, Solano Beach, Del Mar, Encinitas, Carlsbad, Oceanside, Newport Beach, Pales Verdes, Santa Monica Bay, Oxnard, and Santa Barbara. For the most part, SCCWRP moorings were located on the outer shelf (most often, in about 60 m of water) or on the upper slope (usually less than 200 m of water).

Although as many as three shelf-slope sites have been occupied simultaneously for a month or more, the majority of SCCWRP records were obtained on individual mooring deployments. Measurements were also made in San Gabriel and Santa Monica submarine canyons. Only mooring data subsequent to 1979 are available in computer format and thus have been included quantitatively in this paper. Figure 2.3 shows the location of these data. The SCCWRP current meters, which are of a tiltmeter design specific to SCCWRP, have been inter-compared with an EG & G Geometries vector measuring current meter (Hendricks 1985). The comparison was reasonable, and thus we expect the SCCWRP data to provide useful information on current speed and direction below the wave-dominated upper layers.

Comprehensive current measurements have been made by SAIC off Newport Beach (see Figure 2.3). The array varied from three to five moorings in bottom depths of 35 to 80 m. The array was maintained from June 1986 to July 1989; however, only the data from 1986 were available for this discussion. A comprehensive set of direct current measurements have been made by Engineering Science to study the small bight south of San Diego harbor. A total of 15 tiltmeter type current meters were deployed for a period of 13 months in water depths from 10 to 7S m (see Figure 2.3).

Other direct current measurements have been obtained in the region: in particular, off Newport Beach and in the San Diego trough by the Pacific Marine Environmental Laboratory of NOAA (G. Connor pers. commun.), and in the mid-Santa Monica basin by the Navy (A. Bratkovich pers. commun.). However, these data are not yet available for public use. Extensive measurements were made on the San Onofre shelf (water depths from 10 to 35 m) over a period of about 10 years (Erdman 1987) (see Figure 2.3, MRC data). Although the records are not continuous in time, they are unique in providing excellent coverage of shallow bottom depth and also near-surface regions of the water column. Vector-type current meters were used for all measurements. These data are now available in summary form (spatially averaged) and will be used in the discussion.

Direct measurements of current speed and direction are usually recorded at intervals of 20 minutes to 1 hour. The data are usually presented as north-south (v) and east-west (u) components of the velocity field. The data are generally filtered (smoothed) to hourly intervals, and often are filtered or smoothed again to remove tidal and higher frequencies (a cut-off frequency of 40 hours is common, with a Lancotz-cosine filter). These data, which will appear to be much smoother than the original data, are useful for identifying current events that occur over periods of a few days or a season. Known as "subtidal data", these data are usually presented at 6-hour intervals as north-south or-east-west velocity components or as a vector, as a function of time for several months. To identify possible seasonal variations, data are further averaged into monthly means for some presentations.

The now-standard technique of empirical orthogonal eigenfunction (EOF) analysis (Kundu and Allen 1976) is used in this chapter. This technique is simply a convenient way of describing the variability in data sets and is similar in many ways to the principal component analysis often used by biologists. Basically, correlations between stations are used in a least squares analysis to select the most efficient set of temporal patterns with which the data can be represented. Then both the temporal patterns and the maps of spatial amplitudes or weights are inspected to search for similarity to patterns expected for particular physical processes. The analysis will suggest several patterns (for example, pattern a, b, c, . . .), each of which accounts for a certain amount of the variability in the observed data set. Thus, at any location, the total variability is made up of a specific amount of each pattern's amplitude (that is, weights) (for' example, 0.1 X pattern a + 0.5 X pattern b + . . .).

The temporal pattern might be simply a seasonal variation. If one area has a strong seasonal variation, it might have a weight of 1.0, while another with a weak seasonal variation might have a weight of 0.1. A third might show a variation exactly opposite to the first: Its weight would be -1.0. Thus , a map showing the weights over an area would show how the seasonal cycle varies from place to place. In this paper, the weights of the EOFS are denoted amplitudes, in keeping with common usage. A pattern need not be related to any physical process. However, in practice, at least the first pattern (or mode, as such patterns are called) which represents the most dominant variability can often be related to a physical process.

Currents at subtidal frequencies are generally oriented in the direction of local isobaths. In the SCB, the isobaths are extremely convoluted and are not usually oriented north-south. Flow directions are said to be poleward when they have an upcoast component and equatorward when they have a downcoast component. In keeping with common usage, both currents and wind stress direction are described by the direction to which they are directed. Wind is usually described by the direction from which it blows (for example, southerly to-designate wind from the south).

SEASONAL PATTERNS

CURRENTS

CalCOFI hydrographic data allow a comprehensive description of the large-scale eastern boundary currents that bathe the SCB. Syntheses .and interpretation of the CalCOFI data by Hickey (1979), Tsuchiya (19S0), Chelton (1980, 1984), and, most recently, Lynn and Simpson (1987) provide descriptions of the seasonal and spatial structure of the California Current, the Southern California Countercurrent, and the California Undercurrent in this and other regions. However, the spatial resolution of the CalCOFI data set excludes regions shallower than 500 m, that is, much of the slope and all of the shelf, and provides no spatial details on scales of approximately 20-40 km. In the ensuing discussion, large-scale patterns are described using CalCOFI data; smaller scale details, in particular the shelf circulation, are described, for the most part, using available direct current measurements. Hydrographic data collected in the SCB between September 1974 and April 1977 with a much finer resolution than standard CalCOFI data furnish additional information on nearshore current structure

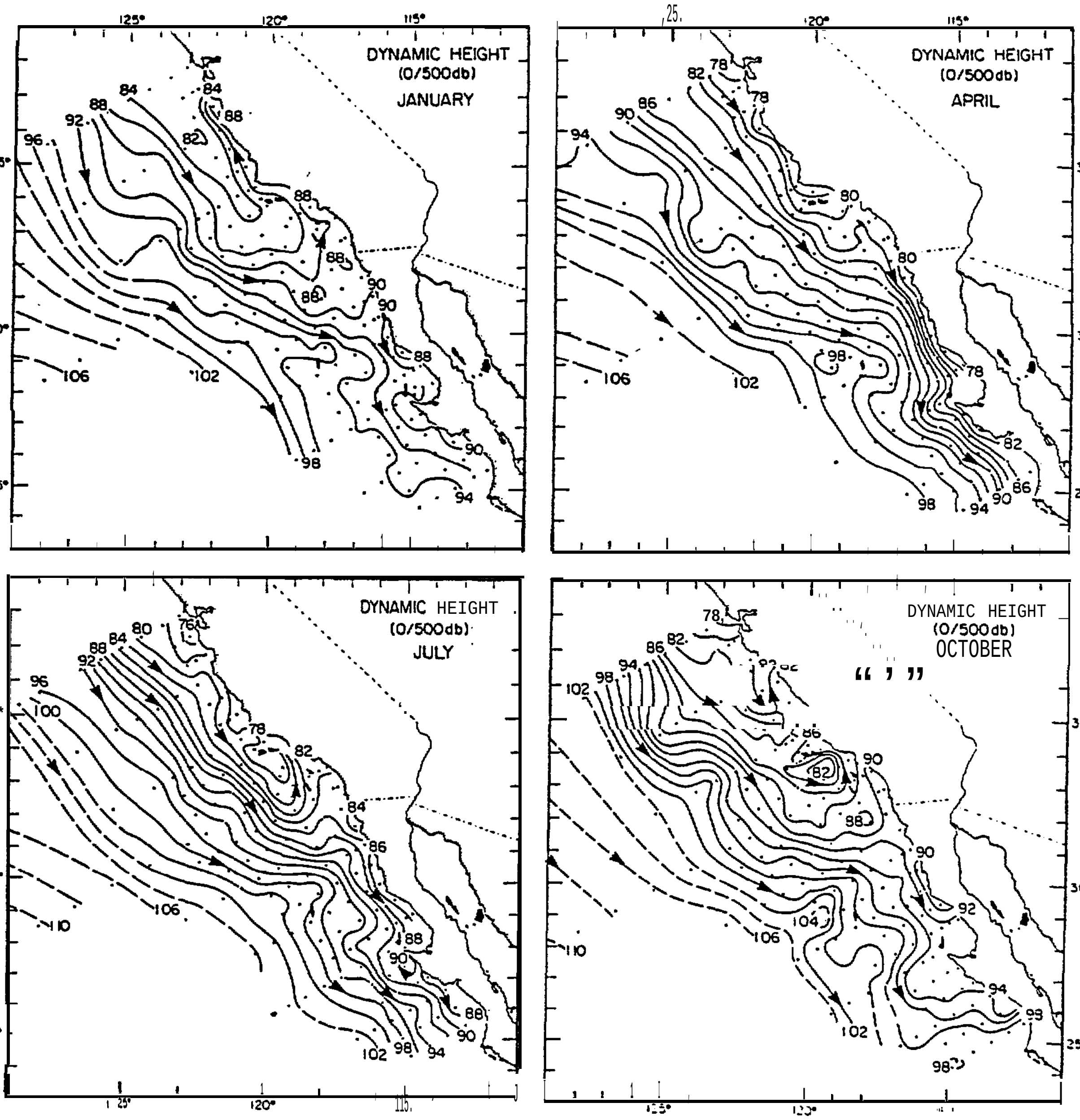
(Tsuchiya 1980).

The California Current, which is fed by the West Wind Drift, is the eastern limb of the North Pacific gyre. The current flows equatorward along the U.S. west coast throughout the year, with maximum speeds approximately 300 km offshore of the coast (Hickey 1979; Lynn and Simpson 1987) (Figure 2.4). Currents over the continental shelf are not generally considered to be part of the California Current and will be discussed separately. The California Current is surface intensified, with maximum monthly mean speeds at the surface on the order of 10 cm s^{-1}, decreasing to about 2 cm s^{-1} at a depth of about 200 m (Figure 2.5). The California Current has a significant seasonal variation, with the seasonal maximum in summer (Hickey 1979; Lynn and Simpson 1987). The majority of the equatorward transport of the California Current occurs from 200 to 500 km offshore, seaward of the SCB. The total transport of the California Current along a section from the coast through the SCB to 1200 km offshore (Figure 2.5) varies from 5.8 Sverdrups in January to 7.8 Sverdrups in July (1 Sv. = 10^6 m^3 S-l).

The California Current turns shoreward near the southern U.S. border, and a branch of the current turns poleward into the SCB, where it is generally known as the Southern California Countercurrent or Eddy (Figure 2.4). This countercurrent is strongest in summer, when it is eddy-like (that is, flow rejoins the California Current), and in winter, when poleward flow through the Santa Barbara Channel can be continuous with the flow north of Point Conception (Hickey 1979). During spring, the countercurrent appears to be essentially absent; that is, flow enters the SCB, but turns equatorward rather than poleward (Figures 2.4 and 2.5).

A poleward-flowing undercurrent occurs beneath the shoreward side of the California Current in most seasons at all west coast locations (Figures

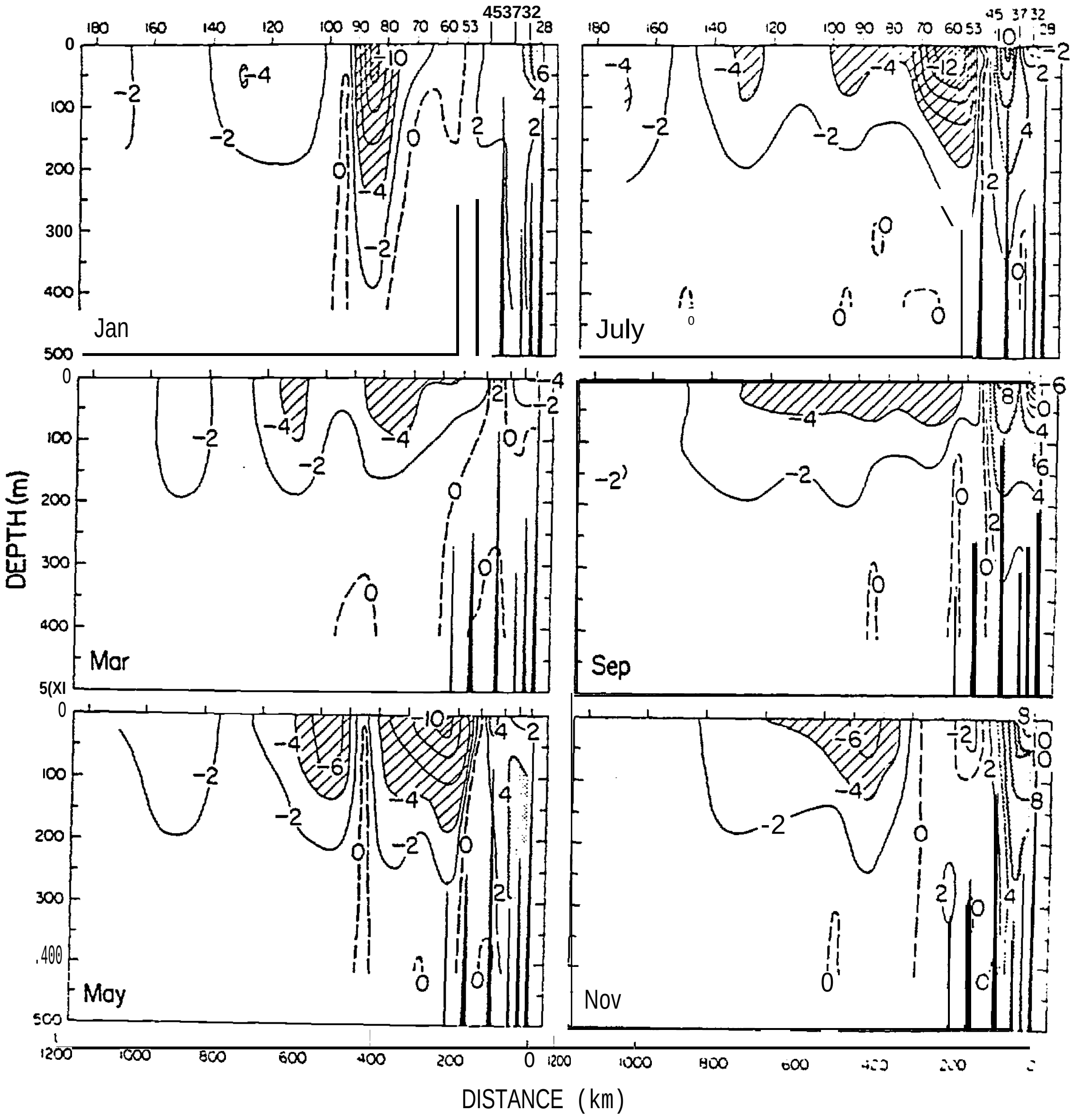
Figure 2.4. Mean dynamic height (dyn cm) of the sea surface relative to 500 dbar (approximately 500 m) for four periods (of approximately 60 days) centered about January, April, July, and October. Contour interval is 2 dyn cm (from Lynn and Simpson 1987).


DYNAMIC HEIGHT
(0/500db)
JANUARY
DYNAMIC HEIGHT
(0/500db)
APRIL
DYNAMIC HEIGHT
(0/500db)
JULY
DYNAMIC HEIGHT
(0/500db)
OCTOBER
125°
120°
115°
35°
30°
25°
106
102
98
94
90
88
84
82
92
96
86
80
78
110
100
76
104

2.10b

Figure 2.5. **Geostrophic** velocity (cm S-l) relative to 500 dbar for odd **months** along **CalCOFI** line 90 (see Figure 2.2). Contour interval is 2 cm s^{-1}. Equatorward flow in excess of 4 cm S-l is shaded. The Channel Islands and ridges are delineated by the black spikes emanating from the bottom of the graph.

RELATIVE GEOSTROPHIC FLOW ($cm \cdot s^{-1}$)
CALCOFI LINE 90

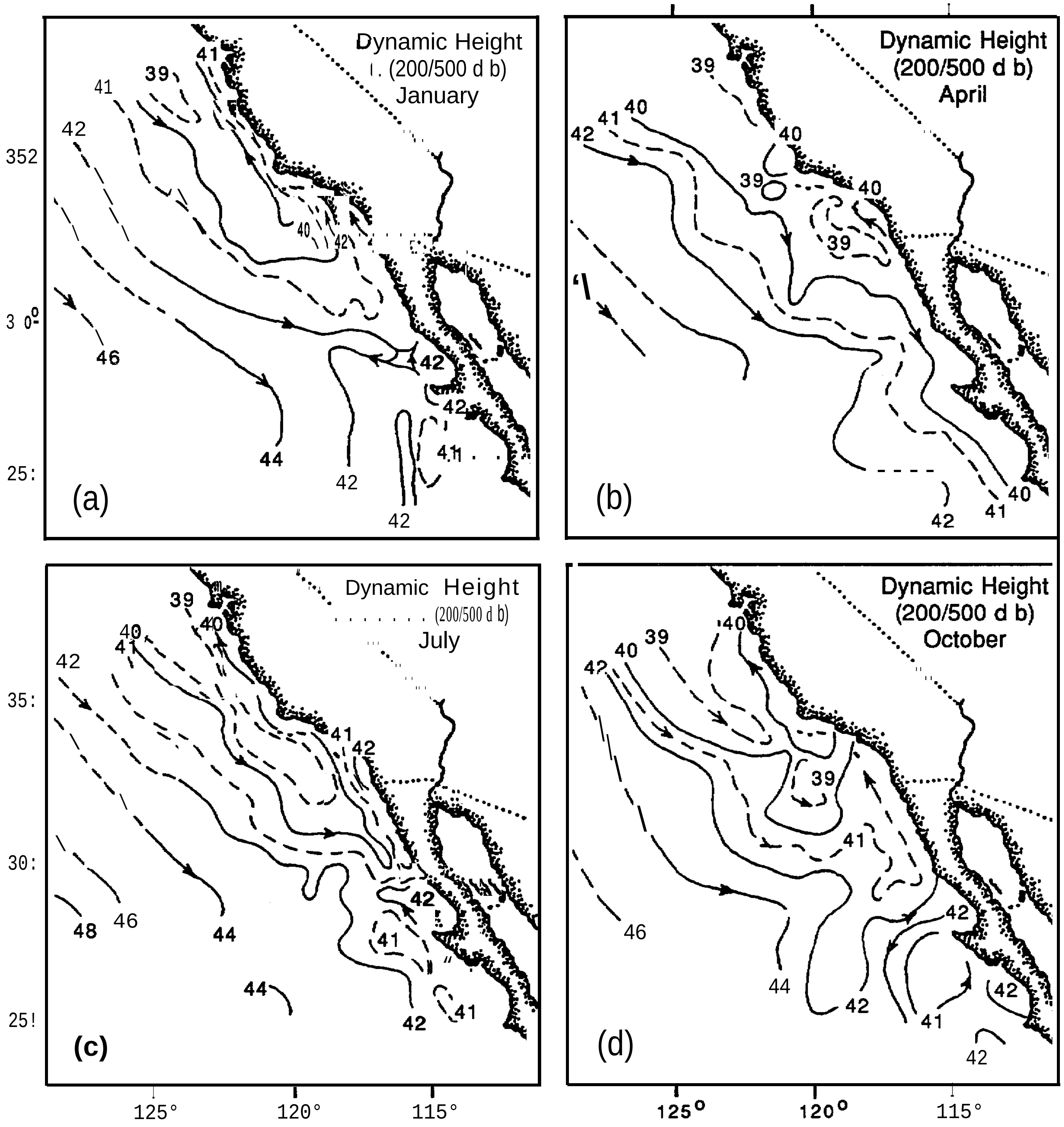


2.5 and 2.6). The undercurrent is distinguished from surface currents by its characteristic water properties, which are of southern or equatorial, rather than subarctic, origin (Tsuchiya 1980). The undercurrent at most locations is relatively narrow, having a somewhat high-speed core that is generally located over the continental slope (Hickey 1979, 1989a,b). The undercurrent at all west coast locations has a seasonal maximum in late summer (corresponding to that of the California Current) and a minimum in spring. The undercurrent has a second seasonal flow maximum in early winter at most locations, but often the winter maximum occurs at the sea surface and it is unclear whether the winter and summer poleward flows are dynamically the same (Hickey 1979; Chelton 1984; Lynn and Simpson 1987).

In the SCB, the continental slope is less well defined than in regions to the north and south, since the area is populated with a number of islands and ridges. The large-scale CalCOFI data set, which has only four data points inside the SCB, suggests that the undercurrent occurs throughout the entire bight, with a width perhaps slightly broader than in regions outside the SCB (compare Figure 2 in Chelton 1984 with Figure 2.5). Direct current measurements over a much finer spatial scale in the Santa Monica Basin suggest that the undercurrent is strongest over the nearshore continental slope (Hickey 1990a). Of course, this Santa Monica Undercurrent might represent only one of multiple cores. The exact spatial structure of the undercurrent within the SCB and its relationship to the upper water column California Countercurrent (are they really distinct features?) are the subjects of on-going research programs. If the poleward flow in the countercurrent and undercurrent are lumped together, we find that the SCB is flushed by a minimum transport of 0.8 Sverdrups in April, and by a maximum transport of 1.8 Sverdrups in October.

A contoured section of geostrophic velocity across the SCB illustrates

Figure 2.6. Mean **dynamic** height (dyn cm) at 200 dbar (approximately 200 m) relative to 500 dbar (approximately 500 m) for four periods (of approximately 60 days) centered about January, April, July, and October. Contour interval is 1 dyn cm (from Lynn and Simpson 1987).


Dynamic Height
(200/500 d b)
January
(a)
41
39
41
42
40
42
46
42
42
41
44
42
42
Dynamic Height
(200/500 d b)
April
(b)
39
40
41
42
40
39
40
39
42
41
40
Dynamic Height
(200/500 d b)
July
(c)
39
40
40
41
42
41
42
42
41
48
46
44
44
42
41
Dynamic Height
(200/500 d b)
October
(d)
40
39
40
42
39
41
42
46
44
42
41
42
42
352
3 0°
25:
35:
30:
25!
125°
120°
115°
125°
120°
115°

2.11b

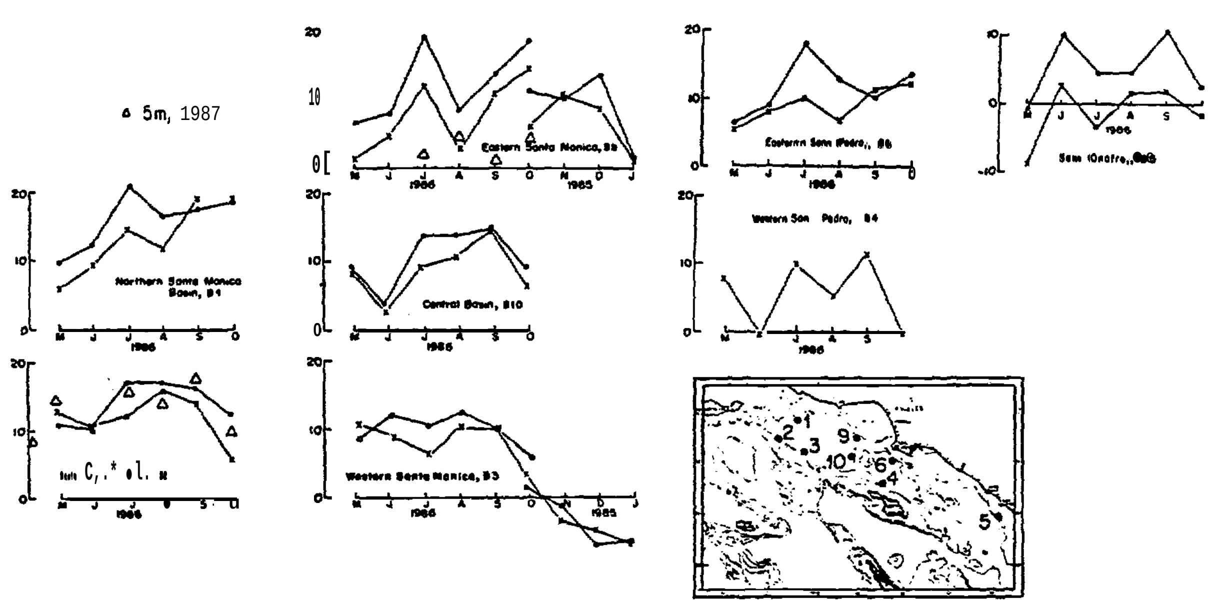
graphically that the islands in the SCB are not an impediment to the large-scale flow (Figure 2.5). This result affirms the large-scale nature of the flow field. The topography channels the large-scale flow in two respects: first, the island chain on the southern side of the Santa Barbara Channel divides the Southern California Countercurrent into two branches, one which enters the Santa Barbara Channel and one which passes to the south of the island chain (Hickey 1990a; Lynn and Simpson 1987). Second, the offshore banks of the borderland serve to divide the countercurrent from the California Current. Of course, some local perturbations of the flow field in the vicinity of the islands would also be expected.

As already mentioned, direct current measurements in the SCB exhibit some differences from the CalCOFI results. In particular, direct measurements indicate that the subsurface maximum in poleward flow over the slope (the undercurrent) is both stronger and more continuous in time than indicated by the geostrophic data. For example, seasonal mean directly-measured current speeds are on the order of 15-20 cm s^{-i}, cf. 2-10 cm S-l in the geostrophic data. The direct measurements in the Santa Monica region (Hickey 1990a), as well as those in the Santa Barbara Channel region (Gunn et al. 1987), suggest that poleward flow persists beneath the surface layers, even during the spring, in contrast to the CalCOFI results. Last, direct current measurements in the Santa Monica basin suggest that during at least one winter, equatorward flow occurs on the west side of the basin (Hickey 1989a) (Figure 2.7, data for western Santa Monica). This relatively small-scale feature is not resolved by the geostrophic large-scale data set.

Whereas the currents over the continental slope are predominantly poleward due to the presence of the large-scale countercurrent and undercurrent, currents over the mainland continental shelves in the SCB,

Figure 2.7. Monthly mean approximately 40 m and approximately 100 m current speeds (cm s^{-1}) at selected locations in the SCB during 1986 and 1985. Because the velocity at these upper water column locations is strongly aligned either along the slope or across the sills, speeds very nearly represent the **along-isobath** or across-sill component of velocity. Positive speeds indicate an **upcoast** flow direction; negative speeds indicate a **downcoast** flow direction. Data from both 1985 and 1986 are available at some sites during October. To provide a qualitative estimate of an annual cycle, 1985 data have been added at the end of the 1986 data set (from **Hickey** 1990a).

ALONG SHORE VELOCITY

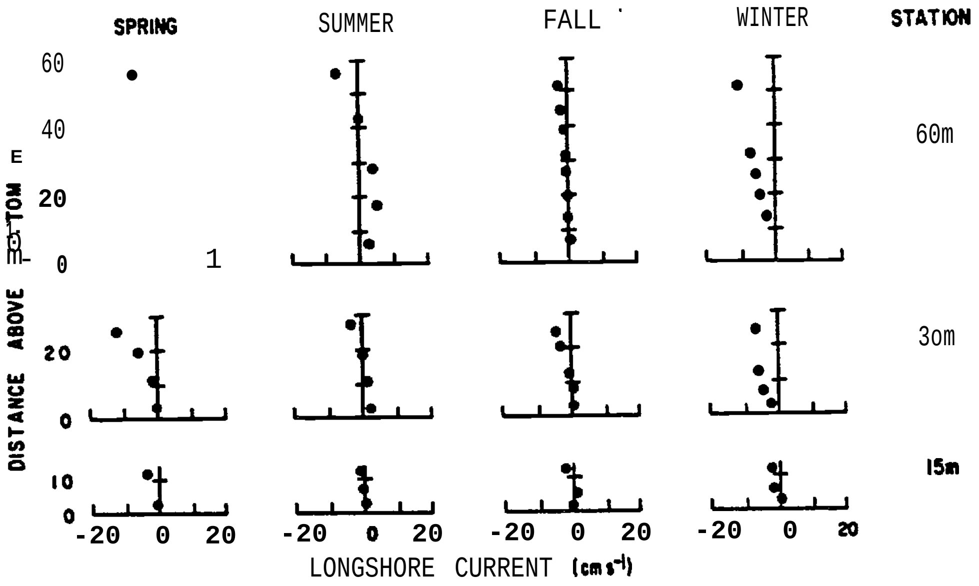


seaward of the very nearshore zone (that is, >10 m), appear to be predominantly equatorward, at least in the upper water column (0-15 m). As mentioned previously, the SCB shelf is not at all continuous; rather, several headlands indent the coastline in the northern SCB so that the shelves are almost disconnected from one another. Even the most continuous length of shelf from Newport Beach to Del Mar is an order of magnitude shorter than the shelves north of the SCB (approximately 100 km vs. 1000 km long). On the wide Santa Monica shelf, measurements at depths of 5 and 10 m from the surface in 30 m of water at a location roughly one-third the distance from the southern end indicate that the seasonal mean flow is equatorward during fall and winter (Hickey 1990a). On the narrow shelf north of San Diego, equatorward flow occurs in the upper layer (approximately 5-10 m) in 15, 30, and 60 m water depths in every season (Winant and Bratkovich 1981) (Figure 2.8). The strongest equatorward flow occurs in winter (60 m depth) or spring (15 and 30 m depth).

Equatorward flow has also been observed in several year averages for winter and summer at all bottom depths (10-35 m) on the shelf off San Onofre (Erdman 1987). The strongest equatorward mean flows (up to 7 cm S-l) occur in summer and in the upper layers (3-10 m) at this location. The magnitude of the equartorward flow and the thickness of the equatorward flowing layer both increase in the offshore direction. In all cases, the magnitude of the mean equatorward flow on both narrow and wide shelves (approximately 5-10 cm s^{-1}) is much less than that of the poleward flow over the slope.

Poleward flow over the narrow shelf off Del Mar was observed in the lower half of the water column at the 30 m and 60 m sites, the signature of the poleward undercurrent discussed previously (Winant and Bratkovich 1981). Net poleward, sub-pycnocline flow has also been observed on the narrow shelf off Pales Verdes (Hendricks 1980, 1982) and the somewhat wider shelf off San

Figure 2.8. Distribution of mean longshore currents off Del Mar in bottom depths of 60, 30, and 15 m for the periods 16 May-27 June 1978 (spring), 27 July-n September 1978 (summer), 21 October-4 December 1978 (fall), and 21 December-26 March 1979 (winter). Mooring locations are shown in Figure 2.3.


SPRING
SUMMER
FALL
WINTER
STATION
60m
30m
15m
DISTANCE ABOVE BOTTOM m
60
40
20
0
1
20
0
10
0
-20
0
20
LONGSHORE CURRENT (cm s⁻¹)

Diego (Hendricks 1977) and Newport Beach (Hendricks 1980, 1982).

Tsuchiya (1980) presents evidence in geostrophic (hydrographically derived) current data for the occurrence of equatorward flow over the upper slope from Newport Beach to just north of San Diego. Although his instantaneous data illustrate that equatorward flow can occur in all seasons, he makes the interesting suggestion that the strength of the equatorward flow is related to the strength of the poleward flow farther offshore, being strongest when the poleward flow is weakest. This conclusion would be consistent with the occurrence of the strongest equatorward flow nearshore during the spring, as suggested also by the monthly-averaged direct current measurements.

Although currents have been measured at many sites on the coastal side of the SCB, the measurements, for the most part, are not simultaneous. To attempt to develop more detailed seasonal flow patterns for the SCB, monthly mean data from all available data sets have been included in three seasonal maps: summer (August-September), winter (November-January), and spring (April-May) for 5-20 m, 30-50 m, and 80-120 m water column depths (Figure 2.9a,b,c). Occasionally, data are included that exceed the depth range specified. The actual depth of such data is given in Figure 2.9. In this depiction of seasonal current patterns, the effects of interannual variability, which can be significant (see below), have been disregarded. However, note that the majority of the data from Dynalysis, Hickey, Engineering Science, SAIC, and Winant and Bratkovich each represent a single year (although, in each case, a different year). A second year of data for these sources is indicated with a dashed arrow.

Results substantiate, for the most part, the previous discussion while adding local detail in the vicinity of some topographic features. In

Figure 2.9a. Monthly mean measured velocity vectors for available data in the SCB region for three depth intervals for spring (April, May). The various data sets are described in the text. In general, the data sets are from different years and, thus, the figure ignores “the effects of interannual variability. April vectors are shown as one-sided arrowheads; May vectors are shown as two-sided arrowheads. A second year of data from the same source is shown as a dashed arrow. Numbers in parentheses indicate depths of data that were slightly outside the given range. Decimal numbers indicate magnitudes of vectors that exceeded map borders or that were shortened for clarity (shown by a zigzag in the vector).

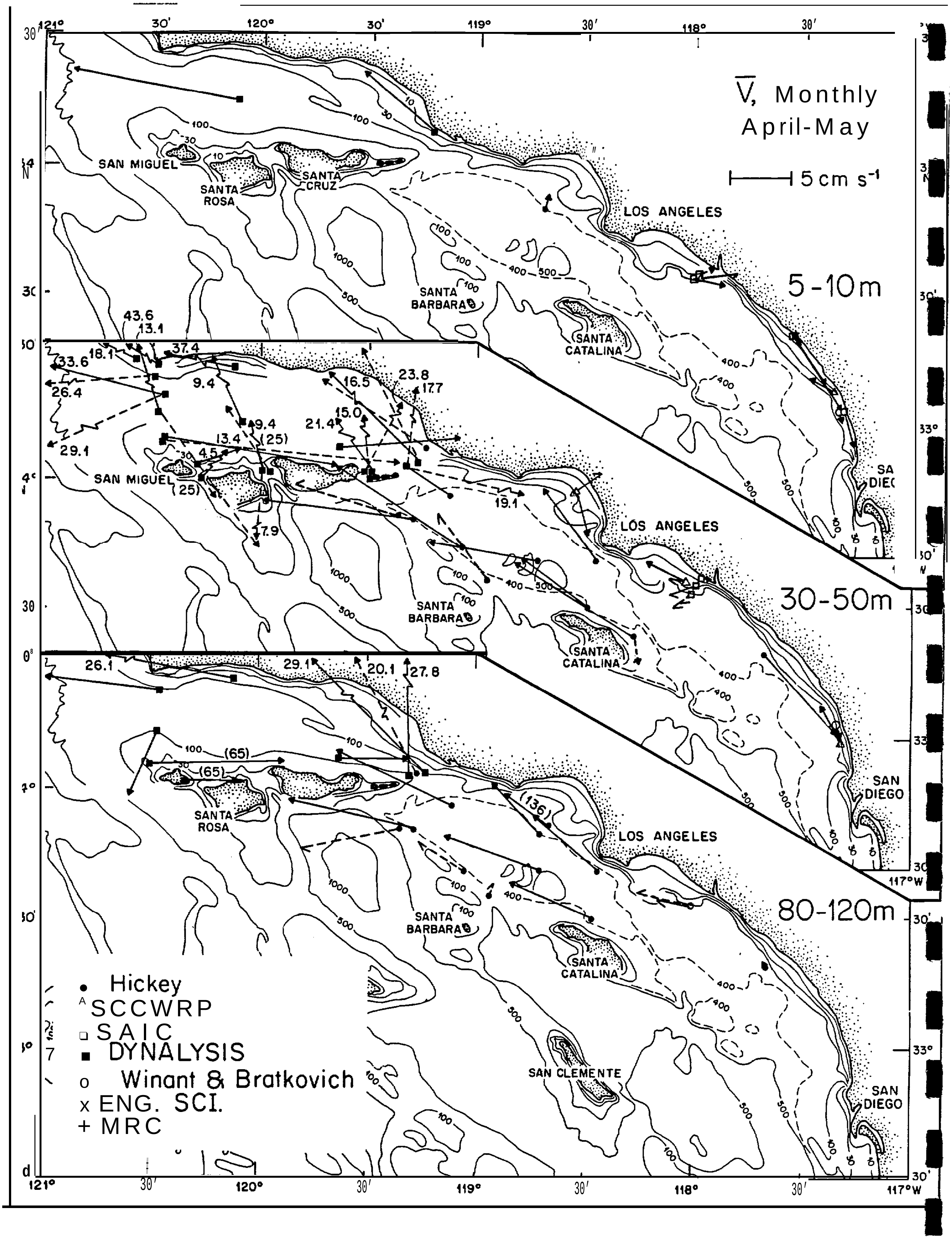

V̄, Monthly
April-May
5 cm s-1
5-10m
30-50m
80-120m
121°
30'
120°
119°
118°
117°W
34°N
33°
SAN MIGUEL
SANTA ROSA
SANTA CRUZ
LOS ANGELES
SANTA BARBARA
SANTA CATALINA
SAN CLEMENTE
SAN DIEGO
100
1000
500
400
43.6
13.1
37.4
33.6
18.1
26.4
9.4
16.5
23.8
17.7
29.1
21.4
15.0
13.4
(25)
4.5
19.1
17.9
26.1
29.1
20.1
27.8
(65)
(136)
Hickey
SCCWRP
SAIC
DYNALYSIS
Winant & Bratkovich
ENG. SCI.
MRC

Figure 2.9b. Monthly mean measured velocity vectors for available data in the SCB region for three depth intervals for late summer (August, September). The various data sets are described in the text. In general, the data sets are from different years and, thus, the figure ignores the effects of interannual variability. August vectors are shown as one-sided arrowheads; September vectors are shown as two-sided arrowheads. A second year of data from the same source is shown as a dashed arrow. Numbers in parentheses indicate depths of data that were slightly outside the given range. Decimal numbers indicate magnitudes of vectors that exceeded map borders or that were shortened for clarity (shown by a zigzag in the vector).

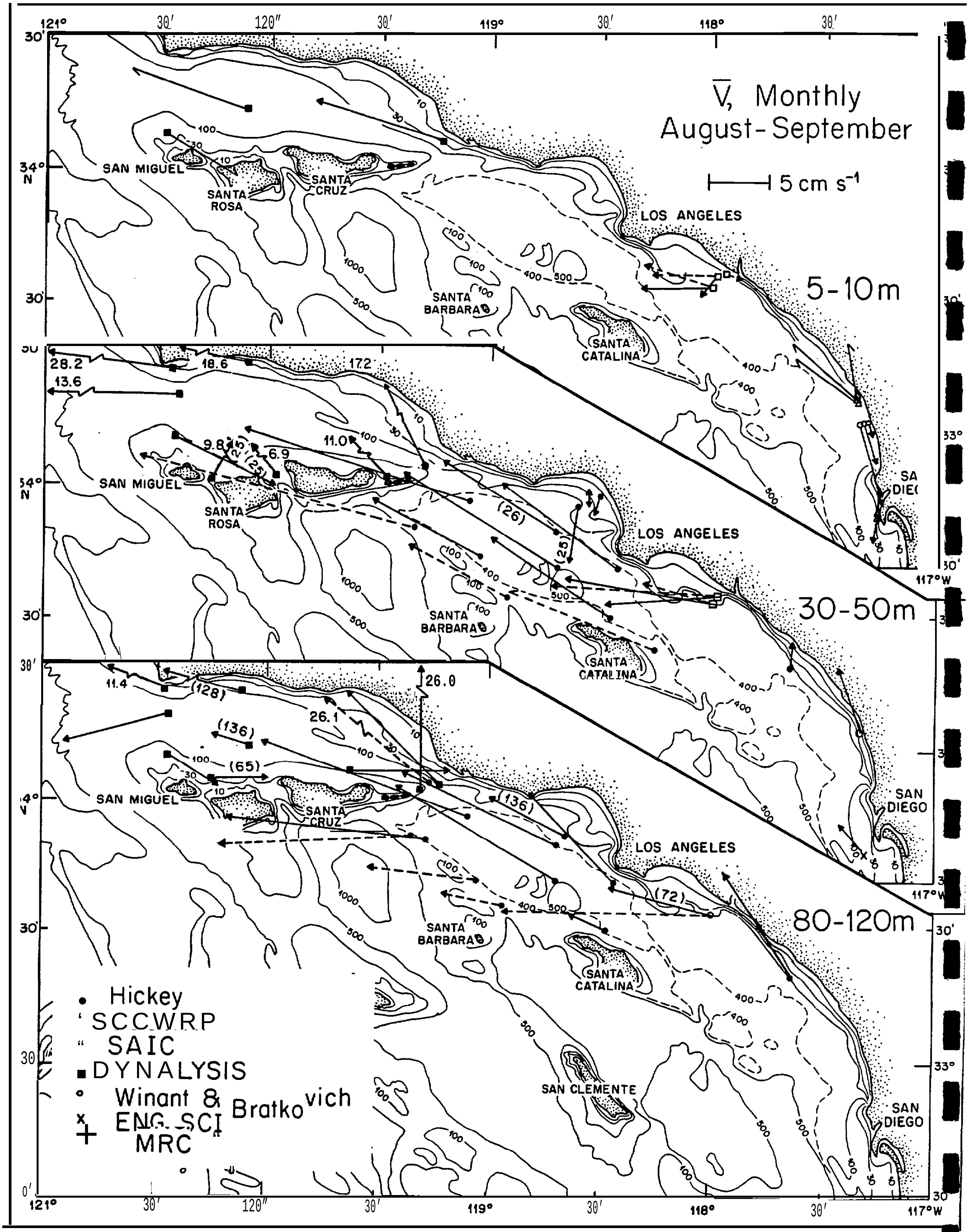
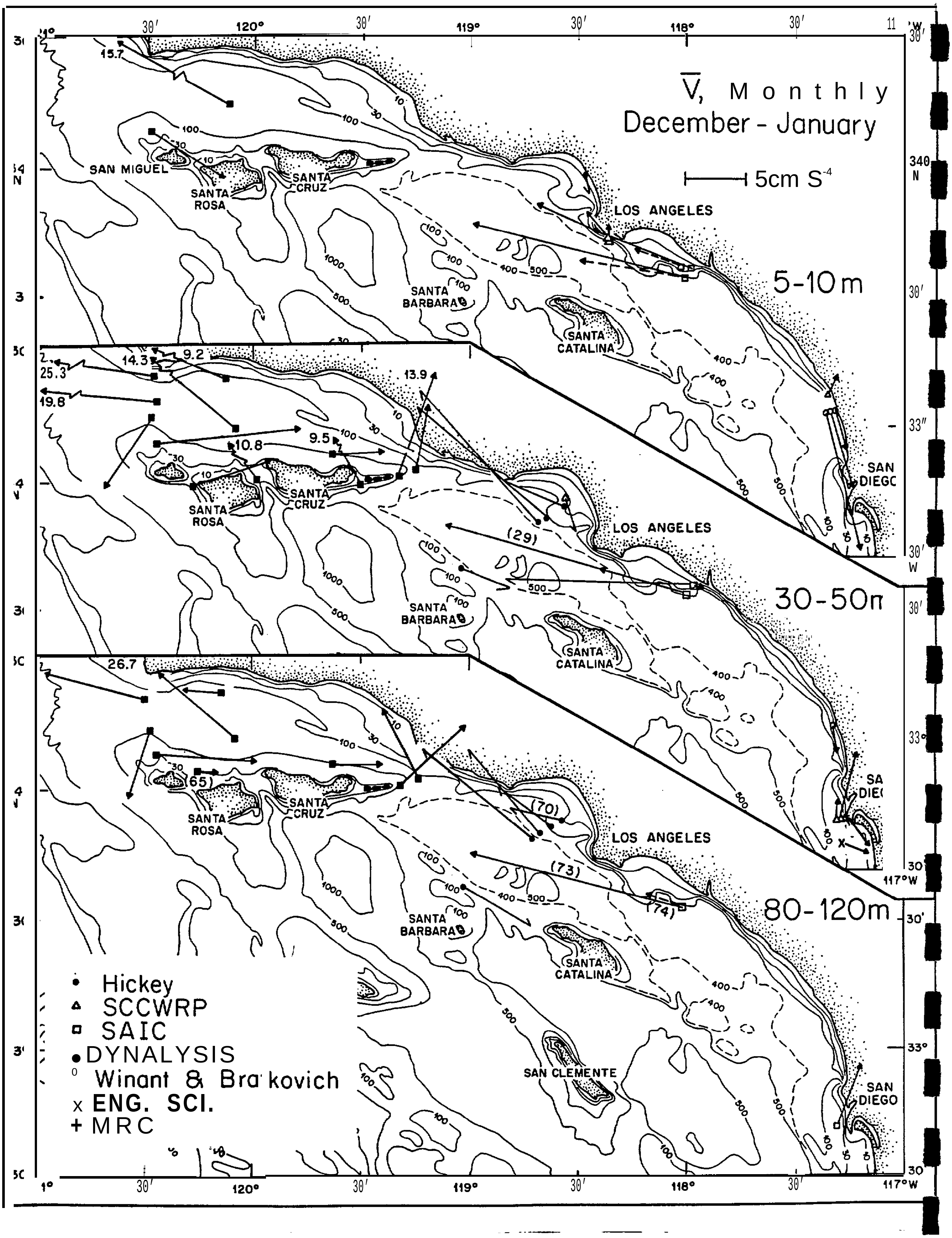

V̄, Monthly
August-September
5 cm s⁻¹
5-10m
30-50m
80-120m
SAN MIGUEL
SANTA ROSA
SANTA CRUZ
SANTA BARBARA
SANTA CATALINA
SAN CLEMENTE
LOS ANGELES
SAN DIEGO
121°
30′
120″
119°
118°
117°W
34° N
33°
28.2
13.6
18.6
17.2
11.0
9.8
6.9
(25)
(26)
11.4
(128)
26.1
26.0
(136)
(65)
(72)
100
400
500
1000
• Hickey
‘ SCCWRP
“ SAIC
■ DYNALYSIS
° Winant & Bratkovich
x ENG. SCI
+ MRC

Figure 2.9c. Monthly mean measured velocity vectors for available data in the SCB region for three depth intervals for winter (December, January). The various data sets are described in the text. In general, the data sets are from different years and, thus, the figure ignores the effects of interannual variability. December vectors are shown as one-sided arrowheads; January vectors are shown as two-sided arrowheads. A second year of data from the same source is shown as a dashed arrow. Numbers in parentheses indicate depths of data that were slightly outside the given range. Decimal numbers indicate magnitudes of vectors that exceeded map borders or that were shortened for clarity (shown by a zigzag in the vector).



V̄, Monthly
December - January
5cm S-4
5-10m
30-50m
80-120m
SAN MIGUEL
SANTA ROSA
SANTA CRUZ
LOS ANGELES
SANTA BARBARA
SANTA CATALINA
SAN CLEMENTE
SAN DIEGO
15.7
25.3
19.8
14.3
9.2
13.9
10.8
9.5
(29)
26.7
(65)
(70)
(73)
(74)
10
30
100
400
500
1000
120°
119°
118°
117°W
30′
34° N
33°
Hickey
SCCWRP
SAIC
DYNALYSIS
Winant & Bra'kovich
ENG. SCI.
MRC

particular, the seasonal maps illustrate clearly the extent to which the mean flow follows the direction of local, relatively shallow isobaths. For example, the flow on the San Pedro shelf is directed more westward (or eastward) only during spring in the upper layers than that off Pales Verdes or San Onofre. The majority of the flow vectors in the Santa Monica and Santa Barbara basins trend to the northwest. The flow vectors are directed more westward south of Santa Cruz Island as the flow is forced to bifurcate at the entrance to the Santa Barbara Channel.

The direction of flow at the eastern end of the Santa Barbara Channel appears to be extremely sensitive to the exact location, and, possibly, to the angle of the incident flow; that is, if the flow Is incident from the Santa Monica slope, the flow at the channel mouth might tend west northwest; however, if the flow is incident from the southwest, the flow at the channel mouth would be expected to tend northeast. The most strongly northeastward flow at the mouth is observed in January when southwestward flow occurs on the western side of the Santa Monica Basin. (Remember, however, that data in the Santa Barbara Channel and Santa Monica Basin are from different years.) It is possible that flow across the Santa Cruz sill in winter is eastward rather than westward, as observed in the other seasons. No data are available with which to substantiate this hypothesis.

Data from the Santa Barbara Channel illustrate clearly net inflow through the island channels as well as the existence of an eastward flow on the southern side of the basin. In the channel between Santa Rosa and Santa Cruz Islands, measurements during the spring period for one year indicate outflow on the western side and inflow on the eastern side of the channel. The eastward flow along the southern side of the basin, which is strongest in spring, seems to be related to upwelling events off Point Conception (Brink and Muench 1986). One set of spring measurements suggests that outflow from the Santa Barbara Channel to the Santa Monica Basin can occur occasionally on the western side of the eastern channel entrance. The drifter studies as well as hydrographic surveys indicate that Santa Barbara Channel circulation consists of two counterclockwise gyres (Kolpack 1971; Brink and Muench 1986). The direction of the current meter data at mid-basin, which is more northward- the local isobath direction (Figure 2.9), is consistent with the existence of two, rather than one, gyres over the basin.

The composite maps provide additional information on flow direction over the shelf areas. For the most part, equatorward flow occurs in the top 5-10 m and is stronger at mid- and outer-shelf locations. Below the surface layers, the flow is likely to be poleward, especially during summer and fall. The direction of mean shelf currents may <u>appear</u> at first sight to be more variable than the direction of slope or basin currents. This is due in part to the smaller magnitude of the mean flow over the shelf, which may then more easily be biased due to short period current fluctuations. However, the majority of the apparent variability is most likely caused by the fact that the layer of equatorward flow can be very thin, and hence, may be missed by a particular sampling scheme, and also, the location of the transition to the strong poleward flow that predominates over the slope can vary with time.

WATER PROPERTIES

Lynn and Simpson (1987) recently updated the seasonal variation of the large-scale (≥7,100 km) water properties of the California Current system, including the SCB. Earlier studies by Tibby (1941), Sverdrup and Fleming (1941), Wooster and Jones (1970), and others have also described the basic water mass characteristics. Water properties peculiar to the SCB have been described recently by Jackson (1986). The California Current system includes three distinctive water masses. The Pacific Subarctic water, which enters from the north, is characterized by relatively low temperature, low salinity, high dissolved oxygen, and high nutrients (Reid et al. 1958). North Pacific Central water, which enters from the west, is characterized by relatively warm temperature, high salinity, and low dissolved oxygen and nutrients (Reid et al. 1958). Pacific Equatorial water, which enters from the south, is characterized by relatively high temperature, high salinity, low dissolved oxygen, and high nutrients (Pickard 1964).

The equatorward advection of Pacific Subarctic water by the California Current is well illustrated in a map of salinity on the $\sigma_t=25.0$ surface (Lynn, et al. 1982; Lynn and Simpson 1987) (Figure 2.10). A tongue of low salinity occurs well offshore in the vicinity of the strongest equatorward flow. The tongue is bent shoreward and then poleward near the coast off San Diego as the California Current is drawn into the SCB where it becomes the Southern California Eddy or Countercurrent. North Pacific Central water is apparent as a high-salinity region offshore. This water does not, in general, enter the SCB directly, and consequently is less readily identified In water properties in the SCB. For the most part, water in the SCB can be treated as a mixture of subarctic and equatorial water types (Tibby 1941).

The poleward advection of equatorial type water (alternately called "southern" water)is illustrated by maps of salinity and oxygen on the $\sigma_t=26.6$ surface (Lynn et al. 1982; Lynn and Simpson 1987) (Figure 2.11). This σ_t surface corresponds generally to a depth interval of 200-300 m, where, as previously discussed, strong poleward flow generally occurs. The jet-like nature of the poleward flow is confirmed by the narrow tongue of high-salinity, low-oxygen water adjacent to the coast. As with the surface

Figure 2.10. Salinity on the density surface $\sigma_t=25.0$ during July, as derived from 1950-1978 averages of CalCOFI data. The intersection of this density surface with the sea surface is indicated by a bold line. Where density is less (shown shaded), surface salinity is given. Contour interval is 0.1 (from Lynn et al. 1982).

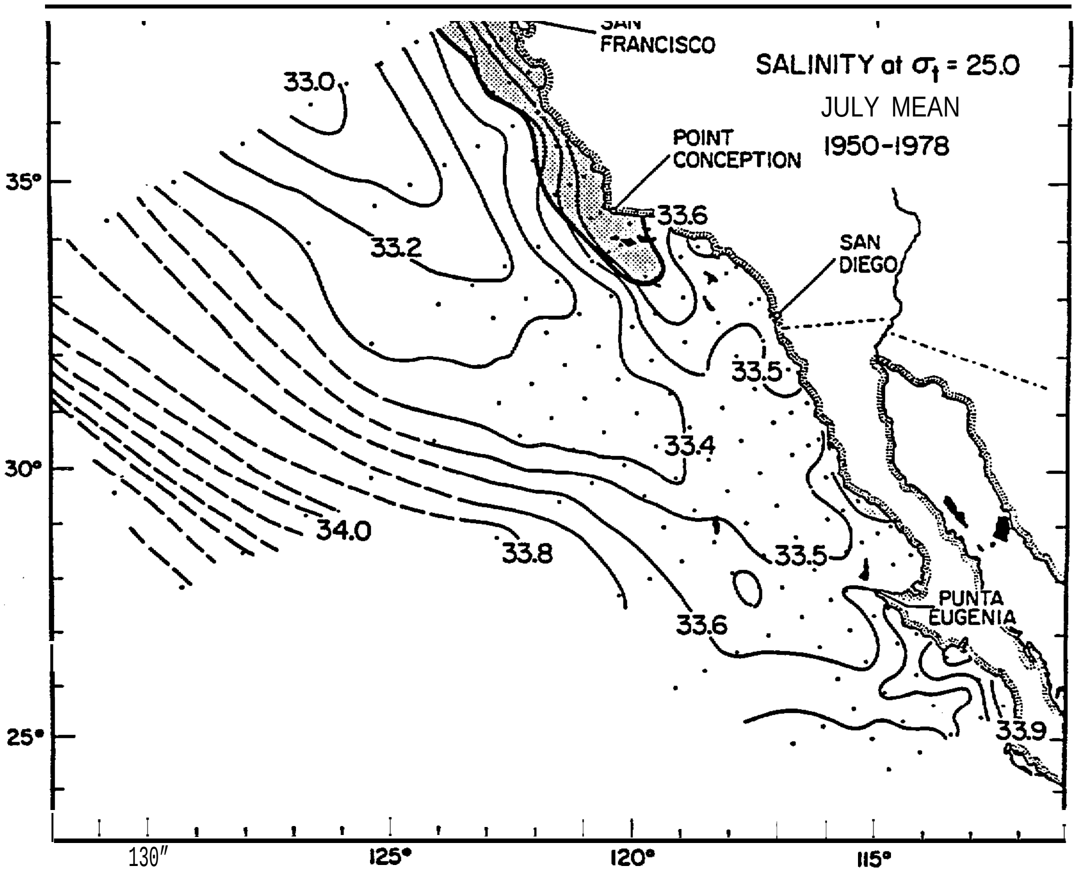
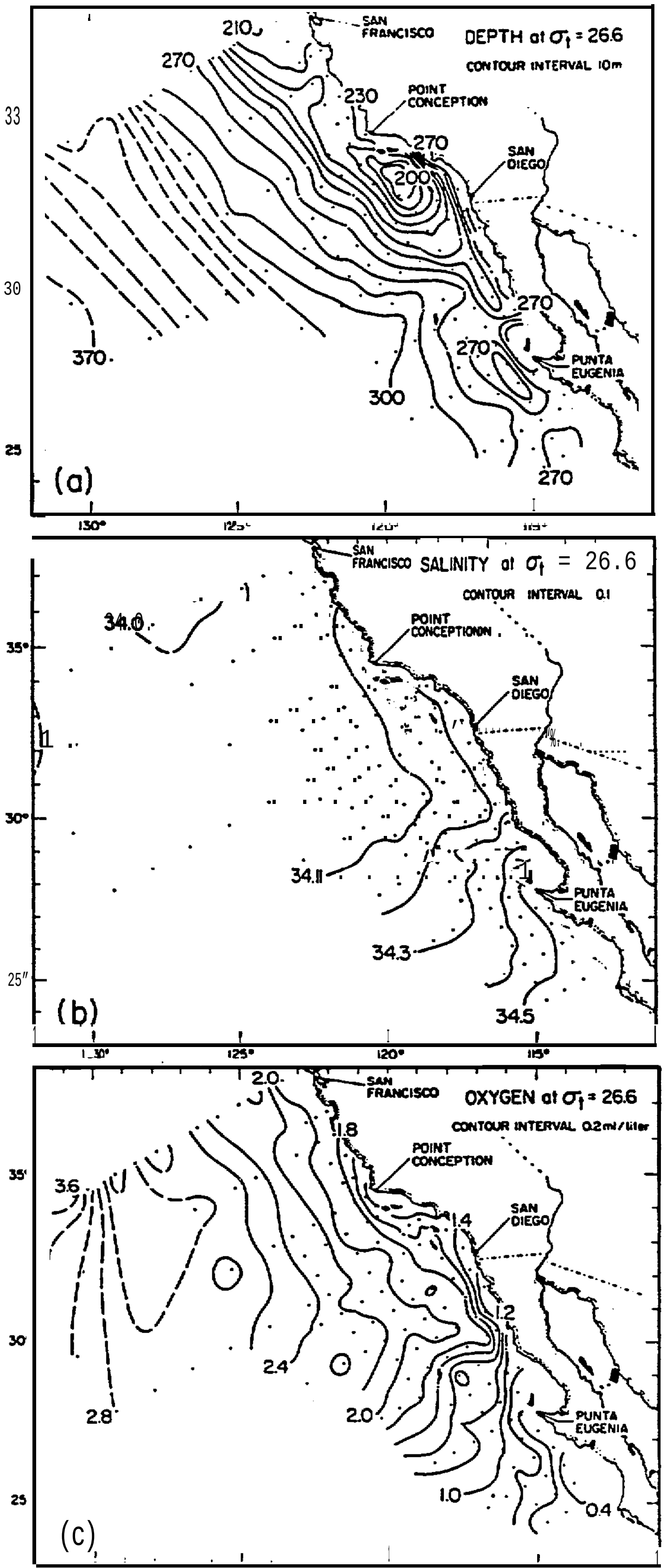

SAN FRANCISCO
SALINITY at σ_t = 25.0
JULY MEAN
1950-1978
POINT CONCEPTION
SAN DIEGO
PUNTA EUGENIA
33.0
33.2
33.6
33.5
33.4
34.0
33.8
33.5
33.6
33.9
35°
30°
25°
130°
125°
120°
115°

Figure 2.11. salinity, oxygen, and depth on the σ_t=26.6 density surface during July as derived from 1950-1978 averages of CalCOFI data (from Lynn et al. 1982).

JULY MEANS (1950-1978)



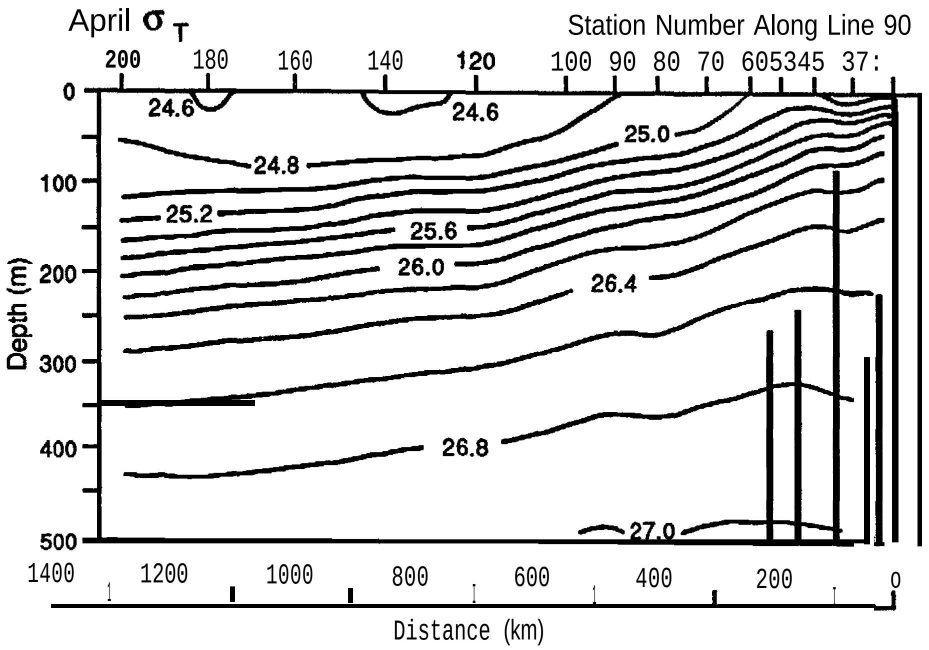
2.17d

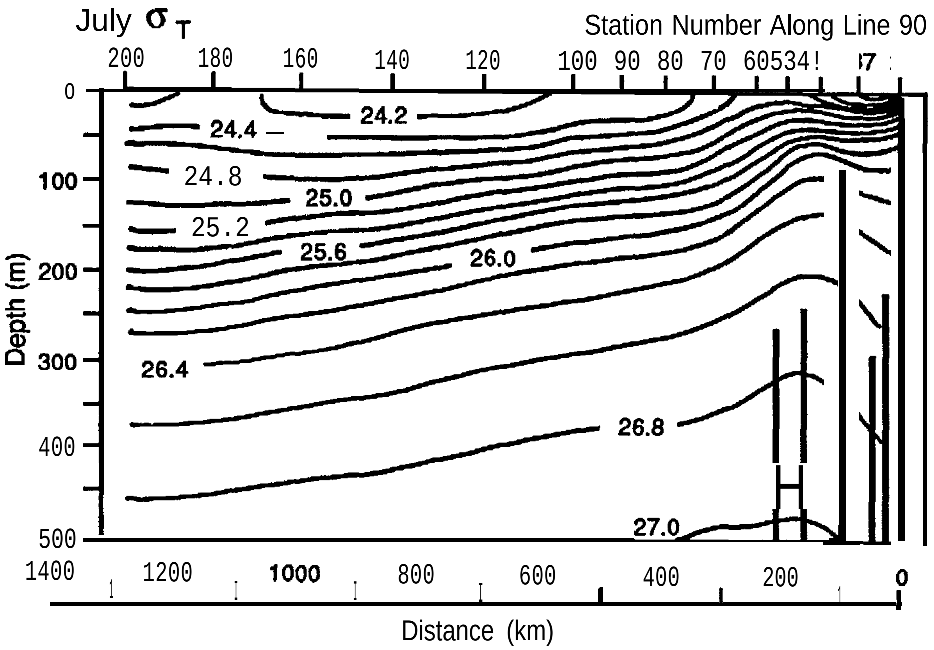
waters, spatial gradients in the water properties occur as the water is mixed laterally and vertically with surrounding waters.

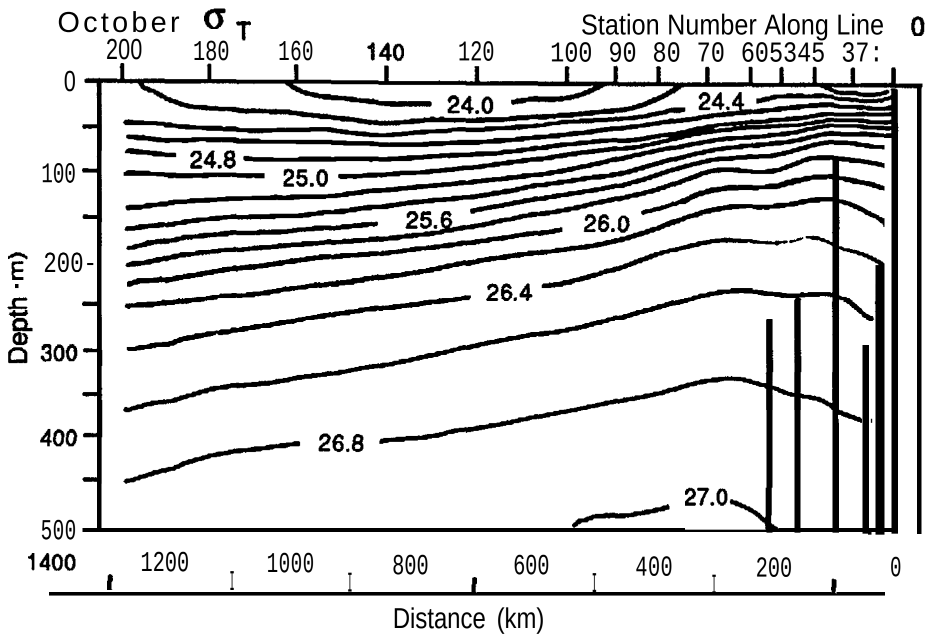
Seasonal changes in the large-scale structure of the salinity, temperature, density, and oxygen fields in the SCB can be described from contoured sections of averages of data along CalCOFI line 90, which crosses the SCB (Figure 2.2). Seasonal maps of all CalCOFI data averaged over the period 1950-1978 are presented in Lynn et al. (1982). Eber (1977) presents contoured depth-time charts of water properties for the period 1950-1966. The density field in all seasons has the characteristic upward tilt towards shore and downward tilt inshore of the outer SCB below the upper 100 m that is indicative of the offshore equatorward flow and the nearshore poleward flow in the SCB (Figure 2.12a). The doming of the isopycnals is most pronounced during the summer when the currents are strongest. Isopycnals (as well as isotherms and isopycnals) move distances of 50 m to 100 m in their seasonal march, with the maximum excursions occuring at depths of 50-300 m.

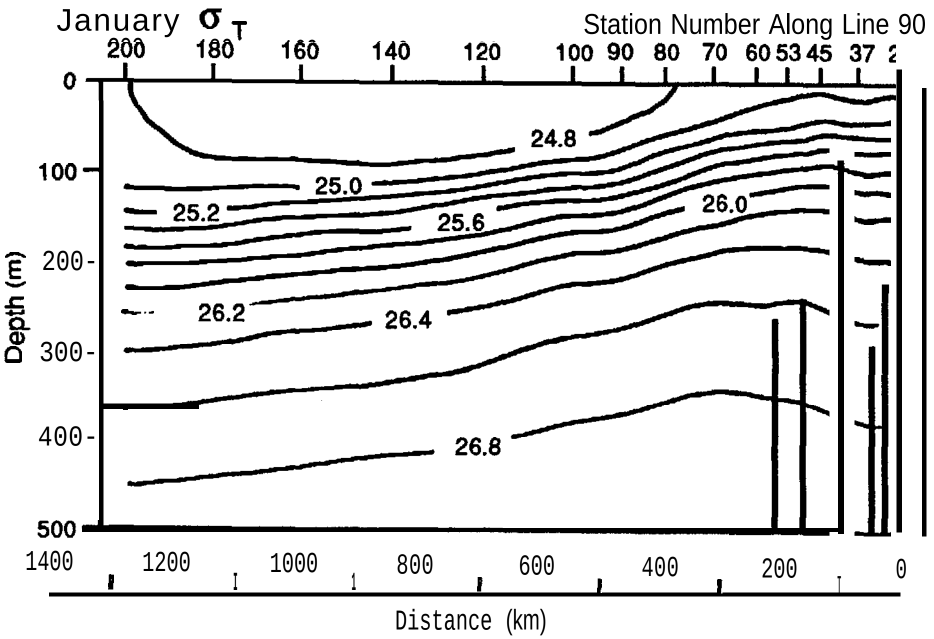
During spring at all depths, and during the other seasons in the upper layers only, the isopycnals adjacent to the coast tilt upward toward the coast. This upward tilt is indicative of the equatorward flow and coastal upwelling usually observed near the coast. Because of the coastal upwelling, the maximum density (minimum temperature, maximum salinity), occurs a month or two earlier nearer the coast than farther offshore (for example, just outside the SCB) (see data in Jackson 1986). The upward tilt of the isopycnals provides, via upwelling, a source of nutrients to the coastal waters. A strong pycnocline is apparent over the SCB during the summer. This pycnocline develops in response to seasonal warming (Figure 2.12b) and the strong stratification is maintained through early fall. Near-surface stratification is maintained in the SCB even during the winter

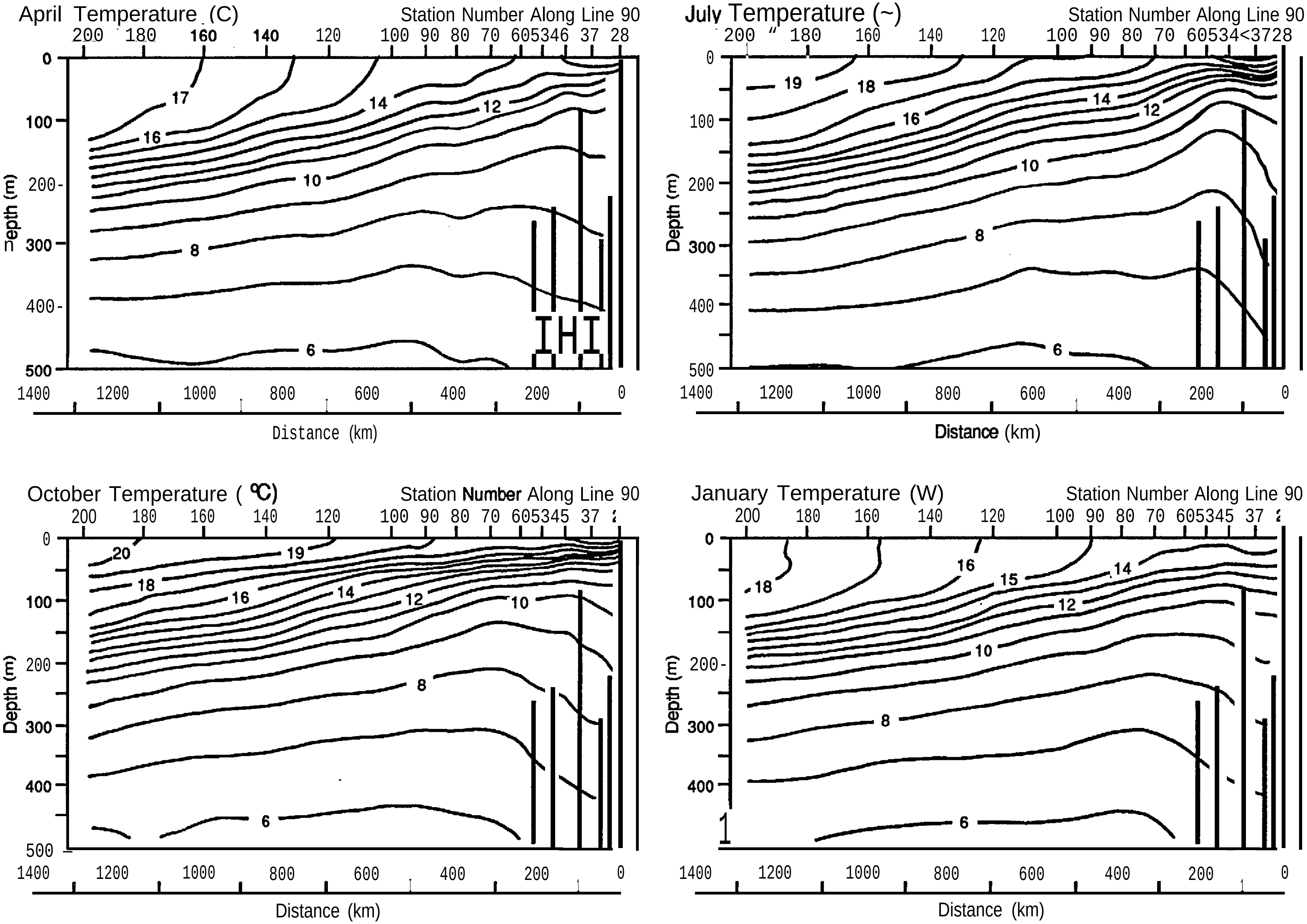
Figure 2.12a. Contoured sections of seasonal averages of density along CalCOFI line 90 (see Figure 2.2). Data were averaged over about 60 days centered on the months listed in the header. The Channel Islands and ridges are delineated by the black spikes emanating from the bottom of the graph (from Lynn et al. 1982).


April σT
Station Number Along Line 90
200
180
160
140
120
100
90
80
70
605345
37:
0
100
200
300
400
500
Depth (m)
24.6
24.6
24.8
25.0
25.2
25.6
26.0
26.4
26.8
27.0
1400
1200
1000
800
600
400
200
0
Distance (km)


July σT
Station Number Along Line 90
200
180
160
140
120
100
90
80
70
60534!
37
0
100
200
300
400
500
Depth (m)
24.2
24.4
24.8
25.0
25.2
25.6
26.0
26.4
26.8
27.0
1400
1200
1000
800
600
400
200
0
Distance (km)


October σT
Station Number Along Line 0
200
180
160
140
120
100
90
80
70
605345
37:
0
100
200-
300
400
500
Depth ·m)
24.0
24.4
24.8
25.0
25.6
26.0
26.4
26.8
27.0
1400
1200
1000
800
600
400
200
0
Distance (km)

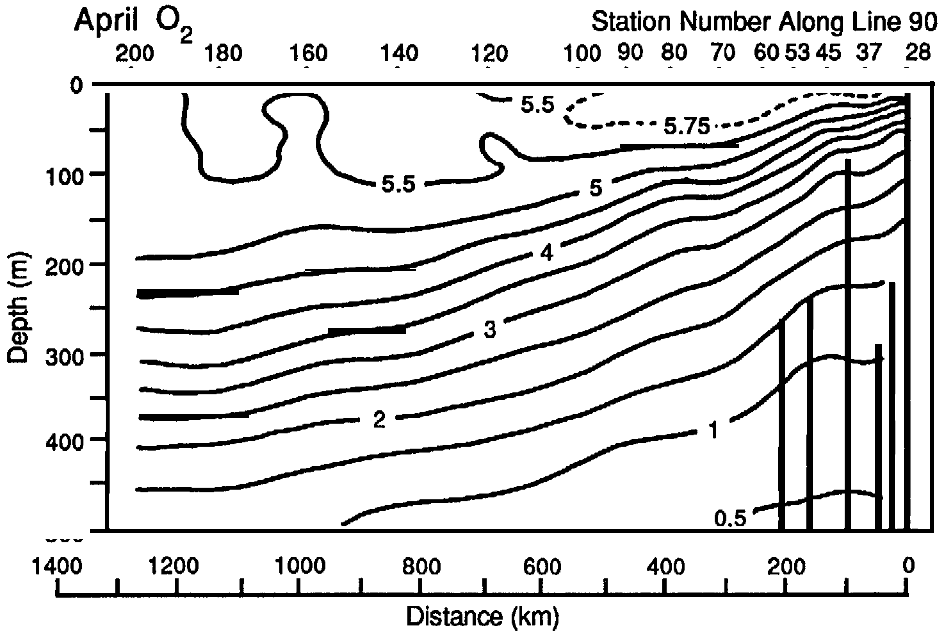

January σT
Station Number Along Line 90
200
180
160
140
120
100
90
80
70
60
53
45
37
0
100
200-
300-
400-
500
Depth (m)
24.8
25.0
25.2
25.6
26.0
26.2
26.4
26.8
1400
1200
1000
800
600
400
200
0
Distance (km)

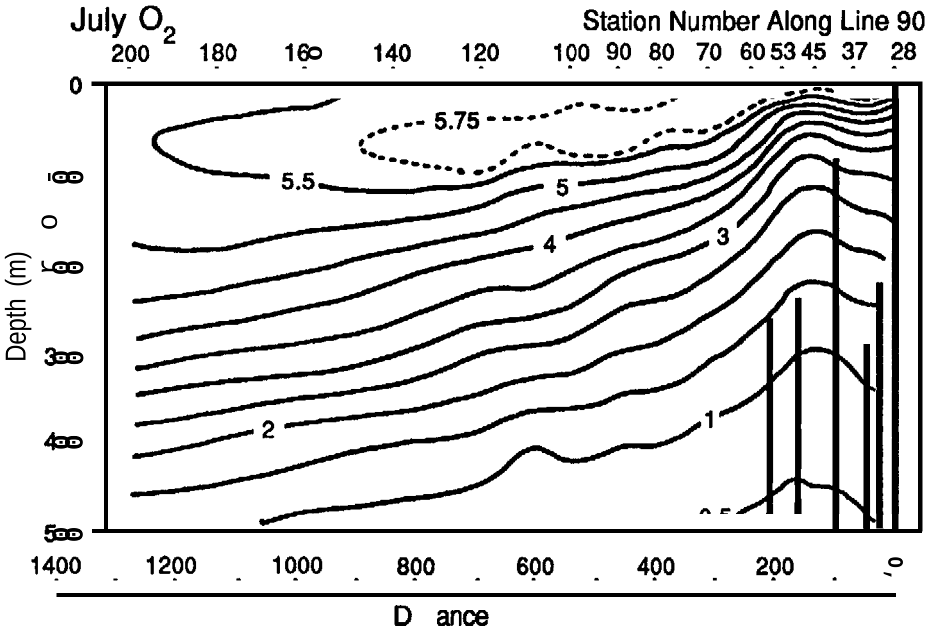

April Temperature (C)
Station Number Along Line 90
200 180 160 140 120 100 90 80 70 605346 37 28
17
16
14
12
10
8
6
0
100
200
300
400
500
Depth (m)
1400 1200 1000 800 600 400 200 0
Distance (km)
July Temperature (~)
Station Number Along Line 90
200 180 160 140 120 100 90 80 70 60534<3728
19
18
16
14
12
10
8
6
Depth (m)
Distance (km)
October Temperature (℃)
Station Number Along Line 90
200 180 160 140 120 100 90 80 70 605345 37
20
19
18
16
14
12
10
8
6
Depth (m)
Distance (km)
January Temperature (W)
Station Number Along Line 90
200 180 160 140 120 100 90 80 70 605345 37
18
16
15
14
12
10
8
6
Depth (m)
Distance (km)

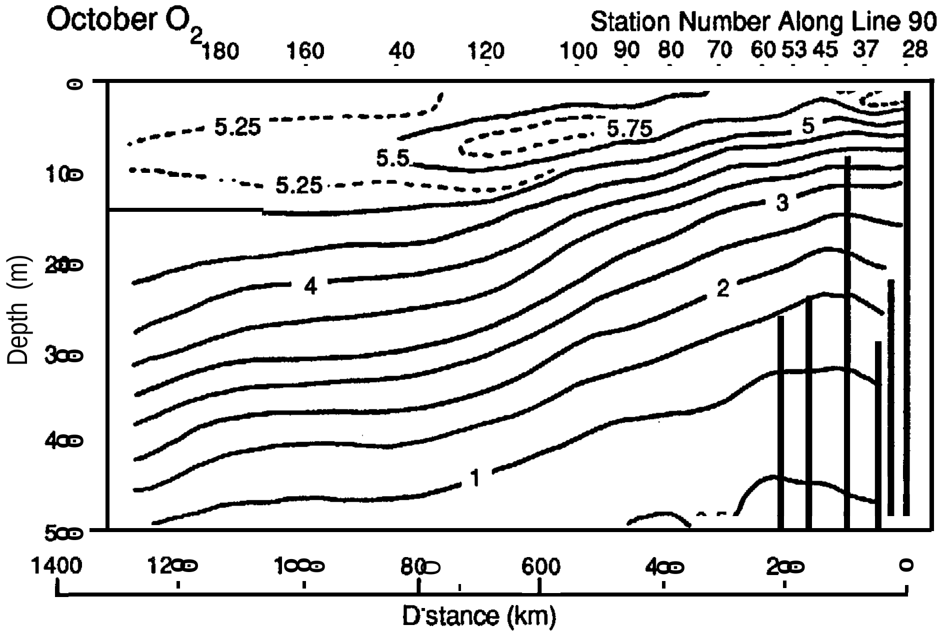
2.18c

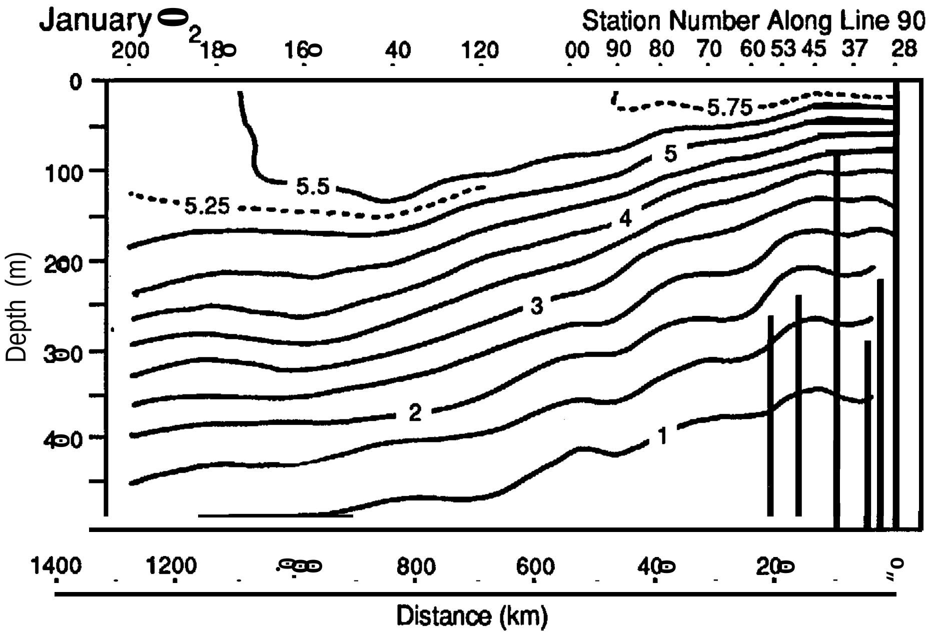
Figure **2.12b.** Contoured sections of seasonal average of temperature along **CalCOFI** line 90 (see Figure 2.2). Data were averaged over about 60 days centered in the months listed in the header. The Channel Islands and ridges are delineated by the black spikes emanating from the bottom of the graph (from Lynn et al. 1982).

Figure **2.12c.** Contoured sections of seasonal averages of oxygen along **CalCOFI** line 90 (see Figure 2.2). Data were averaged over about 60 days centered in the months listed in the header. The Channel Islands and ridges are delineated by the black spikes emanating from the bottom of the graph (from Lynn et al. 1982).


April O_2


July O_2


October O_2


January O_2

season. Waters offshore of the SCB, which are subject to more intense wave action, do not develop as strong a seasonal thermocline or pycnocline.

The temperature field beneath the surface layer has roughly the same structure as the density field (compare Figures 2.12a and 2.12b): the thermocline tilts upward toward the coast and domes over the Channel Islands, particularly in summer and fall. Thus, water within the SCB at undercurrent depths (200-400 m) is typically at least 1°C warmer than that offshore at similar depths. Upwelling of cold deep water is apparent next to the coast in all seasons, but is strongest during the spring. Warmest surface waters occur in early fall. The temperature in the surface waters increases in the offshore direction. In general, the surface waters inside the SCB are 2-4*C colder than those in the regions offshore of the SCB.

Oxygen isopleths, like those of temperature and density, tilt upwards toward the coast (Figure 2.12c). Doming over the Channel Islands, although less dramatic than it occurs in the temperature field, is observed to be strongest in the summer. Upwelling of high oxygen water is evident near the coast in the upper layers, particularly in the spring and summer. The high oxygen water characteristic of the equatorward flowing California Current is evident as a subsurface maximum in regions offshore of the SCB. The region of highest oxygen occurs closer to the coast in spring and winter.

SUBTIDAL FLUCTUATIONS

CURRENTS

The SCB is continuously bathed in current fluctuations of large amplitude (approximately 20-40 cm s^{-1}) with dominant long periods (10 to 30 days) (Hendricks 1976; Hickey 1990a). This result may be somewhat surprising to investigators familiar with other west coast nearshore regions, such as the Coastal Ocean Dynamics Experiment (CODE) area off

Northern California (**Winant** et al. 1987) or the Oregon-Washington coast (**Hickey** 1989a); the circulation in these shelf regions is predominantly wind-driven. The relatively light winds in the SCB might lead one to expect the currents to be correspondingly small. However, large amplitude fluctuations have been observed in the upper 200 m in and over the Santa Barbara (Brink and **Muench** 1986-), Santa Monica, and San Pedro basins (**Hickey** 1990a), and on the shoreward side of the San Diego Trough as far south as San Diego (Hendricks 1976). In the Santa Barbara Channel, the dominant fluctuations are coherent over the entire basin, including all the inter-island passages (Figure 2.13). The investigators concluded that these fluctuations were of a very large spatial scale. The fact that similar fluctuations occur also in the Santa Monica and San Pedro basins and at least on the edge of the San Diego Trough suggests that this is indeed the case.

The current fluctuations, like the mean flow, tend to follow the regional curvature of basin 200 m depth **isobaths,** except in the very near surface and near-bottom frictional boundary layers (Hendricks 1976; **Hickey** 1990a). Over the shoreward slope of the Santa Monica basin, currents **can** attain speeds of more than 40 cm s^{-1} for a week or two or more (Figure 2.14). Such speeds would imply very short residence times in the SCB, if the currents were similar at all locations. As discussed below, however, the currents have considerable spatial variability, such as might be attributed to eddies or other physical processes, so that actual residence times could be much longer. This is particularly true in the near-surface layers, where mean flows are much smaller and the eddy field is much stronger (**Hickey** 1990a). Longshore similarity scales appear to be on the order of about 20 km over the upper slope (Hendricks 1982; **Hickey** 1990a).

Figure 2.13. Correlations of first velocity EOF with velocity time series at a mid-channel location at the eastern entrance to the Channel. The length of the arrow is proportional to correlation magnitude. Orientations are relative to having flow directly westward at a mid-channel location at the western entrance to the Channel. Time lags (positive for the western entrance stations leading) are shown in parentheses for lag magnitudes greater than 0.75 d (from Brink and Muench 1986).

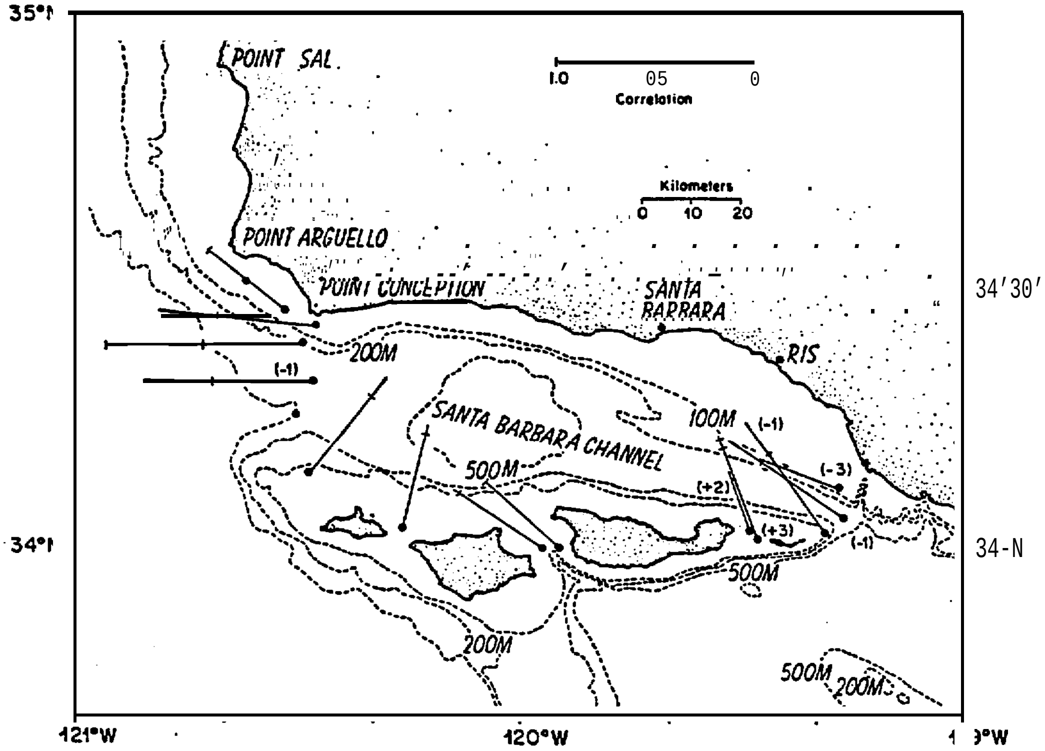
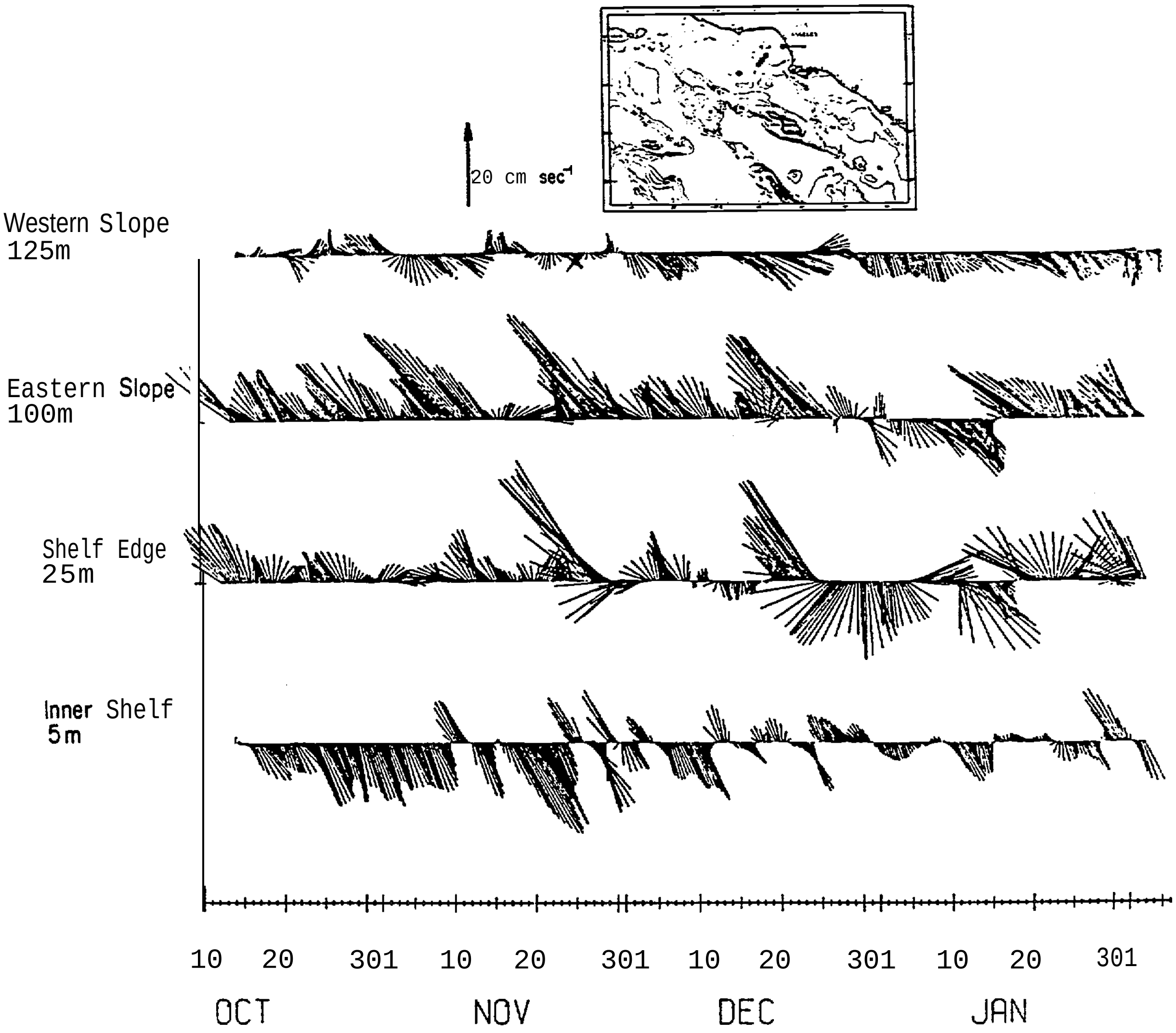

35°N
POINT SAL
1.0 05 0
Correlation
Kilometers
0 10 20
POINT ARGUELLO
POINT CONCEPTION
SANTA BARBARA
RIS
34′30′
200M
(-1)
SANTA BARBARA CHANNEL
100M
(-1)
(-3)
500M
(+2)
(+3)
(-1)
34°N
34-N
500M
200M
500M
200M
121°W
120°W
°W

Figure 2.14. Six-hourly velocity time series at sites on a section across the Santa Monica Basin and shelf during October 1985-February 1986 (from **Hickey** 1990a).



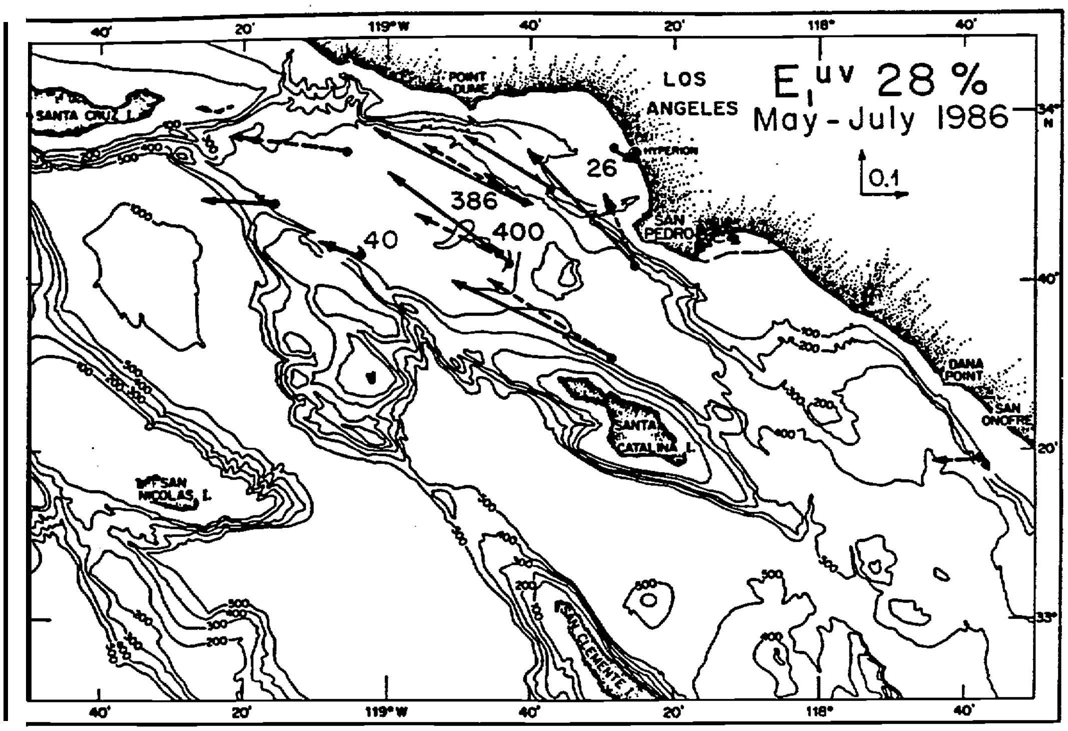
20 cm sec⁻¹
Western Slope
125m
Eastern Slope
100m
Shelf Edge
25m
Inner Shelf
5m
10
20
301
10
20
301
10
20
301
10
20
301
OCT
NOV
DEC
JAN

Surface turbidity data in Thornton (1981) illustrate clearly the mesoscale eddy structure in surface currents over these nearshore basins.

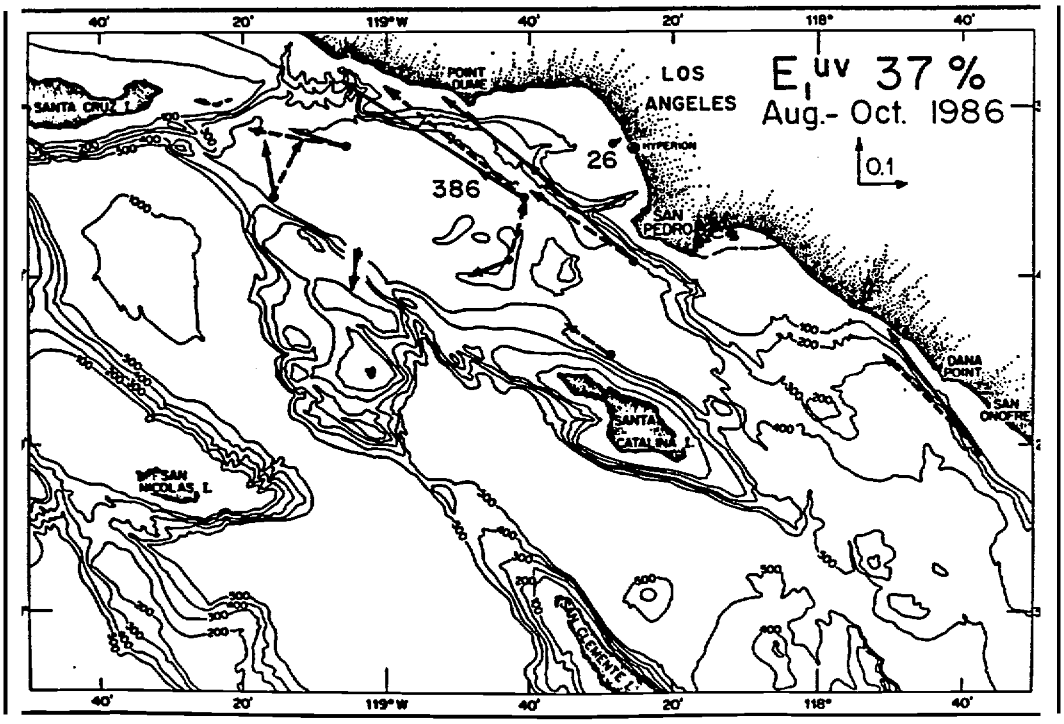
The longest period fluctuations have a subsurface maximum at about 100m from the surface in the Santa Monica-San Pedro area (Hickey 1990a), but may shoal toward the west in the Santa Barbara Channel (Blumberg et al. 1987). The amplitude of the fluctuations increases from a minimum in spring to a maximum in fall and winter (Hickey 1990a). Hickey (1990a) uses the technique of EOF analysis to determine the spatial structure of the very long period (approximately 20-30 days) fluctuations over the Santa Monica-San Pedro basins. The long period fluctuations discussed above and shown as examples in Figure 2.14, are well described by spatial structures like those shown in Figure 2.15. The long period fluctuations are stronger on the eastern side of the Santa Monica-San Pedro basins during winter (Figure 2.14) and fall (Figure 2.15). This is not the case, however, during the early summer, when fluctuations are of relatively constant amplitude across the entire basin (Figure 2.15). A seasonal change in the temporal, as well as the spatial pattern of the fluctuations, is also evident (Figure 2.16): during spring and early summer, spatially coherent pulses have very long periods (approximately 30 days); during late summer and fall, coherent pulses have shorter periods and their amplitude increases.

Likely candidates to account for these basin-scale fluctuations include local and freely propagating waves (or both) generated by remote wind forcing or some other mechanism, and eddy advection by the mean flow. The relatively weak wind stress makes local wind forcing seem highly unlikely, and Hickey (1990a) and Brink and Muench (1986) find little evidence of strong correlation of basin currents with the local wind fields in the Santa Monica and Santa Barbara basins, respectively. Brink and Muench (1986) also demonstrate that remote wind forcing up to 200 km downstream of the Santa

Figure 2.15. Amplitude of the first velocity EOF at upper water column locations in the Santa Monica-San Pedro basins and in the San Diego Trough during May-July 1986 (upper panel) and August-October 1986 (lower panel). Solid lines represent the approximately 100 m depth, dashed lines the approximately 40 m depth. Other depths are indicated by actual numbers. The percent variance accounted for by the EOF is shown in the upper right hand corner of the figures (from Hickey 1990a).



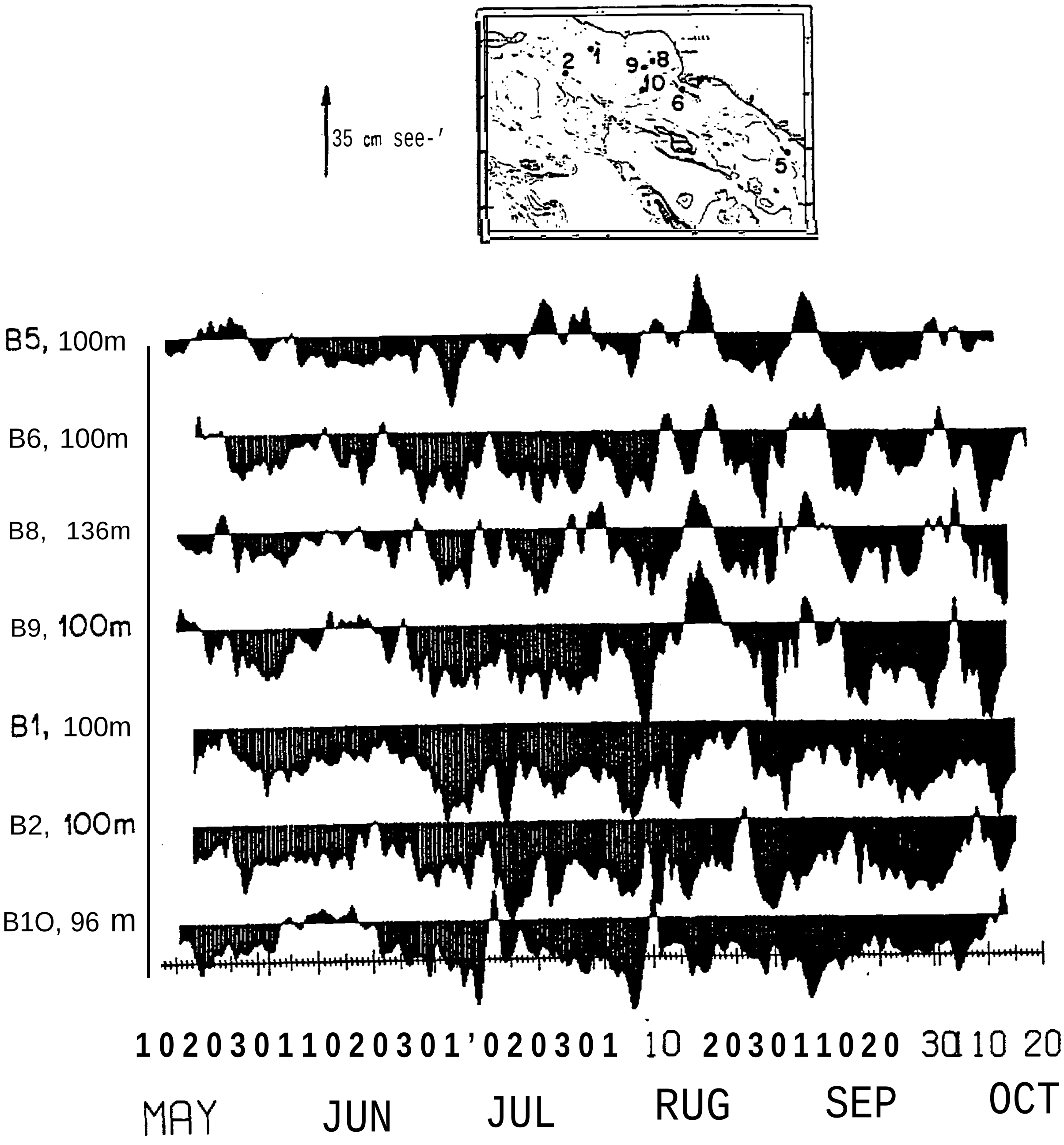
E_1^{uv} 28 %
May - July 1986
0.1
LOS ANGELES
POINT DUME
HYPERION
SAN PEDRO
DANA POINT
SAN ONOFRE
SANTA CRUZ I.
SANTA CATALINA I.
SAN NICOLAS I.
SAN CLEMENTE I.
26
386
400
40
40'
20'
119°W
40'
20'
118°
40'
34° N
40'
20'
33°



E_1^{uv} 37 %
Aug.- Oct. 1986
0.1
LOS ANGELES
POINT DUME
HYPERION
SAN PEDRO
DANA POINT
SAN ONOFRE
SANTA CRUZ I.
SANTA CATALINA I.
SAN NICOLAS I.
SAN CLEMENTE I.
26
386
40'
20'
119°W
40'
20'
118°
40'

2.21b

Figure 2.16. East-west component of velocity during May-October 1986. Onshore flow is positive. Station locations are shown on the inset map (from Hickey 1990a).


35 cm see-'
2
1
9
8
10
6
5
B5, 100m
B6, 100m
B8, 136m
B9, 100m
B1, 100m
B2, 100m
B1O, 96 m
10 20 30 1 10 20 30 1' 0 20 30 1 10 20 30 1 10 20 30 10 20
MAY
JUN
JUL
RUG
SEP
OCT

Barbara Channel is not related to the observed variance. They find no support for poleward propagation of the signals from San Diego to the Santa Barbara Channel during the spring season investigated.

On the other hand, Denbo and Allen (1986) demonstrate that sea-level signals generated off Baja California propagate through the SCB in a manner consistent with coastal-trapped wave theory. Basically, this theory demonstrates that longshore wind stress off Baja California causes long (a few thousand kilometers) undulations in the sea surface with amplitudes of a few centimeters height. These "waves," which hug the continental shelf and slope, travel poleward at speeds of a few hundred kilometers a day. As the waves pass by a given location, the currents are also affected: They are accelerated first poleward and then equatorward (that is, one might see pulses of currents superimposed on any mean flow). The waves can be modified by local wind at a given location, the degree of change being dependent on the magnitude of the local longshore wind stress. Such waves are common over the Pacific Northwest shelf (Hickey 1989a).

It appears likely that the fall and winter Santa Monica Basin fluctuations, which are more strongly trapped over the shoreward slope of the basin, may be the signature of freely propagating coastally trapped waves. The time delay between the occurrence of signals at San Onofre and at San Pedro during late summer 1987 was consistent with poleward travel at roughly the speed of a first mode shelf wave in this region (approximately 175 km d-l at a period of 10 days) (Hickey 1990a). However, the travel speed decreased by an order of magnitude poleward of San Pedro. We can only conclude that the driving mechanism(s) for fluctuations in the currents over the basins in the SCB are at present poorly understood.

Fluctuations in currents over much of the relatively wider (approximately 20 km) Santa Monica shelf are not strongly related to the slope current fluctuations (Figure 2.14). **Hickey** (1990a) demonstrates that although the outer-shelf currents are primarily related to the slope and basin currents, the inner-shelf currents are significantly correlated with (that is, show a strong similarity with statistical significance at the **95%** level of confidence) the **longshelf** component of local wind stress. On the relatively narrow (approximately 4 km) shelf south of San Pedro to San Diego, on the other hand, correlation with the local wind stress is barely significant (**Winant** 1983; **Winant** and **Bratkovich** 1981). It is tempting to suggest that a large percentage of the variance associated with fluctuations over the narrower shelf areas, as on the outer shelf in the wider shelf areas, is related to the large-scale basin and slope fluctuations discussed previously. Indeed, dominant time scales in the **Winant** and **Bratkovich** data appear to be relatively long (approximately 20 days); the **maximum** energy occurs in fall and winter and the energy in the fluctuations increases from the **inner** to the outer shelf in all seasons (**Winant** and **Bratkovich** 1981). However, the longshelf scales over which correlations are significant are relatively short (approximately 25 km) over the 50-day summer period of the observations (**Winant** 1983). It is possible that correlation scales for these long-period fluctuations were not well resolved by the relatively short data set.

Subtidal scale fluctuations have been observed at all depths throughout the water column in the Santa Monica and San Pedro basins and over their slopes (**Hickey** 1990a). The amplitude of such fluctuations decreases dramatically below 200 m from the surface, to amplitudes of approximately 5 cm s^{-1} at depths of approximately 700 m from the surface. Small (≤5 cm S-l) fluctuations are observed even below the depth of the deepest sill (**Hickey** 1990b). Similar fluctuations are expected to occur throughout the rest of the SCB. Much larger subtidal velocity fluctuations (up to 30 cm s^{-1}) with periods of 5-10 days have been observed in the bottom 100-200 m over the Santa Monica Basin sills and should be expected on the sills between other basins (Hickey 1990b).

Flow, both the near-surface and near the bottom, can be substantially altered by the effects of friction. The retarding force of the bottom tends to both diminish the amplitude of the flow and to change its direction in a layer whose thickness is on the order of 5-20 m over the shelf and slope. In general, the flow is rotated a few degrees to the left of its direction above the boundary layer. Thus, flow in the bottom boundary layer is directed offshore for poleward flow, and onshore for equatorward flow. The cross-isobath flow can provide a mechanism for net offshore transport of sediment. In the near-surface layers, a local wind-driven component of flow occurs. This frictional current is superimposed on any large-scale currents, and is particularly important over the shelf, where the larger-scale currents may be small. The thickness of the frictional surface layer varies from 5 to 40 m, often being delimited by the pycnocline. Over shallow shelf areas, surface and bottom frictional layers may overlap.

Submarine canyons occur frequently over the continental slopes in the SCB and may be important for the offcoast dispersal of sediment to basin floors. For the most part, however, the canyons have a relatively small width (<5 km) and, therefore, can be expected to have a correspondingly minor effect on regional circulation. Indeed, recent current measurements over Redondo Canyon (just north of Pales Verdes) at a depth of 30 m suggest that the flow passes directly over the canyon with no apparent modification. SCCWRP measurements at a mooring within Santa Monica and San Gabriel canyons showed no significant correlation between canyon and shelf flows (Hendricks

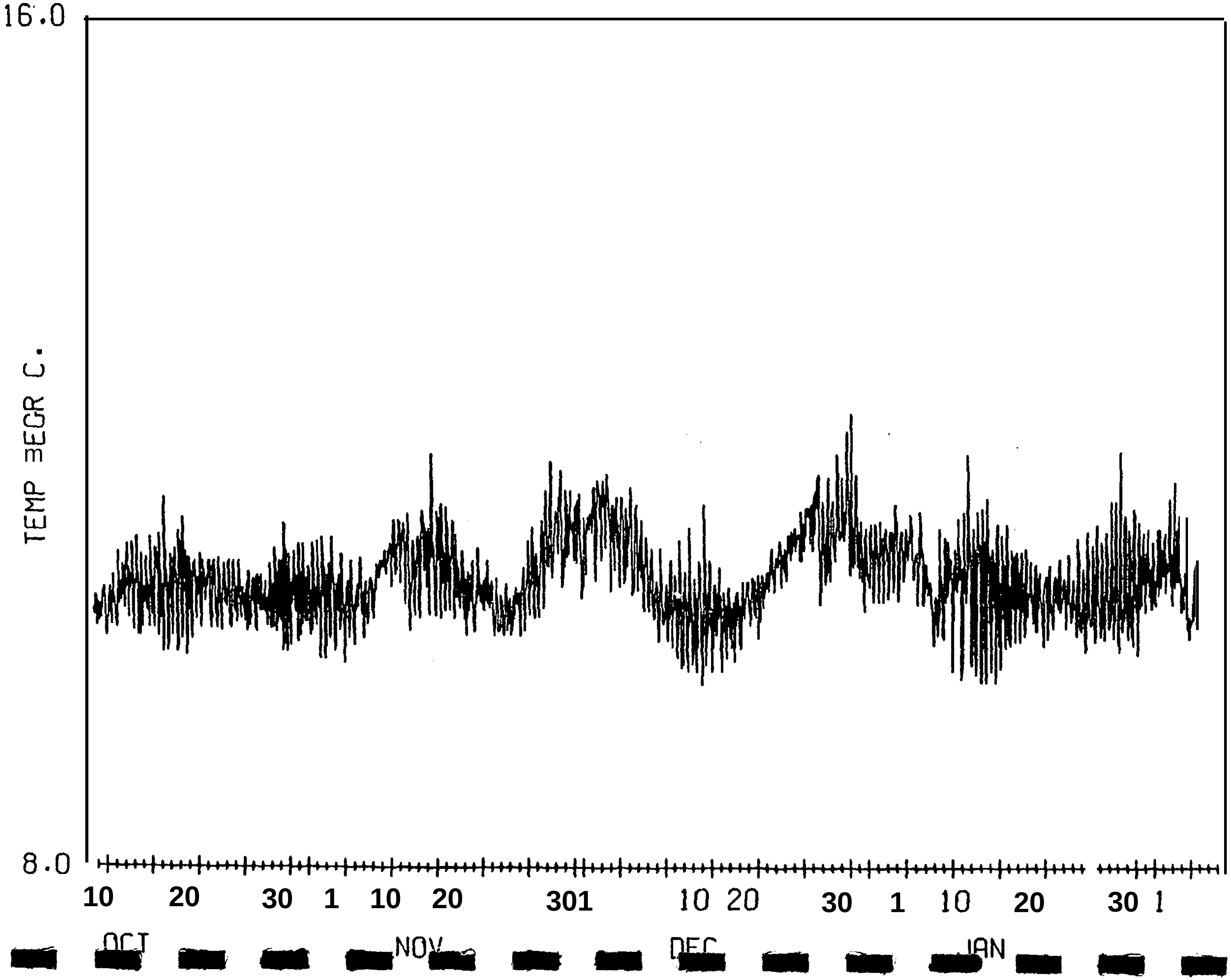
1980, 1984). Below the lip of these canyons, **subtidal** fluctuations as well as net flows are weak, the currents **being** dominated by higher frequency fluctuations including diurnal and semi-diurnal tides. Model studies of canyon circulation and the effect of canyons on the regional circulation suggest that even very narrow canyons such as occur in the SCB should have some effect on the overlying circulation, especially in the density fields (**Klinck** 1989). Thus, it is possible that, as has been demonstrated for somewhat wider canyons off Washington, a mean and fluctuating eddy (or both) is trapped within the canyon, and the density field is perturbed over the canyon walls **(Hickey 1990c).** Maximum velocities may occur also over the steep canyon walls where measurements are difficult to obtain. The flow in such submarine canyons and the effects of the canyons on the near flow and in the density field is being examined as part of ongoing research programs.

WATER PROPERTIES

Temperature time series from a location just below the **pycnocline** over the Santa Monica slope illustrate that water properties undergo relatively large amplitude fluctuations with roughly the ssme temporal scales as those of the velocity field (Figure 2.17). For example, water temperature at 40 m from the surface can change by as much as 2°C over a period of several days. Many of these changes are a result of vertical displacement of water masses that occur as the longshore current changes in speed. The density field adjusts to maintain **geostrophic** equilibrium. For this case, the changes in the density (temperature and salinity) field precede those in the horizontal velocity field. Higher frequency (tidal and **supra-tidal)** fluctuations are also apparent in the record. These are due to vertical excursions related to the semi-diurnal tide and to internal waves (see next section).

Satellite sea-surface temperature (SST) data indicate that the SCB

Figure 2.17. Time series of temperature at a location over the Santa Monica slope at a depth of approximately 100 m from the surface during winter 1985.


16.0
8.0
TEMP DEGR C.
10
20
30
1
10
20
301
10 20
30
1
10
20
30 1
OCT
NOV
DEC
JAN

2.25b

contains a rich mesoscale eddy field, at least in the very near-surface layers. The depth of such features appears to be at least the depth of the seasonal thermocline (Fiedler 1988). The scales of the many features appear to be relatively short (approximately 20-40 km), in comparison with the relatively large scales (approximately 200 km) associated with eddies in the offshore California Current (Simpson et al. 1984). This suggests that many of these features may be generated locally--either by horizontal or vertical current instabilities or by interaction of the mean flow with the highly irregular SCB bottom topography. The advection of such eddies by the mean flow will produce local changes in temperature and salinity as the eddy passes by a particular point. To the extent that the mesoscale eddy field is significant at a depth of approximately 40 m from the surface, some of the temperature fluctuations in the record shown in Figure 2.17 could be attributed to horizontal eddy advection.

Patches of cold water that occur in response to local wind-driven upwelling are apparent in satellite SST maps. For example, such patches are frequently observed in Santa Monica Bay and over the San Pedro shelf and might be expected on the seaward side of islands in the SCB. Upwelling of cold water occurs during periods of equatorward-directed winds when warmer surface waters are moved offshore and replaced by deeper water. Such effects are, for the most part, confined to the shelf regions. As noted by Jackson (1986), upwelling in the SCB is weaker and less frequent than in regions to the north of the SCB, a result of the generally weaker winds in the area. Dorman and Palmer (1981) used sea-surface temperature records in the SCB to demonstrate that significant upwelling events occur only a couple of times per year and last for 1-2 weeks. Whether or not there are regions in which shelf waters move offshore in jets and squirts, such as is commonly observed off Northern California (Kelly 1985), has not been specifically addressed. However, because the **winds** in this region and, hence, the **wind-**driven shelf currents are much smaller than in regions north of the SCB, the occurrence of such jets (and, if they occur, their strength) is not to be expected to parallel that of the other coastal regions.

Upwelling, and a major plume associated with it, has been studied off Point Conception (Atkinson et al. 1986). During wind-driven **upwelling** events along the coast north of Point Conception, a southwest directed plume of cold water emanates from the Point Conception area. The plume often turns eastward and enters the Santa Barbara Channel on its southern side, sometimes traveling all the way to the eastern entrance of the Channel. The cold water plume is very evident in maps of satellite SST. The plume has a major effect on time-variable water properties in the Santa Barbara Channel extending to depths of 50-70 m on the south side of the Channel. However, the plume water appears to be entirely recirculated within the Channel, that is, it does not affect water properties in nearshore basins farther south, such as Santa Monica. However, satellite data show that plume water often enters the SCB to the south of the Santa Barbara Channel, where it impacts water properties in the offshore basins (Atkinson et al. 1986). The contribution of the Point Conception **upwelling** plume to the **SCB** in terms of nutrient supply is likely to be an order of magnitude greater than that of local **upwelling.**

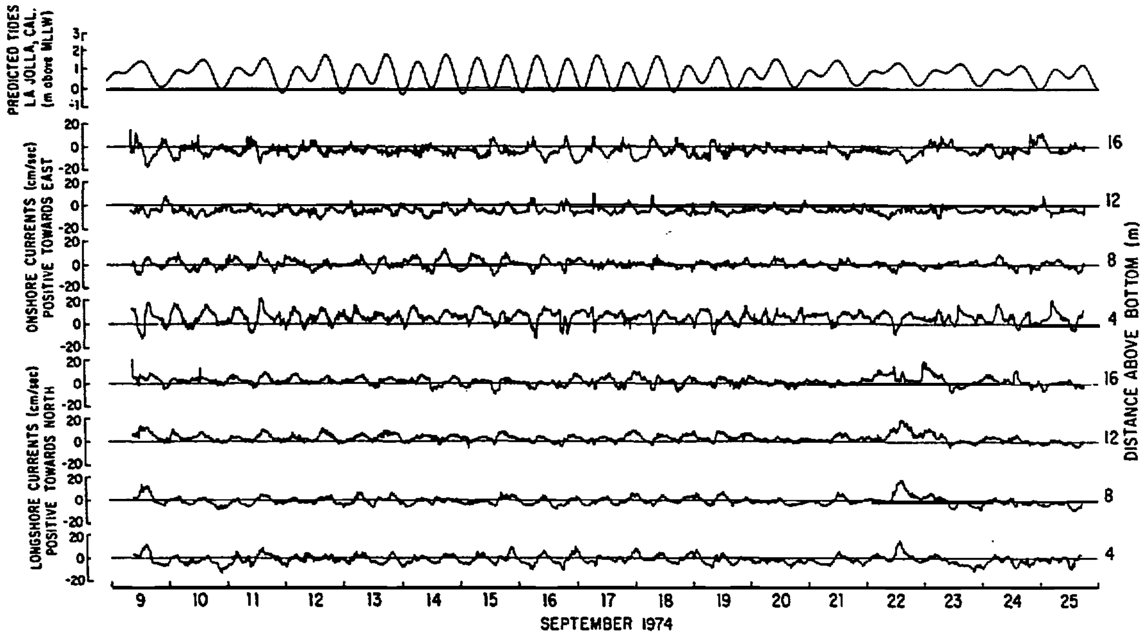
TIDAL FLUCTUATIONS

Spatially comprehensive analyses of tidal and higher-frequency current and water property fluctuations are available only for the Southern California mainland shelf. The measurements were collected in three separate experiments by Winant (1983) and Winant and **Bratkovich** (1981), as described above. The first experiment provided detailed vertical resolution of currents at one site during the summer; the second described cross-shelf structure of current and temperature fluctuations and their seasonal variation; and, the third experiment focused on long shelf correlation of current fluctuations during the summer.

Results indicate that, at least for the shelf, the fluctuations can be divided roughly into a tidal band (periods of a few hours to one day) and a supra-tidal band (periods on the order of a few hours to a few minutes) (Winant and Olson 1976; Winant and Bratkovich 1981). The tidal band includes not only tidally forced fluctuations, but inertial and also wind-forced fluctuations. The authors made no attempt to separate these several forcing mechanisms: Most analyses were performed on the whole tidal band and are, for the most part, dominated by the semi-diurnal and near-diurnal periods. At these latitudes the inertial period is approximately 22 hours, so that the diurnal tide and inertial peaks are indistinguishable in the standard spectral plots presented in the authors' papers. At mid-shelf during the summer the diurnal signal is much stronger near the surface than near the bottom, suggesting that inertial signals may be significant (Winant 1983).

A representative record from Winant and Olson (1976) illustrates that tidal band velocities over the shelf during the summer often exceed those of subtidal currents (Figure 2.18). In these records, obtained in a water depth of 17 m, semi-diurnal cross-shelf tidal currents are on the order of 10 cm S-l and are strongly baroclinic (depth and, presumably, density-dependent). Maximum velocities occur not in the central water column, but in the surface and bottom boundary layers. Vertical shear as large as 50 cm s^{-1} was commonly observed over the 12 m instrument span. Longshelf currents also exhibit semi-diurnal periodicity. Longshelf velocities are on the order

Figure 2.18. Current and tidal fluctuations, 9-25 September 1974. The bottom four traces represent the longshore currents, and the next four traces represent the onshore currents, while the top trace is a prediction of tidal elevation for La Jolla, California (from Winant and Olson 1976).

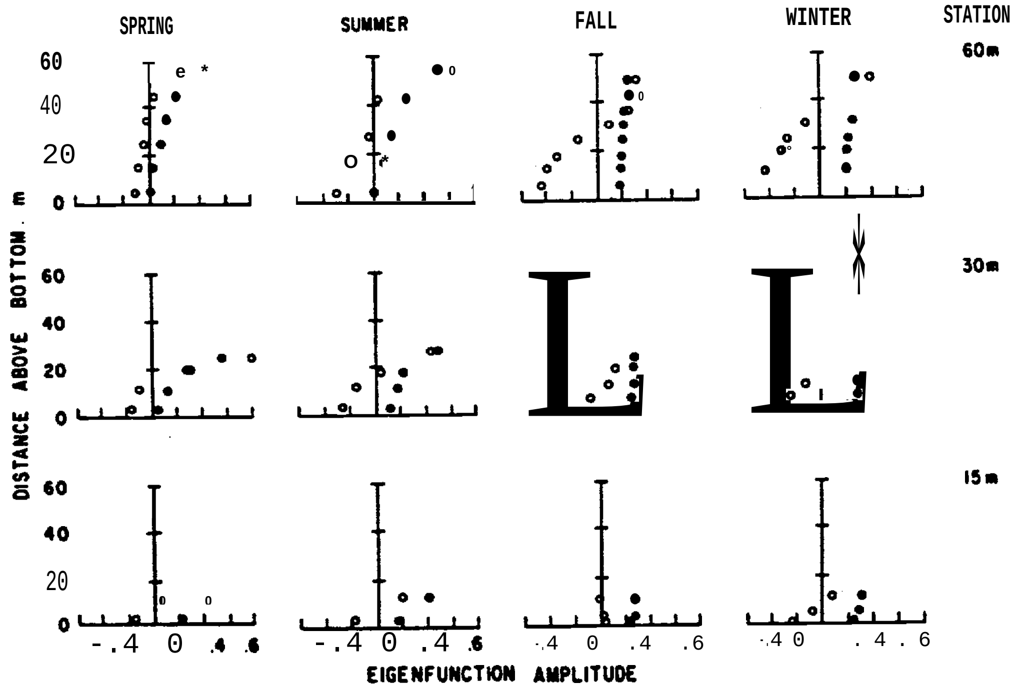

PREDICTED TIDES
LA JOLLA, CAL.
(m above MLLW)
3
2
1
0
-1
ONSHORE CURRENTS (cm/sec)
POSITIVE TOWARDS EAST
LONGSHORE CURRENTS (cm/sec)
POSITIVE TOWARDS NORTH
20
0
-20
16
12
8
4
DISTANCE ABOVE BOTTOM (m)
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
SEPTEMBER 1974

of 10 cm s^{-1}. However, in contrast to the cross-shelf currents, the longshelf currents are relatively barotropic (depth independent). The dominant semi-diurnal longshelf fluctuations are not generally phase-locked with the surface tide (Winant and Olson 1976; Winant and Bratkovich 1981), consistent with their baroclinic nature. This is evident in the cross-shelf currents shown in Figure 2.18. The more barotropic longshelf currents are phase-locked with the surface tide only on the shallow inner shelf (Figure 2.1s).

EOF analysis at individual sites in 15, 30, and 60 m bottom depths (the inner, mid, and outer shelf, respectively) illustrate that these basic characteristics are similar across the shelf and in every season (Figure 2.19). However, details of the vertical structure of the fluctuations is a function of season and location, presumably due to stratification differences. For example, the zero crossing for the first mode for cross-shelf velocity occurs at 30-40 m at the shelf edge, at approximately 15 m over the mid-shelf, and at approximately 10 m on the inner shelf. Vertical shear in the cross-shelf currents is at maximum in summer and fall on the outer shelf, but in spring at mid-shelf. The amount of variance in cross-shelf currents in the tidal band is also a strong function of season, decreasing from 24 $cm^2 S^{-2}$ in spring to approximately 12 $cm^2 S^{-2}$ in summer and fall and 7 $cm^2 s^{-2}$ in winter. Variance in longshelf currents, on the other hand, is relatively constant throughout the year (approximately 30 cm^2 S-2), consistent with the barotropic (not density-related) nature of these fluctuations.

Cross-shelf tidal band currents decrease toward shore, so that on the inner shelf, the energy of the cross-shelf currents is an order of magnitude less than that on the outer shelf (Winant and Bratkovich 1981). The relationship between the cross-shelf and longshelf velocity components also

Figure 2.19. Seasonal distribution of the amplitude of the largest **eigenvectors** of the longshore (.) and cross-shelf (o) **tidal-band** (periods between 36 and 4 hours) currents on a section across the shelf near Del Mar, California (see Figure 2.3 for locations) (from Winant and **Bratkovich** 1981).


SPRING
SUMMER
FALL
WINTER
STATION
60m
30m
15m
DISTANCE ABOVE BOTTOM . m
60
40
20
0
-.4 0 .4 .6
EIGENFUNCTION AMPLITUDE

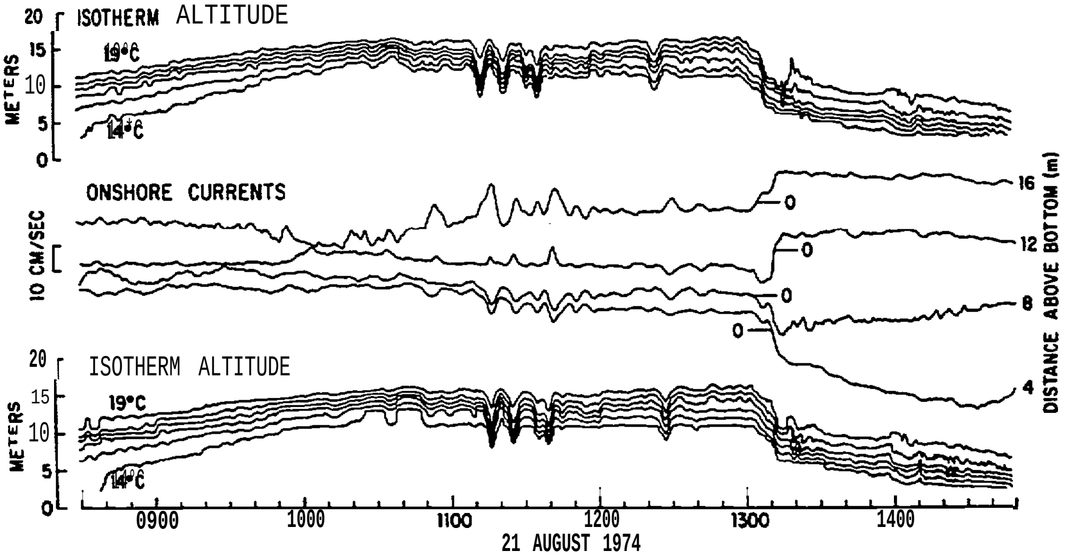
changes across the shelf: The two components are coherent, with approximately a 90° phase lag on the outer shelf, but are decoupled on the inner shelf. Cross-shelf currents and temperature are correlated at all shelf locations at tidal and higher frequencies, with a phase difference of approximately 90° near the bottom of the water column and approximately 270° near the surface. These phase differences suggest that the internal tide has the configuration of a standing wave in the cross-shelf plane (Winant and Bratkovich 1981).

Longshelf correlation scales for both cross-shelf and longshelf currents in the tidal band are, with one exception, very short (≤ 5 km). Near the bottom, at mid-shelf, some evidence suggests that cross-shelf tidal currents propagate poleward. The phase speed is on the order of 100 cm S-l.

Supra-tidal current fluctuations are ubiquitous over the Southern California shelf during periods of strong stratification (La Fond 1962; Cairns 1967). These internal waves progress toward the coast with phase speeds of 15-25 cm s^{-1} (Winant and Olson 1976; Winant and Bratkovich 1981). Such fluctuations are apparent in Figure 2.18 as the jitter superimposed on the tidal currents. A blow-up of a portion of the record in Figure 2.18 illustrates the details of the internal wave currents and their associated temperature fluctuations (Figure 2.20). The current speeds are on the order of 3 cm s^{-1} and, as with the tidal band currents, the internal wave currents are larger in the upper and lower boundary layers than in the interior of the water column.

Winant and Olson (1976) illustrate that the observed velocity and temperature fluctuations are consistent with a three-layer model of the density field, consisting of two well-mixed layers separated by a pycnocline in which density increases linearly with depth. The variance due to such

Figure 2.20. Temperature structure and onshore currents on 21 August 1974 offshore of San Diego. The top and bottom panels represent isotherm heights as a function of time as interpolated from measurements taken with vertical thermistor arrays located west (upper panel) and east (lower panel) of the current meter array. The thermistor arrays are 45 m apart and are located 130 m south of the current meter array (from Winant and Olson 1976).



ISOTHERM ALTITUDE
20
15
10
5
0
METERS
19°C
14°C
ONSHORE CURRENTS
10 CM/SEC
0
16
12
8
4
DISTANCE ABOVE BOTTOM (m)
ISOTHERM ALTITUDE
0900
1000
1100
1200
1300
1400
21 AUGUST 1974

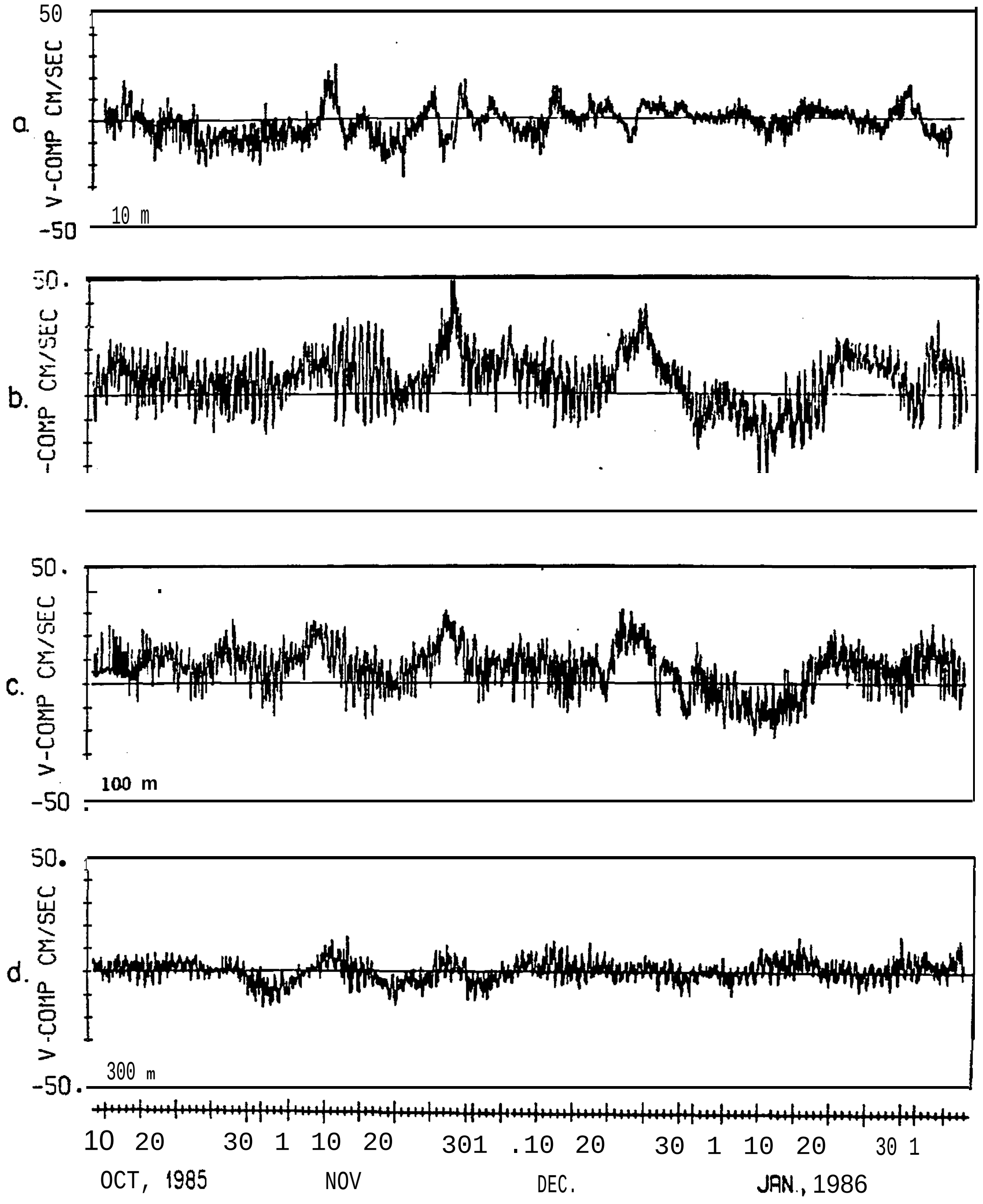
high frequency internal waves is a strong function of the density stratification and, hence, season. The variance associated with the high frequency band is a factor of 2-3 greater in spring and summer than in fall and winter at all locations on the shelf (Winant and Bratkovich 1981).

The broad details of the above results for the tidal band should be applicable in all narrow-shelf coastal areas in the SCB, for example, from Newport Beach to San Diego. Tidal currents around islands, in inter-island passages, over sills, over the continental slope, and over wider shelves would be expected to have significantly different characteristics than those described above. In particular, for wider shelves, the internal tide might be expected to propagate toward shore, as observed off Oregon (Torgrimson and Hickey 1979), rather than forming a standing wave. The high-frequency internal wave results would be expected to have a broader applicability, since they depend only on the density profile and not on the underlying bottom topography, except perhaps in very shallow areas. Thus, we would expect high-frequency internal waves to occur near the seasonal pycnocline over shelves, slopes, and basins in the SCB. The exact vertical structure and current amplitude would depend on the local density stratification.

Although detailed analyses of tidal currents have not been performed for wide shelf or continental slope areas in the SCB, available hourly data can provide some insight into the spatial characteristics of the tidal band currents. In particular, data collected over the Santa Monica shelf and slope suggest that tidal currents on the inner shelf may be weaker than those on the narrower Southern California shelf in the same water depth (approximately 5 cm S-l amplitude, Figure 2.21).

In contrast, tidal currents over the shelf edge and slope are larger than those over the shelf (approximately 15-20 cm S-l) (Figure 2.21). They are also strongly baroclinic, decreasing by a factor of 2 by a depth of

Figure 2.21. North-south velocity at selected depths over the Santa Monica inner shelf (a) and slope (b, c, and d).

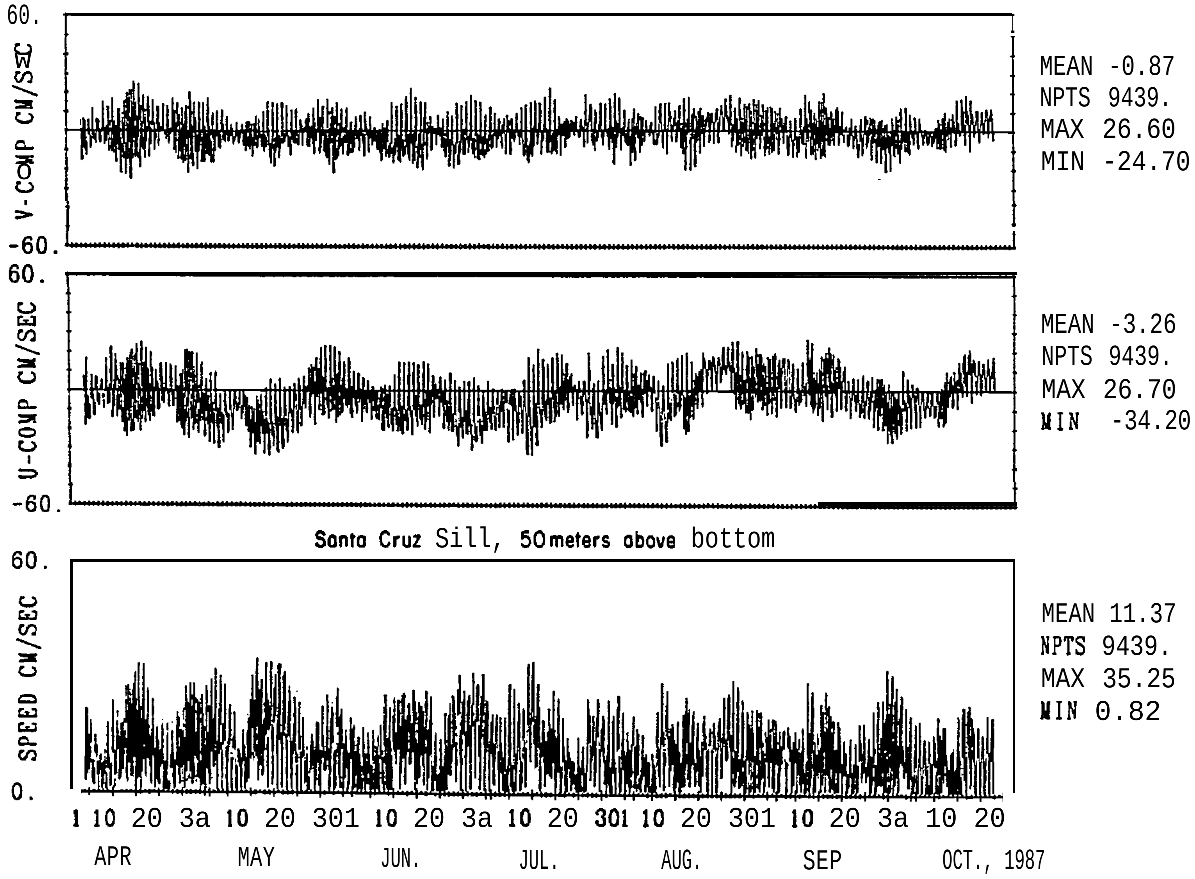

50
V-COMP CM/SEC
a.
10 m
-50
50.
-COMP CM/SEC
b.
50.
V-COMP CM/SEC
c.
100 m
-50
50.
V-COMP CM/SEC
d.
300 m
-50.
10 20 30 1 10 20 301 .10 20 30 1 10 20 30 1
OCT, 1985
NOV
DEC.
JAN., 1986

about 100 m and by a factor of 4 by approximately 300 m (Figure 2.21). Tidal currents are also large in the upper 100 m over the open basin. However, they are consistently largest in the upper layers at locations near steep continental slopes. At depths well below the seasonal pycnocline, tidal current energy is much reduced (approximately 10 cm s^{-1}), except near regions of irregular topography. For example, tidal velocities exceeding 30 cm s^{-1} occur at depths of several hundred meters in the vicinity of the Santa Cruz sill (Figure 2.22). Analyses of tidal band currents for the Santa Monica-San Pedro region are part of an ongoing research program, from which results should be available in 1990.

Barotropic tidal currents within the Santa Barbara Channel basin and on the outer edge of the Santa Barbara shelf appear to be of the same order as those for the SCB (approximately 10 cm s^{-1}) (Blumberg et al. 1985). Calculated ellipses for the semi-diurnal lunar tide suggest that baroclinic tidal currents may be weaker in the upper 100 m of the water column than those on the Southern California shelf. The semi-diurnal tide is in phase throughout the Santa Barbara Channel, including the inter-island passages. Tidal currents in the passages are approximately four times as strong as those over the basin, reaching speeds of 50 cm s^{-1} on strong ebbs (Blumberg et al. 1985).

As discussed in the section on seasonal variation of water properties, the water in the SCB is predominantly a mixture of two water masses: subarctic, characterized by low temperature, low salinity, and high oxygen; and equatorial, characterized by high temperature, high salinity, and low oxygen. Subartic water is advected equatorward in the California Current and turns shoreward and poleward in the SCB. Equatorial water is advected from the south into the SCB by the California Undercurrent. For each water

Figure 2.22. North-south (v) and east-west (u) components of velocity and speed at a location on the Santa Cruz sill, 50 m above the bottom.

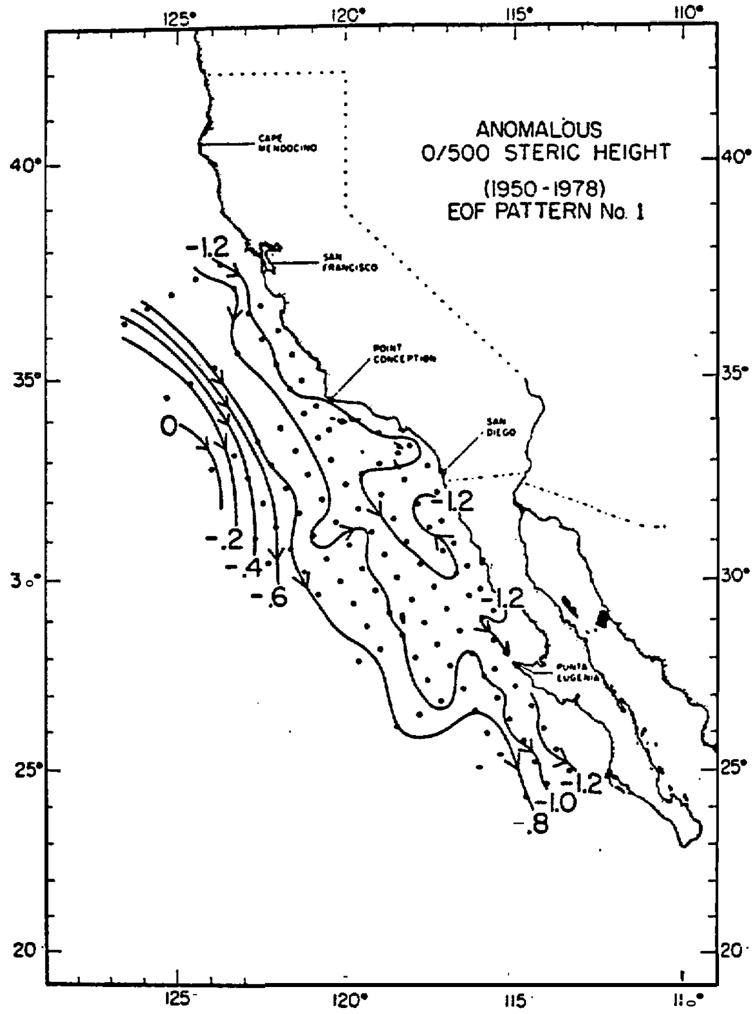

Santa Cruz Sill, 50 meters above bottom

mass, the characteristic properties decrease in the direction of the current pathway, indicating that mixing of the water mass has occurred (see Figures 2.10 and 2.11). Although the average seasonal patterns appear relatively smooth, the actual mixing is not smooth or continuous in either time or space. Rather, Gregg (1975) shows that the SCB is a region of spatially inhomogenous and active turbulent mixing. Water profiles typically demonstrate 5-30 thick layers of the interleaving water masses. The intrusions are sometimes recognizable over distances of a few km, but sometimes are not recognizable over distances as short as 2 km. The features disappear in a few hours, implying rapid mixing. Indeed, intense microstructure activity is observed at the vertical boundaries of the intrusions. Gregg (1975) attributes the mixing to shear instabilities as well as double diffusion phenomena.

INTERANNUAL FLUCTUATIONS

The California Current system, in which the SCB is embedded, undergoes significant year-to-year fluctuations (Chelton et al. 1982). Some of these fluctuations can be related to basin-wide processes such as occurrences of El Nine. In particular, the dominant EOF of the 0/500 db steric height data (a proxy, with certain assumptions for sea-surface height) for the Southern California region for the period 1950-1980 indicates a weakening of the equatorward flowing California Current during most El Nino periods and, of course, the reverse, between El Nino events (Figure 2.23). The relationship between the California Current fluctuations as represented by the principal EOF and the El Nino events can be seen by comparing the northward transport associated with the EOF pattern with the eastern tropical Pacific sea-surface temperature, which is often used as a proxy for the El Nino signal (Figure 2.24). This EOF accounts for roughly 30% of the interannual

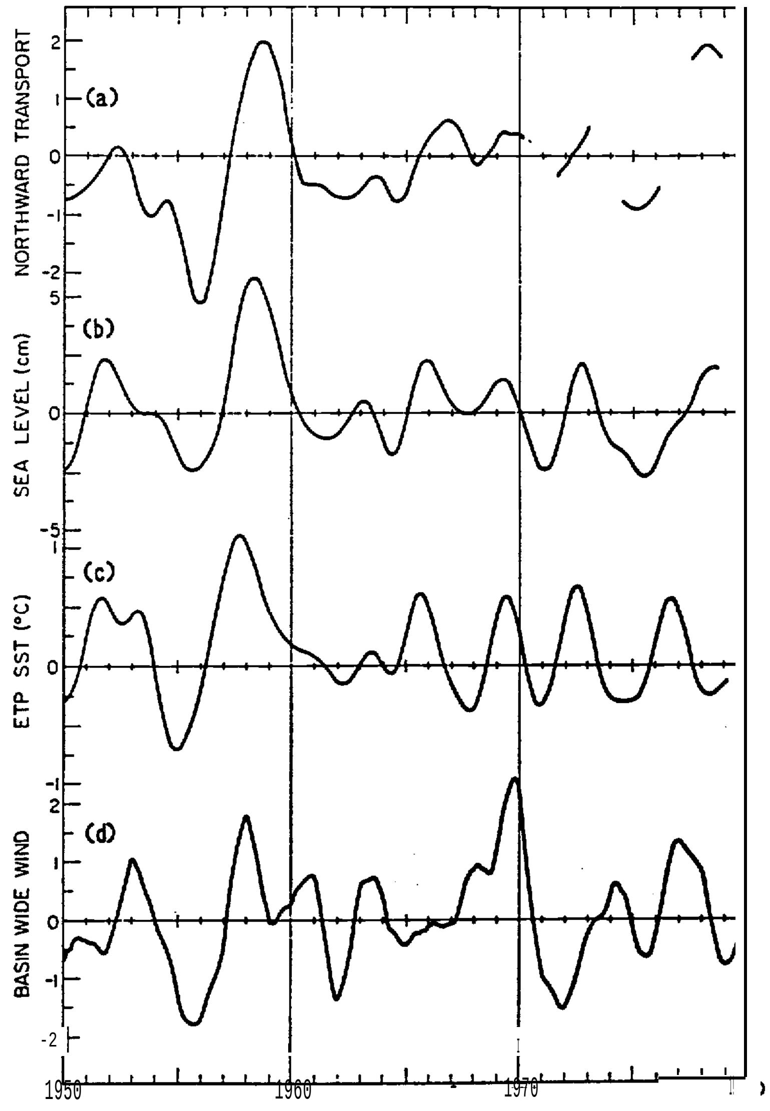
Figure 2.23. The principal spatial EOF of interannual 0/500 db steric height. The function values have been normalized to have a mean square value of 1. Arrows indicate direction of flow when the amplitude time series shown in Figure 2.24a is negative. Positive values of the time series correspond to a reversal in the anomalous flow (from Chelton et al. 1982).



ANOMALOUS
0/500 STERIC HEIGHT
(1950-1978)
EOF PATTERN No. 1

2.33b

Figure 2.24. Low frequency (double 13-month running mean) time series of: (a) northward transport; (b) the average California sea level at San Francisco, Los Angeles, and San Diego; (c) eastern tropical Pacific sea-surface temperature; (d) the amplitude time series of the principal atmospheric pattern (from Chelton et al. 1982).

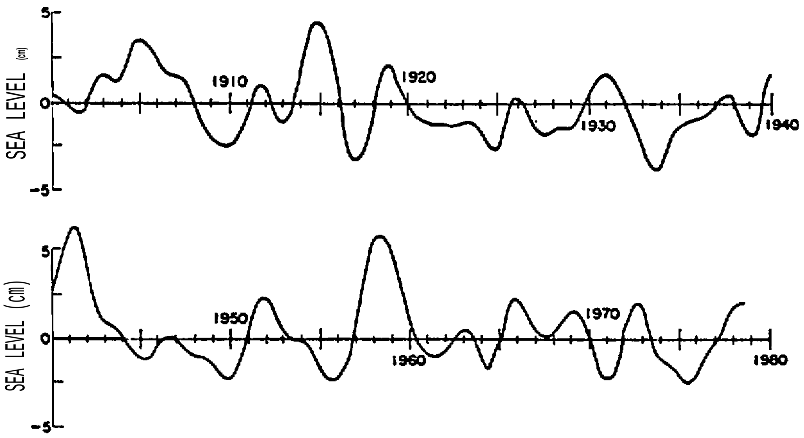

NORTHWARD TRANSPORT
(a)
2
1
0
-1
-2
SEA LEVEL (cm)
(b)
5
0
-5
ETP SST (°C)
(c)
1
0
-1
BASIN WIDE WIND
(d)
2
1
0
-1
-2
1950
1960
1970

variability in steric height. The amplitude pattern of the EOF decreases offshore, indicating that the largest interannual effects occur nearshore. The interannual changes in currents are on the order of 2-4 cm S-l (Chelton et al. 1982).

Chelton et al. (1982) demonstrate that coastal sea level for the period 1950-1980 is highly correlated with fluctuations in the transport of the California Current (Figure 2.24). The authors use this relationship to extrapolate the time series for interannual fluctuations in the California Current backward in time to 1900 (Figure 2.25). The data suggest that significant current fluctuations have occurred throughout this century, with a dominant period of 5-7 years. Related fluctuations also have been demonstrated for sea-surface temperature, as well as zooplankton volume in the California Current (Chelton et al. 1982). During El Nino events, the water is warmer than between El Nino events and zooplankton biomass is reduced. Temperature fluctuations are typically on the order of 1°C. Interannual fluctuations in sea surface salinity also occur (Chelton et al. 1982). However, the amplitude of these fluctuations is relatively small (approximately 0.1 ^{o}/oo), and the fluctuations do not demonstrate a fixed relationship to El Nino events. Interannual fluctuations in water properties throughout the water column are also expected. To our knowledge, however, these have not been examined.

The causes of the observed interannual variability in currents and water properties have not been unequivocally determined. However, coastal sea level data suggest that at least some of the variability may be due to the poleward propagation of coastal-trapped waves which originate in the tropics as a response to the El Nino phenomenon (Chelton and Davis 1982; Enfield and Allen 1983). The El Nino signal travels poleward at speeds of approximately 140 km d-l. This conclusion has recently been validated with

Figure 2.25. Low frequency (double 13-month running mean) sea level from 1900 to 1979 averaged over San Francisco, Los Angeles, and San Diego. With some caution, this time series can be interpreted as an index of large scale physical and biological variability over the last 80 years; low sea level corresponds to above normal equatorward transport and zooplankton biomass and vice versa for high sea level (from Chelton et al. 1982).


SEA LEVEL (cm)
5
0
-5
1910
1920
1930
1940
SEA LEVEL (cm)
5
0
-5
1950
1960
1970
1980

a two-layer model of the California Current system, forced by long waves of equatorial origin (that is, forced by the actual winds along the equator) as well as by local winds along the coast (Pares-Sierra and O'Brien 1989). Over 75% of the interannual variability in sea level in the SCB was accounted for solely by the equatorial (remote) forcing.

Not only do the seasonal means of currents and water properties exhibit interannual variability, the statistics of the fluctuations can also vary considerably from year to year. It is well known that coastal weather patterns undergo significant interannual variability, some of which is related to the occurrence of El Nine. For example, winter storms (during El Nine) tend to be more vigorous and coastal winds are more poleward (Huyer and Smith 1984). These differences in the strength and direction of the local wind field can affect the direction and strength of currents both over the basins and over the shelves for the several-day scale, as well as the depth of the mixed layer and the location of the thermocline. Moreover, year-to-year changes in the along-coast structure of the wind field can affect the relative importance of local wind forcing and remote wind forcing at a particular site. For example, coastal-trapped waves generated off Baja California might make important contributions to the Southern California Current variance during one year, but insignificant contributions the next year. Last, the mesoscale eddy and meander-jet field may be drastically altered by interannual changes in the local wind and thermal forcing.

BASIN WATER RENEWAL

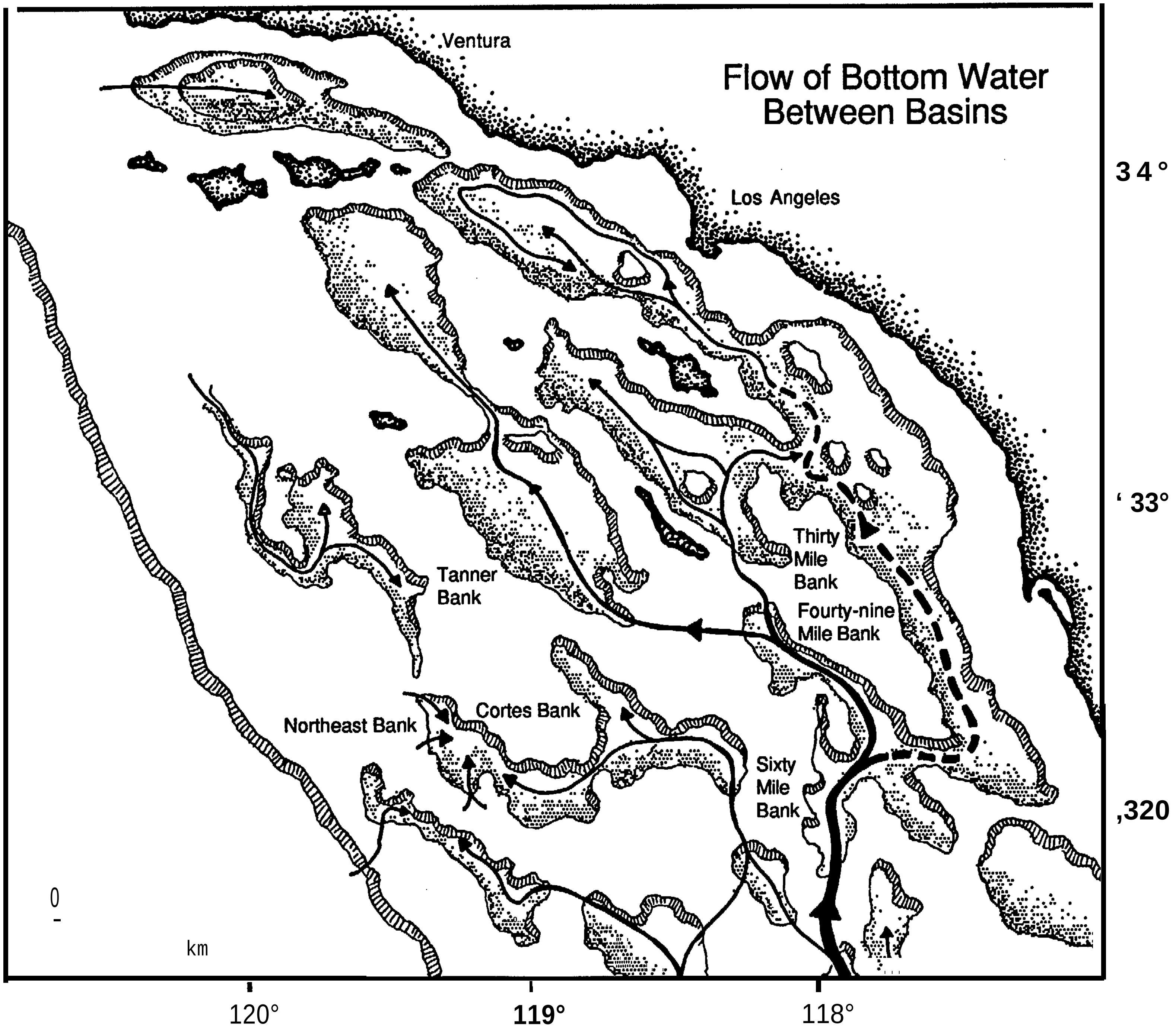
In each basin of the SCB the water is cut off from direct contact with other waters of the bight below the depth of the deepest sill of the basin; that is, horizontal advection of water is restricted by the basin walls. Renewal (or freshening, in the sense of an input of oxygen, which is depleted over time by organisms) occurs via either vertical mixing or by flow over the basin sills into the basins (Jackson 1986). Water flowing over the basin sills is generally denser than that at the same depth within the basin and therefore sinks to some deeper depth (often the basin bottom) where it spreads laterally and, presumably, also mixes (vertically and laterally) with the basin water. The "new" water flowing over the sill displaces "old" water from the basin.

Exact rates and mechanisms of renewal for the SCB are poorly understood. However, because the sills tend to shoal poleward, most of the basins are primarily renewed from the south (exceptions being the Santa Barbara Channel and Tanner Basin). This is illustrated by Emery (1960), who used water properties to trace the pathway of bottom water from basin to basin in the SCB (Figure 2.26). To our knowledge, this work has not generally been extended in the last 30 years, except in the Santa Monica-San Pedro basins. An array of current meters located around the perimeter of these basins demonstrate that the circulation below the deepest sill depth (>740 m) consists of a counterclockwise gyre (Hickey 1990b). Net speeds are on the order of 0.5 cm s^{-1}. In contrast with Emery (1960), Hickey's current data indicates net flow <u>from</u> Santa Monica Basin into San Pedro Basin on the western side of the mid-basin knoll (Figure 2.26). Several day-period fluctuations in the below sill-depth flow also occur, and the amplitude of these fluctuations is an order of magnitude greater than that of the mean flow (Hickey 1990b). These fluctuations appear to be related to upper water column (0-250 m) flow variability.

Current measurements on the sill that separates the San Diego Trough from San Pedro Basin suggest that some basin water renewal can occur several times each year (Hickey 1990b). However, CTD data illustrate that renewal

Figure 2.26. Paths followed by waters flowing from basin to basin in the Southern Continental Borderland as indicated by water properties. Width of lines is rough indicator of transport volume (from Emery 1960). Note new short arrows in Santa Monica and San Pedro basins, derived from direct measurement of currents (from **Hickey** 1990a).

2.36b


Flow of Bottom Water Between Basins

may occur during one year but not in the next **(Hickey 1990d).** These results are consistent with estimates based on oxygen consumption rates in the sediment (approximately 500 days; Jackson 1986). Renewal events, with current speeds of approximately 30 cm s^{-1} in the bottom approximately 100 m, occur over periods of several days. Water upwelled from the San Diego Trough over the sill into the San Pedro Basin during such events is approximately 1°C colder than water occurring at sill height in the basin. The ultimate fate of the water after it crosses the sill--in particular, the depth to which it sinks, how it spreads and mixes within the San Pedro-Santa Monica basins--is presently unknown, but is under investigation as part of an ongoing research program. Available CTD data on a long-sill transect suggest that current fluctuations (and, hence, renewal events) may be driven by upper water column (that is, 100-200 m) flow **(Hickey 1990b).**

Flushing rates of water in the Santa Barbara Channel Basin were studied with water property analysis during 1969-1971 (**Kolpack** 1971; **Sholkovitz** and Gieskes 1971). For this relatively shallow (590 m) basin, rapid water renewal was observed as a result of an intense coastal upwelling event off Point Conception. No continuous current measurements were available to determine the exact timing and frequency of such events, nor has the time-variable below sill-depth circulation been described. **CalCOFI** data indicate that the Santa Barbara Channel has overturned at least several times in the last 40 years, although not necessarily every year (**Sholkovitz** 1972). To our knowledge, water renewal rates and below sill-depth circulation in other California basins have not been studied.

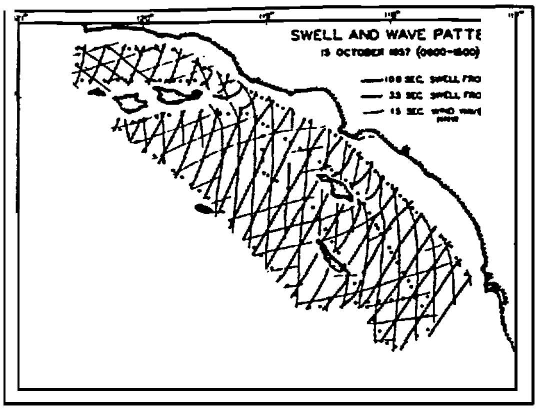
WAVE CLIMATE

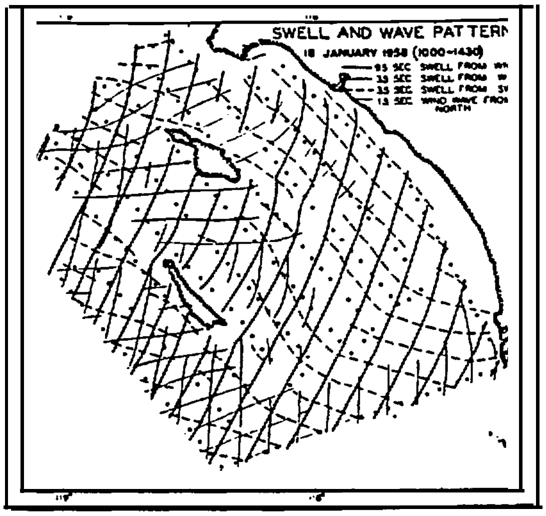
The best qualitative description of the seasonal wave climate in the SCB is given by Emery (1958). Data acquired during airplane flights were used to develop maps of wave and swell patterns for each season (Figure 2.27). Because the data were acquired using airplanes, there is an inherent "good weather" bias in the results, as we show below. The maps show that the predominant swell in all seasons is from the west-northwest, with periods near 10 s. This swell comes from the North Pacific. During summer, a longer period swell originating from the southern hemisphere can impinge on the area. Shorter period, southward traveling, locally generated wind waves are superimposed on the longer period swell.

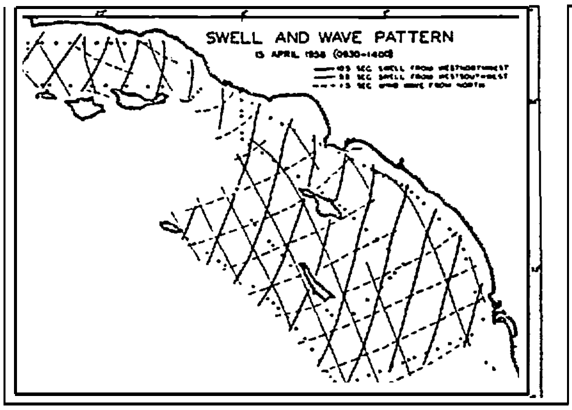
Since the mid 1970s, an array of wave measurement stations has been maintained along the California coast (Seymour and Sessions 1976). Data including significant wave height, wave period, and energy spectra are provided in monthly reports for each station. The data have been included in a database by the Minerals Management Service (Larson pers. comm.). Unfortunately, they have not, to our knowledge, been utilized to provide an updated qualitative summary of the wave climate in the SCB. Stations in the SCB are primarily located at the-coast, where sheltering effects are significant. However, at least one station is maintained at a relatively offshore location in the SCB (Begg Rock, in Figure 2.3).

Examples from the monthly data reports illustrate dramatically the sheltering effects of the islands; that is, the spectral amplitudes are an order of magnitude smaller at Sunset Beach than at Begg Rock (Figure 2.28a). The data also illustrate a seasonal change in the dominant swell period at Begg Rock from approximately 14-18 s in winter to 5-10 s in summer. The long period winter swell is generated by North Pacific storms, whereas the shorter period waves are generated more locally. At Sunset Beach the summer wave spectra are dominated by the very long period swell (16-18 s) coming from the southern hemisphere that was described by Emery (1958). Begg Rock is sheltered from this long period summer swell. Spectra during a major

Figure 2.27. Seasonal swell and *wave* pattern for the SCB (Emery 1958). Circles show positions of observation points along airplane flight lines. The spacing of swell and wind-wave crests is arbitrary and carries no implication regarding wave lengths.


SWELL AND WAVE PATTE
15 OCTOBER 1957 (0800-1500)
100 SEC. SWELL FRO
33 SEC. SWELL FRO
15 SEC. WIND WAVE NNW


SWELL AND WAVE PATTERN
18 JANUARY 1958 (1000-1430)
85 SEC SWELL FROM W
35 SEC SWELL FROM W
35 SEC SWELL FROM SW
13 SEC WIND WAVE FROM NORTH


SWELL AND WAVE PATTERN
15 APRIL 1958 (0830-1400)
105 SEC SWELL FROM WESTNORTHWEST
SEC SWELL FROM WESTSOUTHWEST
15 SEC WIND WAVE FROM NORTH

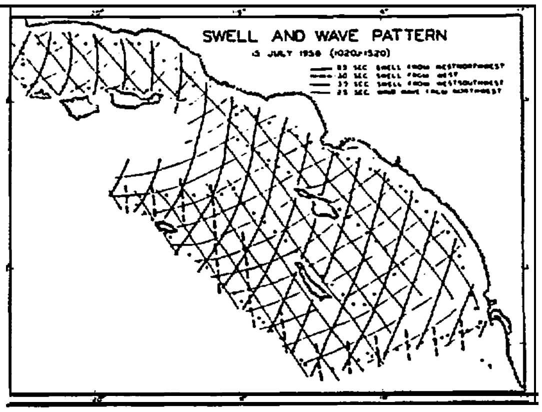
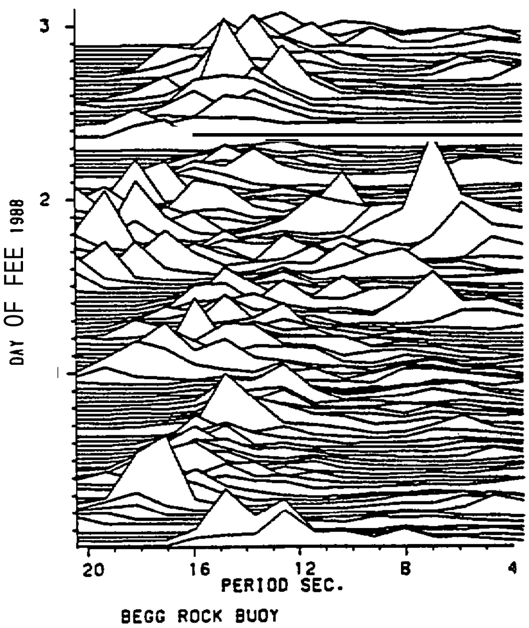
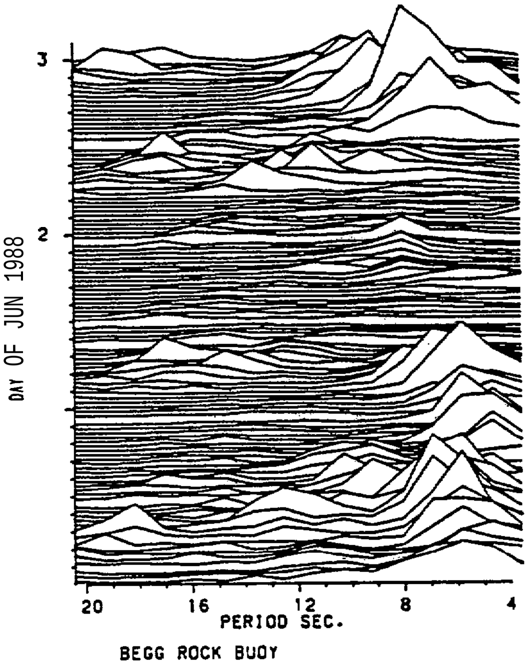

SWELL AND WAVE PATTERN
15 JULY 1958 (1020-1520)
SEC SWELL FROM WESTNORTHWEST
SEC SWELL FROM WEST
SEC SWELL FROM WESTSOUTHWEST
SEC WIND WAVE FROM NORTHWEST

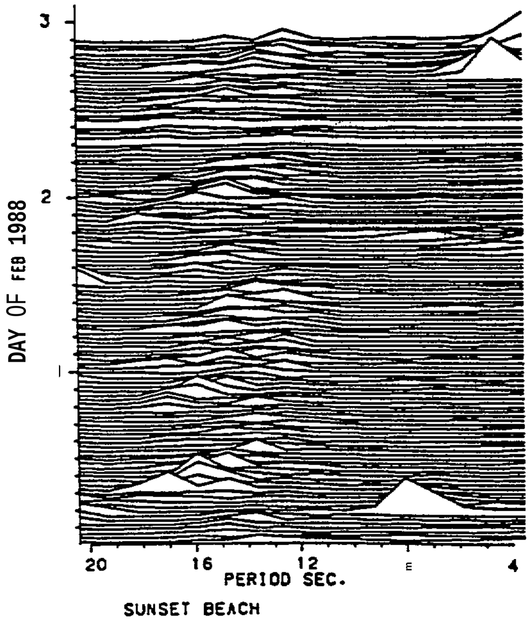
Figure 2.28a. Energy spectra of waves at Begg Rock and Sunset Beach during typical winter and summer months. Station locations are given in Figure 2.3. At 2041 on 2 February at Sunset Beach the total wave energy was 0.8 x 10^3 cm^2 and the significant wave height was 1.1 m. At the time of the largest peak at Begg Rock (0.8 x 10^3 on 17 February), the total energy was 4.8 x 10^3 cm^{-2} and the significant wave height was 2.S m (adapted from the Coastal Data Information Program 1988).

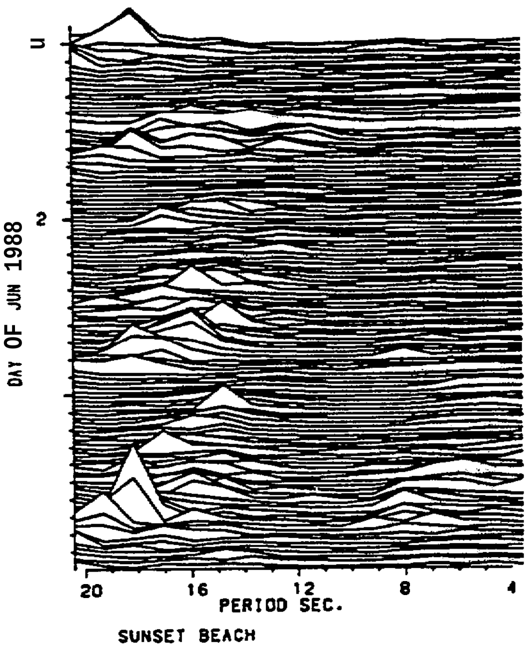
WAVE ENERGY SPECTRA FEB 1988

WAVE ENERGY SPECTRA J N 9 8







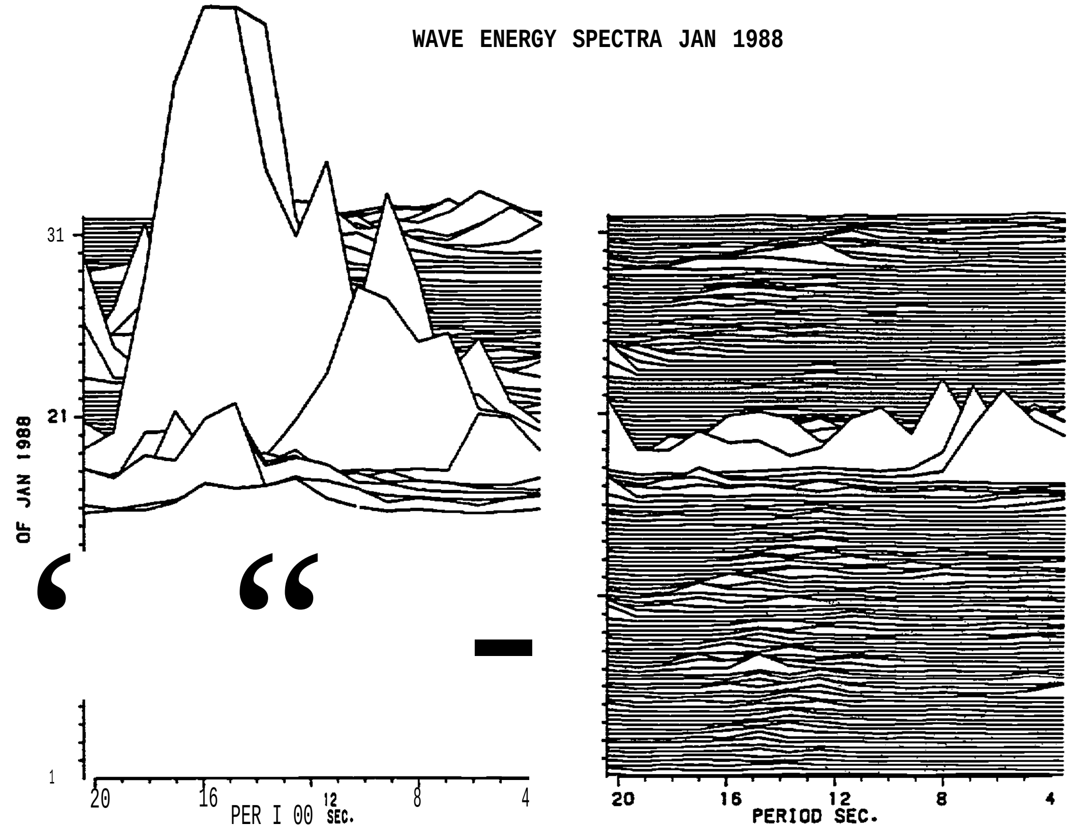


winter storm period are dramatically different from those during a typical winter period (Figure 2.28b). Severe waves such as these are usually generated from storms that develop between Hawaii and the Pacific coast. The wave amplitudes are an order of magnitude greater in all frequency bands. The dominant wave period is about 16 s. These waves are also felt at the coast, although their amplitude is significantly reduced (Figure 2.17).

The SCB is dotted with islands whose presence should alter the wave progression by reflection and refraction. In the Emery (1958) study, significant refraction was noted only near the mainland shores and near the islands. Cross-swell in the lee of islands was not detectable over large areas; nor was reflection. However, shorter period swells and wind waves were influenced by island shadowing effects. Since Emery (1958), research on the wave climate of the SCB has focused on the details of the effect of the islands on the wave climate. The offshore islands and ridges shelter the coast significantly from the effect of the deep-ocean gravity waves. Much of the wave energy is dissipated in island surf zones or reflected back to the deep ocean. Behind each island there is a shadow zone, wherein energy of a particular wave might be expected to be zero. However, the wave energy can be spread into the lee of islands by wave refraction, scattering over shoals, diffraction, wave-current interactions, and non-linear effects (Pawka et al. 1984). Wave refraction (Pawka et al. 1984) and non-linear effects are thought to be the dominant processes (Vesecky et al. 1980).

The waves in the SCB are refracted to impinge on the coast more directly shoreward. However, the direction is not exactly shoreward, and the interaction of the waves with the topography in the SCB generates a net southeastward longshore drift in the surf zone. This drift is responsible

Figure **2.28b.** Energy spectra of waves at Begg Rock and Sunset Beach, during a major winter storm. Station locations are given in Figure 2.3. At Sunset Beach at 0846 on 17 January the total wave energy was 2.5 x 10^3 cm^2 and the significant wave height was 2.0 m, whereas at Begg Rock at the peak of the severe storm at 1710 on the same day the total energy was 64.0 x 10^3 cm^2 and the significant wave height was 10.1 m (adapted from the Coastal Data Information Program 1988).



WAVE ENERGY SPECTRA JAN 1988

BEGG ROCK BUOY

SUNSET BEACH.

for much of the sediment movement along the coast (Emery 1960).

SUMMARY AND PROSPECTUS FOR FUTURE RESEARCH

Available data allow the characterization of many of the properties of the physical circulation in the SCB. Seasonal mean currents below the pycnocline over the slope are on the order of 20-30 cm s^{-1} and are generally poleward inside the SCB except, perhaps, in the immediate vicinity of local islands and banks. Above the pycnocline, it is likely that equatorward flow may occur, at least during spring. However, this has not been substantiated with direct current measurements. Seasonal mean currents over the shelf are smaller than those over the slope and tend to be equatorward, particularly in the very near-surface layers (<15 m) and over the mid- and outer shelf. Poleward sub-pycnocline flow is usually observed during summer and fall on the shelves. Several day scale pulses of currents are typically 20-40 cm s^{-1} in the upper 200 m of the water column. Tidal and higher frequency currents can be as large as 10 cm s^{-1}. Interannual differences in the currents are in the range of a few cm s^{-1}. Thus, instantaneous currents below the pycnocline in the upper 200 m over the slope can occasionally attain speeds as large as 60 cm s^{-1} over the slope and the basins. Speeds over the shelves are somewhat lower.

The circulation of the SCB is dominated by the effects of the large-scale Eastern Boundary Current system, the California Current. The California Current flows equatorward offshore of the Channel Islands, roughly 200-500 km seaward of the coast. The current has a seasonal maximum in summer. It bends shoreward south of San Diego, then poleward, recycling water through the SCB in the large-scale Southern California Eddy. During spring the eddy disappears, and flow at the surface tends to be equatorward throughout the SCB. A poleward undercurrent, the California Undercurrent, occurs in the SCB within approximately 100 km of the coast. Although specific details of the seasonal mean flow will differ from location to location within the SCB, the seasonal variation of the flow over the basins and their slopes (maxima in summer and winter), the existence of strong seasonal poleward means (except in surface layers during spring), and the general occurrence of subsurface maxima in the poleward flow (except, perhaps, in late winter and early spring) seem to be general and reproducible features of the flow field. The magnitude of the poleward transport varies from 0.S to 1.8 Sverdrups, with maxima in the late summer-fall period.

The dominant water properties are also determined by the large-scale current system. Relatively low temperature, low salinity, high oxygen, high nutrient water enters the system from the north via the California Current. Relatively high-temperature, high-salinity, low-oxygen water enters the system from the south via the California Undercurrent. Isopleths of most water properties bow upward to the outer edge of the SCB and downward across the rest of the SCB to the coast. During spring, properties also tilt upward to the coast in response to wind-forced seasonal upwelling. Properties vary seasonally at all locations as the strength of the large-scale current systems vary (changing the slopes of isopleths) and the local upwelling varies. Sub-pycnocline isopleths rise and fall as much as 50-100 m annually, attaining their shallowest depth during summer just offshore of the SCB and during spring on the coastal side of the SCB. Water properties also fluctuate on subtidal and supratidal scales, primarily in response to vertical advection by the flow field.

Large amplitude pulses of currents are superimposed on the seasonal means and it is these pulses, rather than the seasonal means, that should be considered in estimating particle transit times for the SCB. Transit times could range from a week to a month below the near-surface layers (0-30 m), and perhaps several times that in the surface layers, where at least the mean flow is generally much smaller. Although such pulses have to date only been examined in the Santa Barbara Channel and in the Santa Monica-San Pedro basins, it is likely that such pulses occur throughout the SCB. The scales of the pulses are shorter ($\leq$ 20 km) in the near-surface layers than deeper in the water column, suggesting that many of the pulses may be the result of relatively small-scale eddies. Such eddies might be generated, for example, as the large-scale flow is forced past the various islands and banks in the SCB. It is clear that <u>some</u> of the current pulses, at least next to the coast, are a result of coastally trapped long waves. Current fluctuations on the shelves are relatively less energetic than those over the slopes and basins. The fluctuating shelf currents on the wider shelves (20-30 km) are at least partially due to local wind-stress fluctuation.

The results summarized in this chapter demonstrate a clear difference between results obtained from large-scale hydrographic data and results obtained from direct current measurements. The direct measurements, in general, indicate much higher current speeds, because of the increased sampling frequency, and much richer spatial variability, when sufficient stations are included. It is clear that if particle residence times are an issue, direct current measurements must be included in experimental programs.

Information on surface currents in the SCB is particularly limited as the result of the difficulty and expense of maintaining surface current measurement arrays. Any future studies should include direct measurements of the near-surface currents and their vertical structure--which implies that a combination of EulerIan (moorings) and Lagrangian (drifters) techniques be employed.

Very little is known about the effect of the irregular topography that occurs in the SCB on either the large-scale mean currents or in the current pulses, such as propagating coastally trapped waves. In truth, little is known about such effects in any coastal region. Studies are just beginning on such processes and models are being developed that can resolve such effects as the scattering of shelf waves that occur near sharp bends in the topography or the generation of eddies by constrictions in the flow channel. The SCB might be an ideal candidate for testing models of this next generation. Of course, such a modeling study must include a set of direct measurements for ground truth analysis.

Acknowledgements

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CHAPTER 3 CHEMICAL OCEANOGRAPHY AND GEOCHEMISTRY

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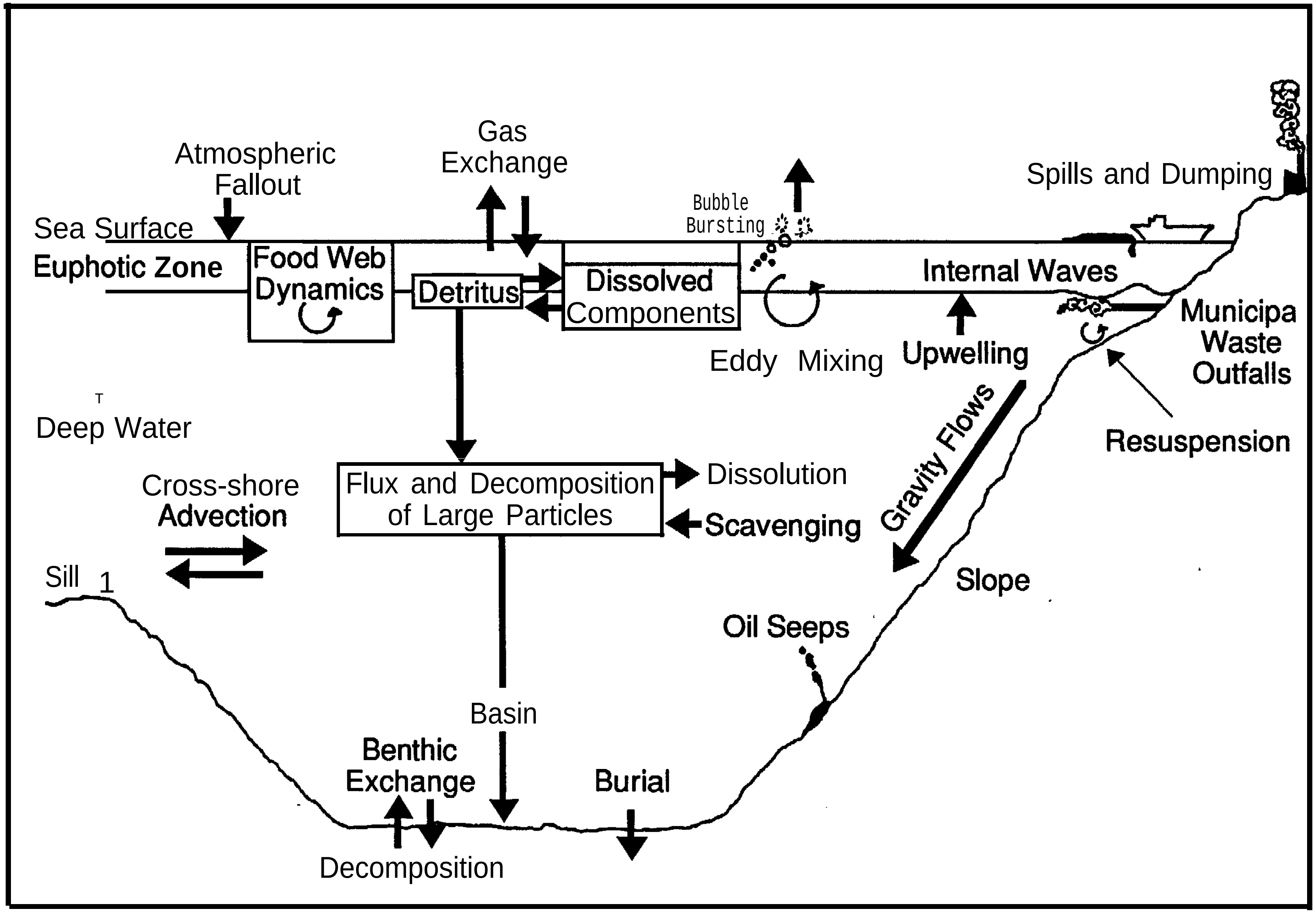
INTRODUCTION

BOUNDARY CONDITIONS AND OBJECTIVES

The Southern California Bight (SCB) comprises a network of deep-sea basins close to shore which trap coastal sediments. Water circulation is constrained below the basin sills, some of which are at depths intersecting the oceanic oxygen minimum zone. Consequently, nearshore (inner) basin sediments are anoxic and preserve sedimentation records. In addition, upper water column motions are also restricted by the land masses and by diminished local wind effects caused by coastal mountain topography. Because this is an eastern rather than a western boundary current, the general circulation is dynamically restricted (Jackson et al. 1989). These complex circulation patterns influence the biological as well as geochemical environments in the region. The geochemistry of the dissolved and particulate phases discussed in this chapter pertains to the water column from the sea-air interface to about 2000 m below. The sedimentary record is confined to a few hundred years. The chemical components are identified as autochthonous (formed *in situ* in the SCB of marine origin) or of allochthonous sources (not originally formed in the SCB, originating outside of the SCB and mainly land-derived).

The cycling and fate of chemical components and elements in the SCB are determined by a complex interplay of various biological, chemical, and physical processes (Figure 3.1). The elements most significantly affected by biological activity are those used by organisms for their cellular, structural, and energetic needs. Among these are carbon, nitrogen, phosphorous, and silicon. They are classified as "macronutrients" because they are assimilated in relatively large amounts (although sometimes present in low concentrations in the surrounding environment). One or more of these elements may become limiting, depending on the rates of supply and utilization. In the SCB the ratio of N:P in surface water is about 6, whereas the (Redfield) ratio in living phytoplankton is 16. This suggests that nitrogen is limiting in bight waters (Eppley and Helm-Hansen 1986). Other elements whose behavior could potentially be affected by biological cycles are among the list of so-called "micronutrients" (Fe, Mn, Cu, Zn, Mo, v, co). These elements are required by organisms only in trace amounts, and typically occur at sub-nanomolar to micromolar concentrations. Recent

Figure 3.1. Inputs and **biogeochemical** processes in the SCB. Arrows between boxes suggest flows of matter and energy (modified from **Carlucci** et al. 1986; Williams 1986a).


Atmospheric Fallout
Gas Exchange
Bubble Bursting
Spills and Dumping
Sea Surface
Euphotic Zone
Food Web Dynamics
Detritus
Dissolved Components
Internal Waves
Municipa Waste Outfalls
Eddy Mixing
Upwelling
Resuspension
T
Deep Water
Cross-shore Advection
Flux and Decomposition of Large Particles
Dissolution
Scavenging
Gravity Flows
Sill 1
Slope
Oil Seeps
Basin
Benthic Exchange
Burial
Decomposition

studies have indicated that the cycling of other chemical constituents believed to be non-essential (for example, Cd, Ni) may also be directly affected by the activities of living organisms (Bruland et al. 1978; Bruland 1980). Finally, biological activity indirectly affects the cycling of a variety of other non-essential elements and compounds by numerous mechanisms (such as scavenging, complexation by biogenic ligands, bioturbation, etc. These processes, which together control the spatial and temporal distribution of chemical substances in the SCB, will be discussed later in greater detail. The distribution of trace metals, naturally occurring radionuclides (23%, ^{23}*U, ^{210}Pb), stable isotopes (^{13}C, ^{15}N), and anthropogenic elements (^{239}Pu, ^{137}Cs, Pb, Cr, Cu, etc.) will be reviewed. Sources and fluxes of specific organic compounds as well as selected anthropogenic pollutants (DDT, PCBs, polycyclic aromatic hydrocarbons, etc.) will also be considered. The coupling between biological, physical, and chemical components of the system is emphasized in order to embody the dynamics of the ecosystem.

The chapter is presented in five parts. The first discusses the sources of inorganic and organic components in the SCB and attempts to provide budgets of the various inputs (organic carbon, water, and suspended or sinking particles). Water column dynamics is treated in the second section, which concludes with an overview of contaminant transport and fate in the water column, using specific examples. The third section provides a brief overview of sediment dynamics in the SCB. Here, physical transport processes are discussed and characterization of the sediments as well as the depositional environments are described. The fourth section focuses on the distribution and post-depositional fate of organic and trace inorganic substances in sediments of the SCB. The major findings are summarized in section five, where gaps in current knowledge are identified and recommendations are made concerning areas for further research.

SYSTEM DYNAMICS AND MAJOR PROCESSES

The material introduced into the water column is adsorbed on or incorporated into particulate which eventually settle to the sea floor (Figure 3.1). The relationship between the production of organic matter in oceanic surface waters and its decomposition and partitioning into different phases during transit through the water column prior to sedimentation can, therefore, best be understood from the geochemistry of sinking (or settling) particulate. Particulate organic matter **(POM)** is an important food source for many pelagic organisms, and the remineralization of associated organic matter affects the regeneration of nutrients (Knauer et al. 1979) and oxygen consumption (Suess 1980). Lipids, substances which are soluble in organic solvents such as methanol, **methylene** chloride, or hexane (Wakeham et al. 1980; **Gagosian** et al. 1982; Matsueda and Handa 1986), amino acids, proteins (Lee and **Cronin** 19S2; **Muller** et al. 19S6), and carbohydrates **(Tanoue** and Handa 1987) have been investigated in sediment trap particulate from various oceanic regimes, including the SCB (Crisp et al. 1979; Venkatesan and Kaplan 1987). The data from these studies suggest that microbial decomposition and zooplankton grazing also affect the flux and composition of organic matter associated with sinking particles.

DISTRIBUTION OF PHASES AND THEIR INTERRELATIONSHIPS

The dissolved, suspended, and sinking organic and inorganic matter and the deposited sediments are dynamically interrelated in the marine ecosystem. The dissolved material is arbitrarily defined as those materials passing through a filter having nominal pore sizes of 0.5-1.2 um, and it consists of both organic and inorganic components. The suspended particulate can be considered as those retained by 0.2-1 um nominal pore size filters (Williams 1986a). These fine particles are too small to sink rapidly through the water column (sinking flux <1 m d-l; McCave 1975) and, thus, can be horizontally advected to adjacent areas. The suspended particulate are comprised of organic detritus and clay minerals in addition to significant bacterial populations (Williams 1986a). Because of the ease of lateral advection, the suspended particles may not reflect the true characteristics of the overlying surface waters.

Rapidly sinking materials are collected by sediment or "particle interceptor" traps deployed in the water column over various time intervals ranging from a few days to a few months. The large particles such as fecal pellets and "marine snow," aggregates of living and detrital organic material (Silver and Alldredge 1981) account for most of the vertical settling flux of organic and inorganic detritus because of their high sinking rates (Deuser and Ross 1980; Honjo and Roman 1978), although they comprise only a small part of the total particulate matter pool in seawater.

Settling (sinking) particles can play a major role in removal of dissolved components (that is, radionuclides, metals, organics, and other materials) from the euphotic zone into subsurface waters (Goldberg 1961; Lal 1977). Studies of Williams and Zirino (1964), Suess (1970), and Meyers and Quinn (1973) suggest that metal oxides scavenge a portion of the dissolved organic matter and that amino acids and lipids are probably adsorbed onto clay minerals and carbonates. However, particles repackaged (metabolically altered) by bacteria and other microheterotrophs from dissolved and suspended organic material are believed to provide organic matter to zooplankton at depth (Fuhrman et al. 1980; Figure 3.1).

Upwelling (from March to June in the SCB) processes can also transport fine particles to the surface, where they coalesce to form larger particles, repackaging organic and inorganic matter. These, in turn, can be ingested by zooplankton and expelled as sinking fecal pellets. Thus, some chemical components are found at enhanced concentrations farther offshore as a result of the remobilization and recycling of fine particles (Williams 1986a). Both dissolved material and suspended particulate are also scavenged by marine snow (Silver and Alldredge 19S1).

Even though a number of data sets are available on the vertical distribution of soluble and suspended particulate inorganic and organic components in the SCB, especially from the nearshore environment (compare references in Eppley 1986; Johnson et al. 1988; Williams and Druffel 19S7), the complex chemistry of these phases is not well understood. Information regarding sinking particulate matter is scant and i's just beginning to accumulate (Crisp et al. 1979; Venkatesan and Kaplan 1987, 1988; Williams 1987, 1988; Southern California Coastal Water Research Project 19S7).

PREVIOUS STUDIES

The fate of chemical (inorganic and organic) components in the SCB sediments has been both studied and reviewed rather extensively by a limited number of groups such as Southern California Coastal Water Research Project (SCCWRP), the University of California at Los Angeles and at San Diego (UCLA, UCSD), the Los Angeles County Sanitation Districts (Joint Water Pollution Control Plant, JWPCP), and the Department of Energy-sponsored California Basin Study (CaBS) Program (Thompson et al. 1986; Mankiewicz et al. 1978; Venkatesan et al. 1980; Eganhouse and Kaplan 1988; Eppley 1986; Katz and Kaplan 1981; Stun et al. 1986; Finney and Huh 1989; and Jackson et al. 1989, among others). Dissolved inorganic nutrients (NH_4^+, NO_3^-, PO_4^{-3} and $SiO_3^{'2}$) and other hydrographic properties have also been measured in coastal waters of the SCB since the early part of this century (compare references in Williams 1986a). Major research programs in progress or recently completed in the SCB are listed in Table 3.1. Extensive programs concerned with element cycling and food-chain relations evolved after 1945 at the Scripps Institution of Oceanography (UCSD). These included efforts by the Marine Life Research Group and the Food Chain Research Group (FCRG), results of which are summarized in numerous papers and unpublished reports. The work done by FCRG from 1974 through 1984 on primary production, plankton biomass, organic detritus, and nutrient distributions has recently been summarized in a book by Eppley (1986). In addition, California Cooperative Oceanic Fisheries Investigations (CalCOFI), a hydrographic monitoring program, has maintained an extensive sampling effort on a regional basis since 1949. The sampling grid consists of stations stretching from California's northern border to the tip of Baja California, Mexico (Figure 2.15 in Jackson 1986). Approximately 12 of these stations fall within the confines of the SCB as defined here.

As one might expect, information on the distribution and, particularly, the post-depositional fate of organic and inorganic substances in a region as large as the SCB is extremely spotty. The first and only systematic bight-wide survey for a variety of inorganic and organic substances in sediments was initiated in the mid-1970s under auspices of the Bureau of Land Management (BLM). This project involved extensive chemical analyses of sediments (mostly surface sediments) collected throughout the SCB and sinking particulate from four stations. Much of these data remain unpublished, although a few papers attempting to summarize aspects of the project have appeared in the primary literature (Crisp et al. 1979; Ng and Patterson 1982; Reed et al. 1977; Venkatesan et al. 1980).

In 1969 SCCWRP was established for the purpose of investigating the

Table 3.1. Major studies in oceanography and geochemistry in the SCB.

Type of Study	Program (Agency)	Time Frame	Source of Data
Nutrients, hydrography, elemental cycling, food-chain relations	Marine Life Research Group and Food-Chain Research Group (FCRG) (Department of Energy)	1945 to 1984	papers, reports, Eppley 1986
Hydrographic monitoring program	California Cooperative Oceanic Fisheries Investigations (CalCOFI) (State of California)	1949 to date '	annual reports of CalCOFI conferences, atlases Eppley 1986
Upwelling studies	Organization of Persistent Upwelling Structures (OPUS) (National Science Foundation)	1981 to date	reports, papers
Chemical and biological studies	Southern California Baseline Study (Bureau of Lend Management)	1976-1979	reports, papers
Coastal pollution	Southern California Coastal Water Research Project (SCCWRP) (Five agencies of local government sanitation districts)	1969 to date	annual, biennial reparts, papers
Biogeochemical cycling	California Basin Studies (CaBS) (Department of Energy)	1985- to date	reports, papers

ecology of the SCB and, in particular, effects of human activity on the coastal ecosystem. SCCWRP has conducted extensive surveys of chlorinated hydrocarbon and trace metal distributions in sediments around the major municipal waste outfall systems on the continental shelf as well as in outfall effluents and storm runoff. Results of these studies have appeared in a series of annual and biennial reports (SCCWRP 1973, 1974, 1975, 1976, 1978, 1980, 1982, 1987) and in numerous publications (Mearns et al. in press).

In 1985, the multidisciplinary project known as CaBS was initiated and funded by the U.S. Department of Energy (California Basin Study; Jackson et al. 1989). The purpose of this project is to gain a better understanding of the processes responsible for the cycling of natural and anthropogenic substances in California's nearshore basins. A wide range of organic and inorganic chemical constituents are being measured in basin sediments as well as in dissolved and particulate material settling in the water column in an effort to reconstruct the depositional history of the sediments and to evaluate the linkage between biogeochemical cycling in the water column and processes occurring at the sea floor. These and other studies currently ongoing will greatly enhance our understanding of the dynamics of the basin systems.

In a recent report titled "The State of Santa Monica Bay," the Southern California Association of Governments (SCAG 1988) summarized a significant portion of the data gathered by SCCWRP, City of Los Angeles (Hyperion), and Los Angeles County (JWPCP) treatment plants on effluent characteristics, chemistry of sediments, and biota in the vicinity of the outfalls.

SOURCES

The organic matter and trace elements in the marine ecosystem are contributed by autochthonous (marine) as well as allochthonous (terrestrial) sources. The marine component in the SCB derives from primary production and submarine oil seeps. The major inputs of terrestrial origin include domestic and industrial waste discharges, surface runoff from rivers and urban storm drains, dry and wet atmospheric fallout, ocean dumping, and eroded shales from coastal areas. The nature and magnitude of waste discharges and runoff are better characterized than the diffuse sources such as atmospheric fallout and ocean dumping. Data on erosion of the Monterey shale deposited along the coast of California is scant. oil seepage could be an episodic or a chronic event, whereas inputs from sewage are essentially constant (Table 12.1, Chapter 12). In contrast, storm runoff is episodic and mostly active during winter months (December to February, but occasionally extending into September, October, and March). In addition, strong north and northwesterly Santa Ana winds during spring and summer (March to July) blow seaward down slopes and valleys from the deserts and influence aerial fallout in the SCB. An attempt is made here to evaluate and estimate the magnitude of inputs of the organic and trace metal constituents from these various recognizable sources to the SCB. For a more detailed treatment of spatial and temporal distribution of selected anthropogenic inputs, refer to Chapter 12.

AUTOCHTHONOUS SOURCES

The mean primary production (P) of the SCB is calculated to be 390 mg C m^{-2} d-l based on the empirical algorithm developed by Eppley and Helm-Hansen (1986), where

$$P = \exp(-3.78-0.372T + 0.227D)$$

D = daylength set at 12 hours, and T = temperature anomaly assumed to be zero. Using this expression, one arrives at a total production over the approximate area of the SCB (78,000 km^2, after Emery 1960) which ranges from 1.1 to 1.6 x 10^7 mt of carbon per year (Table 3.2) compared to the average global oceanic primary production of approximately ‘3 x 10^{10} mt of C per year. Thus, the primary production in the SCB (approximately 400 mg C m^{-2} d-l) is nearly twice the average oceanic value, and it falls in between the ranges estimated for the Peru upwelling region (approximately 1000 mg C m^{-2} d-l) and the Scotia Sea of the Antarctic Ocean (approximately 200 mg C m^{-2} d-l; Eppley and Helm-Hansen 1986). However, the SCB is rich in primary productivity relative to the central subtropical gyre of the North Pacific (approximately 200 mg C m^{-2} d-l; Eppley and Helm-Hansen 1986). The Eppley and Helm-Hansen study covered a region encompassing the San Diego Trough, the Santa Monica and San Pedro basins, and the narrow coastal strip of continental shelf between Los Angeles and San Diego (Figure 1.4 in Carlucci et al. 1986). It did not extend offshore beyond 107 km or north towards Santa Barbara Basin and Point Conception, where surface primary productivity is generally higher than in the central and southern parts of the SCB (Owen and Sanchez 1974). The total bight-wide production estimate, therefore, is probably at the lower limit.

In addition to phytoplankton, microzooplankton also contribute to the particulate and organic matter to the sediments. On average, about 132 mg C m^{-2} d-l of particulate organic carbon was contributed to the ocean by microzooplankton in 1967, Beers and Stewart 1970) estimated on the basis of data taken at three stations off La Jolla. Carbon from microzooplankton comprised about 20% of total zooplankton carbon in the upper 100 m. Extrapolating from this value, the C contribution from total zooplankton of the SCB is estimated to be about 1.9 x 10^7 mt yr^{-1} (Table 3.2), assuming again the area of the SCB to be 78,000 km^2. Zooplankton and phytoplankton,

Table 3.2. Particulate, water, and total organic carbon budgets for the SCB,

	Input Rates		
	Particulates[a] (mt yr^{-1})	Water (1 yr^{-1})	Total Organic Carbon (mt yr^{-1})
Autochthonous inputs			
Primary production	4.1×10^{7} [b]		$1.1\text{-}1.6 \times 10^{7}$ [c]
Zooplankton	3.8×10^{7} [d]		1.9×10^{7} [d]
Oil seeps	$2 \times 10^{3}\text{-}5.8 \times 10^{4}$		$1.4 \times 10^{3} - 3.9 \times 10^{4}$
Advective flow of California Countercurrent and Undercurrent		$2.5\text{-}5.7 \times 10^{16}$ [e]	$1.2\text{-}2.7 \times 10^{7}$ [e]
Allochthonous inputs			
Municipal waste discharges	2×10^{5} [f]	1.7×10^{12} [f]	5.0×10^{4} [f]
Industrial waste discharges:[e]			
a. Petroleum-related	3.4×10^{3}	1.1×10^{11}	
b. Metallic, fish cannery, miscellaneous chemical	2.1×10^{3}	3.5×10^{10}	
Thermal discharges		7.7×10^{12}	
Surface run-off			
Sediments	9.6×10^{6} [g]		
Suspended solids	$2.7\text{-}5.4 \times 10^{5}$ [h,e]	2.4×10^{11} [e]	$1.5\text{-}6.7 \times 10^{4}$ [e]
Shale erosion	6.4×10^{4}		$6.4 \times 10^{2} - 1.2 \times 10^{4}$
Dumping (dredge material)	$5.8 \times 10^{5} - 1.4 \times 10^{6}$		$9.5 \times 10^{3} - 2.4 \times 10^{4}$ [i]
Atmospheric deposition:			
a. Dry fallout			
fine particulate	$8.9 \times 10^{3}\text{-}8.9 \times 10^{4}$		$2.1 \times 10^{3}\text{-}2.1 \times 10^{4}$
fine elemental carbon			$3.4 \times 10^{2}\text{-}3.4 \times 10^{3}$
total suspended particulate	$2.9 \times 10^{4} - 2.9 \times 10^{5}$		
b. Rain washout	?	?	?
Particulate interceptor trap measurements	$1.9\text{-}7.1 \times 10^{7}$ [j]		$1.3\text{-}3.6 \times 10^{6}$ [j]

---

[a] Particulates, sediments, or suspended solids except for oil seeps, where the liquid oil is referred to.

[b] Based on phytoplankton production (500 g m^{-2} yr^{-1}) and attached marine algae and sea grass (20 g m^{-2} yr^{-1}) data of Emery (1960).

[c] Based on primary productivity $\cong$ 0.39 g C m^{-2} d^{-1} (Eppley and Helm-tlansen 1986) and 0.46 to 0.56 g C m^{-2} d^{-1} (Smith and Baker 1982).

Table 3.2. (continued)

[d] Average POC of microzooplankton = 0.132 g C m^{-2} d-l (Beers and Stewart 1970). This constitutes about 20% of total zooplankton carbon in the upper 100 m. Extrapolating to total zooplankton, POC = 0.66 g C m^{-2} d-l. Assuming TOC is 50% of the particulate flux from zooplankton (macro- and micro-zooplankton), total particulate flux from the zooplankton can be estimated.

[e] Hickey (Chapter 2); organic carbon based on dissolved organic carbon = 40 urn 1^{-1} (after Williams 1986a and Holm-Hansen et al. 1966).

[f] Average of 1984 to 1986 data (SCCWRP 1987) computed for particulate and water. TOC calculated from refractory organic carbon (≅ 25%) (from Eganhouse and Kaplan 1988 and fram coprostanol data of Venkatesan and Kaplan 1989).

[g] Schwalbach ond Gorsline (1985).

[h] Based on Eganhouse and Kaplan (1981); Eganhouse (1982).

[i] Inputs calculated from a single dumpsite based on the range of amount allowable for disposal.

[j] Recent estimote for the SCB of average flux of total mass and organic carbon from February-May and May-October 1986 trap deployments off Santa Monica Basin from 850 m and 350 m water depths (Williams 1986b; Jackson et al. 1989).

For **remaining dots, refer to text for explanation.**

thus, apparently contribute equally to the organic carbon and particulate matter in the ocean. However, only a small fraction of these inputs eventually get deposited in the sediments. While about two-thirds of the primary production may be recycled in the **euphotic** "zone, the remaining third sinks out of this **euphotic** zone, most probably as aggregates of fecal pellets, etc. The sinking flux of particulate appears to be correlated with surface primary production (Deuser and Ross 1980; **Honjo 1982).**

The carbon from primary productivity is augmented by inputs from local natural oil seeps in the SCB that have been active throughout the Holocene **(Wilson et** al. 1974). The **circum-Pacific** belt, including the **SCB,** is estimated to contribute approximately **48%** of the total global marine petroleum seepage (0.27 x 10^6 out of 0.6 x 10^6 mt; Wilson et al. 1974). Of the total 190 seepages cited by Wilson et al. (1974), about 60 zones were located by Wilkinson (1972) in the 2600 km^2 offshore California area from Point Conception to Long Beach. Some zones are continuously active, while others are only sporadically active. Estimates of seepage rates range from 16 m^3 d-l to more than 160 m^3 d-l (Allen et al. 1970; Wilson 1973). Surprisingly little comprehensive compositional information on these natural **oil** seeps exists except for the reports of Delaney (1972), **Sivadier** and **Mikolaj** (1973), and Reed and Kaplan (1977). Since direct information pertaining to seepage rates from many areas is scant, any organic matter input from seeps can only be estimated crudely. The active areas in the SCB from Point Conception to Long Beach can be estimated to have contributed seep material in the 1970s in the range of 2-56 x 10^3 mt yr'^{1} (after multiplying the volume of seep, 2.3-58 x 10^3 m^3 **yr^{-1}** [Wilson et al. 1974 ; Fischer 1978], by the average specific gravity [0.9,7 g cm'^{3}] of California oils [**Tissot** and **Welte** 1981]). Assuming that the seep oil contains approximately 70% organic carbon, the total organic carbon **(TOC)** input to the SCB can be approximated to be 1.4 x 103-3.9 x 10^4 mt yr^{-1} (Table 3.2). This is an upper limit estimate of TOC contribution from seeps because a significant portion of the nearshore seeps is probably gradually incorporated into the food web (Spies and DesMarais 1983).

Advection via the California Current could play a significant role in mobilizing autochthonous as well as allochthonous materials in various regions of the SCB (Drake et al. 1985). However, limitations in the available data currently make it difficult to calculate the fluxes of various constituents. Nevertheless, mass transport' rates of some trace components were estimated by SCCWRP (1973). Assuming that the trace metal and chlorinated hydrocarbon concentrations of open ocean waters are representative of California Current waters and that the advective flow rate of the California Current is about 2 x 10^{13} m^3 yr^{-1}, they (SCCWRP) estimated that the mass transport rates of trace metals, DDT, and PCB by advection far exceed the mass emission rates from all other sources. Based on the recent measurements of Hickey and Kachel (pers. comm. 1989), these values could be even higher since the advective flow rate of the California Current determined by these authors is greater by a factor of about 10 (1.8-2.5 x 10^{14} m^{3} yr^{-1}). Estimates of mass emission rates in California Current waters such as these probably represent upper limits because the California Current generally flows outside of the Santa Rosa-Cortes Ridge and, thus, essentially bypasses the SCB. The mean circulation in the SCB is dominated by the poleward surface (the California Countercurrent) and subsurface flows (the California Undercurrent; Chapter 2). Considering the magnitude of this poleward transport (which varies from2.5 to 5.7x 10^{13} m^3 yr^{-1}; Chapter 2), the mass transport rates of several trace metals, DDT, and PCB are recalculated here, using the concentration data of SCCWRP (1973); they are presented in Table 3.3. An estimate of the advected organic carbon is included in Table 3.2. Note again that the advective flow of the California Countercurrent could transport enormous quantities of land-derived components to the entire SCB.

ALLOCHTHONOUS SOURCES

Seven of the largest municipal waste dischargers (Oxnard, Hyperion, JWPCP, CSDOC, SERRA, Encina, and Point Loma) release, on average, 1.7 x 10^{12} l of water and 2 x 10^{5} mt of suspended solids into the coastal waters of the SCB annually (SCCWRP 1987). In addition, wastewaters from petroleum-related industries, metallic, fish cannery, and others discharge waste and cooling waters of the order of 1.5 x 10^{9} and 8 x 10^{12} l yr^{-1}, respectively. The volume of surface runoff from storm drains and rivers which enters the coastal waters could be quite comparable to that from municipal wastes (2.4 x 10^{11} l yr^{-1}), or 1-2 orders of magnitude greater during episodic flooding (Schwalbach and Gorsline 1985). A flow of about 1000 times as great as the total combined flows listed above is also estimated to contribute by advected ocean water (2.5-5.7 x 10^{16} l yr^{-1}) to the SCB (Chapter 2). Consequently, a wide variety of organic and inorganic components are introduced into the water as well as sedimentary environments. It is, therefore, pertinent to estimate the influences of these important external sources on chemical balances in the SCB.

About 80% of the municipal effluent produced in the coastal counties of Southern California is directly discharged into the coastal waters of the SCB (SCCWRP 1973). Part of the approximately 20% that remains is reused; the rest is discharged at different inland locations and probably transported to the ocean via surface runoff. Consequently, significant amounts of suspended solids (Table 3.2) from the effluents containing a wide

Table 3.3. Estimated mass emission or transport rates (metric tons per year) of selected organic compounds and trace metals to the SCB.

Constituent	Municipal wastewater	Surface run-off	Oil seeps	Shale erosion	Vessel[f] coating
Total organic carbon[a]	5×10^4	$(1.5\text{-}6.7)10^4$	1.9×10^3	6.4×10^2- 1.2×10^4	
Hydrocarbons	1.7×10^4 [b]	$<9.7\times10^3$ [c]	greater than the above values		
Total DDT	0.05 [d]	0.1 [e]			
Total PCB	0.25 [d]	0.1 [e]			<1
Coprostanol	260 [k]	?			
Silver	15 [d]	0.3 [e]			
Chromium	60 [d]	37 [e]			1
Mercury	<1 [d]	0.3 [e]			4
Lead	64 [d]	51 [e]			10
Copper	135 [d]	31 [e]			386

Table 3.3.(continued) Estimated mass emission or transport rates (metric tons per year) of selected organic compounds and trace metals to the SCB.

Constituent	Ocean [f] dump ing	Rainfall washout	Dry fallout	Advective transport [1]	sum of columns 1-8
Total organic carbon[a]	9.5xlo^{3}- 2.4x10^{4}		2.1xlo^{3}- 2. 1X10^{4}	1.2-2.7x10^{7}	$\underline{<}$1.7x10^{5}
Hydrocarbons					>2.7x10^{4}
Total DDT	<1		0.5-2 “i	250-570	$\underline{<}$3
Total PCB	<1		approx. 2 [h]	250-570	$\underline{<}$4
Coprostanol					260
Silver	1.5	33 [g]		7.5X10^{3}-1.7X10^{4}	50
Chromium	28	78 [g]	51 [j]	5X10^{3}-1.1X10^{4}	255
Mercury	1.5	* [f]		7.5X10^{2}-1.7X10^{3}	14
Lead	28	1014 [g]	1872 [j]	7.5X10^{2}-1.7X10^{3}	3039
Copper	28	390 [g]	242 [j]	7.5X104-1.7X10^{5}	1212

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[a] see Table 3.2.

[b] **Eganhouse** and Kaplan 1982.

[c] **Eganhouse** and Kaplan 1981.

[d] 1987 data from **SCCWRP** 1987.

[e] Young et al. 1980. Data reported for water year October 1978-September 1979 from Los Angeles River, San Gabriel River, and **Ballona** Creek.

[f] **SCCWRP** 1973.

[g] Calculated from **Lazrus** et al. 1970 and **Bruland** et **al.** 1974.

[h] Bascom et al. 1979.

[i] Young et al. 1976.

[j] Young and Jan 1977. The estimated input in a 100-by-100 km zone off Los Angeles and Orange counties in 1975 is extrapolated here to the total area of the SCB.

[k] **Venkatesan** and Kaplan 1989.

[1] Advective flow rate and organic carbon, see Table 3.2.; concentration in water of other constituents from **SCCWRP** (1973).

spectrum of organic and inorganic constituents are deposited along the coastline or find their way to deeper parts of the basins.

Municipal waste discharge is the major contributor of anthropogenic heavy metals and chlorinated hydrocarbons to the shelf sediments (Brown et al. 1986; Kettering 1981; Stun et al. 1988; Venkatesan et al. 1980; and Young et al. 1977a, among others). Quantitative estimates of inputs of these various components from waste discharges have also been computed since 1971, much of this work emanating from the systematic studies at **SCCWRP** (Biennial and Annual Reports). Since 1971, the flow of water has increased by approximately 30%, while suspended solids have been reduced by approximately 50$ (see Figure 12.2). Sharp decreases in emissions of trace contaminants from the **outfalls** have been observed since monitoring began in 1971 (**SCCWRP** 1987). The output of DDT appears to have attained a plateau around 50 kg yr^{-1} from 310 kg **yr**$^{-1}$ in 1984, but PCBS have declined steadily from 1340 to 250 kg **yr**$^{-1}$ (Figure 3.2; see Figure 12.3). With the exception **of** silver, 9 of the 10 measured metals (As, Cd, Cr, Cu, Hg, Ni, Pb, **Se, and Zn)** are at lowest reported levels (Figure 3.3).

Municipal wastewater particulate contain approximately 25% of refractory organic carbon (**Eganhouse** and Kaplan **1988;** Myers 1974). Considering that the average annual mass emission of total suspended solids from major discharges of SCB during 1984-1986 is approximately 2 x 10^{5} **mt** (**SCCWRP** 1987), municipal **outfalls** should contribute at least 5 x 10^{4} mt yr^{-1} of organic carbon to the oceanic regime. This value agrees remarkably well with the estimate of sewage carbon calculated from the fecal **sterols (coprostanol** and **epicoprostanol)** content in the wastewater effluents (**Venkatesan** and Kaplan 1990). This estimate is slightly larger than the organic carbon possibly contributed to the SCB from oil seeps and 3 orders of magnitude less than that from primary productivity. It is interesting to

Figure 3.2. Mass emissions (metric tons yr^{-1}) of DDT and PCBS to the SCB (SCCWRP 1987).

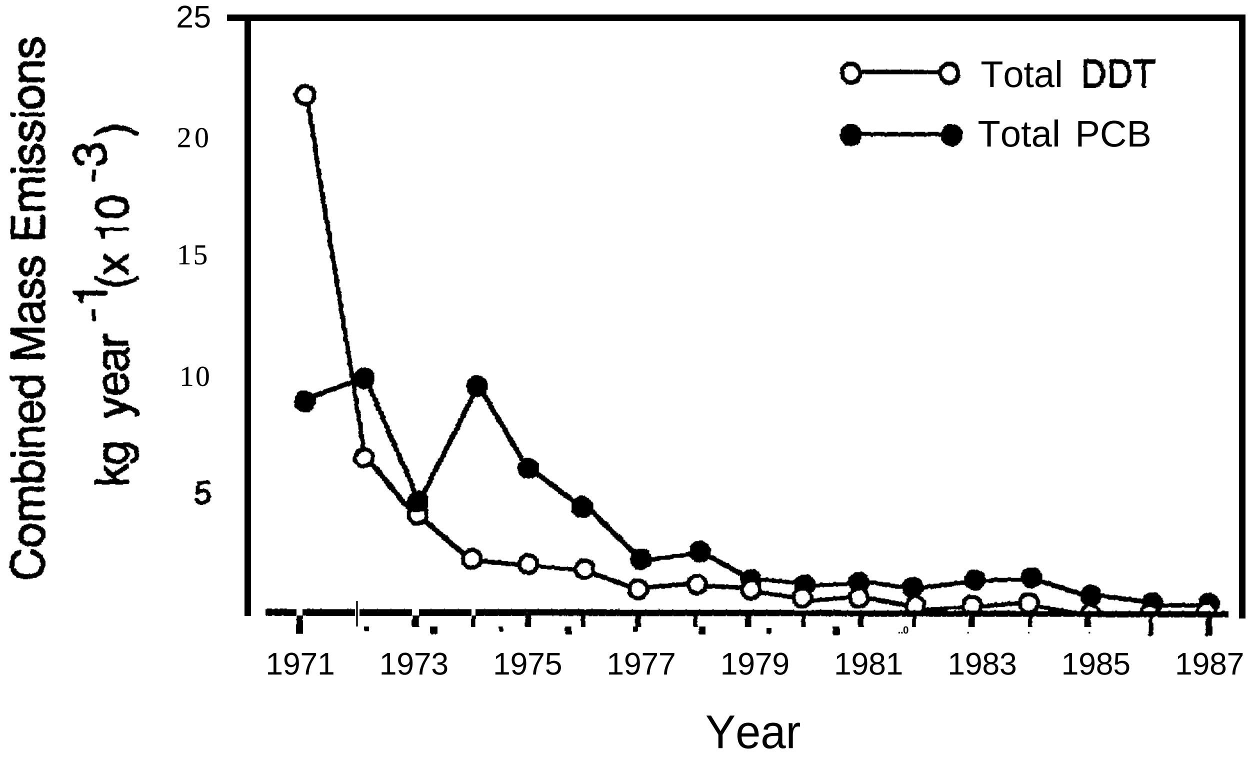
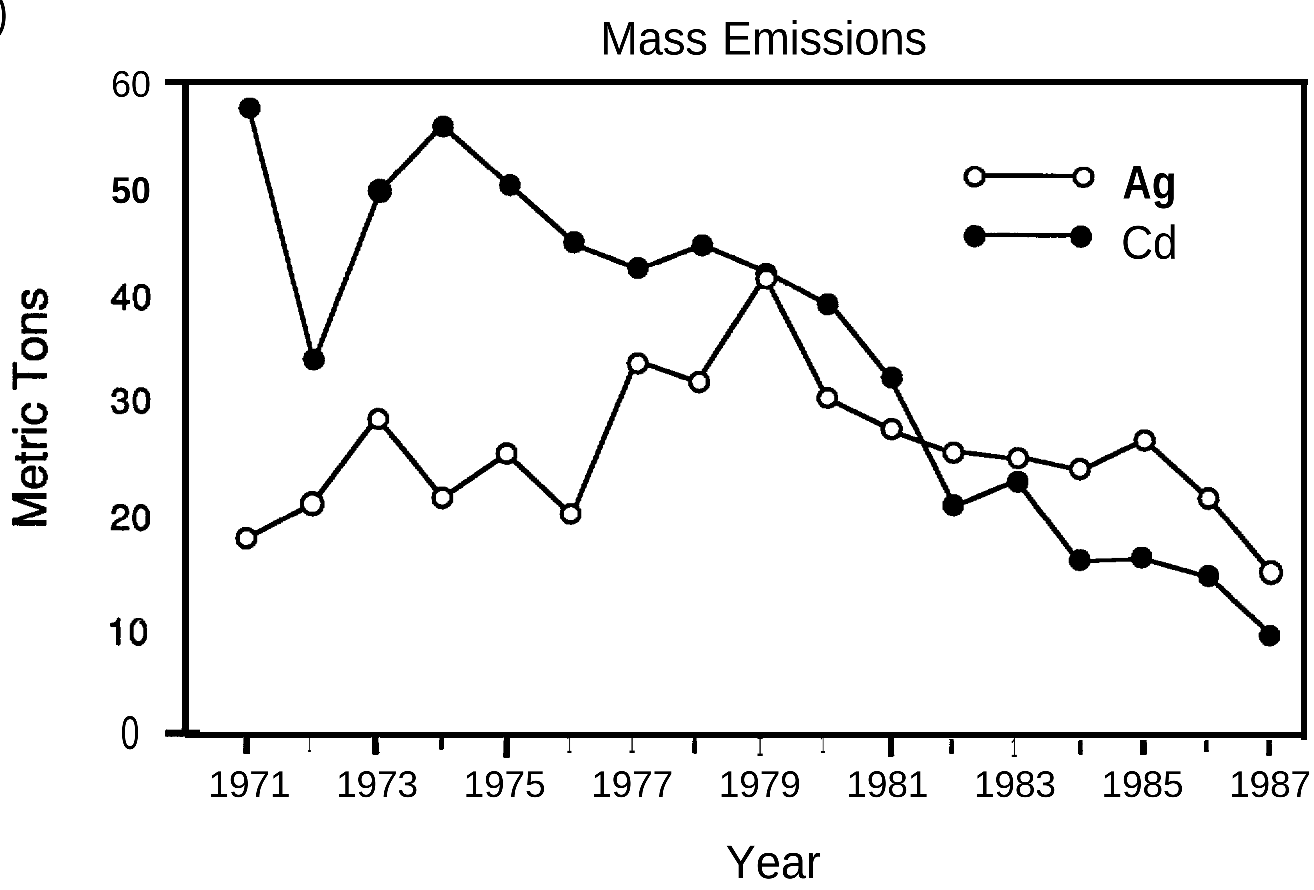
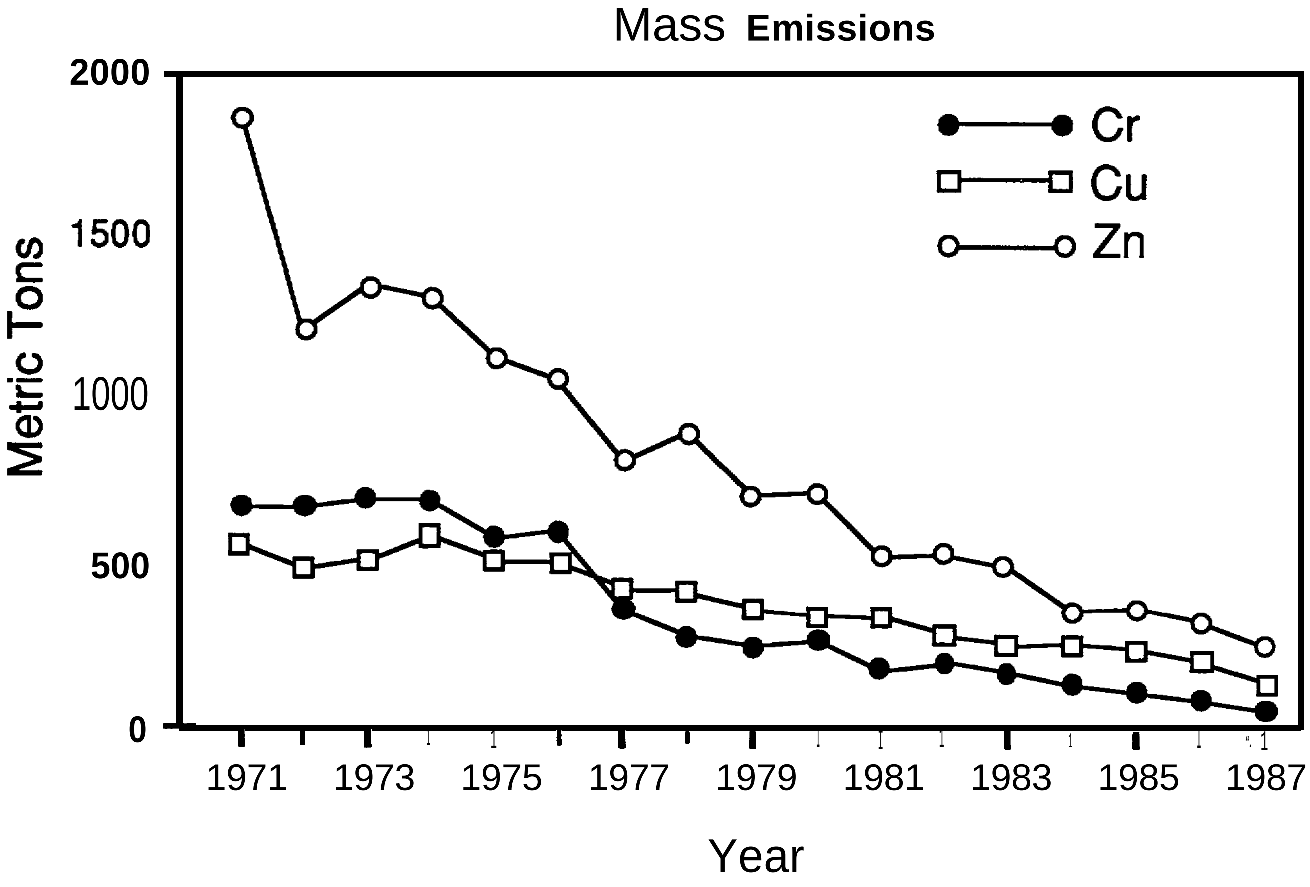

Combined Mass Emissions
kg year $^{-1}$(x 10 $^{-3}$)
25
20
15
10
5
Total DDT
Total PCB
1971
1973
1975
1977
1979
1981
1983
1985
1987
Year

Figure 3.3. Emissions (metric tons yr^{-1}) of (a) silver and cadmium and (b) chromium, copper, and zinc to the SCB from seven municipal waste discharges from 1971 to 1987 (SCCWRP 1987).

(a)


Mass Emissions
60
50
40
30
20
10
0
Metric Tons
Ag
Cd
1971
1973
1975
1977
1979
1981
1983
1985
1987
Year

(b)


Mass Emissions
2000
1500
1000
500
0
Metric Tons
Cr
Cu
Zn
1971
1973
1975
1977
1979
1981
1983
1985
1987
Year

compare the input of particulate organic carbon from wastewater discharge with the natural flux of particles from planktonic and pelagic food web debris: Whereas the sewage carbon emission is 5×10^4 mt yr^{-1}, the natural flux of TOC sinking out of the euphotic zone was estimated to be 25.6 g C m^{-2} yr^{-1} (Williams 1986b). Thus, the TOC input from wastewater discharge is approximately equivalent to the natural planktonic flux calculated for an area of 1960 km^2. However, the input of municipal waste is localized and significant. Recently improved wastewater treatment technologies and other similar projects to be implemented in the near future should further reduce the contaminant emissions Into the SCB (Schafer 1989).

Most industrial wastes originate from petroleum-related industries of onshore and offshore oil production, shipping, and other tanker activities. The petroleum waste discharges are located in the vicinity of Santa Barbara Channel, Santa Monica Bay, and off Orange County coastal areas. The discharge of particulate and water from other industries, that is, metallic and fish cannery (Table 3.2), is approximately of the same order of magnitude as that from petroleum industries. While the effluent flow from the industrial wastes comprises about 9$ of the total municipal wastewater discharge in the SCB, the estimated mass emission rate of suspended solids from the former sources is only 2.8% relative to that released from the latter dischargers. Practically no data exist in the open literature regarding the contribution of organic and inorganic constituents from industrial wastes to the California coastal waters.

Fourteen major thermal-power generating stations and a nuclear power-generating station (San Onofre) together discharge approximately 8×10^{12} 1 yr^{-1}) of cooling water into the Southern California coastal regime (including bays and estuaries) (Table 3.2). Cooling water is indeed the largest type of discharge to the SCB. Young et al. (1977b) investigated the input of six trace metals (Cd, Cr, Cu, Ni, Pb, and Zn) in both sea water influent and effluent of eight major generating stations located along the Ventura, Los Angeles, and Orange County coastlines. The annual inputs of these trace metals from cooling waters were estimated to range from 0.3 to 2.1 mt yr^{-1}. This constitutes less than 1% of the combined input from storm runoff, aerial fallout, municipal wastewater, and thermal discharge. Retention basin waters (consisting of acid-cleaning wastes, fireside boiler wash water, and floor drainings) were not discharged during the time of sampling. The periodic discharge of these basin waters would be expected to contribute additional trace metals (as much as 4 orders of magnitude; Young et al. 1977b) as well as organic contaminants to the effluent cooling water. However, data pertaining to organic constituents are not readily available.

Approximately 300 rivers, streams, and storm drains discharge into the SCB and 6 of these--all major rivers with tributaries (Ventura, Santa Clara, Calleguas, Los Angeles, San Gabriel, and Santa Ana)--make large contributions to coastal sediments. Using the data of Brownlie and Taylor (1981) and Taylor (1981), Schwalbach and Gorsline (1985) estimated the "actual" discharge of sediments from Point Conception to Baja California into the SCB to be about 9 x 10^6 t yr^{-1} (Table 3.2). Considering the reduction in sediment yields by flood control, damming, etc. (Brownlie and Taylor 1981), they also projected "natural" discharge rates (which could be systematically higher In drainages accompanying urban developments) to be around 13 x 10^6 t yr^{-1}. This is probably an underestimate of modern sediment inputs, because agricultural land use and progressive deforestation tend to enhance natural sediment yields (Meade 1969). The discharge from streams could range up to 1-2 orders of magnitude greater than observed during normal years (during the exceptional flood events of 1941 and 1969, for example). These two major events contributed more than half of the influx from small streams during the past 50 years (Brownlie and Taylor 1981). Yet, very limited data exist to correlate the storm flow characteristics with the mass emission rates of numerous constituents which are washed into the SCB during storm runoff as well as dry-weather flows (Eganhouse and Kaplan 1981; Eganhouse et al. 1981; SCCWRP 1987).

As much as 70% of the total surface runoff could derive from storm flows, and a major portion of the suspended silt (94$) and total organic carbon (86$) are discharged into the SCB during winter storm season lasting from November through April (SCCWRP 1973; Water Resources Data for California 1986). Mass emissions of oil and grease are apparently of equal magnitude in storm and dry-weather flows (SCCWRP 1973).

The emission of suspended silts in storm runoff ranges from 2.7 to 5.4 x 10^5 mt yr^{-1} (Eganhouse and Kaplan 1981; SCCWRP 19″73) and appears to be fairly constant over a decade (Table 3.2). This is approximately equivalent to the suspended solids discharge rates from municipal wastewater outfalls in the 1980s, although the chemical composition of the two types of solids is quite different (Eganhouse and Kaplan 1981; Eganhouse et al. 1981). The Santa Clara River is the single most important source of sediment in Southern California, although it discharges only about 10% of the total surface runoff flows from the Los Angeles Basin (SCCWRP 1973). The highest concentration of suspended silt was reported from the Santa Clara River (7600 mg 1-1), followedby samples from Santa Ana River (1800 mg l-l). Ballona Creek and the Los Angeles River contained silt concentrations in the range of 300-400 mg 1^{-1} during the storm in 1970-1971. This is comparable to the average concentration of suspended solids content (715 mg l-l; ranging from 30 to 1000 mg 1^{-1}) determined in the Los Angeles River runoff after a storm event in 1978 (Eganhouse et al. 1981). Apparently the stringent flood control measures from rivers such as Los Angeles and Santa Ana rivers have greatly reduced the mass emission rates of silt, although the Los Angeles River has averaged about 77% of the total storm runoff water carried from the Los Angeles Basin over the decade (Young et al. 1980).

The estimate made by Schwalbach and Gorsline (1985) of the suspension (natural) discharge (12×10^6 t yr^{-1}) from river sediments in Southern California over the entire Holocene is an order of magnitude greater than the recent storm runoff estimates of SCCWRP (1973) and Eganhouse and Kaplan (1981). This is probably because Schwalbach and Gorsline (1985) have integrated the data over the entire Holocene, and a large range in values is conceivable, because terrigenous silt could enter in occasional large pulses during exceptional events, as described previously. Further, note that the data of Eganhouse and Kaplan (19S1) are based on only one storm event.

The total organic carbon emission rate from surface runoff to the SCB in modern times is of the same order of magnitude as that from sewage outfalls, a factor that emphasizes the potential importance of surface runoff to the ecosystem of the SCB. The limited data available on chlorinated hydrocarbons (SCCWRP 1973) suggest that the mass emission rate of these compounds from runoff during the early 1970s was roughly 1% of that observed from municipal wastewaters at that time, although the rates are similar today (Young et al. 1980). A comparative study of storm runoff in the Los Angeles River by Young et al. (1980) shows that most of the trace metals investigated (Ag, Cd, Cr, Cu, Hg, Ni, Zn, Fe, Mn) exhibited only a minor decline in flow-weighted mean concentrations over the decade. However, total PCB decreased by about a factor of eight (Los Angeles River storm runoff in 1971-1972: 2.6 mg l-l; in 1979-1980: 0.31 mg l-l). This trend is to be expected because the use of PCBS was banned in the mid-1970s. Similarly, the concentration of lead decreased by a factor of 6 (Los Angeles River storm runoff in 1971-1972: 940 mg l-l; in 1979-1980: 160 mg l-l). This probably results from federal regulation (initiated in 1975) of the use of leaded gasoline and other fuel additives (National Research Council 1980). Because gasoline is the largest source of lead to the environment (U.S. Environmental Protection Agency [EPA] 1983), federal regulation has resulted in significant declines in lead concentrations in precipitation (Eisenreich et al. 1986; Likens 1983) and in the air of large metropolitan areas. A recent statistical survey by Alexander and Smith (1988) also confirms that concentrations of dissolved lead declined significantly in water samples in nearly two-thirds of 306 locations (National Stream Quality Accounting Network Program) on U.S. rivers from 1974 to 1985. A strong decrease in concentration of dissolved lead observed at several stations from California rivers implies much less influx of lead from land to the SCB in recent years.

Comparison of contents of trace metals from runoff and wastewater in 1979 and the entire decade (1970-1979) shows that the annual mass emissions of most of the constituents via wastewater discharge exceed (by an order of magnitude) runoff emissions via Los Angeles Basin storm channels (Young et al. 1980). Lead and zinc are exceptions because of their automotive uses (lead being an antiknock agent, zinc being used in the molding of tires) and are thus important runoff inputs to the SCB.

Harmful wastes have been barged farther out into the sea and dumped, either without packaging or after encapsulation in metallic drums. Very little data are available in the open literature on the contaminants contained in these wastes, but they include such things as radioactive and industrial wastes, oil drilling muds and cuttings, refuse and garbage, and military explosives. Drums could probably be corroded in a decade, releasing the material gradually. Only oil refinery and chemical wastes are believed to contribute significant amounts of pollutants in the SCB (SCCWRP 1973). Practically all dumping ceased as of 1972-1975 (Chartrand et al. 1985), with the exception of dredged material (sediments dredged from the Los Angeles, Long Beach, and San Diego ports and from the naval station at San Diego). Currently LA-3 (33°31′42″ N; 117°54′48″ W at a water depth of 457 m off 8 km south, southwest of Newport Harbor) is the active interim site for disposing of dredged material, while LA-2 (centered at 33°37′06″ N; 118°17′24″ W at a water depth of 118-320 m off Point Fermin, 9 km from the breakwater at San Pedro), and LA-5 (at the outer edge of the continental shelf at a depth range of 130-190 m and 14 km from the entrance to San Diego Bay [see Chapter 12]) are inactive because their site designation has elapsed. But the latter two sites will probably be designated as permanent sites in the future (Patrick Cotter, EPA, pers. comm. 1989).

The average amount allowable for disposal at the above mentioned sites is 200,000 to 500,000 yd^3 (2.62-6.54 x 10^5 m^3) per site per year. Assuming that the dredged sediments from the Southern California harbors have an average percent total organic carbon content of 1.65 (from three replicate samples from 12 harbor locations extending from San Diego Bay to Los Angeles Harbor; Anderson and Gossett 1987), the organic carbon input from the volume of dredged material dumped into a dumpsite can be estimated. An average specific gravity of 2.2 is also assumed in the calculations. About 9.5 X 103-2.4 x 10^4 mt yr$^{'1}$ of organic carbon is estimated to be contributed to the SCB environment from a single dumpsite (Table 3.2).

Sedimentary rocks and shales such as those of the western Transverse Ranges generally disintegrate to produce fine-grained debris. Surface runoff should, therefore, receive sizable contributions from eroded shales such as the Monterey shale (Miocene) along the coast of California.

Unfortunately, no data exist pertaining to the extent of contribution of eroded shale to the SCB. However, the sediment budgets discussed by Schwalbach and Gorsline (1985) from Southern California drainages obviously encompass contributions from shale erosion. Taylor (1983) estimated that an average of approximately 12 x 10^6 m^3 of sedimentary debris is eroded annually from the Southern California coastal drainage systems. Fifty percent of this volume is comprised of fine silt and clay, but a sizable fraction of this can be expected to be derived from the eroding coastal shales. Thus, a gross estimate of mass emission from shale erosion can be attempted here. Of the mainland shoreline distance of 327 km, 87% is estimated to be erosional (Emery 1960), and Monterey shale is found almost continuously along this shoreline (Obradovich and Naeser 1981). Assuming that up to 1 m depth of this shale is eroded at the rate of approximately 10 cm yr^{-1}, the volume of sediment input to the SCB from shale erosion amounts to 2.9 x 10^{10} cm^3 yr^{-1}. Assuming a specific gravity of 2.2 on an average (for diatomite, which is common in Monterey shale), the sediment input from shale erosion is equivalent to approximately 6.4 x 10^4 mt yr^{-1}. This constitutes roughly 1% of the contribution of sediment load from surface runoff, or 10$ from waste discharge. The total organic carbon (TOC) input from the shale is approximately 6.4 x 10^2 to 1.2 x 10^4 mt yr^{-1} (Table 3.2) when we base estimates on the TOC percentage for shale, which could range from 1 to 18% (Curiale et al. 1985). The upper limit of TOC leads to an input estimate that almost equals the contribution from surface runoff or waste discharge. The estimate given here is based on assumptions which require verification.

Thousands of different organic compounds are emitted to the atmosphere from natural and pollution sources (Finlayson-Pitts and Pitts 1986; Kawamura and Kaplan 1987; Gagosian et al. 1987; and Mazurek and Simoneit 1984, among others). It is estimated by the Southern California Air Quality Management District (AQMD) that, in 1983, 600 t d-l of particles were emitted into the atmosphere. These particles undergo photochemical reactions that generate numerous compounds and adsorb sulfate, nitrate, and other reactive species (Arey et al. 1989; Finlayson-Pitts and Pitts 1986).

There have been suggestions that some of the photochemical species, especially PAH compounds, may accumulate in lipid-containing films on the ocean surface by surface tension effects. These could become toxic to eggs and larvae (Hardy and Gucinski 1988). Studies on atmospheric nitrogen budgets in the Pacific Ocean suggest that atmospheric nitrate deposition may add to the nutrient content of this oceanic regime (Logan 1983; Uematsu et al. 1985; Prospero and Savoie 1989) and affect productivity. Each of the airborne compounds has its own characteristic chemical and physical properties and associated atmospheric sources, residence times, and sinks. However, data on aerial fallout rates of trace components into the SCB are scant . In view of the very limited rainfall in Southern California, approximately 20-40 cm yr^{-1} (National Climate Data Center 1988) dry aerial fallout rather than wet deposition is expected to be the dominant airborne mechanism in the SCB. However, strong westerly Santa Ana winds transport fine material from nearby arid terrain into the SCB during the months March through July. As evidence of the importance of dry deposition, ships offshore have been found coated with fine dust during these episodes (Emery 1960).

Gray et al. (1986) have described the spatial and temporal distribution of aerosol carbon concentrations over an entire annual cycle in the Los

Angeles area, with a reference site on San **Nicolas** Island. Their data from the island are used below to compute the flux of total suspended particles, total fine organic and elemental carbon in the SCB. The fine carbonaceous particles emitted from most combustion processes (**Cass** et al. 1982; **Muhlbaier** and Williams 1982; **Siegla** and Smith 1981) contain organic compounds as well as black non-volatile soot that has a chemical structure akin to impure graphite (Rosen et al. 1978). The black soot is referred to as elemental carbon, light absorption by which plays a significant role in the earth's radiation budget (**Cess** 1983; Patterson et al. 1982).

Assuming that the concentration of components measured by Gray et al. (1986) for San **Nicolas** Island is representative of the entire SCB area of 78,000 km^2, a gross estimate of the fluxes is computed as follows (after the method of Duce and **Gagosian** 1982):

Dry deposition of atmospheric particulate matter is estimated, using the deposition velocity νd, where

$$\nu d = F/M$$

and M is the mass of aerosol in the atmosphere in micrograms per cubic centimeter, F is the flux of atmospheric particles to the surface (ug cm-2), and νd is the deposition velocity (cm s^{-1}). For particles collected by Gray et al. (1986) which are less than 2.1 um, a deposition velocity (νd) range of .05-0.5 cm S^{-1} at wind speeds of 5-10 m s^{-1} should be applicable (**Slinn** and **Slinn** 1980). Using this velocity range and the known concentrations of the particles (Gray et al. 1986), F is calculated. The estimated annual dry deposition for the SCB is presented in Table 3.2. The data are available only for fine particles, which comprise approximately 31% of the total suspended particles. Assuming that the above parameters are equally valid for the total suspended particles by analogy with the fine particles, the flux of the former can be estimated.

This computation shows that total suspended particles and the total fine organic carbon flux to the SCB via dry fallout is less by 1-2 orders of magnitude than that from wastewater discharge or surface runoff. Similarly, by the extrapolation of the La Jolla fallout, Chow and Earl (1970) found that lead from combustion of leaded gasoline could account for as much as 2400 t of fallout over the SCB. The annual dry fallout of chlorinated hydrocarbons in February 1972, however, has been estimated to be approximately 2-4 mt, which was lower than from municipal wastewaters (**SCCWRP** 1973; Young et al. 1976).

Rabinowitz (1972) noted that although the concentrations of lead in wild oats (7-22 **ug** g-l) from the islands in the SCB were lower by an order of magnitude than those found on the mainland, the island concentrations were above the natural levels (2-3 **ug** g-l). This indicates a significant flux, in the past, of atmospheric lead, other trace metals, and probably also organic constituents to the waters of the SCB from the urban centers. However, the emissions of both inorganic and organic components into the atmosphere have been curtailed recently by source controls such as the federal regulation of the lead content of leaded gasoline from 1975 (National Research Council [NRC] 1980) and the cessation of DDT production after 1982 by Montrose Chemical Corporation of Los Angeles County.

The particle flux from dry fallout computed above may be a realistic estimate. **Fleischer** (1970) attributes the increasing fine silt and **clay**-size quartz offshore to **eolian** deposition superimposed on the **fluvial** gradient offshore. The range **in** the particulate input rate quoted in Table 3.2 is consistent with the estimate of **Fleischer** (1970), who reported the **eolian** contribution to be less than 10^6 t $\mathbf{yr^{-1}}$.

Lazrus et al. (1970) determined the concentration of different metals in rainfall over Santa Catalina Island from September 1966 to January 1967. Assuming an average annual rainfall rate of 40 cm (National Climate Data Center 1988) over the SCB, the rough estimate given by them indicates that the mass deposition rates of mercury, lead, and manganese exceeded the flux from wastewater and runoff (for example, mass deposition rate of lead approximately 400 mt yr^{-1} from rainwater vs. that from municipal discharge which was 243 mt yr^{-1} in 1971; after **SCCWRP** 1987). These results are consistent with the findings of **Bruland** et al. (1974), who noticed enhanced fluxes of lead, zinc, and copper in more recently deposited sediments as opposed to iron, nickel, and manganese whose levels are uniform with depth (Table 3.3). A close similarity in anthropogenic sedimentary fluxes and in the rainfall washout fluxes for many elements was also obvious. This implies the significance of an atmospheric transport of these metals. Measurements of anthropogenic metal fluxes in the outer basins would help confirm this observation. Similar flux values seaward would support atmospheric transport, and a progressive decline in the flux in outer basins would reflect, in contrast, wastewater entries.

Although several organic compounds (over 300) have been measured in air, rainwater, fog, and mist in and around Los Angeles (**Grosjean** 1982; **Kawamura** and Kaplan 19S3; Steinberg and Kaplan 1984), no similar studies have been conducted, to date, from the islands off coastal Southern California, hence the task of computing flux estimates of various organic constituents via rainfall into the SCB is currently impossible.

Reductions in ocean discharges from municipal **outfalls** over the last decade (Schafer 1989) and consequent combustion of sludge for energy recovery undoubtedly warrant a more important role of atmospheric deposition than ever before in contaminant inputs to the SCB. Yet, research efforts involving wet and dry deposition over the SCB have not been extensive to date.

Table 3.3 presents a summary of mass emission rates of organic carbon and trace constituents from various sources to the SCB. All data under advective transport, except organic carbon (under column 9), were calculated from concentration data compiled by SCCWRP (1973). Mass transport rates of organic carbon were calculated from the dissolved organic carbon (approximately 40 uM 1^{-1}) data of Williams (1986a) for Santa Monica Basin and of Helm-Hansen et al. (1966) for San Clemente Basin on the assumption that these values are representative of California Countercurrent waters. Column 10 represents the total constituent mass emission rates from municipal wastewater, surface runoff, oil seeps, shale erosion, vessel coating, ocean dumping, rainfall washout, and dry fallout.

For organic carbon and all the trace components listed, the contribution from advective transport is much greater than the sum from all other sources. Of the non-advective sources, the input from municipal wastewater and atmospheric deposition are the primary sources of most of the trace constituents. A few other trace metals such as cobalt, iron, and manganese (not listed in Table 3.3) from surface runoff exceed the contribution from municipal wastewaters (SCCWRP 1973). It is clear from the data that vessel coating contributes major amounts of copper while ocean dumping may be a significant source of DDT and PCB to the SCB. Dry 'and wet deposition contributed significant amounts of lead to the SCB until the 1970s . This compilation (Table 3.3) also indicates that data on contribution of several constituents such as hydrocarbons and total organic carbon from other sources are lacking. Thus, further study is required to determine the net advective transport of various constituents and to understand the influence of advective transport on the spatial distribution of these compounds.

The environmental fate of organic carbon is governed by the physical and chemical characteristics of the organic constituents. These characteristics ultimately control their reactivity, mobility, and stability within the water and sedimentary columns. Although the relative magnitudes of contributions of organic carbon from different sources are compared here, it should be noted that organic carbon from various inputs is not equally reactive.

For example, most of the organic carbon in the municipal wastewater effluent is relatively refractory (Eganhouse and Kaplan 1988; Venkatesan and Kaplan 1990) as a result of the chemical and biological treatment processes. Much of the organic carbon derived from river and storm runoff comprises humic or insoluble organic matter, although relatively more "labile," or reactive, carbon is to be expected in runoff (Eganhouse 1982), for lack of pretreatment, unlike in municipal wastewaters. Organic matter derived from the Monterey shale is mainly "kerogen," an insoluble solid material, and the extractable bitumen contains relatively "stable" compounds (the reactive functional groups are lost over geological periods of its formation). oil seeps also contain to a major extent relatively refractory, defunctionalized components. Organic carbon derived from plankton (primary productivity) contains mainly labile compounds (with functional groups) which undergo rapid transformation, degradation, and remineralization through the water column. Microbial and photochemical oxidation as well as in situ chemical reactions transform the nature of this reactive organic matter. For example, labile organic remains such as amino acids and monosaccharides are metabolized completely to carbon dioxide and water by microorganisms. In contrast, many other compounds (that is, lignin, humic acids) survive post-depositional attack because of physical protection or unique structural characteristics. Thus, the refractory species may become enriched in the biogeochemical cycles.

WATER COLUMN PROCESSES

INTRODUCTION

In this section we discuss processes affecting the cycling of organic and inorganic chemical species in coastal waters of the SCB. The approach we have taken is to first describe the natural system, whereby the water column is divided into (1) near-surface waters (the upper 200 m), (2) intermediate waters (>200 m to basin sill depths), and (3) deep basin waters. The final subsection provides a brief discussion of anthropogenic effects. Specific examples of perturbations of the system resulting from inputs of trace organics and metals are presented.

For present purposes we have adopted the simplified definition scheme of Williams (1986a), wherein the distribution of chemical species between "particulate" and "dissolved" phases is set at the 0.4-0.5 um cutoff. Particulate matter is further subdivided into “suspended” and "sinking" particles. The former consist of mineral grains, bacteria, phytoplankton cells, protozoans, and detrital aggregates generally having diameters less than approximately 50-100 um (Beers 1986; Shiner 1982). These particles are easily maintained in suspension by the action of currents and, consequently, they dominate the mass of particulate matter collected by traditional water bottle samplers (McCave 1975). By contrast, the large, rapidly sinking particles, although relatively rare in the water column, are believed responsible for most of the vertical flux of particulate matter to deeper waters and sediments (McCave 1975; see references in Fowler and Knauer 1986). They range in size from 10^2-10^4 um in diameter, have settling speeds of 10 to 10^3 m d-l, and consist of mixtures of **biogenic** and **lithogenic** materials in the form of intact organisms, skeletal parts, fecal pellets, and macroscopic aggregates (identified earlier in this chapter as marine snow). Because traditional water bottle sampling is inefficient at capturing the large sinking particles, sediment traps (or particle interceptor traps-PIT) and large volume original-site filtration systems (Bishop and Edmond 1976) have been developed for this purpose.

The distinction between “dissolved” and “particulate” is somewhat obscured by the existence of **colloids** which represent a size transition between dissolved monomolecular species and the majority of the mass of suspended particles in seawater (1-70 um; Sharp 1973; Stumm and Morgan 1981). Using the 0.4-0.5 **um** cutoff as an operational definition, aggregates of large organic compounds (such as high molecular **weight humic** substances-10^4-10^5 **daltons),** clays, and iron oxide phases can be classified as particles based on their separation by filtration. Meanwhile, smaller aggregates in the colloidal size range, small bacterial cells, and members of the **picoplankton** (0.2-2 **um)** may pass the same filters. The recent introduction of ultrafiltration techniques has extended the particle size cutoff to the sub-nanometer range, greatly enhancing the **ability** to distinguish between suspended particulate, colloidal, and dissolved species. However, difficulties can arise with this technique because of adsorption of dissolved organic matter on the filters and clogging of the pores with consequent retention of particles smaller than the nominal pore size of the filter **(Carlson** et al. 1985).

NATURAL SYSTEM DYNAMICS

Overview

In succeeding paragraphs we discuss **biogeochemical** processes occurring in three portions of the water column: (1) near-surface waters (0-200 m); (2) intermediate waters (200 m to basin sill depth); and (3) deep basin waters. These divisions reflect significantly different environments with regard to their biology, chemistry, and physics. In broadest terms, the chemical composition of a parcel of coastal seawater is determined by the properties of the source waters, mixing rates of adjacent parcels (vertically and horizontally), and the rates of processes that result in consumption or production of a given (chemical) species. The spatial distribution of these species in the water column is thus governed by an interplay of the physical, chemical, and biological factors that affect these rates.

As discussed earlier (Chapter 2), coastal waters in the SCB are density stratified. During summer months, solar heating within the SCB strongly affects the temperature of surface waters. Maximum temperatures approach 20°C, and the mixed-layer depth ranges from 5-10 m, depending on location. Advection dominates in the intervening period, during which minimum surface temperatures are approximately 14°C with the mixed layer ranging from 10-30 m in depth. Stratification strongly inhibits vertical mixing between layers of different density. Thus, vertical concentration gradients in the water column (particularly in the upper 200 m) are much stronger than horizontal gradients. Measurable variations in water chemistry along isopycnals result mainly from mixing of adjacent water parcels and temporal variations in source strength (Jackson 1986).

As noted above, vertical gradients in temperature and salinity in the surface waters of the SCB result from seasonal solar heating superimposed on advection. However, gradients of non-conservative chemical constituents in the upper 200 m (for example, nutrients, particulate organic matter, trace metals), while largely established outside of the SCB, are sustained and locally modified by biological activity. The intermediate waters (200 m to basin sill depths) are subject to less intense biological activity and show weak (or no) vertical concentration gradients. Thus, the spatial distribution of chemical species in this portion of the water column is dominated by advection. Deep basin waters show weak density stratification, but horizontal advection is greatly restricted by the presence of basin slopes. Exchange occurs mainly through eddy diffusional mixing between deep and upper (above the sill depth) basin waters and variable flows over the sills. Rapid exchange of deep basin waters, presumably brought on by strong coastal upwelling, has been documented for at least one inner basin, Santa Barbara (Liu 1979; Reimers et al. 1990; Sholkovitz and Gieskes 1971). Because the sills of inner basins (Santa Barbara, Santa Monica, San Pedro) intersect the oxygen minimum zone, the oxygen content of bottom waters is generally low (<5 uM O_2; ‘cry 1960). This leads to suboxic metabolism (denitrification) in basin waters and at the benthic boundary layer. Such reactions and chemical exchange across the sediment-water interface affect the distribution of biologically active substances in the deep basin environment.

Near-Surface Waters

Air-sea interactions

The sea surface is of great importance to the biogeochemical cycles of numerous elements. It acts as both a source and sink for natural and anthropogenic substances and supports an active and unique biological community (the neuston). Materials deposited at the surface of the ocean from the atmosphere may become associated with particulate matter, some of which probably originates by particle aggregation during wave-induced bubble transport (Wallace and Duce 1978). The aggregation of particulate matter also facilitates removal of materials to deeper waters. Once formed, these particulate may undergo dissolution, complexation, and decomposition reactions. At the same time, sea salts and other dissolved and particulate inorganic (NO_3^-, PO_4^{-3}) and organic species as well as gases are injected into the atmosphere via bubble bursting or diffusive processes (Duce and Hoffman 1976; Lion and Leckie 1981). Unfortunately, knowledge of the exchange of chemicals across the air-sea interface in the SCB is extremely limited. However, information concerning the chemistry of sea-surface films has recently begun to accumulate (Cross et al. 1987; Henrichs and Williams 1985; Williams et al. 1986).

Williams (1967) first documented the enrichment of dissolved and particulate organic matter (carbon, nitrogen, and phosphorus) and nitrate in sea-surface film samples relative to subsurface (15-20 cm) seawater taken off San Diego. Particulate organic matter (POM) is enriched in nitrogen and phosphorus relative to the dissolved organic matter (DOM) in the surface film. The enrichment of nitrogen and phosphorus in surface film particulate suggests a recent origin for these materials, whereas the dissolved material may have undergone more reworking.

Henrichs and Williams (1985) and Williams et al. (1986) performed extensive physical, chemical, and microbiological analyses of sea-surface films and subsurface water samples from eutrophic and oligotrophic waters off Baja California. They found no significant difference in chemical composition between films collected in these environments; however, film and subsurface waters showed qualitative and quantitative compositional differences. When the amounts of proteinaceous (P), carbohydrate (CA), and lipoidal fractions (L) of the films are combined, only approximately 50$ of the particulate organic carbon (POC) and approximately 30% of the dissolved organic carbon can be accounted for (Table 3.4). The corresponding percentages of POC and DOC composed of the combined P, CA, and L fractions for subsurface waters are 51 and 23%, respectively. Hydrolyzable amino acids are enriched (relative to carbohydrates) in the surface film when compared to subsurface waters (Henrichs and Williams 1985). Similarly, non-polar hydrolyzable amino acids are more abundant than other amino acids in the surface film samples. On average, lipids contribute approximately 18$ of the POC and ≤3% of the DOC carbon pools. The identities of the remaining uncharacterized fractions (that is, the majority of the carbon) remains unknown, although measurements of the hydrophobic humic substances suggest that this fraction may account for as much as an additional 30% of the DOC (Williams et al. 1986). These findings are consistent with observations by others (see references in Hunter and Liss 1979) that the majority of the DOC and POC in sea surface films is present as complex macromolecular substances having properties similar to proteoglycans and glycoproteins.

Approximately 16-19% of the POC appears to come from living microplankton (dominantly dinoflagellates >1 um) and bacterial (>0.2 um) carbon. These organisms comprise approximately half of the protein + carbohydrate carbon. Surprisingly, the surface film does not appear to be consistently enriched with respect to numbers of total or metabolizing bacteria relative to subsurface waters, but the amino acid utilization rate (on a per cell basis) of the metabolically active bacteria, as measured by ^{3}H-glutamic acid and ^{3}H-leucine uptake, is higher in films (Carlucci et al. 1985). This may reflect the greater availability of amino acids in surface films.

In the vicinity of urban centers, sea-surface films receive significant contributions of anthropogenic substances. This leads to enrichment factors (such as concentration in microlayer-subsurface) for hydrophobic organic

Table 3.4. Distribution of dissolved and particulate organic carbon among various compound classes in surface film and subsurface seawater samples (modified from Williams et al. 1986).

Sample[a]	POC[b] (umol C l^{-1})	P	CA	L	(P + CA + L)	(MP + B)
		(% of POC)[c]				
		Cruise SF-2				
s. film	20	13	22	31	66	20
10 cm	12	16	23	19	54	23
SF/10 cm	1.7	0.8	1.0	1.6	1.2	0.9
		Cruise SF-3				
s. film	37	16	12	4	33	12
10 cm	17	15	16	17	48	15
SF/10 cm	2.2	1.1	0.8	0.2	0.7	0.8

Sample[a]	DOC[b] (umol C l^{-1})	P	CA	L	(P + CA + L)
		(% of DOC)[c]			
		Cruise SF-2			
s. film	100	6	17	3.4	27
10 cm	76	4	17	2.8	23
SF/10 cm	1.3	1.5	1.0	1.2	1.2
		Cruise SF-3			
s. film	144	12	21	1.1	34
10 cm	96	6	17	2.3	25
SF/10 cm	1.5	2.0	1.2	0.5	1.4

[a] S. film--surface film; 10 cm--subsurface water from 10 cm below air-sea interface; SF/10 cm--surface film/subsurface water (mean concentration ratio).

[b] POC, DOC particulate and dissolved organic carbon concentration means (n=5 for Cruise SF-2, n=3 for Cruise SF-3).

[c] Mean percent total POC or DOC represented by different fractions of the carbon pools. P, CA--protein, and carbohydrate carbon, respectively, passing 35 um Nitex netting, but retained by 1.0 um glass fiber filter; L--50% of lipid carbon passing the 35 um Nitex netting; MP, B--microplankton and bacterial carbon, respectively, passing the 35 um netting, but retained by a 0.2 um Nuclepore filter.

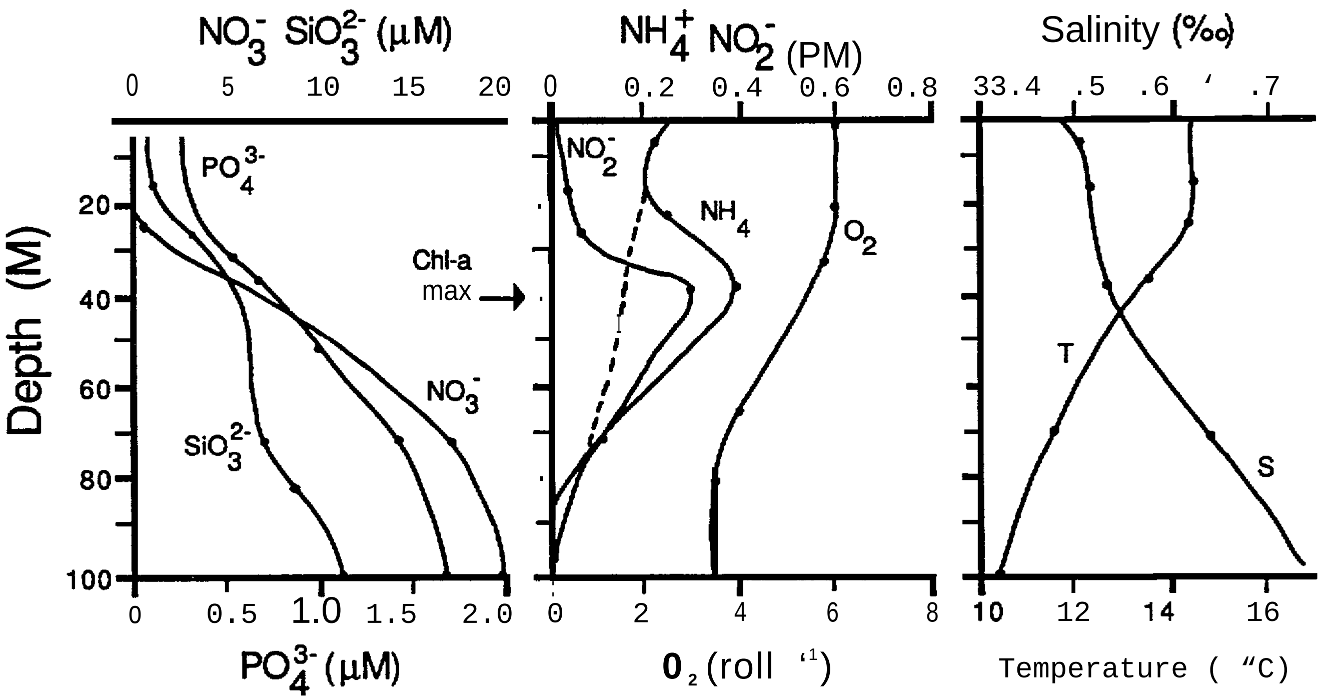
substances and heavy metals ranging from 10^1 to 10^5 (see references in Hardy 1982; Lion and Leckie 1981). Recently, Cross et al. (19S7) conducted a survey of nearshore sites in the vicinity of the San Pedro Channel, Los Angeles-Long Beach harbors, San Pedro Bay, and Santa Monica Bay. They found that the concentrations of Ag, Cr, Cu, Fe Mn, Ni, Pb, Zn, chlorinated hydrocarbons (DDT, PCB), and polycyclic aromatic hydrocarbons in microlayer samples collected at offshore stations were approximately 2-3 orders of magnitude lower than those in samples obtained from harbor stations. In general, the more contaminated sites contained higher particulate (as opposed to dissolved) metal concentrations. The polycyclic aromatic hydrocarbon (PAH) compositions of the harbor samples were dominated by lower molecular weight species--for example, naphthalene, phenanthrene--and their alkylated homologs, suggesting an uncombusted fossil fuel origin. Offshore samples contained larger relative contributions from the higher molecular weight PAH, indicating possible inputs from the atmosphere. Higher abundances of o,p'- and p,p'-DDT isomers (as opposed to the metabolize, DDE) were observed in the harbor samples. This probably reflects the continued input of DDT wastes from the dominant source of these compounds in Southern California, the Montrose Chemical Corporation (see Section V, "Distribution and Fate of Chemical Constituents in Sediments"). In contrast, the DDT composition at the Santa Monica Bay site was dominated by p,p'-DDE, most likely derived from older, weathered sources such as the Pales Verdes Shelf (MacGregor 1976).

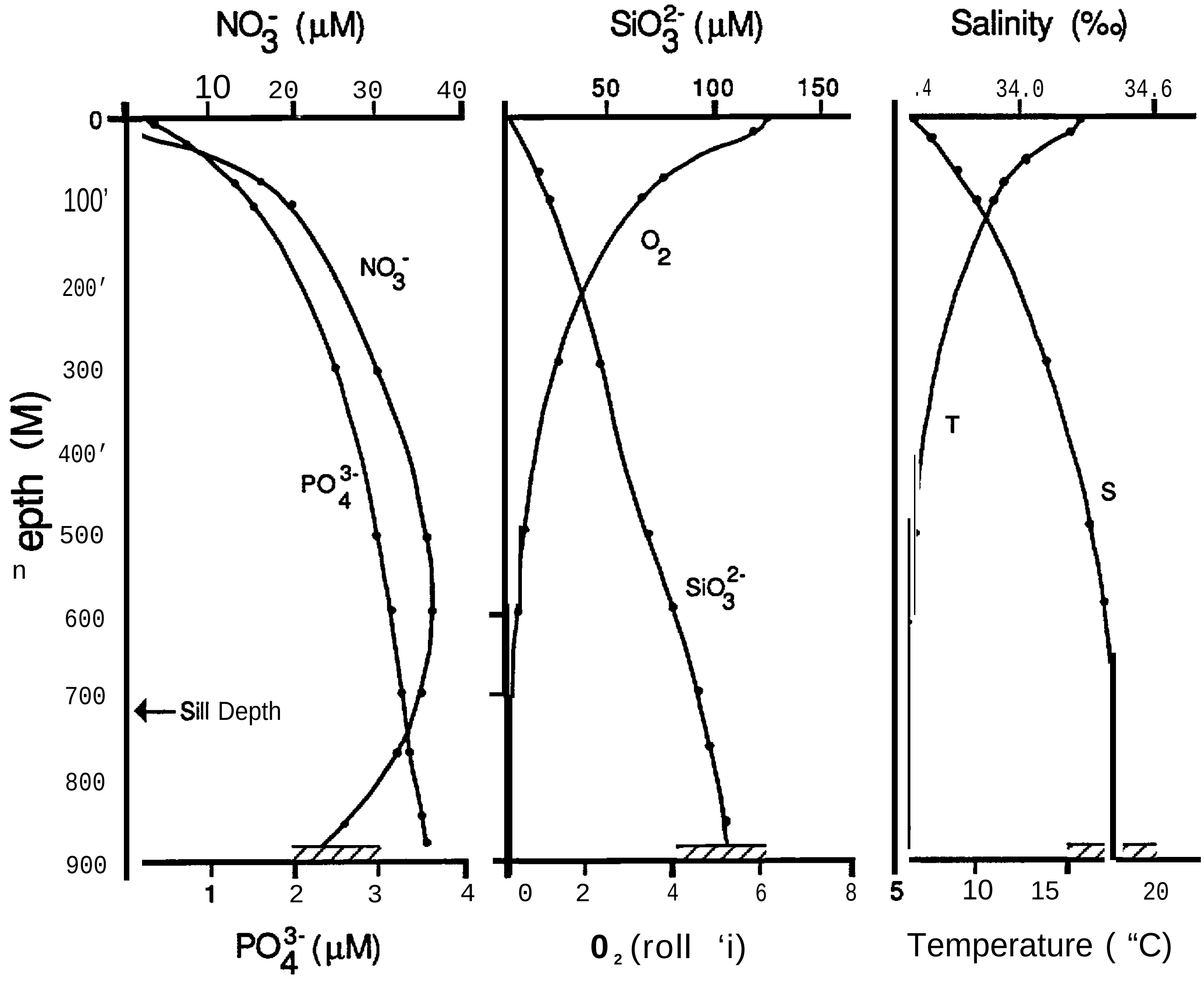
Nutrients: Distribution and Cycling

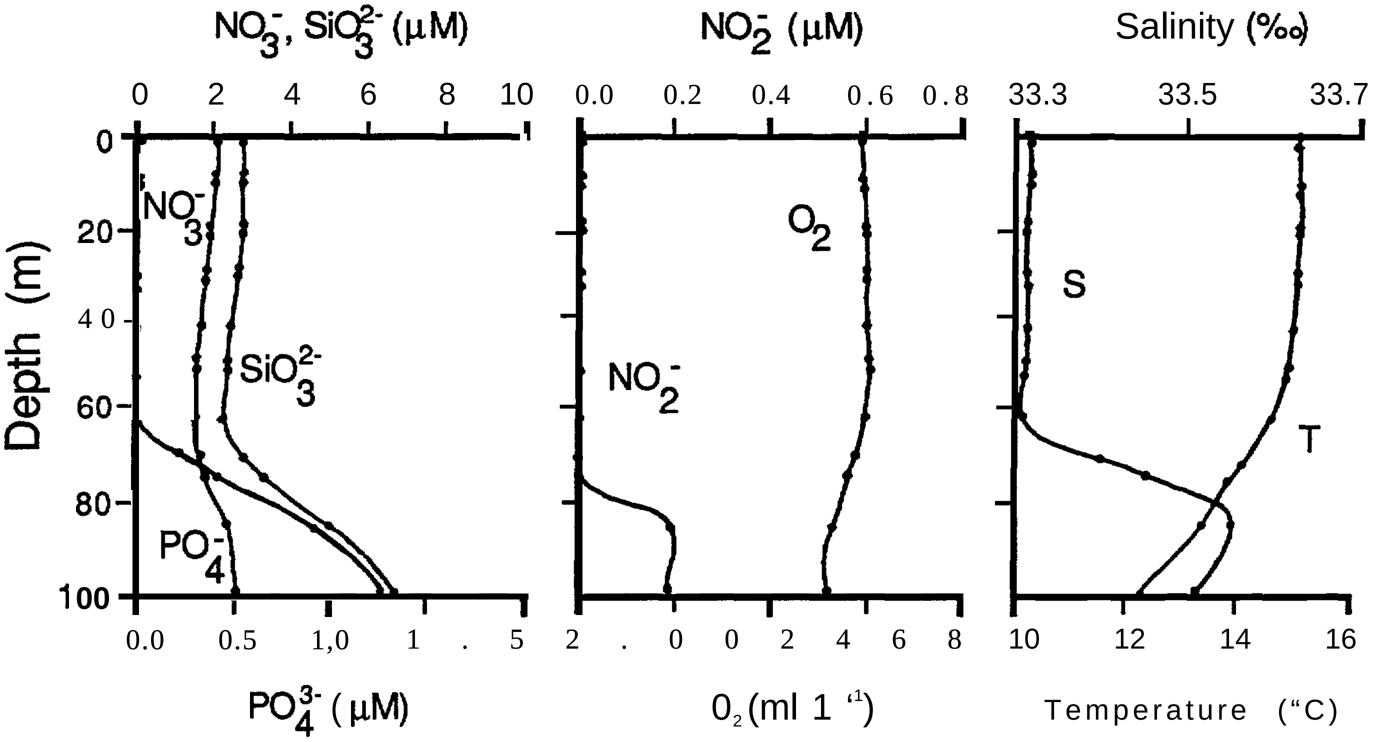
Waters within the SCB originate from at least five identified sources: (1) the westwind drift, (2) the subarctic Pacific via the California Current, (3) the equatorial Pacific, (4) the central North Pacific (which mixes with subarctic Pacific waters at the surface of the western margin of the California Current), and (5) a mixture of deep subarctic and equatorial waters (Jackson 1986). Near-surface waters in the SCB appear to be influenced strongly by contributions from the northern source (via the California Current; Sverdrup and Fleming 1941), which is characterized by low salinity (33.9-34.0 0/00), low temperature (5-10°C), and relatively high oxygen and phosphate content (Emery 1960), and the southern water, which is more saline (34.3-34.4 0/00), less oxygenated, and warmer. Transport in the upper water column is to the northwest via the large counterclockwise eddy known as the Southern California Countercurrent. Figure 3.4 depicts profiles of oxygen, phosphate, nitrate, nitrite, ammonium, and silicate for stations in San Pedro-Santa Monica basins (Williams 1986a) and for many of the same constituents at station 90.70 (32°5.1'N, 120°38.5'W; located in the California Current) from CalCOFI Cruise 8S05. The similarity of many of the profiles is evident.

Referring to Figure 3.4a, typical concentrations of dissolved nutrients in surface waters of the SCB (0-20 m) are as follows: nitrate-0 to 0.2 uM, nitrite-0 to 0.1 uM, phosphate-0.1 to 0.5 uM, silicate-<5 uM, ammonium-0.3 UM. With increasing water depth, concentrations of nitrate, phosphate, and silicate rise dramatically until, at a depth of approximately 100 m, the rate of changes declines. Dissolved oxygen shows a trend that is inverse to nutrients, with surface water concentrations at or near saturation levels (approximately 0.27 mM), decreasing rapidly thereafter with increasing depth below about 50-100 m. In deep inner basin waters, concentrations of oxygen are extremely low (< approximately 5 uM). Concentrations of nitrate typically decline below sill depths owing to the occurrence of denitrification in the suboxic basin environment (Liu 1979; Sholkovitz

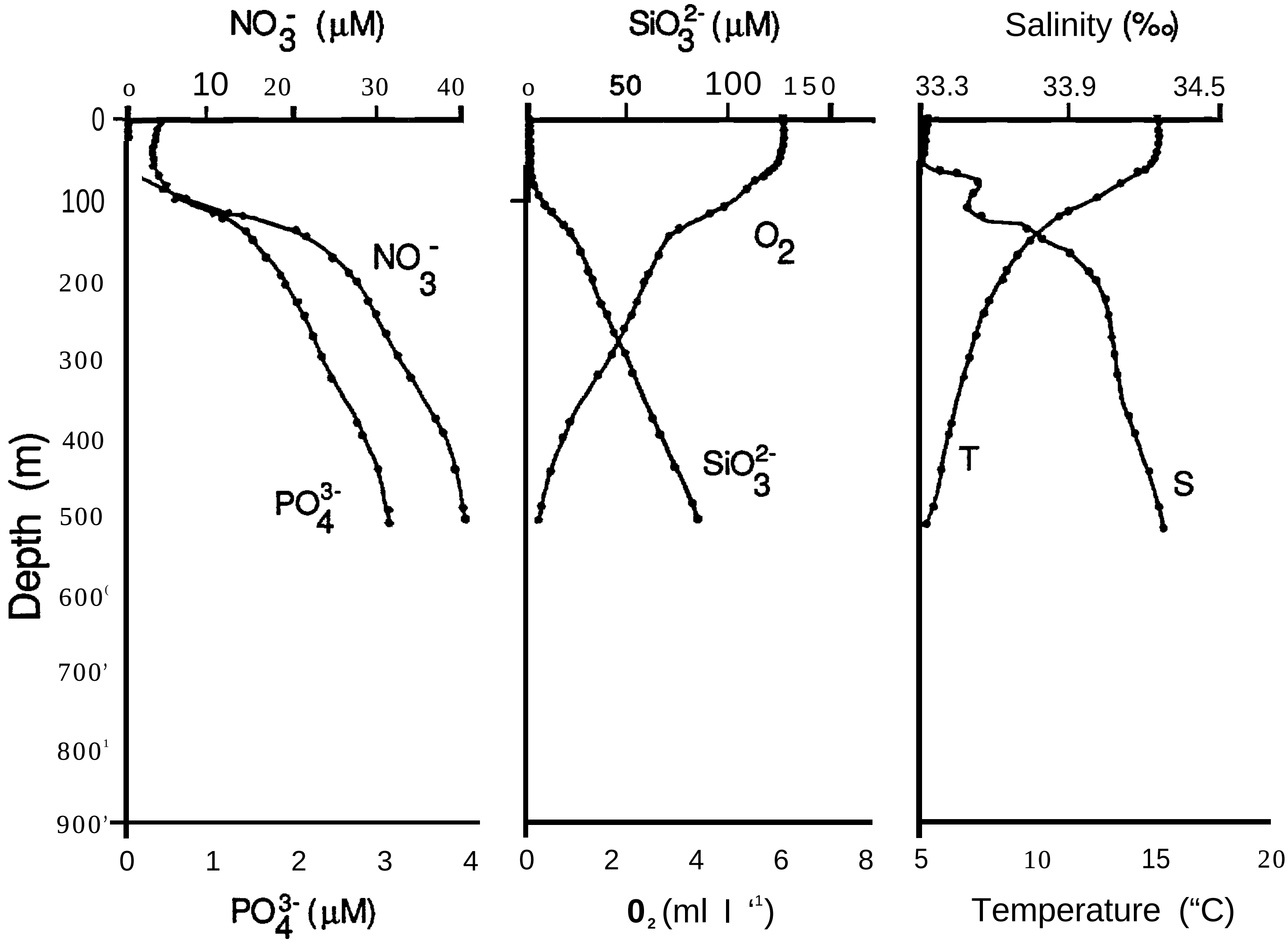
Figure 3.4. Vertical profiles of nutrients, dissolved oxygen, temperature, and salinity at (a) a location in San Pedro-Santa Monica basin, 23-29 March 1982 (after Williams 1986a) and (b) at CalCOFI station 90.70 in the California Current (CalCOFI cruise 8805, 5 April 1988).


NO_3^- SiO_3^{2-} (μM)
0 5 10 15 20
NH_4^+ NO_2^- (PM)
0 0.2 0.4 0.6 0.8
Salinity (‰)
33.4 .5 .6 .7
Depth (M)
20
40
60
80
100
PO_4^{3-}
SiO_3^{2-}
NO_3^-
Chl-a max
NO_2^-
NH_4
O_2
T
S
0 0.5 1.0 1.5 2.0
PO_4^{3-} (μM)
0 2 4 6 8
0_2 (roll ‘1)
10 12 14 16
Temperature (“C)


NO_3^- (μM)
10 20 30 40
SiO_3^{2-} (μM)
50 100 150
Salinity (‰)
.4 34.0 34.6
0
100’
200’
300
400’
500
600
700
800
900
Depth (M)
NO_3^-
PO_4^{3-}
Sill Depth
O_2
SiO_3^{2-}
T
S
1 2 3 4
PO_4^{3-} (μM)
0 2 4 6 8
0_2 (roll ‘i)
5 10 15 20
Temperature (“C)



NO_3^-, SiO_3^{2-} (µM)
0 2 4 6 8 10
NO_2^- (µM)
0.0 0.2 0.4 0.6 0.8
Salinity (‰)
33.3 33.5 33.7
Depth (m)
0 20 40 60 80 100
NO_3^-
SiO_3^{2-}
PO_4^-
O_2
NO_2^-
S
T
0.0 0.5 1,0 1.5
2.0
0 2 4 6 8
10 12 14 16
PO_4^{3-} (µM)
0_2(ml 1 $^{-1}$)
Temperature ("C)



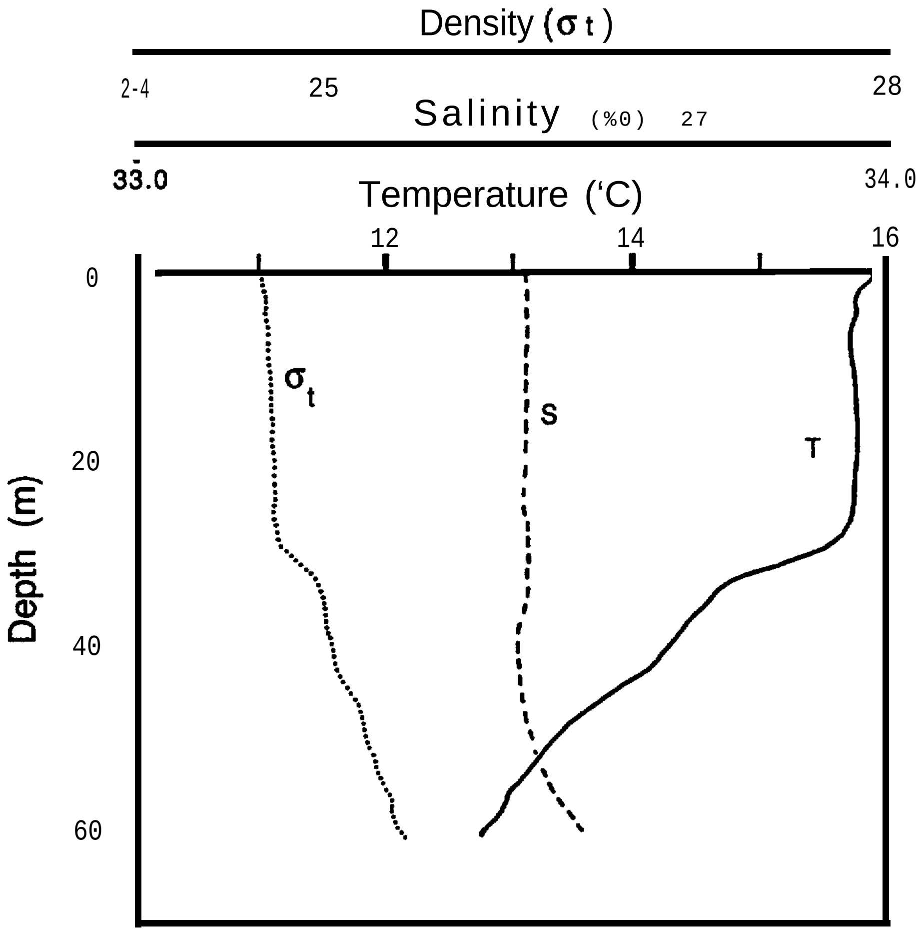
NO_3^- (µM)
o 10 20 30 40
SiO_3^{2-} (µM)
o 50 100 150
Salinity (‰)
33.3 33.9 34.5
Depth (m)
0 100 200 300 400 500 600 700 800 900
NO_3^-
PO_4^{3-}
O_2
SiO_3^{2-}
T
S
0 1 2 3 4
0 2 4 6 8
5 10 15 20
PO_4^{3-} (µM)
0_2(ml l $^{-1}$)
Temperature ("C)

1972). Thus, nitrate may reach a maximum concentration at water depths just above the sill depth of the inner basins. Nitrite and ammonium show subsurface **maxima** in the upper water column in response to activities of vitrifying bacteria (see below). These nitrogen species are essentially confined to the upper 100 m due to their rapid assimilation.

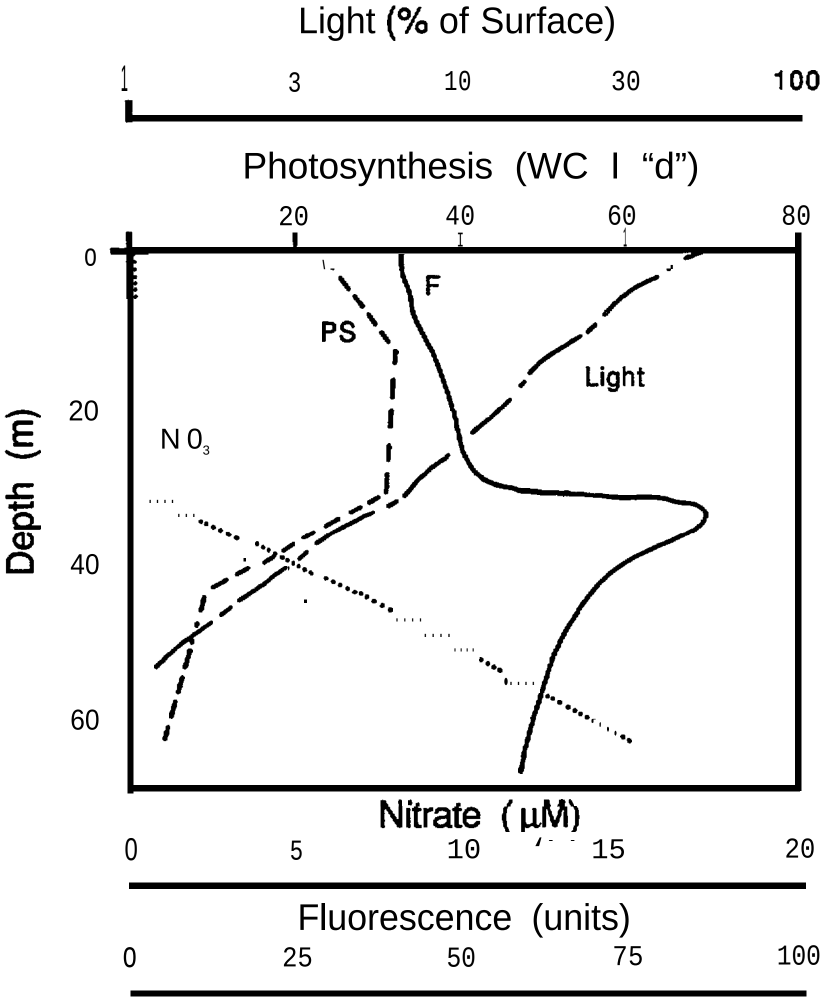
Seasonal variations in the temperature and density structure of the water column are similar within the SCB. The main differences appear in the rate at which isotherms descend or rise seasonally for nearshore (shelf) and offshore areas. The **euphotic** zone, defined as the depth below which respiration exceeds photosynthesis (or below which light illumination is <1% that at the surface), ranges from approximately 50 to 100 m. Within the **euphotic** zone, light intensity and nutrient concentrations vary inversely such that **phytoplankton** at each depth experience unique conditions for growth **(Eppley** 1986). An example of the distribution of light intensity, nitrate concentration, and other **hydrographic** parameters in the upper water column for an offshore region of the **SCB** is shown in Figure 3.5. In this figure, the standing stock of **phytoplankton** (represented by chlorophyll *a*) is low in the surface waters where the photosynthetic rate and light levels are high. Nitrate concentration is essentially nil. Below the mixed layer (approximately 30 m), photosynthesis is light-limited, but the standing stock increases dramatically, giving rise to a subsurface chlorophyll *a* maximum. This is possible because of the increased availability of nitrate and lack of vertical mixing of the phytoplankton in deeper waters.

Eppley et al. (1979a) have demonstrated an inverse relation between the depth of the **nitracline** and primary production, presumably reflecting a balance between the vertical mixing rate of nitrate and its uptake by **phytoplankton.** When integrated over the upper 50 m of the water column along a cross-shelf transect extending 125 km offshore, the concentration of

Figure 3.5. Distribution of light intensity, photosynthetic rate (PS), and hydrographic properties in the euphotic zone at a site 52 km offshore along CalCOFI line 90 (after Eppley 1986).



Density (σ t)
2-4
25
28
Salinity (%0) 27
33.0
34.0
Temperature ('C)
12
14
16
0
20
40
60
Depth (m)
σ_t
S
T

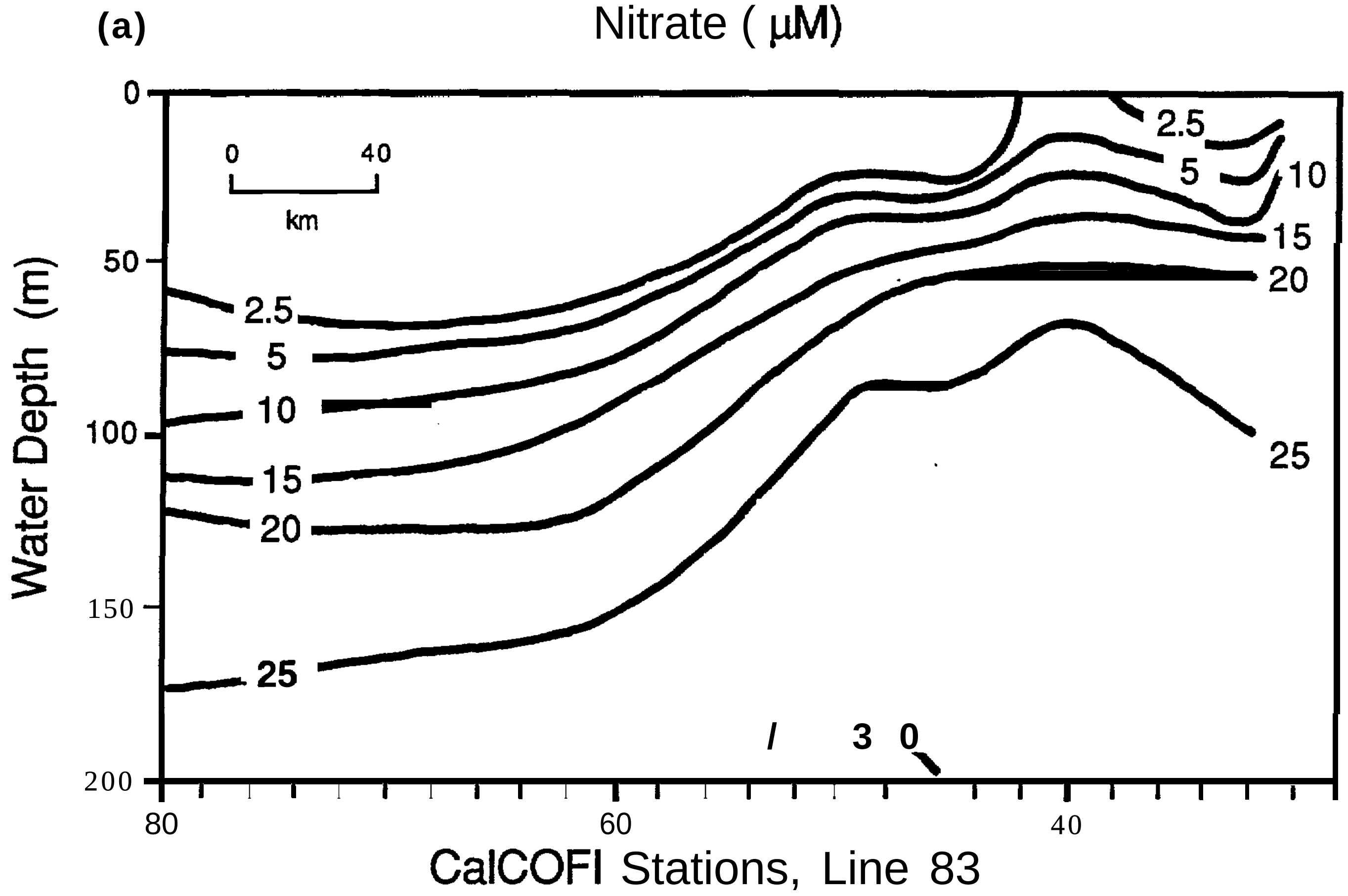


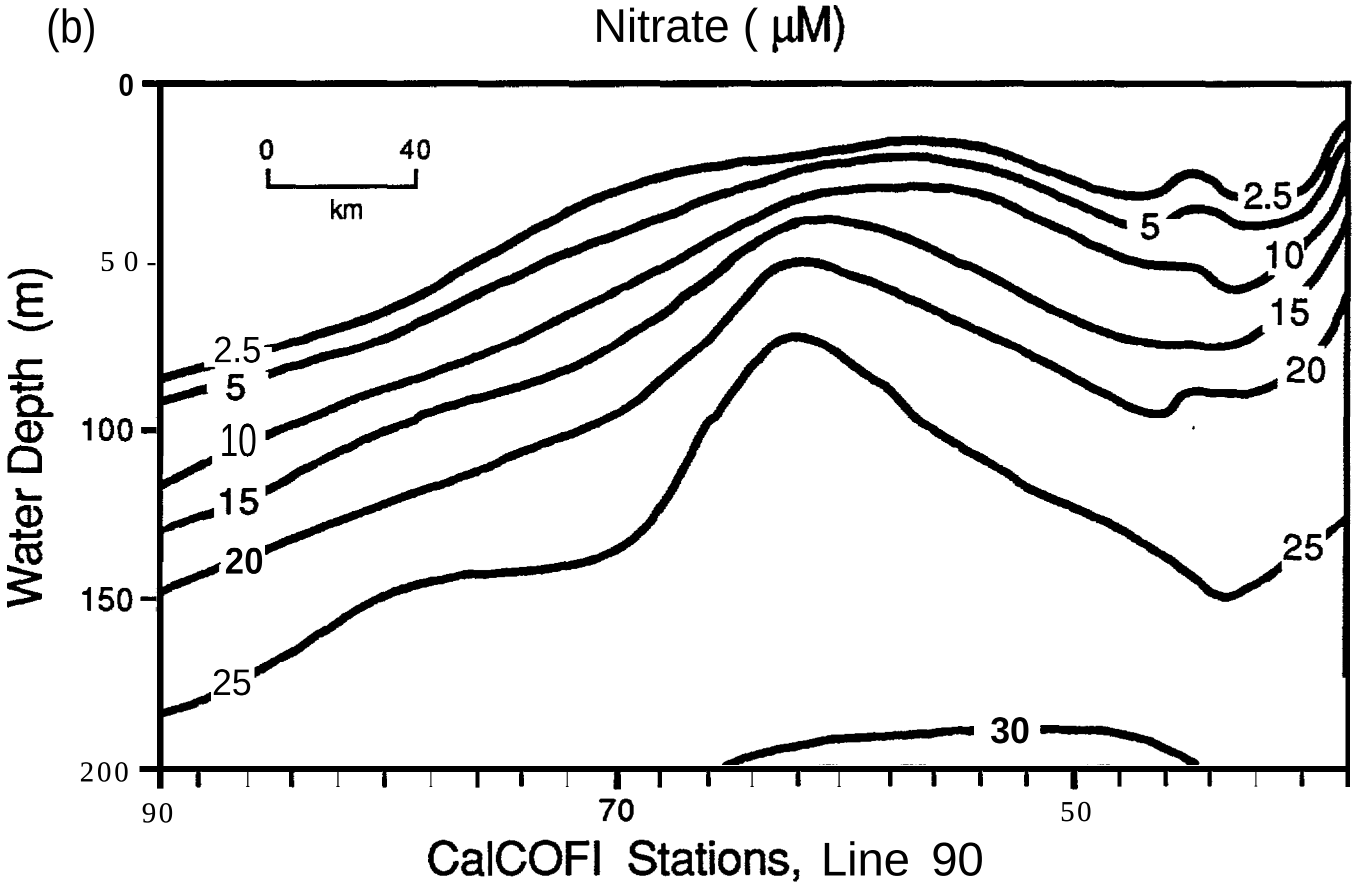
Light (% of Surface)
1
3
10
30
100
Photosynthesis (WC I "d")
20
40
60
80
0
20
40
60
Depth (m)
F
PS
Light
N 0₃
Nitrate (µM)
0
5
10
15
20
Fluorescence (units)
0
25
50
75
100

nutrients increases at inshore locations (Mullin 1986). This gradient results from inshore shoaling of the nutricline (Eppley et al. 1978). However, when concentrations are integrated over depths corresponding to the euphotic zone, no difference between inshore and offshore stations are apparent. Figure 3.6 illustrates the distribution 'of nitrate as of August 1988 along two cross-shore CalCOFI transects originating near the coastline and extending into the California Current. Although inshore shoaling of the nitracline is evidenced along both transects, the cross-shore variations are irregular. In fact, there appears to be a regional bulge in the nitracline between stations 50 and 60 (at the outer margin of the SCB). As expected from the findings of Eppley et al. (1978), these cross-shore variations in depth of the nitracline compare favorably with the distribution of phytoplankton biomass revealed by satellite imagery of chlorophyll concentration (Eppley 1986).

There are several mechanisms by which nutrient-rich deep waters can be mixed into the euphotic zone. One of these, coastal upwelling, results in the offshore displacement of warm, low-density, nutrient-depleted surface waters. These waters are replaced through onshore advection of deeper waters with consequent shoaling of the thermocline over the shelf. Coastal upwelling on the west coast of North America is most intense in areas offshore of Oregon and Northern California. However, upwelling also occurs in the SCB, most significantly in the area off Point Conception, during early spring and summer months (March to July) with the onset of north-northwesterly winds. Figure 3.7 shows an 18-month time record for nutrient and oxygen concentrations at a station 10 km off Corona del Mar (Barcelona et al. 1982). These data illustrate the effect of coastal upwelling events on temperature, salinity, and nutrient distributions. The base of the

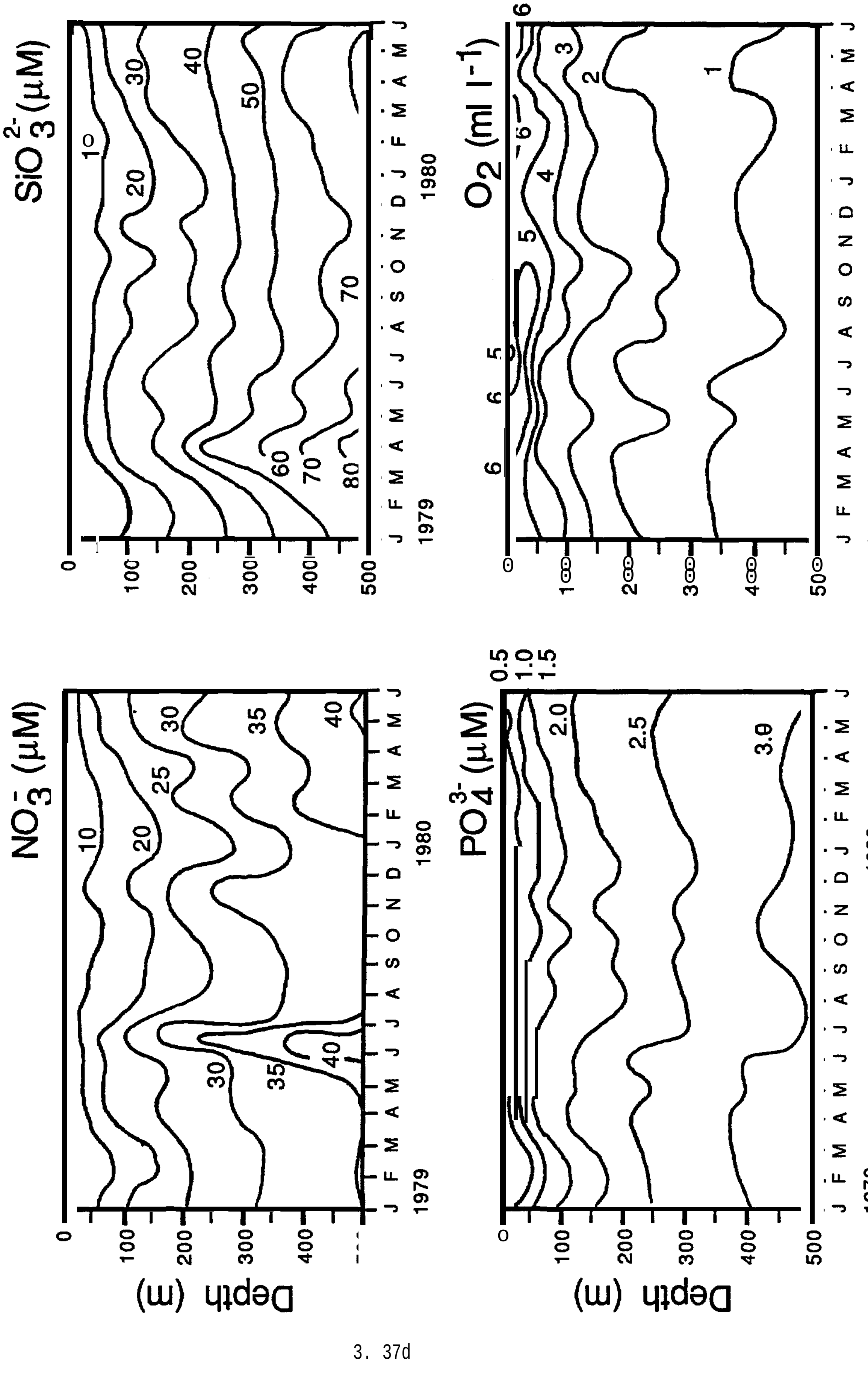
Figure 3.6. Distribution of nitrate along two cross-shore transects: (a) line 83; (b) line 90 (after CalCOFI data, cruise 8808, August 1988).


(a)
Nitrate (µM)
0
40
km
0
50
100
150
200
Water Depth (m)
2.5
5
10
15
20
25
30
80
60
40
CalCOFI Stations, Line 83


(b)
Nitrate (µM)
0
40
km
0
50
100
150
200
Water Depth (m)
2.5
5
10
15
20
25
30
90
70
50
CalCOFI Stations, Line 90

3. 37b

Figure 3.7. Temporal variations in nutrient, temperature, and oxygen distributions over an 18-month period at a station 10 km offshore Corona del Mar (after Barcelona et al. 1982).


NO$_3^-$ (μM)
SiO$_3^{2-}$ (μM)
PO$_4^{3-}$ (μM)
O$_2$ (ml l^{-1})
Depth (m)
0
100
200
300
400
500
J F M A M J J A S O N D J F M A M J
1979
1980
10
20
25
30
35
40
50
60
70
80
0.5
1.0
1.5
2.0
2.5
3.0
1
2
3
4
5
6

thermocline is compressed from 100 to 40 m as "plumes" of colder, nutrient-rich deep waters intrude the upper 200 m of the water column. The effects at this site are greatest below 100 m, and there is little or no observable change in nutrient concentrations in the euphotic zone (approximately upper 50 m) at this location (water depth=500 m). One would expect greater perturbations of nutrient distributions in the upper water column inshore of these depths with consequent impacts on primary production. An example was provided by Tent (1981), who demonstrated a relationship between records of phytoplankton abundance (namely, diatom blooms) off the Scripps Institution of Oceanography pier over a 20-year period and the occurrence of upwelling episodes.

Another mechanism by which nutrients can be transported vertically from deeper water to the euphotic zone in nearshore shelf regions are the (meter-range) oscillations in isopycnals generated by semi-diurnal tidal motions and internal waves. Winant and Bratkovich (1981) have shown that motions occurring at these frequencies represent a significant contribution to the power spectrum of longshore and cross-shore currents in the SCB. Semi-diurnal tidal motions and internal waves modulated at frequencies on the order of 5-15 minutes thus can pump nutrients into the surface mixed layer of the ocean. Armstrong and LaFond (1966) observed short-term variations in nutrient concentrations at fixed depths near the nutricline that were correlated with temperature fluctuations oscillating at frequencies characteristic of internal waves. Cullen et al. (1983) extended these observations over several days and showed that internal tides probably bring about mixing between layers via dissipation of shear instabilities.

As noted above, density stratification of the water column results in the vertical zonation of certain biological communities. Distributions of metabolizes generated by these communities reflect the net result of production and utilization processes. Such zonation was first noted in the SCB by Helm-Hansen et al. (1966) for waters overlying Santa Catalina Basin. One of these metabolizes, ammonium, is produced during the heterotrophic degradation of organic matter (ammonification). Ammonium is rapidly taken up by phytoplankton and, in Southern California coastal waters, has been estimated to account for 30-40% of the nitrogen assimilated during primary production (Eppley et al. 1979a). Ammonium can also be oxidized to nitrite by two genera of vitrifying bacteria, *Nitrosococcus* and *Nitrosomonas*. Nitrite, in turn, is oxidized to the most common form of combined nitrogen, nitrate, by bacteria of the genus *Nitrobacter*.

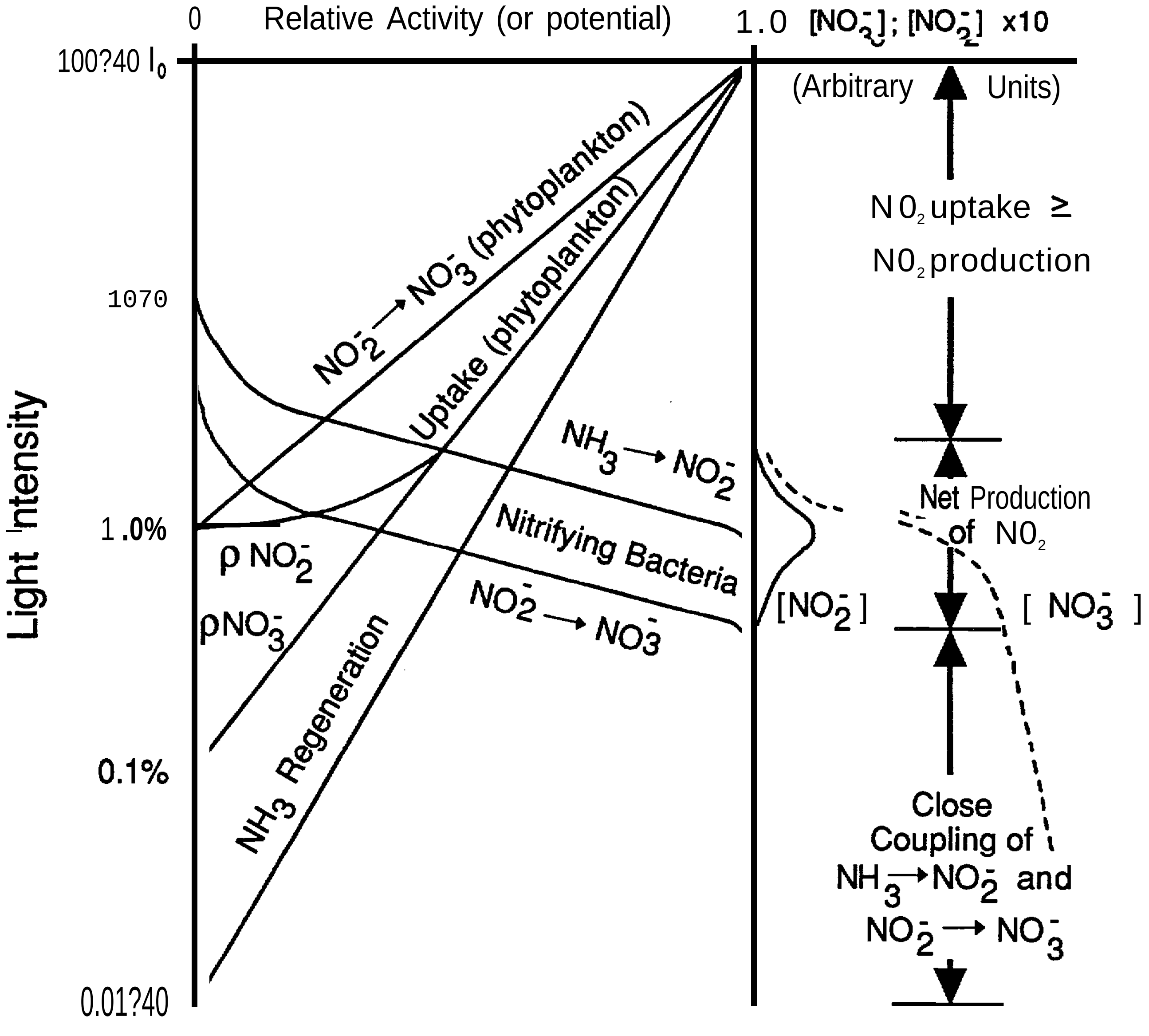
As noted earlier, ammonium and nitrite concentrations in the SCB in the sub-micromolar range are essentially restricted to the upper water column (<100 m; see Figure 3.4a). A possible exception is the occurrence of measurable ammonium in suboxic deep waters of nearshore basins such as the Santa Barbara Basin (Liu 1979), where vitrification rates are reduced and degradation of organic matter by denitrification and sulfate reduction (in sediments) can occur. Subsurface maxima in ammonium concentrations have been observed by Eppley et al. (1979b). However, the vertical distribution of ammonium is highly variable both spatially and temporally. Local sources of ammonium may be important, as evidenced by the elevated concentrations in waters of Santa Monica Bay that are believed to be due to the discharge of municipal wastes (Eppley et al. 1979b; Thomas and Carsola 1980).

Nitrite profiles typically exhibit a subsurface maximum (primary nitrite maximum) positioned at or near the base of the euphotic zone in the upper part of the nitracline (Mullins et al. 1985; Olson 1981a). Olson (1981a,b) demonstratedby ^{15}N tracer studies that the primary nitrite maximum in Southern California arises from oxidation of ammonium, presumably by vitrifying bacteria. He presented a model (Figure 3.8) for the formation of a nitrite maximum, the position of which was determined by photoinhibition of ammonium oxidation in surface waters coupled with reduced uptake of nitrite by phytoplankton. (Ward [1985] and Wardet al. [1982] later confirmed the photoinhibition of ammonium-oxidizing bacteria off Southern California and the Washington coast.) The reduced uptake of nitrite was postulated as being the result of differential rates of uptake for nitrite and nitrate within the nitracline. The low abundance of nitrate in the upper part of the nitrite maximum was subsequently attributed to greater photoinhibition of the nitrite-to-nitrate conversion (Olson 1981b). Olson (1981a) further proposed that the declining nitrite concentrations in deeper waters was attributable to increased conversion of nitrite to nitrate.

Particles: Formation, Distribution and Fluxes

The dominant source of particulate matter in surface waters (especially the euphotic zone) of the SCB is autochthonous biological production. These particles include free-living primary producers and associated members of the planktonic food web, suspended detritus, fecal pellets, and macroscopic aggregates (marine snow). The latter range in size from <1 mm to several centimeters in diameter and are believed to sink at rates of tens to hundreds of meters per day (Alldredge 1979; Shanks and Trent 1980). Consequently, they, along with zooplankton fecal pellets, are believed to be important sources of the vertical flux of particulate matter to the benthos. Although patchy in distribution and compositionally variable, marine snow is present throughout the water column and consists of complex associations of planktonic organisms, fecal pellets, exoskeletons, lithogenic debris, and bacteria (Hebel et al. 1986; Silver et al. 1978; Silver and Alldredge 1981).

Figure 3.8. Conceptual model of processes contributing to formation of a primary nitrite maximum. NO_3^- and NO_2^- are nitrate and nitrite uptake rates, respectively (after Olson 1981a).

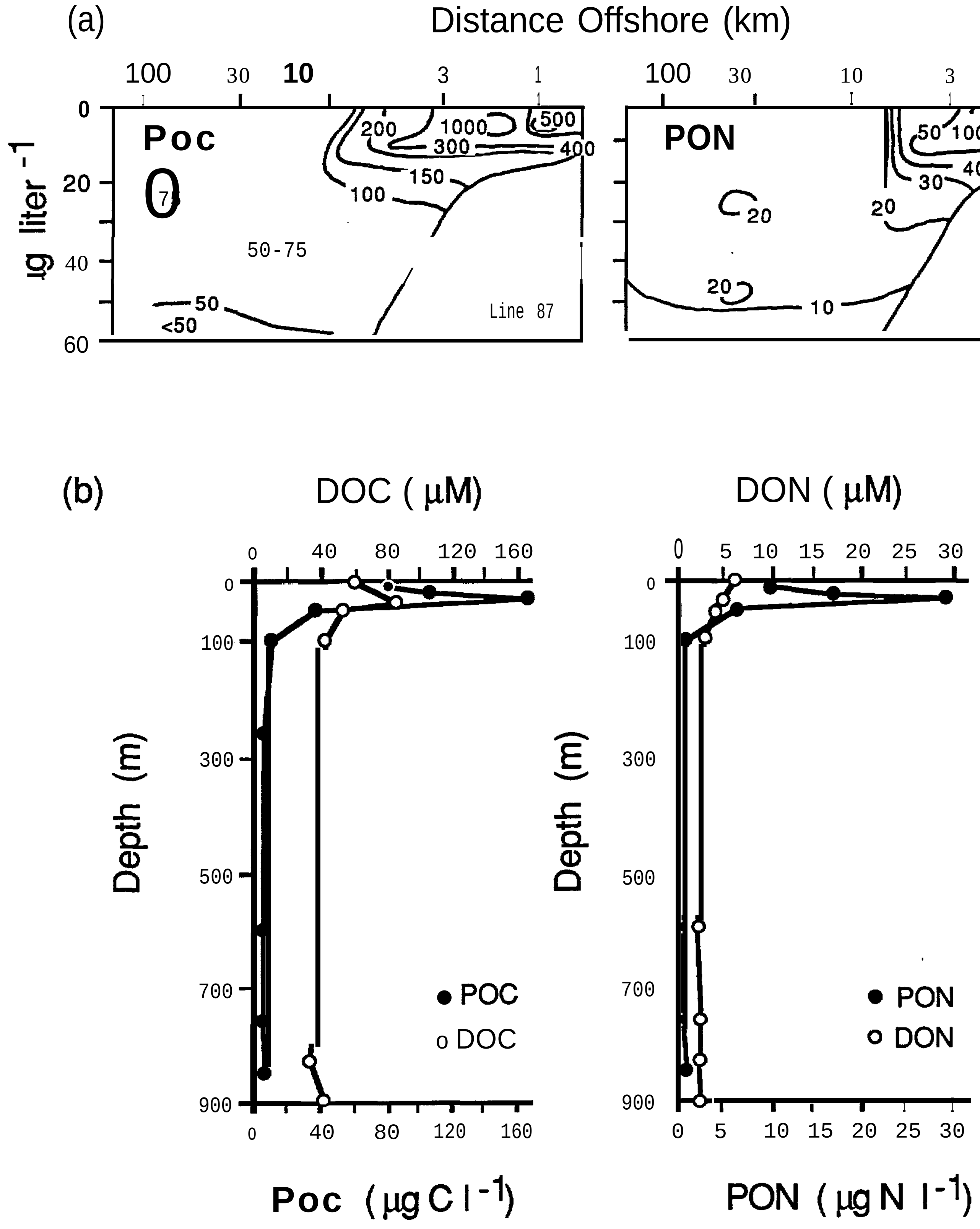

0
Relative Activity (or potential)
1.0
[NO_3^-]; [NO_2^-] x10
(Arbitrary Units)
100?40 I_0
1070
1 .0%
0.1%
0.01?40
Light Intensity
$NO_2^- \rightarrow NO_3^-$ (phytoplankton)
Uptake (phytoplankton)
$NH_3 \rightarrow NO_2^-$
Nitrifying Bacteria
$NO_2^- \rightarrow NO_3^-$
ρNO_2^-
ρNO_3^-
NH_3 Regeneration
NO_2 uptake ≥
NO_2 production
Net Production of NO_2
[NO_2^-]
[NO_3^-]
Close Coupling of
$NH_3 \rightarrow NO_2^-$ and
$NO_2^- \rightarrow NO_3^-$

The density of macroscopic aggregates in surface waters is highly variable (Fowler and Knauer 1986), but ^{14}C-production rates within them can exceed that of the surrounding, aggregate-free, seawater by as much as 50 times (Alldredge and Cox 19S2). Under-upwelling conditions, as much as 20-60% of all primary production can occur on them (Knauer et al. 19S2; Prezelin and Alldredge 1983). Alldredge (1979) estimated that, on average, 34% of the POC and 26% of the particulate organic nitrogen (PON) in surface waters of Santa Barbara Channel was present in the form of macroscopic aggregates.

Knowledge of the chemical composition of particulate organic matter (POM) in the upper water column of the SCB is limited. Siezen and Mague (1978) found that nearly all of the PON and approximately 40-50% of the POC could be accounted for by protein amino acids. Similarities in the proportions of protein organic carbon reported for cultured phytoplankton led Eppley et al. (1977) to conclude that the vast majority of the POC was of recent biogenic origin. Assuming this is the case, the remaining 50% of the POC would be expected to consist of carbohydrates and lipids. Similarly, Helm-Hansen et al. (1966) demonstrated that the POM in the upper 75 m of the water column over Santa Catalina Basin had a C:N:P ratio of 100:18:3 (similar to living phytoplankton grown in nitrogen-deficient waters), whereas suspended POM from deeper sections' yielded ratios depleted in nitrogen and phosphorus. These observations support the idea that the vast majority of the particulate organic matter in the surface waters of the SCB are of recent biological origin and that the fraction represented by relatively older, refractory detritus is minor. Whereas the living plankton biomass generally accounts for less than one-half of the total POC in surface waters, blooms can lead to abundances exceeding 70% (Eppley et al. 19s3).

Figure 3.9 illustrates the distribution of particulate organic carbon

Figure 3.9. Distribution of particulate organic carbon (POC) and particulate organic nitrogen (PON) (a) along a cross-shore transect corresponding to CalCOFI line 87 (after Eppley et al. 1977) and (b) at station 305, Cruise SCBS-18, May 1981 in Santa Monica Basin (after Williams 1986a).


(a)
Distance Offshore (km)
100
30
10
3
1
0
20
40
60
µg liter -1
Poc
0
7
200
1000
500
300
400
150
100
50-75
50
<50
Line 87
100
30
10
3
1
PON
50
100
200
40
30
20
20
20
10
Line 87
(b)
DOC (µM)
0
40
80
120
160
0
100
300
500
700
900
Depth (m)
● POC
o DOC
0
40
80
120
160
Poc (µg C l -1)
DON (µM)
0
5
10
15
20
25
30
0
100
300
500
700
900
Depth (m)
● PON
○ DON
0
5
10
15
20
25
30
PON (µg N l -1)

3 .41b

(and PON) along a cross-shore transect corresponding to CalCOFI line 87 and vertical profiles at a station along this transect within Santa Monica Basin. Also shown are vertical profiles for dissolved organic carbon (and dissolved organic nitrogen [DON]) based on information presented by Williams (1986a). Surface water POC concentrations at nearshore stations generally reach 100-300 ug C 1^{-1} and decline by approximately an order of magnitude within a distance of 100 km offshore. Similar patterns are seen for PON. The high particulate organic matter concentrations observed at the inshore stations along transect S7 in Figure 3.9a are believed to reflect elevated plankton stocks caused by nutrient enrichment associated with municipal wastewater discharges in Santa Monica Bay. Often there is a subsurface POC (and PON) maximum corresponding to the chlorophyll a maximum. With increasing water depth, however, POC concentrations decrease rapidly until, at depths below 100-300 m, a concentration of approximately 1 ug 1^{-1} is reached. If one assumes that the POC observed at greater depth represents the background refractory detrital component throughout the water column, it is seen that this fraction represents less than 1% of the total POC pool in surface waters. This is consistent with the hypothesis that the vast majority of the POC in the euphotic zone is of recent biogenic origin.

Particulate organic carbon near the surface of the ocean is either recycled or lost to deeper waters by sinking. Aside from its importance to nutrient generation at depth and its vital role in supplying energy to the benthos, sinking particulate matter provides an effective vehicle for transporting trace inorganic and organic pollutants to the deep ocean (Bruland and Franks 1979; Bruland et al. 1981; Crisp et al. 1979; and Venkatesan and Kaplan 1988, among others). Consequently, it is important to characterize the factors affecting the residence time of particulate matter in surface waters and its vertical flux out of them. Eppley et al. (1983) defined the residence time of POC in surface waters of the SCB as the ratio of POC to “new production” (estimated either by nitrate assimilation rates and the POC/PON ratio or by fluxes measured in sediment traps positioned below the euphotic zone; see below). They found that the residence time of POC was inversely related to the total l*C production. Furthermore, residence times estimated for offshore sites during the period 1974 to 1979 ranged from less than 10 days (high l*C production) to several hundreds of days (during oligotrophic conditions), the wide differences being attributable to changes in ocean climate (for example, El Nine) and upwelling intensity. The long residence times observed during certain periods (1976 and 1977), rather than reflecting resistance of the POC to degradation, imply a high rate of recycling, with turnover times on the order of 11 days. Rapid turnover means that the particulate organic matter is recycled numerous times before sinking to deeper waters. Eppley et al. (1983) calculated the number of times a POC atom would be recycled before escaping the euphotic zone at between 1 (during upwelling) to nearly 20 times (during oligotrophic periods). This suggests that during periods of high production, POC generated in surface waters would likely settle to the sea floor, whereas oligotrophic conditions would favor transport of suspended particles generated in the euphotic zone out of the SCB. This is consistent with the view that high productivity enhances operation of the grazing food chain and, therefore, promotes the generation of large particles such as zooplankton fecal pellets and macroscopic aggregates (Prezelin and Alldredge 1983) capable of sinking from the euphotic zone. Oligotrophic conditions favor functioning of the “microbial loop” (Azam 1986), whereby recycling of POM is carried out efficiently, and production of large particles with rapid sinking rates is reduced.

Deuser and Ross (1980) first noted the seasonal coupling of primary productivity and the vertical flux of particulate matter to the deep sea. It was evident that this coupling could only be achieved by transport of particulate matter at rates on the order of 10^1-10^3 m d-l, a requirement that established (along with earlier theoretical considerations; McCave 1975) the importance of the relatively rare, large particles in dominating the vertical flux of particulate matter in the ocean. These relationships were formalized in a quantitative empirical model by Suess (1980), who used the results of early sediment trap studies. Eppley and Peterson (1979) showed that the proportion of "new production" arising from input of nutrients to the euphotic zone (through upwelling and diffusion from deeper water) was directly related to total production in cases where total production was below 200 g C m^{-2} yr^{-1}. The proposed relationship was developed using data from sites in the SCB, among others. As a percentage of total production (g C m^{-2} yr^{-1}), new production within the SCB was estimated at 15 to >60$, depending on location and time. Under steady-state conditions, the rate of "new production" should equal the downward vertical flux of particulate matter from the euphotic zone. Assuming this is the case, simultaneous measurement of vertical fluxes (using sediment traps) and total production in the euphotic zone should afford an opportunity to estimate new production and test its relationship to total production.

Early work by Knauer and Martin (1981) for a coastal site 80 km off the Monterey Peninsula indicated that the flux of particulate carbon and nitrogen at the base of the euphotic zone represented 22% of the primary productivity (Table 3.5). These studies were performed over a 6-day period and involved contemporaneous measurements of primary productivity. Previous investigations conducted under upwelling and non-upwelling conditions at a

Table 3.5. Summary of sediment trap studies from the SCB and adjacent areas.

Study	Location[a]	Deployment Depth[b] (m)	Flux ($g\ m^{-2}\ d^{-1}$)			Other Parameters[c]
			Mass	OC	N	
Soutar et al. (1977)	SBB	150	0.55	--	--	
	"	30/A	0.82	--	--	
	"	10/A	4.65	--	--	
	"	100	2.19	--	--	
	"	10/A	2.46	--	--	
	"	150	0.82	--	--	
	"	10/A	1.6	--	--	
	SPB	150	0.3	--	--	
	"	10/A	0.3	--	--	
	SB	150	1.4	--	--	
	"	180	0.5	--	--	
	"	40/A	0.8	--	--	
	"	10/A	0.8	--	--	
	"	150	0.3	--	--	
	"	10/A	8.0	--	--	
Knauer et al. (1979)	30 km off Monterey	50	--	0.43	0.057	^{210}Pb,FP,P
		250	--	0.25	0.025	
		700	--	0.12	0.013	
		50	--	0.091	0.011	
		250	--	0.052	0.006	
		700	--	0.049	0.004	
Knauer and Martin (1981)	80 km off Monterey	35	--	0.31	0.061	PP
		65	--	0.15	0.026	
		150	--	0.080	0.012	
		500	--	0.025	0.008	
		750	--	0.023	0.002	
		1500	--	0.071	0.009	
Dymond et al. (1981)	SBB	341	1.83	0.064	--	Al,Si,Mg,K,Ca, Fe,Mn,Ni,Cu,Zn, Ba,$CaCO_3$
	"	381	1.96	0.073	--	
	"	213	2.12	0.074	--	
	"	328	1.27	0.047	--	
	"	162	1.01	0.032	--	
Crisp et al. (1979)	SBB	30/A	1.12	0.040	--	markers,AHC, SHC,UCM,$\delta^{15}N$, $\delta^{13}C$,$\delta^{32}S$,ESR, C/N
	SNB	30/A	0.27	0.009	--	
	SMB	30/A	0.49	0.76	--	
	SPB	30/a	0.76	0.034	--	
Bruland et al. (1981)	SBB	30/A	2.01	--	--	Fe,Cu,Zn,Cd, Pb,^{210}Pb,^{228}Th, ^{232}Th
	SBB	30/A	1.96	--	--	
	SNB	30/A	0.40	--	--	
	SMB	30/A	0.46	--	--	
	SPB	30/A	1.00	--	--	

Table 3.5. (continued) Summary of sediment trap studies from the SCB and adjacent areas.

Study	Location[a]	Deployment Depth[b] (m)	Flux (g m^{-2} d^{-1})			Other Parameters[c]
			Mass	OC	N	
Karl and	160 km	100	--	0.064	0.010	ATP,RNA,
Knauer	off Big Sur	300	--	0.031	0.0056	nucleic acid
(1984)		500	--	0.023	0.0042	synthesis,PP
		600	--	0.022	0.0034	O_2,FP,LH,Al
		700	--	0.015	0.0020	
		900	--	0.031	0.0053	
		1100	--	0.021	0.0021	
		1400	--	0.015	0.0023	
		1700	--	0.015	0.0023	
Noriki	**Calif.**	510	0.081	0.030	--	%clay,TVS
and	Current	720	0.082	0.031	--	opal,
Tsunogai	**(EP5)**	1250	0.070	0.026	--	$CaCO_3$
(1986)		3370	0.054	0.018	--	
		4220	0.046	0.013	--	
	Calif.	500	0.019	0.008	--	
	Current	720	0.015	0.005	--	
	(EP7)	1250	0.015	0.003	--	
		3380	0.017	0.004	--	
		4220	0.016	0.003	--	
Matsueda	ENP	740	0.099	0.023	0.0032	HC,lipids,
and	(Stn. 5)	940	0.104	0.018	0.0023	markers
Handa		1440	0.044	0.007	0.0010	
(1986)		3440	0.047	0.007	0.0009	
		4240	0.069	0.009	0.0011	
	ENP	720	0.020	0.004	0.0006	
	(Stn. 7)	920	0.017	0.003	0.0004	
		1420	0.017	0.002	0.0003	
		3420	0.016	0.001	0.0001	
		3820	0.016	0.001	0.0001	
	ENP	670	0.039	0.004	0.0006	
	(Stn. 11)	870	0.002	0.003	0.0005	
		1370	0.037	0.002	0.0003	
		3370	0.030	0.002	0.0002	
		3670	0.021	0.002	0.0002	
Nelson et al. (1987)			(see Table 3.C.3)			CO_3-C,chl-a, phaeo-a, transmis. PP,SI, NO3$^-$,δ^{15}N

Table 3.5. (continued)

[a] Location designations as follows: SBB--Santa Barbara Basin; SMB--Santa Monica Basin; SPB--San Pedro Basin; SB--Soledad Basin; ENP--Eastern North Pacific.

[b] Deployment depths given in form, n/A, represent traps positions n meters above sea floor.

[c] Abbreviations: TVS--total volatile solids; P--phosphorus; FP--fecal pellets; PP--primary productivity; AHC--aromatic hydrocarbons; SHC--saturated hydrocarbons; marker--molecular markers; UCM--unresolved complex mixture (hydrocarbons); ESR--electron spin resonance; LH--larvacean houses; HC--total hydrocarbons; chl-a--chlorophyll a; phaeo-a--phaeophorbide a; transmis.--transmissivity; S1--surface irradiance.

site 30 km offshore had suggested higher percentages (upwelling: 53%-carbon; 39%-nitrogen; non-upwelling: 34%-carbon, 23%-nitrogen; Knauer et al. 1979). However, primary productivity was not measured in these studies. In both cases, the estimated vertical flux of particulate organic matter decreased with increasing water depth at the site, the greatest changes occurring in the upper 500 m of the water column. This identifies the upper water column as an active site of recycling or remineralization, as reflected in vertical profiles of nitrate, silicate, and phosphate (Figure 3.4).

Nelson et al. (19S7) reported results of sediment trap studies in the Santa Monica-San Pedro basin in which free-drifting sediment traps (FST:short term-2.5 days) deployed at 100 mwere used to estimate particle fluxes from the euphotic zone (approximately 53 m). Comparison of the fluxes of POC with primary productivity measured in the overlying waters during the trap deployments suggested that only 5$ of the carbon being fixed in the euphotic zone was reaching deeper waters. This flux is approximately an order of magnitude lower than predictions of new production based on previous productivity measurements in this area (that is, new production approximately 50% total production; Eppley and Peterson 1979), raising questions about the general applicability of short-term sediment trap fluxes to estimation of new production. The authors pointed out that sediment traps are "areal integrators," incorporating fluxes of small and large particles settling from different points of origin as determined by the horizontal currents. Difficulties can thus arise when short-term deployments are used because of weak temporal and spatial coupling of biological processes occurring in the euphotic zone and fluxes measured in the underlying water column.

Recent efforts by the CaBS project have resulted in further <u>direct</u>

comparisons between estimates of “new production” and the flux of particulate carbon and nitrogen below the **euphotic** zone (at 100 m) at sites within the Santa Monica-San Pedro basin (as measured by free-drifting sediment traps; Jackson et al. 19S9). During five cruises from 1985-1987, they found trap fluxes of PON ranging from 14.8 to 49.4 mg N m^{-2} d-l with a mean of 28.6 mg N m^{-2} d-l. By comparison, new production estimates ranged from 18.2 to 33.0 mg N m^{-2} d-l with a mean of 23.2 mg N m^{-2} d-l. The trap flux/new production ratios varied from 0.81 to 2.4 with an average of 1.3, suggesting that the estimates are in reasonable agreement.

In general, the comparisons made for POC showed that trap fluxes exceeded new production estimates. This signals efficient retention of nitrogen during recycling and selective release of carbon, presumably during zooplankton grazing, to deeper waters via fecal pellet production, release of **larvacean** houses, or formation of macroscopic aggregates enriched in carbon (**Alldredge** 1979). Based on these measurements, the flux of particulate organic carbon from the **euphotic** zone would appear to represent approximately 45$ of the primary production, in agreement with earlier work (**Eppley** and Peterson 1979). The remaining POC is apparently recycled rapidly in the upper 100 m of the water column.

Dissolved Organic Matter

The vertical distribution of dissolved organic carbon (DOC) and nitrogen (DON) are shown in Figure 3.9b for a station within Santa Monica Basin. These data were obtained using the classical **persulfate oxidation**-infrared detection method with preliminary UV irradiation for DON. Recent work with high temperature combustion procedures has suggested that the classical wet oxidation methods may underestimate marine DOC and DON concentrations by as much as 50-500$, the lost fraction apparently consisting of biochemically "labile" components of the DOM pool (Sugimura and Suzuki 1988; Suzuki et al. 1985). Until controversy surrounding the determination of marine DOC is resolved, these profiles must be regarded as tentative depictions (minimum concentrations) of the actual distributions.

Concentrations of DOC and DON within the euphotic zone (upper 100 m) are in the range of 50-150 UM and 3-6 uM, respectively. With increasing depth below the euphotic zone, concentrations reach background levels of approximately 33-50 UM (DOC) and 1-4 UM (DON). The biologically labile fraction of dissolved organic matter generated in the euphotic zone (by exudation, sloppy feeding, excretion, or autolysis) is rapidly recycled by bacteria and demineralized or transferred to higher trophic levels via the "microbial loop" (see references in Azam 1986). Alternatively, a portion may be directly utilized by phytoplankton (urea, amino acids). It has been noted that the concentrations of DON and dissolved organic phosphorus (DOP) vary inversely with nitrate and phosphate, respectively, in the euphotic zone, and that when [DON + nitrate] is plotted against [DOP + PO_4^{-3}], the slope approximates the Redfield ratio of 16 (Jackson and Williams 1985). This suggests that at least a portion of the dissolved organic nitrogen and phosphorus is available for direct utilization by autotrophic organisms and may, therefore, be an important source of nutrients. C/N/P ratios of DOM are in the range of 100/9.4/0.4 to 100/7.0/0.16 and do not show systematic variations with water depth (Helm-Hansen et al. 1966; Williams 1986a). The reduced nitrogen and phosphorus contents of the DOM compared with the Redfield ratio, its relatively invariant concentration with depth below the euphotic zone, and the constancy of the stable carbon isotope signature (approximately -21.2 to -24.4°/00; Williams and Gordon 1970) suggest that the majority of this material is refractory.

Williams (1986a) has reviewed available literature on the composition of dissolved organic matter off Southern California. If all of the organic compounds identified in surface waters are summed (in terms of carbon equivalents) only about **25%** of the **DOC** can be accounted for. The tally is as follows: total carbohydrates-144 **ug** C 1^{-1} (14.4\$), dissolved free amino acids-1.6 **ug** C 1^{-1} (<0.2%), total hydrolyzable amino acids-26.4 ug C 1^{-1} (2.6%), urea-60 ug C 1^{-1} **(6%),** dimethylsulfoxide-l.2 **ug** C l^{-1} (<0.2%), and oxalic, **glyoxalic,** and **pyruvic** acids-4.5 ug C 1^{-1} (0.4\$). The remainder apparently represents a mixture of **humic** substances, lipids (minor), and other, as yet unidentified, compounds.

Intermediate Waters

Overview

Waters confined between 200 m and basin sill depths (which vary between 500 and 1900 m; Emery 1960) are believed to be primarily of southern origin. This means they are more saline, have lower dissolved oxygen contents, and generally higher nutrient concentrations than the northern source that dominates surface waters in the SCB. Water motion is poleward (northwest) and directed along **isobaths** by the constraints of local bottom topography. The mixing of southern and northern (and other) waters is not complete at all depths. As a result, high resolution vertical profiles of chemical constituents reveal the interdigitation of water lenses with distinct biochemical signatures (Helm-Hansen et al. 1966; Strickland 1968). Recent work by Liu and Kaplan (1989) shows that nitrate in intermediate waters of the SCB is enriched in ^{15}N (approximately 7-12 $O/_{00}$). Because **denitrification** is restricted to inner basin bottom waters, the most likely source of this nitrate is Eastern Tropical North Pacific water. This apparently is carried into the SCB at depth and **transported** north via the

California Undercurrent as a band of phosphate-rich, high-salinity water.

Waters below the euphotic zone do not support the growth of phytoplankton, hence heterotrophic processes predominate. (The only known exception to this generalization is the possibility of carbon production within the oceanic oxygen minimum zone where chemolithotrophic fixation of CO_2 may be occurring [Karl and Knauer 1984].) Thus, the products of in situ decomposition of sinking particles (that is, NO_3^-, PO_4^{-3}, CO_2) are superimposed on chemical distributions inherited from the source waters. Emery (1960) noted that computation of the predicted dissolved oxygen content of intermediate waters based on T-S relations for southern and northern sources resulted in a deficit. Liu and Kaplan (1989) likewise suggest that the apparent oxygen utilization (AOU) changes within intermediate waters. These observations demonstrate that in situ decomposition processes occurring in this part of the water column are not only detectable, but significant.

Vertical Flux and Remineralization of Particulate Matter

Until recently there have been few studies of the vertical flux and decomposition of sinking particulate organic matter in the SCB. A series of investigations carried out in the 1970s focused on the estimation of fluxes of particulate, fecal pellets, organic carbon, nitrogen, and trace inorganic and organic constituents to basin sediments (Bruland and Franks 1979; Crisp et al. 1979; Dunbar and Berger 1981). Other programs were primarily directed at examining questions of trap calibration and design (Bruland et al. 1981; Dymond et al. 1981; Soutar et al. 1977). Information relevant to these and other studies undertaken within the California Current or eastern Pacific is summarized in Table 3.5. Only within the last decade have multi-level and time-series trap arrays been used for purposes of understanding particle transport and rates of remineralization during sedimentation.

Nelson et al. (19S7) reported results of two short-term free-drifting arrays with sediment traps positioned at water depths of 100, 300, and 500 m in the Santa Monica-San Pedro basin and a long-term (six month) trap deployment at 500 and 824 m in San Pedro Basin. The data summarized in Table 3.6 show that with increasing depth, the fluxes of organic carbon and nitrogen to the (short-term) traps deployed at 500 m were ≤ 50% those at 100 m. These differences reflect processes of disaggregation, dissolution, and decomposition of sinking particles. Vertical sampling resolution was insufficient to examine the possibility of lateral advection at these water depths. Only a small fraction (<3%) of the particulate organic carbon flux at all depths during the first short-term deployment could be accounted for by intact microorganisms. However, phytoplankton carbon, as measured by chlorophyll *a* and phaeophorbide *a*, comprised a significant proportion of the total organic carbon flux (10-70%), with increasingly lower percentages found in traps at greater depth in the water column. This is consistent with stable carbon and nitrogen isotope measurements of particulate trapped in San Pedro Basin by Crisp et al. (1979) and in Santa Monica Basin by Jackson et al. (1989) which showed that the sinking POC is primarily of marine origin. The majority of the phytoplankton carbon is apparently associated with fecal material, much of which was derived from the pelagic crab, *Pleuronocodes planipes*. Other investigators have found that fecal pellets can dominate the vertical flux of particles in waters of the SCB (Dunbar and Berger 1981; Soutar et al. 1977).

In the case of the long-term experiment, the deeper trap (positioned 50 m above the basin floor) collected nearly double the amount of solids, organic carbon, and nitrogen as the trap positioned at 500 m. This reflects

Table 3.6. Summary of short-term and long-term sediment trap studies conducted in Santa Monica-San Pedro Basin, 1983 (after Nelson et al. 1987)

Trap	Trap	Flux (mg m^{-2} d^{-1})			%	%
depth	preserv.[a]	Mass	OC	N	Phytopl[b]	uorganism[c]
		Short-term deployment No. 1[d]				
100	L	216	34.5	5.4	22.0	2.0
100	F	242	35.0	5.3	--	--
300	L	131	18.6	3.1	9.5	2.6
300	F	138	13.6	2.2	--	--
500	L	193	14.6	1.8	--	2.9
500	F	256	17.1	2.2	--	--
		Short-term deployment No. 2				
100	L	327	30.0	4.2	69.5	--
100	F	220	26.3	3.2	--	--
300	L	391	37.0	5.1	26.7	--
300	F	393	36.6	4.7	--	--
500	L	240	18.4	2.7	22.7	--
500	F	419	24.9	3.2	--	--
		Long-term deployment[d]				
500	F	167	13.6	1.6	--	--
500	M	239	16.6	2.0	--	--
824	F	440	22.1	2.5	--	--
824	M	401	24.7	3.0	--	--

---

[a] Trap preservatives used: F--formalin; L--no preservative used; M--$HgCl_2$.

[b] Percent of total organic carbon flux represented by phytoplankton (based on pigment fluxes and 40:1 carbon/chlorophyll ratio).

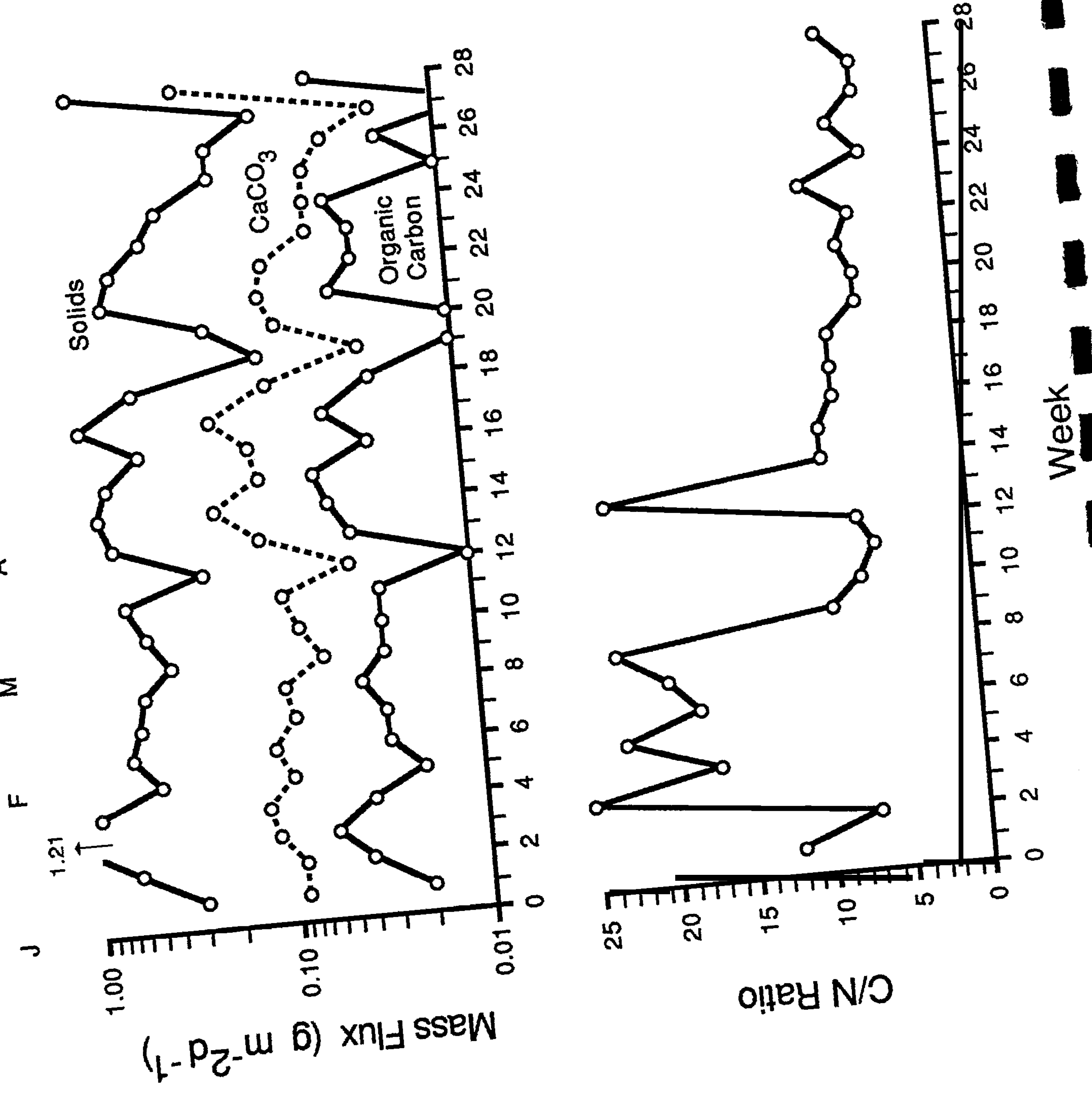
[c] Percent of total organic carbon flux represented by intact microorganisms based on microscopic analysis and cell volume-to-carbon biomass conversion.

[d] Deployments as follows: short-term No. 1-59 hours, 5/17-23/83; short-term No. 2-59 hours, 5/22-25/83; long-term-190 days, 5/23 to 9/29/83.

the introduction of resuspended sediments, presumably originating from shelf and slope environments, into basin waters. Similar results have been reported by Dymond et al. (1981) and Soutar et al. (1977) for the Santa Barbara Basin. Moreover, Shiner (1982) provided evidence that resuspension of slope sediments contributed to the enrichment of suspended particulate aluminum at mid-water depths (below upper 100 m) in Santa Barbara Basin. The episodic nature of resuspension is exemplified by the variable particulate aluminum profiles found on four separate occasions in Santa Barbara Basin (Shiner 1982).

Difficulties arise in comparing fluxes obtained using different sediment traps because of variations in trapping efficiency related to trap geometry and its interaction with differing hydrodynamic conditions. However, examination of Table 3.5 reveals that the intrabasin variations in solids fluxes are as large as interbasin fluxes. The nature and cause of intrabasin variations are unknown, although seasonal upwelling, lateral advection of resuspended material, and turbidity currents have been invoked as mechanisms. Studies currently ongoing in San Pedro Basin examine the long-term variability of short-term particle fluxes to this basin (Sautter pers. comm. 1989). Figure 3.10 provides data on a series of one-week trap collections at a water depth of 500 m over a period of seven months. Fluxes of total particulate matter and organic carbon vary by factors of over more than an order of magnitude and six, respectively. Moreover, the week-to-week variability is quite high. In general, the fluxes are in line with those reported for San Pedro Basin in earlier studies (Crisp et al. 1979; Nelson et al. 1987). However, the unusually high C/N ratios occurring in the months of January and February are anomalous. These either indicate either introduction of terrigenous material and resuspension (or both) and

Figure 3.10. Short-term (l-week deployments) variations in the vertical flux of particulate matter, total organic carbon, and calcium carbonate to sediment traps positioned at 500 m in San Pedro Basin, i988 (after Sautter and Pilskaln pers. comm. 1989).


Mass Flux (g m-2d-1)
1.00
0.10
0.01
1.21
Solids
CaCO3
Organic Carbon
J
F
M
A
M
J
J
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
C/N Ratio
25
20
15
10
5
0
Week

3.51b

lateral transport of sediments from the shelf and slope. The occurrence of a spring bloom during the months of March-May is indicated by maximum fluxes of carbonate and lower C/N ratios approximating the Redfield ratio. Nelson et al. (1987) found C/N ratios ranging from 6.0-8.2 (means of 6.9 and 7.5 for first and second deployments, respectively) for the short-term deployments in May, whereas the ratios in the long-term deep traps were 8.2-8.8 (mean=8.4).

The largest database on the the origin and fate of sinking particulate matter has been developed in the context of the multi-disciplinary CaBS study conducted from 1985-1988. Some of the results of free-drifting sediment traps deployed for short periods of time (24 hrs) have previously been discussed in the context of particulate matter fluxes from the euphotic zone. We now shift attention to studies involving traps moored for longer periods (100-150 days) at depths of 200-850 m in Santa Monica Basin. Although most of these data have yet to be published, we present a brief summary based on reports by Jackson et al. (1989), Williams (1988), and Venkatesan and Kaplan (1988).

Sediment traps were deployed over the eastern slope of Santa Monica Basin (33°51’N 118°38’W; bottom depth approximately 400 m) at depths of 200 and 350 m during i986 (February and May) and 1987 (April and October) for periods ranging from approximately 100 to 150 days. In addition, multiple traps were deployed over the same periods at a location near the center of the basin (33°45’N 118°53’W; bottom depth approximately 900 m) at depths of 100, 500, 700, and 850 m. Particulate fluxes within the basin appear to be on the order of 400-500 mg m^{-2} d-l at shallower depths (100 m), increasing to an average of 620 mg m^{-2} d-i at 850 m water depth. Comparison of samples collected during May and October of 1986 indicates higher fluxes during the spring deployment. This may reflect a seasonal linkage between benthic flux and primary production in overlying waters. However, the data are too sparse at this point to make definitive statements. The average flux agrees well with sediment accumulation rates estimated from ^{210}Pb profiles (630 mg m^{-2} d-l). For comparison, Bruland et al. (1981) and Crisp et al. (1979) reported fluxes of 463 and 493 mg m^{-2} d-l, respectively, for studies conducted in 1977.

Organic carbon shows a flux of approximately 55 mg m^{-2} d-l at 100 m and decreases to 47 mg m^{-2} d-l at 850 m. Below a depth of 500 m there is essentially no change in the flux of organic carbon, and the accumulation measured in the bottom trap agrees well with that estimated by summing burial and diagenetic losses (44 mg m^{-2} d-l). The stable isotopic composition of this material reflects a largely marine autochthonous origin (δ^{15}N = +6.6 to +8.9 $^{o}/_{oo}$; δ^{13}C = -21 to -22 $^{0}/_{oo}$). The variable and occasionally low nitrogen ratios indicate a contribution from terrestrial sources (Sweeney and Kaplan 1980a). Similar depletion of ^{15}N was found for the slope particulate, where one would expect to encounter terrigenous debris. In general, these compositions compare well with the range (+7.09 to +8.05) reported by Nelson et al. (1987) for total organic matter and are slightly lower than Crisp et al. (1979) noted for humic acid and kerogen isolates (+8.3 to +9.4., +10.4 to +13.5).

Venkatesan and Kaplan (1988) reported results of molecular analyses for the May and October 1986 trap deployments. Fluxes of all lipid classes (hydrocarbons, alkanols, fatty acids, sterols) decreased with increasing water depth at rates higher than those observed for organic carbon. This suggests that the lipids associated with sinking particles represent one of the more labile fractions of the particulate organic matter in deep basin waters. The composition of the fatty acids and alkanols indicated contributions from both marine and terrestrial sources, with the former predominating at all depths. However, the terrestrial homologs increased in relative abundance in the deeper traps. This probably reflects a greater resistance to degradation, possibly conferred by association of these compounds with resistant plant parts such as cuticles. This observation is consistent with the fact that these higher molecular weight homologs are found even in sediments deposited on the outer continental shelf (see Section V, "Distribution and Fate of Chemical Constituents in Sediments"). Sediment traps deployed near the slope generally collected greater amounts of lipids than those situated in the basin at comparable depths. This is expected if a significant fraction of the trapped particulate is derived by resuspension and transport from shallower slope or shelf areas. Comparison of fluxes for the fecal sterol, coprostanol, at basin and slope sites confirms the dilution of anthropogenic inputs with distance from land.

Deep Basin Waters

Overview

Offshore basins of Southern California contain waters originating from currents moving over the sills under the influence of gravity. As described by Emery (1960), the temperature and oxygen content of the waters in each basin are largely determined by the quality of waters intersecting the sill depth. Because of the strong vertical gradients exhibited by these properties and differences in the sill depths of the offshore basins, each basin is characterized by unique temperature and dissolved oxygen levels. Under normal conditions temperature and salinity within a given basin are nearly uniform from the sill to the sea floor (Figure 3.4). The same is not true of nutrients and dissolved oxygen. Unfortunately, information on the chemical composition of deep basin waters is limited, consisting largely of data generated in specific investigations.

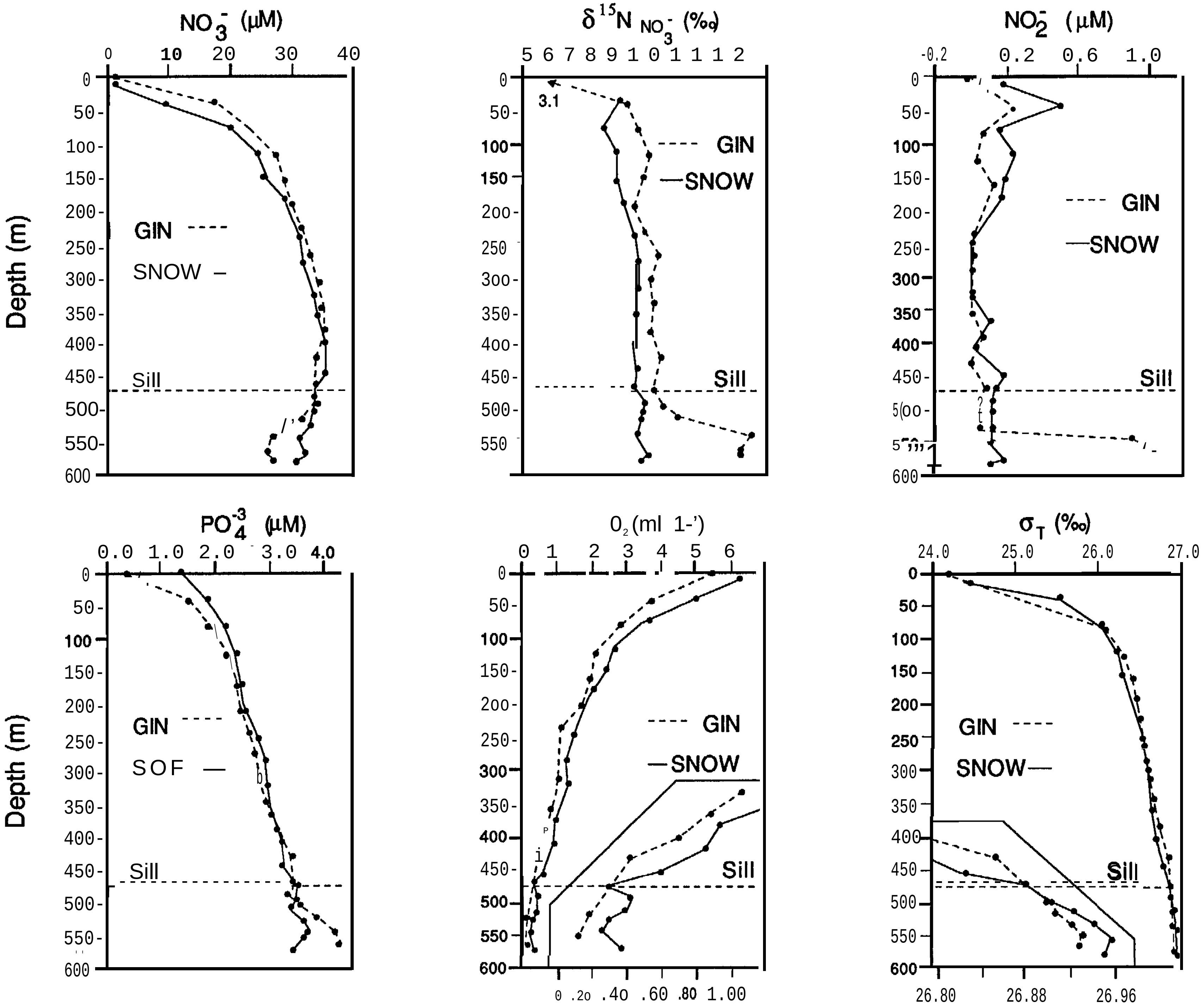
Composition and Exchange of Basin Waters

Because the sills of the inner basins are located at the depth of the oxygen minimum zone (approximately 500-700 m), the dissolved oxygen concentration of deep waters in these basins is low, and bottom sediments may be anoxic and essentially free of benthic fauna. In the Santa Barbara Basin (Liu 1979; Sholkovitz and Gieskes 1971) and San Pedro-Santa Monica basins (Williams 1986a), oxygen concentrations in waters below sill depth are sufficiently depressed to permit active denitrification in bottom waters (and surface sediments). This leads to declining water column nitrate concentrations with approach to the sediment-water interface (Figure 3.4a). Santa Barbara Basin is the shallowest and the best studied of the inner basins. We use it here for discussion, recognizing that its behavior is probably different from that of other basins in the SCB.

Detailed descriptions of the physics and chemistry of Santa Barbara Basin waters. are given in Emery (1960), Liu (1979), Shiner (19S2), and Sholkovitz (1972). Santa Barbara Basin reaches a maximum depth of 590 m with a sill depth of 475 m. Exchange of water apparently occurs by spillover of waters at sill depth, most likely from the west. Frequent small-scale spillovers probably involve movement of cooler, more saline, nitrate-rich and oxygenated waters over the sill and along the slope to the basin bottom. This spillover-caused water movement sometimes results in increased turbidity (Sholkovitz and Soutar 1975) and observable reversals of the nitrate profile near the sediment-water interface (Liu 1979; Shiner 1982). Nitrate is perhaps the best tracer of waters introduced from outside the basin. Under these conditions basin waters are only partially replaced (perhaps 10%; Shiner 1982), but the events lead to small, but detectable, perturbations of the "normal" condition, manifestations of which are discussed below. Although the frequency of these small spillovers is unknown, Liu (1979) reported that among 13 observations that had been taken during normal conditions up to August of 1978, signs of bottom-water disturbance were noted for six of them. If one adds to this list the four sampling periods reported by Shiner (1982), three of which showed evidence of spillover, such perturbations would appear to be the rule (53%) rather than the exception.

"Normal" conditions in the bottom waters of Santa Barbara Basin include active denitrification within a zone estimated to extend approximately 20-40 m above the basin floor (Figure 3.11; Liu 1979). Denitrification in bottom waters and surface sediments results in production of a subsurface nitrate concentration maximum, typically positioned just above sill depth. Nitrate concentrations below the sill decrease by as much as 50% (from around 30-35 uM above the sill to approximately 16 uM near the bottom). Moreover,. because of isotopic fractionation during denitrification (Sweeney et al. 1978), this nitrate is enriched in ^{15}N relative to overlying waters by 1-13°/00, depending upon the extent to which nitrate has been consumed. For example, Liu (1979) found a correlation between $\ln[NO_3^-]$ and its $\delta^{15}N$ value in basin waters with a slope of -7.8 (r^2=0.85). Although present in small concentrations throughout much of the upper water column (surface to sill-approximately 0-0.4 uM), nitrite exhibits a secondary maximum (approximately 0.3-1.1 uM) below sill depth. This maximum is attributable to denitrification, but the concentrations of nitrite are, nonetheless, small, and in no case has nitrite been found to exceed 5% of the combined nitrate + nitrite pool. Nitrous oxide (N_2O) shows a profile characterized by saturation concentrations (approximately 10 nM) at the surface, increasing concentrations with water depth to a maximum near the sill of approximately

Figure 3.11. Vertical **profiles** Of nitrate, nitrite, phosphate, oxygen, σ_T, **and** δ^{15}**N-nitrate** during "normal" (GIN cruise: 22-25 August 1978) and "flushed" conditions (SNOW, SOF: 23-25 August 1977. and 18-22 April 1987, respectively; after Liu 1979).



NO$_3^-$ (μM)
0 10 20 30 40
Depth (m)
0 50 100 150 200 250 300 350 400 450 500 550 600
GIN
SNOW
Sill
δ^{15}N$_{NO_3^-}$ (‰)
5 6 7 8 9 10 11 12
3.1
GIN
SNOW
Sill
NO$_2^-$ (μM)
-0.2 0.2 0.6 1.0
GIN
SNOW
Sill
PO$_4^{-3}$ (μM)
0.0 1.0 2.0 3.0 4.0
GIN
SOF
Sill
O$_2$ (ml l^{-1})
0 1 2 3 4 5 6
GIN
SNOW
Sill
0 .20 .40 .60 .80 1.00
σ$_T$ (‰)
24.0 25.0 26.0 27.0
GIN
SNOW
Sill
26.80 26.88 26.96

40 nM, followed by a precipitous decline below the sill to approximately 1 nM. Nitrous oxide is associated with vitrification, but is consumed preferentially over nitrate during denitrification (Liu and Kaplan 1982). Hence, its distribution in Santa Barbara Basin is controlled by production in the upper water column, loss to the atmosphere at the surface, removal during denitrification below the sill, and exchange between basin and overlying water masses.

Ammonia, present at low concentrations throughout the upper water column (approximately 0.3 uM), increases in concentration near the basin floor (to approximately 0.8 uM), presumably as a result of suboxic (that is, denitrification-water, sediments) or anaerobic (sulfate reduction-sediments) metabolism. Oxidation of ammonia by vitrifying bacteria is effectively prevented by the low oxygen concentrations. Phosphate is present within surface waters at concentrations of approximately 0.5 uM. Concentrations increase rapidly with depth down to approximately 100-150 m and more gradually thereafter to approximately 3.5 uM at the sill. Throughout the upper portion of the water column, nitrate and phosphate concentrations are correlated, with a slope of 14.4 (Liu 1979), slightly lower than the Redfield ratio (16). Below the sill a negative correlation is observed between nitrogen and phosphate concentrations (m=-16.8). Since denitrification yields a delta N/delta P ratio of -84.8 (Richards 1965), Liu (1979) reasoned that phosphate must be generated by processes other than denitrification. Some possibilities include oxygen respiration in the water, sulfate reduction in sediments, and solubilization of iron phosphate. The first two processes are known to occur. The third of these, solubilization of iron phosphate, is consistent with observations made by Shiner (1982), who examined the chemistry of particulate matter *in* deep basin waters. He found that particulate phosphorus and iron were positively correlated at all times (that is, during both "normal" and spillover conditions) but that aluminum, a terrigenous resuspension indicator, tended to follow nitrate. Both iron and phosphorus were low during spillover periods when aluminum and nitrate were high. Shiner (1982) therefore proposed that particulate phosphorus enters the deep basin environment from the east via resuspension of sediments enriched in ferric-hydroxo-phosphate precipitates from the Ventura shelf. The latter were thought to originate from the salt marsh off the Santa Clara River.

Major episodic flushing events have also been described for the Santa Barbara Basin (Liu 1979; Sholkovitz and Gieskes 1971). The frequency of basin flushing is uncertain because of the small number of observations and the poor temporal resolution of the hydrographic surveys. However, Sholkovitz and Gieskes (1971) suggested that flushing in Santa Barbara Basin might occur seasonally, with complete exchange of basin water requiring as little as 1-2 months. Major flushing events are apparently triggered by offshore transport of surface waters during intense upwelling and replacement of deep basin water by denser upwelled water entering from outside the basins at sill depth (Sholkovitz and Gieskes 1971). After examining quarterly CalCOFI hydrographic data taken between 1986-1989, Reimers et al. (1990) concluded that flushing events are indeed coupled to seasonal upwelling, and that the characteristic varving in basin floor sediments is related to the periodic alteration of basin water chemistry and its effects on microbial communities inhabiting the benthic boundary layer.

Using the data of Liu (1979), Figure 3.11 illustrates differences in the vertical distribution of chemical species between "normal" conditions within Santa Barbara Basin and after complete flushing has occurred. Upon completion of flushing, oxygen and nitrate concentrations in bottom waters increase measurably and exhibit relatively uniform profiles from the sill down. Temperature, δ^{15}N-nitrate, and nitrite and phosphate concentrations decrease, reflecting the replacement of basin waters with colder upwelled waters depleted in phosphate. The lowering of nitrite concentrations and δ^{15}N-nitrate values indicates that denitrification has not yet been established. Profiles taken during the course of flushing events (prior to completion) and after flushing show trends that are intermediate between those found during the "normal" and flushed conditions depicted here.

ANTHROPOGENIC EFFECTS

Approximately 21 million human beings inhabit the coastal counties that adjoin the SCB. One might reasonably ask, "What effects, if any, do human activities have on the marine ecosystem off Southern California?" Since this question is addressed at length in Chapter 12, the purpose of this section is to present selected examples of anthropogenic effects in the water column. From information supplied in foregoing sections of this chapter, it should be evident that, except for the possible localized enhancement of primary productivity associated with municipal waste discharge (via introduction of nutrients) in the northern part of the SCB, the dynamics of the dissolved and particulate matter are controlled by natural physical, chemical, and biological processes--especially the latter. These processes, in turn, are largely influenced by variable climatic conditions exemplified by the occurrence of El Nino episodes, the intensity of seasonal upwelling, and episodic storms that affect nearshore waters for short time periods. The principal goal of environmental science is to understand how the natural system functions and interacts with the products of human activity.

Unfortunately, information on the contamination of dissolved and suspended particulate phases of the water column within the SCB is sparse. This is partly caused by the difficulty of measuring trace inorganic and organic constituents at or near their natural abundance levels in seawater (Bruland et al. 1979; de Lappe et al. 1983; and Patterson and Settle 1976, among others). In addition, because many of these substances are particle-reactive, it has proven more useful to examine depositional records preserved in anoxic basin sediments. However, with the advent of sediment traps, it is now possible to estimate the vertical fluxes of these contaminants on environmentally relevant time scales. By contrast, inner basin sediments can, at best, be examined with a temporal resolution of approximately one year. Furthermore, sediment traps can be deployed at sites where the sediment record is disrupted or destroyed by bioturbation or physical mixing processes (for example, central or outer basins; Bruland et al. 1981). For these reasons, we turn attention to the role of sinking particles in transporting trace organic and inorganic contaminants to the benthos. .

Trace Organics

The existing database for trace organic contaminants in the water column of the SCB is extremely limited. The most extensive results come from the BLM studies on hydrocarbon distributions in surface and deep (10 m off the bottom) water samples collected at 41 stations within the SCB (Risebrough and Burlingame 1978). Other investigations include those concerned with hydrocarbon contamination of surface waters in the Coal Oil Point area (Stuermer et al. 1982); various offshore sites in Southern California (de Lappe et al. 1983 and references therein) and the sea surface microlayer (Cross et al. 1987); DDT residues in the California Current (Cox 1971); and the results of sediment trap studies (Crisp et al. 1979; compare

Jackson et al. 1989 and reports to the U.S. Department of Energy from the CaBS).

Because coverage of this subject is so patchy and because of the tremendous impact sediment trap studies have had-on our understanding of contaminant transport processes, we focus on the results presented by Crisp et al. (1979). They investigated particulate matter collected in sediment traps positioned 30-60 m above the bottom of four basins: Santa Barbara, San Nicolas, Santa Monica, and San Pedro. Table 3.7 summarizes some of the data reported in this study.

The highest fluxes of particulate matter were found for Santa Barbara Basin, followed in decreasing order by San Pedro Basin, Santa Monica Basin, and San Nicolas Basin. Hydrocarbon concentrations in the trapped particulate, however, were in the order San Pedro Basin>Santa Monica Basin>Santa Barbara Basin>San Nicolas Basin. Consequently, the ranking of the basins by their rates of hydrocarbon deposition approximated that found for the concentrations. Hydrocarbon fluxes to San Pedro Basin were approximately 25 times those observed in San Nicolas Basin, owing to the proximity of the former to the dominant anthropogenic hydrocarbon sources (Los Angeles County waste outfall, Los Angeles and Long Beach harbors; Eganhouse and Kaplan 1981; Eganhouse and Kaplan 1982a). The vast majority of both saturated and aromatic hydrocarbon fractions in all samples were comprised of chromatographically unresolved mixtures (>80$ in all but one case), signaling the dominance of petroleum inputs. Biogenic hydrocarbons included a series of *n*-alkanes from $\underline{n}$-C_{15-17} (marine) and $\underline{n}$-C_{29-31} (terrestrial), a collection of alkenes having 16-30 carbons with 1-6 double bonds, and trace amounts of $C_{27,29,30}$ pentacyclic triterpanes of the 17β(H),21β(H) stereochemistry. Normal alkanes from the more remote basins

Table 3.7. Summary of sediment trap studies carried out in Santa Barbara, San **Nicolas**, Santa Monica, and San Pedro basins, 1977 (after Crisp et al. 1979).

Basin	HC conc.g (ug g^{-1})	Flux (g m^{-2} yr^{-1})[a]		Ratios[b]		
		Mass	THC	CPI	Pr/Ph	C_{28}/hop
San **Nicolas**	87	100	0.009	3.3	4.3	0.21
Santa Barbara	**177**	410	0.073	3.3	7.0	0.45
Santa Monica	394	180	0.071	1.9	3.2	0.19
San Pedro	890	280	0.249	1.5	2.1	0.21

[a] Hydrocarbon concentration for Santa Barbara Basin and hydrocarbon flux for San Pedro Basin have been corrected from that given in Crisp et al. (1979).

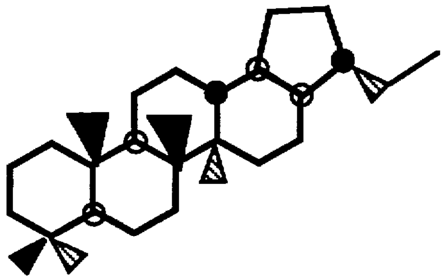
[b] **CPI--carbon** preference index for C_{20} to C_{32}; Pr/Ph--pristane/phytane ratio; C_{28}/hop--ratio of 17α(H),18α(H),21β(H)-28,30-bisnorhopane/hopane ratio.

(Santa Barbara and San Nicolas) showed less evidence of petroleum contamination than did the inner basins near Los Angeles (San Pedro, Santa Monica), as indicated by the higher relative abundance of odd chain-length homologs. In addition, pristane/phytane ratios of the former basins were significantly higher.

Petroleum arising from natural seepage in the SCB is characterized by the abundance of an unusual pentacyclic triterpane (see Figure 3.12), 17a(H), 18α(H),21β(H)-28,30-bisnorhopane. This compound is not present in significant amounts in either municipal waste effluents of Southern California (Eganhouse and Kaplan 1982b) or stormwater runoff (Eganhouse et al. 1981). It is only rarely found in other oils. Although it was found in all trap samples, in no case did it predominate (among the triterpanes) as it sometimes does in seepage oil. It was most abundant (relative to hopane; Figure 3.12) in the Santa Barbara Basin sample, reflecting the importance of seepage in this area.

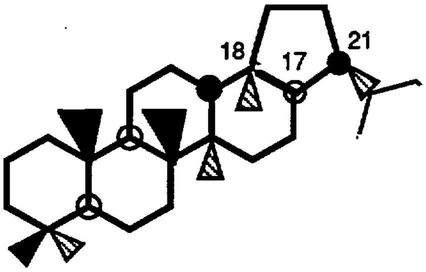
A variety of aromatic and halogenated hydrocarbons were also detected. DDT metabolizes and linear alkylbenzenes were found in samples from Santa Monica Basin and San Pedro Basin, but not San Nicolas Basin and Santa Barbara Basin. The DDT compounds were probably derived from historical deposits on the Pales Verdes Shelf that originated primarily from the Los Angeles County waste outfalls in earlier times (MacGregor 1976). The alkylbenzenes are molecular markers of municipal waste and probably came from contemporary discharges of the time or resuspension of historical deposits on the shelf and slope (Eganhouse et al. 1983). In addition, all four samples contained polycyclic aromatic hydrocarbons derived from a combination of fossil fuel and combustion sources. The occurrence of these compounds at all sites suggests either local sources within each basin (seepage) or long range transport via currents and the atmosphere.

Figure 3.12. Structures of selected compounds found in the SCB.



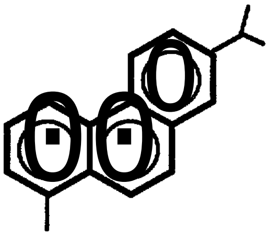
17α (H), 18a (H), **21β** (H)-28,30-bisnorhopane

I.



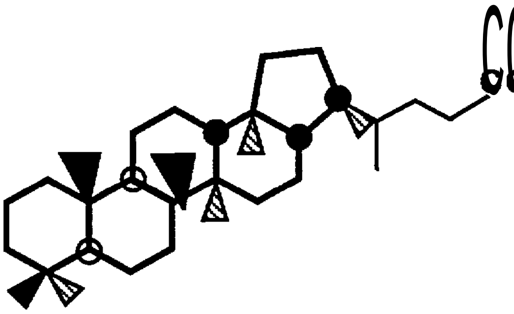
Hopane

H.



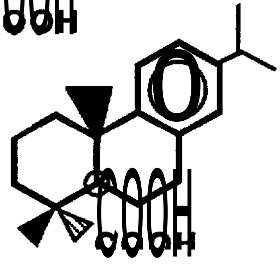
Retene

III.



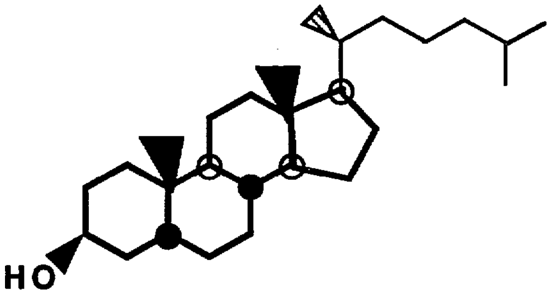
17β(H),18β(H)-bishomohopanoic acid

Iv.



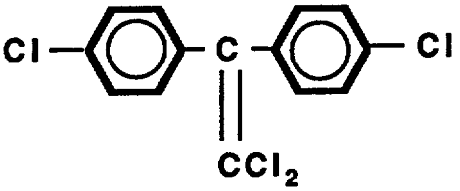
Dehydroabietic acid

v.



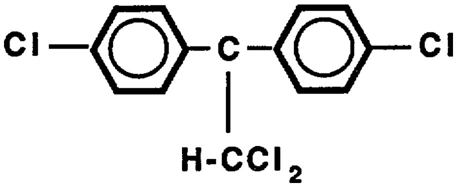
Coprostanol

VI.



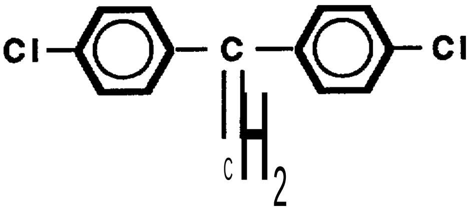
p, p' -DDE

VII.



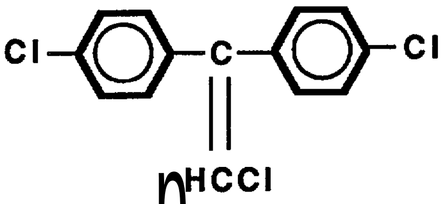
p, p' -DDD

VIII.



p, p' -DDNU

Ix.



p, p'-DDMU

x.

Examination of humic acids and kerogens isolated from these samples for stable isotope composition indicated that they were predominantly of marine origin ($\delta^{15}N$ = +8.3 to +13.5 $^{0}/_{00}$, $\delta^{13}C$ = -19.7 to -22.6 $0/_{00}$). Elemental analysis (CHN), however, suggested some terrestrial input.

It is most unfortunate the no comparable data exists for other central or outer basins within the SCB. The closest approximation are results obtained by Matsueda and Handa (1986) for the Eastern North Pacific within the California Current. They reported total hydrocarbon fluxes in the range of 0.26-2.0 mg m^{-2} yr^{-1} for traps positioned at approximately 700 m at three sites. The composition of these hydrocarbons indicated a dominant biogenic source. The presence of a series of unsaturated hydrocarbons presumed to be derived from planktonic organisms suggested that the hydrocarbons had probably not been reworked extensively. If one assumes that the rate at which hydrocarbons degrade during particle sinking within the SCB are similar to those in the California Current, then the difference in hydrocarbon fluxes to the SCB basins and the California Current reflect differences in the magnitude of petroleum inputs + inputs from primary production. Primary production in nearshore regions of the SCB is approximately ≤ 5 times that within the California Current (Eppley 1986). If one further assumes that the hydrocarbon flux at some depth in the ocean is proportional to primary production in the euphotic zone, the biogenic component of the total hydrocarbon flux at the San Nicolas Basin site represents from 10 to 100%. The lower percentage is more consistent with the molecular evidence discussed above.

Accordingly, the proportion of the total hydrocarbon flux comprised by biogenic hydrocarbons In the inner basins (Santa Monica, Santa Barbara, San Pedro) would be approximately 3% or less. If one further assumes that the average bisnorhopane/hopane ratio for oil seepage in the SCB is 1 (Table 3.8), and that the non-seepage petroleum hydrocarbon ratio is approximately 0.09 (Eganhouse and Kaplan 1988), one can estimate the percentage of seep-derived hydrocarbons being transported to the basins as follows: Santa Barbara-39%, San Nicolas-15%, Santa Monica-12$, and San Pedro-12%. The corresponding seepage fluxes would be: Santa Barbara-28, San Nicolas-1.4, Santa Monica-8.5, and San Pedro-30 mg m^{-2} day^{-1}. Assuming the background biogenic flux is approximately 0.3 mg m^{-2} yr^{-1} (see above), anthropogenic hydrocarbon fluxes are computed (by difference) to be: Santa Barbara-44, San Nicolas-7.3, Santa Monica-62, and San Pedro-219 mg m^{-2} yr^{-1}.

Although these estimates are approximate and based on very few data, they reveal some interesting trends. The flux of seep-derived hydrocarbons to Santa Barbara Basin and San Pedro Basin are approximately equal and are about 100 times greater than biogenic inputs. The flux of seep hydrocarbons to San Nicolas Basin is minor. This is consistent with its isolation from the primary sources, offshore Santa Barbara and Santa Monica Bay (Hartman and Hammond 1981). The fact that Santa Monica Basin has significantly smaller fluxes of seep oil than San Pedro Basin may indicate transport downcoast by longshore currents (Chapter 2). With the exception of the Santa Barbara Basin, anthropogenic fluxes to the basins exceed natural seepage + biogenic fluxes by more than a factor of 4. Moreover, they exceed the seep-related fluxes to San Nicolas Basin, Santa Monica Basin, and San Pedro Basin by factors of more than 5, 7, and 7, respectively. The relative isolation of Santa Barbara Basin from the heavily-populated Los Angeles region and the pervasive oil seepage (and perhaps production) in this area explain the more favorable anthropogenic/seepage flux ratio. Nevertheless, the anthropogenic hydrocarbon flux to Santa Barbara Basin would appear to be only slightly (approximately 30%) less than that in Santa Monica Basin. By

Table 3.8. Estimated fluxes (ug cm^{-2} yr^{-1}) of selected metals to sediments in nearshore basins of the SCB.

study	Flux category[a]	Basins		
		S. Barbara	S. Monica	S. Pedro
		Chromium		
Bruland et al. (1974)	A-1970	2.9	2.6	3.1
	N	10.7	2.1	2.8
Finney and Huh (1989)	A-1986		0.53	
	A-(1970-1971)		1.5	
	N		1.5	
		zinc		
Bruland et al. (1974)	A-1970	2.2	2.1	1.9
	N	9.7	2.8	3.1
Finney and Huh (1989)	A-1986		0.002	
	A-(1970-1971)		0.84	
	N		1.9	
		Cadmium		
Bruland et al. (1974)	A-1970	0.07		
	N	0.14		
		Copper		
Bruland et al. (1974)	A-1970	1.4	1.1	1.4
	N	2.6	1.0	1.2
		Silver		
Bruland et al. (1974)	A-1970	0.10	0.09	0.09
	N	0.11	0.03	0.05
		Lead		
Bruland et al. (1974)	A-1970	2.1	0.9	1.7
	N	1.0	0.24	0.26
Shokes and **Mankiewicz** (1979)	**A-pre-1970**	1.01	0.61	1.2
	A-post-1970	0.19	0.88	1.55
	N	1.66	0.19	0.3
Finney and Huh (1989)	A-1986			
	A-(1970-1971)			
	N			

---

[a] **Flux** category: **A--anthropogenic,** N--natural background.

contrast, the efficient trapping of particle-associated hydrocarbons in the inner basins is illustrated by the greatly reduced flux of anthropogenic hydrocarbons to San Nicolas Basin. Clearly, the inner basins adjoining Los Angeles (Santa Monica, San Pedro) are being heavily contaminated by petroleum hydrocarbons, the vast majority of which are anthropogenic.

Trace Metals

There is a considerably larger body of information on the trace metal concentrations in dissolved, suspended particulate, and sinking particulate phases in the SCB. However, much of the data generated prior to the mid-1970s is of limited use because of inadequacies in the sample collection and handling procedures used at that time (Bruland et al. 1979; Patterson and Settle 1976). The only systematic, regional survey in which acceptable procedures were used occurred in the context of the BLM baseline studies (Bruland and Franks 1978, 1979). In recent years the trace metal investigations have become more disparate, generally focusing on the geochemistry of one or a few elements. The literature for this area has been reviewed up to about 1980 by Katz and Kaplan (1981) and more recently by Williams (1986a).

Bruland et al. (1981) conducted an experiment designed to compare particle fluxes in four offshore basins (Santa Barbara, Santa Monica, San Nicolas, and San Pedro) with sediment accumulation rates. The latter were based on ^{210}Pb measurements made on sediments collected in each of the basins, using box cores. In addition to the radioisotopic and particle mass flux measurements, the concentrations of Pb, Cr, Zn, Cu, Cd, Fe, and Ni were determined in the trapped particulate. Several years earlier, Bruland et al. (1974) had reported trace metal measurements of ^{210}Pb-dated cores from three of these basins, results of which are provided in a later section (see

Table 3.8). Bruland et al. (1981) demonstrated that the particulate fluxes derived from the particle interceptor traps (PIT) fell within 25$ of the sediment accumulation rates (Table 3.9). Moreover, comparison of the total and in HNO_3-leachable concentrations in the PIT samples with those in the surface sediments showed that the trace metal chemistry of trapped particles accurately represented that of the surface sediments. Because San Nicolas Basin does not have anoxic varved sediments, accurate sedimentation rates could not be determined using radiometric dating.

Thus, the observation of higher concentrations of Pb in the PIT samples (whereas concentrations of other metals correlated well between PIT and sediment samples), signaled dilution of modern stable lead inputs by less contaminated sediments deposited at greater depth, probably by bioturbation. As noted above, similar discrepancies were not found for other metals, some of which (Cd, Zn) originate largely from anthropogenic inputs (such as municipal wastes and surface runoff) that enter the marine environment directly near the shore. In other words, trace metals introduced to the nearshore water column are effectively screened from entering central and outer basins, whereas contaminants transported through the atmosphere represent a larger fraction of the metal burden of sinking particles and sediments further offshore. Because the acid-leachable fraction accounted for 93% of the total Pb in the San Nicolas Basin PIT sample, an anthropogenic origin was clearly implicated (Ng and Patterson 1982; Shokes and Mankiewicz 1979).

Table 3.9 provides estimates of the fluxes of trace metals to the sediment traps positioned In the inner basins in 1977, as reported in Bruland and Franks (1979) and Bruland et al. (1981), along with trace metal accumulation rates derived from analyses of sediment cores performed in 1972

Table 3.9. Estimated fluxes and sediment accumulation rates (ug cm^{-2} yr^{-1}) of particulate matter, Pb, Cr, Zn, Cu, and Cd to three inner basins based on sediment trap results of Bruland and Franks (1979) and Bruland et al. (1981), and 210Pb dating of sediments by Bruland et al. (1974).

	Trap Flux (ug cm^{-2} yr^{-1})					
Basin	TPM[a]	Pb	Cr	Zn	Cu	Cd
Santa Barbara Basin	72.4	1.67	--[b]	4.92	1.45	0.080
San Pedro Basin	36.4	2.66	--[b]	4.37	1.71	0.131
Santa Monica Basin	16.9	0.42	1.86	1.86	0.54	0.042

	Sediment accumulation rate (ug cm^{-2} yr^{-1})					
Basin	TPM[a]	Pb	Cr	Zn	Cu	Cd
Santa Barbara Basin	90.	3.1	13.6	11.9	4.0	0.21
San Pedro Basin	28.	1.96	5.9	5.0	2.6	--[c]
Santa Monica Basin	24.	1.14	4*7	4.9	2.1	--[c]

	Trap Flux/Sediment accumulation rate					
Basin	TPM[a]	Pb	Cr	Zn	Cu	Cd
Santa Barbara Basin	0.804	0.537		0.413	0.362	0.379
San Pedro Basin	0.603	1.356		0.874	0.658	
Santa Monica Basin	0.612	0.371	0.386	0.379	0.258	

[a] TPM : total particulate matter (mg cm'^{2} yr^{-1}).

[b] Data believed inaccurate because of contamination (Bruland and Franks 1979), not reported here.

[c] Data not reported (Bruland et al. 1974).

(Bruland et al. 1974). Despite the 5-year hiatus, the fluxes and sediment accumulation rates generally fall within a factor of three. Based on the finding by Bruland et al. (1981) that PIT and surface sediment samples collected at the same time have similar concentrations, one might assume that the differences reflect changes in the fluxes of these metals to basin sediments over time. If so, there seems to have been a measurable and consistent reduction in the flux of Pb, Cr, Zn, Cu, and Cd between 1972 and 1977 in all cases except one, Pb in San Pedro Basin. Such reductions would be predicted on the basis of declining wastewater discharges (Figure 3.3; SCCWRP 1989) and dramatic reductions in the usage of leaded gasoline since the early 1970s (Ng and Patterson 1982).

The anomalous behavior of Pb in San Pedro Basin may reflect the fact that this basin is situated immediately adjacent to the Los Angeles County wastewater discharge on the Pales Verdes Shelf. During the period 1971-1977, this plant discharged between 53 and 62$ of all lead entering the ocean from municipal wastewater treatment plants. Whereas the combined emissions to the SCB decreased by 37%, Pb emissions from this plant decreased by only 22$. Ng and Patterson (1982) estimated that all, one-third, and one-fourth of the industrial lead accumulating in sediments of Santa Barbara Basin, Santa Monica Basin, and San Pedro Basin, respectively, originate from non-sewage sources (that is, aeolian and fluvial). Thus , reduced inputs from non-sewage sources would be expected to have the least effect on San Pedro Basin, followed by Santa Monica Basin and Santa Barbara Basin. On the other hand, declining inputs from wastewater discharge would most affect Santa Monica and San Pedro Basins. The results shown in Table 3.9 suggest that atmospheric fluxes probably declined at a greater rate than those from sewage discharge. Further changes in the sediment accumulation rates of Pb and other metals in the post-1977 era are discussed in Section

V, "**Distribution and** Fate of Chemical Constituents in Sediments."

SEDIMENT DYNAMICS

INTRODUCTION

The following brief discussion of sediment dynamics serves as background for the discussion of transport of organic compounds and other trace or minor components. These important and active biological and chemical components are carried as part of the natural **detrital** load or adsorbed on the reactive surfaces of clays. The **lithogenous** fraction of the particulate, together with siliceous and carbonate **biogenic** tests, skeletal parts, or framework, compose the large fraction of the total particulate load (approximately 90-95$). Thus, a general discussion of this large fraction will serve as a the context for the chemical discussions.

Sediments are"distributed to the Southern California Borderland from several sources by a variety of transport processes, including turbulent fluid traction transport, sediment gravity flows, and mass gravity transport **(Nardin** et al. 1979; Dott 1963; Middleton and **Southard** 1978; Middleton and Hampton 1973). In any given environment or geographic location, typically one process type will be dominant **(Gorsline** 1987). The dominant process will produce characteristic deposit **morphologies** and smaller scale sedimentary structures that also constrain other factors such as biological communities, chemical pathways and processes, and degree of **diagenetic** change during deposition and after burial.

SOURCES

The principal sources of sedimentary material 'in the region are **terrigenous** contributions from stream runoff, coastal erosion, and **aeolian** transport from land to sea (Brownlie and Taylor 1981). Of these, stream runoff is the largest single contributor, providing as much as 80% of the sediment mass (Schwalbach and Gorsline 1985). Next in importance are the biogenic contributions, including carbonate and siliceous tests, shells, and other hard remains as well as organic matter. This source contributes approximately 15-20% of the total sediment mass (Schwalbach and Gorsline 1985). Smaller sources include the ambient transport from beyond the area via ocean current systems, anthropogenic contributions, and chemical precipitates from the water column. These together probably contribute 5% or less, but data are sparse and typically come from a few sampled areas, as is described in this chapter.

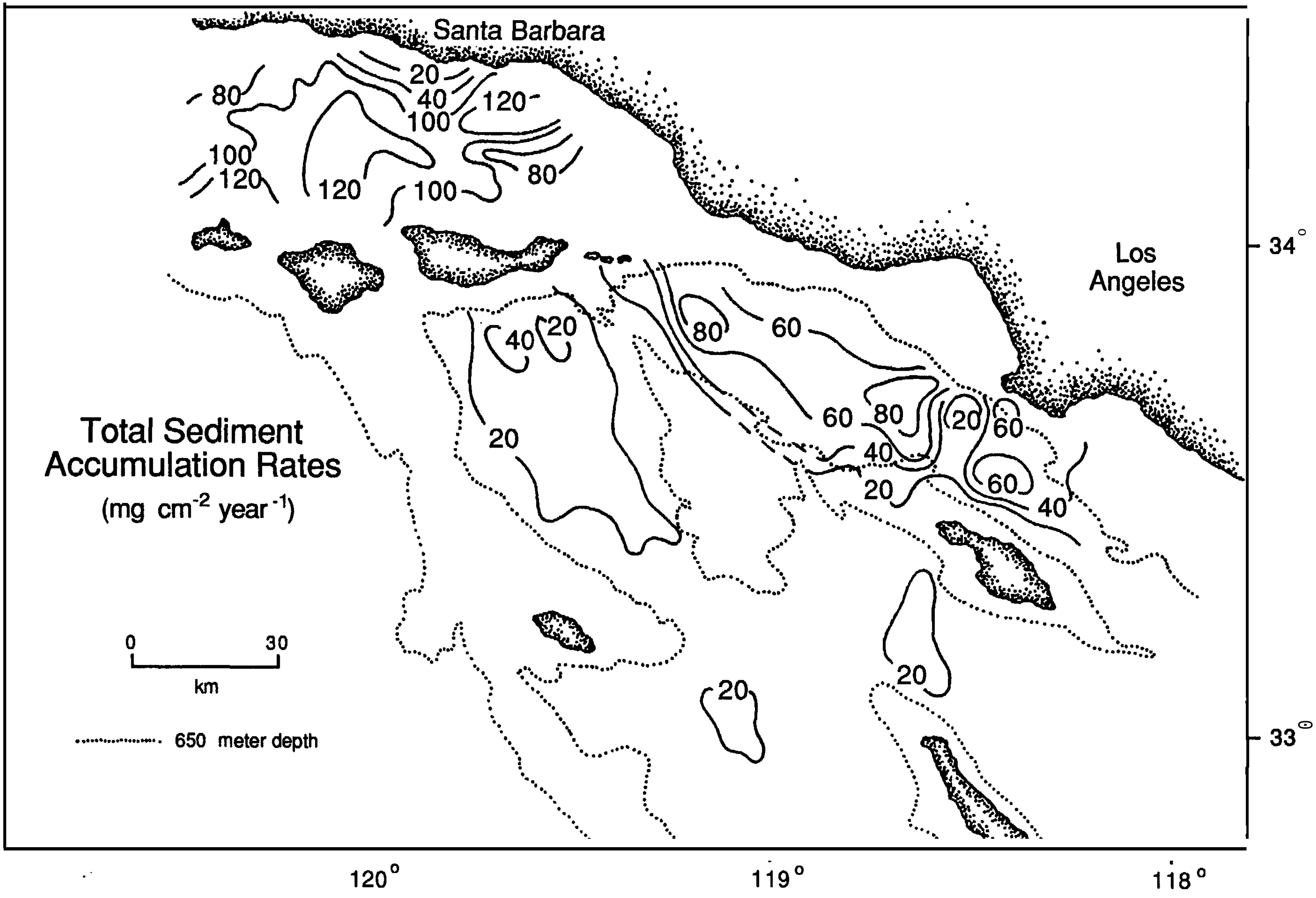
Each source contributes sedimentary material as a function of such factors as climate, ocean circulation, and population. The terrigenous input from streams is governed by the strong seasonality of the region, with most coming during the winter rainy season and also varying over a longer cycle of 20-30 years (Gorsline and Douglas 1987; Brownlie and Taylor 1981). Thus, during much of a typical year, the suspension load is probably primarily biogenic material, and the highest detrital loads come in the winter seasons of the exceptionally wet years. Most recently, the floods of January and February 1969 contributed on the order of 1×10^9 t of detrital material. This contrasts with more typical annual contributions of from 1×10^6 to 1×10^7 t. The long-term (Holocene) average annual rate is of the order of $10\text{-}15 \times 10^6$ t, with a very large cyclical variation over century-long periods. As Brownlie and Taylor noted (1981), the contribution of a half-dozen wet years is greater than the total contribution of the rest of the last century.

The biological contribution also varies over a seasonal cycle and, at any given time, is the dominant component in the water column (as noted earlier). The total mass of biogenic material generated in a given year probably exceeds the detrital contribution, but much of that biogenic input is recycled and only about 5-10% of the total mass reaches the sea floor. There, additional alteration returns more to the water and the ultimate preserved contribution is generally of the order of 5% on an area-wide basis. A strong gradient in contribution to the substrate is observed (Emery 1960; Schwalbach and Gorsline 1985), and Figure 3.13 illustrates this in terms of total accumulation rate. Note that the highest accumulations (approximately 120 mg $cm^{-2} yr^{-1}$ dry weight) are in Santa Barbara Basin; the lowest rates (approximately 5 mg $cm^{-2} yr^{-1}$) are in the outer banks and basins. As a rough rule of thumb, the net accumulation of total sediment mass decreases by a factor of 2 as one progresses from Santa Barbara basin to the outer borderland and the Patton Escarpment at the seaward edge of the region. Organic content in terms of percent by dry weight increases offshore, but as one moves seaward, there is an increase in the highly refractory material and also a rapid decrease in dilution by terrigenous detritals (Emery 1960).

The actual net accumulation rate of the organic fraction diminishes seaward at about the same geometric rate as the total sediment mass accumulation. Fleischer (1971) has suggested that aeolian terrigenous contribution increases offshore, but as for organic content, this actually reflects decreasing dilution. Net accumulation rates of aeolian quartz decreases offshore geometrically.

Anthropogenic contributions appear to increase over time, beginning when European colonization began roughly 200 years ago. This acceleration of the anthropogenic contribution over the last century reflects the burgeoning population growth of the neighboring coastal plains. Prior to federal control and reduction of sewage discharges to the ocean, these

Figure 3.13. Sediment accumulation rates in basins of northern part of the SCB (from **Schwalbach** and **Gorsline** 1985).



Total Sediment Accumulation Rates
(mg cm^{-2} year^{-1})

3. 70b

discharges were locally the dominant sources of particulate. The **geochemical** discussions **examine** these sources and contributions.

TRANSPORT PROCESSES

Particulate are transported by a spectrum of processes. In the nearshore shallow water, where shoaling wave effects dominate, the sands and gravels move **alongshore** within water depths of 15-30 m and predominantly within the beach zones. Finer particles **are** winnowed out in these turbulent zones and move with the prevailing currents. These generally take the form of eddies of various scales that eventually deliver the suspension load to the slopes and deeper areas seaward of the mainland shelves. Deposition and resuspension are common as the fine load proceeds offshore.

In the deeper waters of the central and outer shelf, internal waves, tidal currents, and **thermohaline** currents are the principal transport agents. Long low-amplitude storm waves can sometimes affect the shelf sediments to depths of 50-100 m. Probably most of the active surface wave transport beyond the outer limits of the beach zone (typically 10 m water depth or less) occurs during the relatively rare storm episodes.

Much fine particulate deposition occurs on the mainland slopes, then, after varying residence times, moves to the base-of-slope and the basin floors. In the slope environment, mass movement is a common transport process that periodically transfers large masses to the deep basin floor (**Gorsline** and Teng in press). Strong counter currents move along the upper mainland slope, transferring suspension load to more distant depositional sites.

Fine sediments that pass into the many coastal submarine ***canyons*** (Drake and **Gorsline** 1973; Shepard et al. 1979) eventually are caught up in **down-**canyon transport in the form of turbidity currents, debris flows, and mass movement slump and slide (Gorsline 1981; Reynolds 1987). These build submarine fans at the mouths of submarine canyons, where they debouch onto the basin floor (Reynolds 1984; Gorsline 1981).

Below the depth of their sills, basin waters move slowly (net flow of the order of 1-5 cm s^{-1}, B. Hickey, pers. comm.) and probably do not resuspend fine bottom sediment. In some instances, strong currents have been observed in deep basin waters (J. Warme, pers. comm.) that can reach velocities of 20-30 cm s^{-1}. At that flow rate, some resuspension could occur. In general, deep near-bottom sediment transport is probably dominated by continuous hemipelagic infall of discrete grains and aggregates of either biological or physico-chemical origin, and by episodic geologically instantaneous events such as turbidity currents, mud flows, and slumps (Malouta et al. 1981; Thornton 1981).

As has been noted by Teng and Gorsline (in press), the accumulation rates basin-by-basin from the major northern sources can be described in first order by a model in which the highest rates are in Santa Barbara Basin (approximately 120 mg cm^{-2} yr^{-1}), then decrease by a factor of two in the next adjacent basin (Santa Monica Basin, 60-80 mg cm^{-2} yr^{-1}). This halving sequence continues again in the next farthest basins (San Pedro and Santa Cruz, 20-40 mg cm^{-2} yr^{-1}), then to San Nicolas and Santa Catalina basins (Reynolds and Gorsline 1987; Hams 1987), and finally to the San Diego Trough and in Tanner, Patton, and San Miguel basins in the outer borderland, where accumulation rates are approximately those of the adjacent deep Pacific floor (approximately 5-10 mg cm^{-2} yr^{-1} dry rate).

Certain distributive processes require a minimum level of mass contribution to become effective. Thus, in the nearshore northern basins close to the land sources and where sands can reach the tributary submarine canyons, turbidity currents, debris flows, and slumps and slides are all active distributive processes. All of these basins receive on the order of about 1000 kilotons yr^{-1} of sediment.

In the central basins, gravity processes (slumps and slides) are still active, fine sedimentation dominates, and mass contributions are in the range of 200-500 kilotons yr^{-1}. Below those annual mass rates, hemipelagic particle rain is the dominant process, producing fine-grained draping deposits that accumulate at rates of the same order or less than the rates of tectonic deformation. In the outer basins beyond the Santa Rosa-Cortes Ridge (Tanner, Patton, and San Miguel basins; Bergan 1988), the suspension transport of fine particulate from the California Current system dominates, laying down a relatively homogeneous fine sediment with near-constant silt-clay ratios and diluted to varying proportions by biogenic tests, skeletal, or framework parts. The biogenic fraction is typically the major fraction.

In summary, the studies discussed above establish that the largest contribution of detrital grains comes from stream discharge. The largest streams are located in the northeastern quadrant of the California Borderland; they contribute 75-80% of the average annual particulate load. This area, and the region north of Point Conception, is also the major region of biogenic contribution: About 20-25% of the total average annual mass contribution comes from this latter source. The aeolian offshore contribution and the California Current particulate transport are probably less than 10% in any given locality.

Particulate are transported by a variety of processes, including fluid traction flow, sediment gravity flows, and gravity mass transport (Nardin et al. 1979; Middleton and Hampton 1973). The dominant set of processes is dependent on sediment mass budget levels. Above about 1000 kilotons yr^{-1}, all processes are active. Between 200 and 1000 kilotons yr^{-1}, gravity mass processes dominate. Below about 100 kilotons yr^{-1}, the typical processes are slow particulate rains, and the resulting deposits blanket the underlying topography at rates equal to or less than the tectonic deforming processes. In the high accumulation-rate environments, materials are rapidly buried; in the slowest accumulation-rate environments, materials are slowly buried and are exposed to oxidative processes at the sediment-water interface for a long time. These conditions will markedly affect the types and amounts of organic compounds in the deposits.

DISTRIBUTION AND FATE OF CHEMICAL CONSTITUENTS IN SEDIMENTS

INTRODUCTION

This section discusses the distribution and post-depositional fate of organic and trace inorganic substances in sediments of the SCB. The first half is largely descriptive and concerns two topics: (1) interrelationships between the spatial distribution of chemical substances in sediments of the SCB, their sources, and physical transport processes; and (2) the accumulation of these materials in basin and shelf environments. The second part of this section addresses post-depositional processes affecting the fate of sediments.

The bight-wide spatial distribution of chemical substances largely reflects where the source materials are introduced and processes affecting particulate matter during transport and sedimentation. As discussed earlier, particulate entering or formed in the ocean can undergo decomposition and dissolution, or can be altered by interactions with dissolved materials through adsorption-desorption reactions. Flocculation or biological repackaging (see Figure 3.1) changes the particle size distribution and chemical characteristics of these materials. Upon deposition at the sea floor, particulate matter undergoes further transformations as a result of numerous physical, biological and chemical processes occurring at or near the sediment surface. Hence, the chemical composition of sediments reflects not only the original source materials, but also the processes acting on them during transit in the water column and incorporation into the seabed.

One of the principle aims of geochemistry is to understand the factors controlling sediment chemistry. This is important for a variety of reasons. The surface layers of bottom sediments and associated near-bottom waters, sometimes referred to as the benthic boundary layer, represent a zone that is very active biologically and geochemically (Craven et al. 19S6; Emery and Rittenberg 1952; Reimers and Smith 1986; Smith et al. 1987). Biologically mediated decomposition of labile organic matter and dissolution of mineral phases in this zone lead to the build-up of metabolic products and other soluble species (for example, CO_2, NH_3, CH_4, PO_4^{-3}, and SiO_4^{-4}) in porewaters. At the same time, depletion of oxidants by indigenous heterotrophic organisms (such as O_2, NO_3^-, SO_4^{-2}, HCO_3^-) affects the redox potential and alkalinity of interstitial water. This may lead to chemical precipitation reactions (for example, $Fe^{+2} + S^{-2} \longrightarrow FeS \xrightarrow{S} FeS_2$) that bring about transfer of materials from porewaters to the solid phase. These processes are collectively referred to as organic diagenesis.

The onset of diagenesis may result in establishment of concentration gradients of soluble constituents between porewaters and the overlying seawater. If advective fluxes of porewaters (as a result of compaction) are small, these concentration gradients will drive chemical exchange across the sediment-water interface via molecular diffusion. To the extent that physical resuspension and bioturbation occur, the rate of exchange may be further enhanced (Aller 1982). Thus, processes occurring at the seabed directly link sediment chemistry with that of the overlying waters and provide a means of coupling benthic respiration with primary production in the euphotic zone.

A second concern about sediment chemistry relates to interactions between the biological food web and toxic chemicals deposited in sediments. The sea floor can act as a source of many organic and inorganic contaminants to benthic and pelagic populations (Gossett et al. 1983; Young et al. 1988). Remobilization occurs via resorption from sediment particles and diffusion into overlying or interstitial waters (Brownawell and Barrington 1986). Once mobilized, these substances may be taken up directly by organisms via absorption across membranes. Deposit-feeding benthic organisms are also exposed to contaminants through ingestion of sediment particles. Compounds having the required stability and lipophilicity can become concentrated in higher trophic levels through food web transfer, a process known as biomagnification. If concentrations reach sufficiently high levels, adverse biological effects may occur, as in the case of the population decline of the California brown pelican caused by DDT-induced eggshell-thinning (Keith et al. 1970). Because humans occupy a position at the highest trophic level, ingestion of contaminated seafood by humans may also present significant health risks. Thus, toxic chemicals originally deposited in marine sediments can be transferred and exert effects throughout the biosphere.

SEDIMENTARY ORGANIC MATTER

Background

The concentration of organic matter in sediments depends on its rate of supply, the overall sedimentation rate, and the preservation of organic matter before and after deposition (Tissot and Welte 1981). These factors in combination with the physical oceanographic setting establish the depositional environment. Preservation is enhanced when the oxygen content of the water column is reduced (Emerson 1985), such as in the case of the SCB'S inner basins, whose sill depths intersect the oceanic oxygen minimum zone of Pacific Intermediate Water (Emery 1960; Reid 1965). Higher sedimentation rates also favor preservation, since freshly deposited sediments are more rapidly buried to depths below which oxygen is no longer available. High productivity aids the preservation of deposited organic matter by enhancing the vertical flux of large particles in the form of fecal pellets and macroscopic aggregates (thus, increasing the overall sedimentation rate) as well as by creating a greater demand on oxygen available to heterotrophic organisms in the water column and at the sea floor. If high productivity is coupled with rapid sedimentation, as in the case of Santa Barbara Basin, the oxygen demand may be sufficient to establish anoxia at or near the sediment-water interface, thereby preventing larger life forms from inhabiting (and disturbing) the sediments. These conditions are believed to be most favorable for preservation of the organic matter because anaerobic metabolism of deposited organic matter (that is, sulfate reduction, methanogenesis, fermentation) is apparently less efficient than aerobic metabolism (Claypool and Kaplan 1974; Reimers 1989). Thus, it is the interplay of these factors that determines the overall concentration and accumulation rates of organic matter in sediments of the SCB .

Areal Distribution of Organic Matter in Sediments

Emery (1960) summarized results of early studies on the concentration of total organic matter in sediments of the SCB. In general, these investigations showed that organic matter comprises less than 1$ (dry wt.)

on the mainland shelf, island shelves, and bank tops. In contrast, concentrations of organic matter in basin slopes, sills, and floors range from 5 to 10'%.

Several investigators (see references in Emery 1960) have noted a trend of increasing organic matter concentrations progressing from inner to outer basins, with a precipitous decline in organic content when the continental slope is reached. The maximum in organic content in the outer basin sediments has been attributed to a balance between dilution of organic matter by detrital (lithogenous) sediments under conditions of high sedimentation (further inshore) and poor preservation under conditions at low sedimentation rates (further offshore). Emery (1960) and others (Anderhalt and Reed 1978; Choi and Chen 1976; Thompson et al. 1987) have also noted an inverse correlation between organic content and grain size. Analyses of size-fractionated sediments reveal higher concentrations of organic nitrogen in the finer grain size fractions, with the result that up to 65% of the organic matter may be associated with sediment grains ranging from 1 to 16 microns in diameter (Emery 1960). The association of organic matter with finer sediment fractions is probably attributable to either the nearly equivalent settling velocities of organic particles and fine-grained sediments or the adsorption of organic matter to fine-sized minerals, especially clays (Meyers and Quinn 1973). Because the grain size of basin sediments generally decreases with distance offshore (Emery 1960), it is not surprising that sediments of the offshore basins should be richer in organic matter with increasing distance from land. Conversely, sediments from bank tops and shelf regions which are subject to greater reworking by waves and currents have correspondingly lower organic matter contents.

Vertical Distribution of Organic

Matter in Sediments

Knowledge of the vertical distribution of organic matter in sediments of the SCB is limited by a shortage of data and the disparate nature of the studies that have been undertaken. The analysis of sediment cores has largely been restricted to the basin and mainland shelf environments. Consequently, the following generalizations are based on rather poor coverage of the SCB as a whole.

Numerous investigators (Anderhalt and Reed 197S; Bruland et al. 1974; Doose 1980; Emery 1960; Gorsline et al. 196S; Kalil 1976; Shaw 1988) have documented a decline in the concentration of organic carbon with increasing depth (down to approximately 6-8 m) in consolidated basin sediments. Most often there is a rapid decrease in near subsurface sediments (no more than 50$ within the first meter), with smaller or no changes at greater depth. Patterns within a given basin appear somewhat variable, reflecting either differences in the rates and modes of sediment supply or possibly the character of the organic matter. These downcore decreases have usually been attributed to diagenetic losses (Rittenberg et al. 1955; Sholkovitz 1973). However, it is unclear whether the rates of sulfate reduction and methanogenesis in Santa Barbara and Tanner Basins (Doose 1980; Kaplan et al. 1963; Kalil 1976) are sufficient to account for all of the carbon presumed to have been lost. Recent work by Reimers (1987) and Reimers and Smith (1986) has shown that in San Clemente and Santa Catalina basins and deeper waters of the Patton Escarpment, sedimentary organic carbon concentrations decline rapidly within the upper few millimeters of the sediment column. This apparently results from aerobic respiration of readily degradable organic matter mediated by the indigenous bacterial, meiofaunal, and macrofaunal assemblages.

In shallow cores (approximately 30 cm) from Santa Monica Basin, Finney

Figure 3.14. Vertical concentration profiles of total organic carbon in shallow age-dated cores taken in (a) Santa Monica Basin (Finney and Huh 1989) and (b) San Pedro Shelf (Eganhouse and Kaplan 1988).

Table 3.10. Estimated accumulation rates of organic carbon (mg C cm^{-2} yr^{-1}) in sediments of the SCB.

Basin	Emery (1960)[a]	Others	
		^{21}0Pb	Sediment traps
Santa Barbara	2.7	3.8[b]	2.6[c],1.5[d],2.6[e],2.2[f],2.7[g]
Santa Monica	2.7	1.0[b],1-2[h] 1.0[i],0.6[j]	1.0[c],1.1[d],1.7[j]
San Pedro	0.94	1.4[b]	1.6[c],1.3[d]
San Diego	0.5		
Santa Cruz	1.2		
Santa Catalina	1.3		
San Clemente	0.78		
San Nicolas	0.61	0.63[b]	0.63[c],0.43[d]
East Cortes	0.56		
No Name	0.22		
Tanner	0.56		
West Cortes	0.33		
Long	0.5		
Continental Slope	0.44		
Deep-sea floor	0.06		
Top of basin slope	0.06		
Ventura Basin	2.8		
Los Angeles Basin	1.8		

---

[a] Accumulation rates have been converted to organic carbon basis by dividing values given in Emery (1960) by 1.8.

[b] Based on sediment accumulation rate data of Bruland et al. (1981) and organic carbon data of Anderhalt and Reed (1978).

[c] Based on vertical flux measurements (Bruland et al. 19S1) and organic carbon data of Crisp et al. (1979).

[d] Based on vertical flux measurements and organic carbon data reported by Crisp et al. (1979).

[e] Based on data given by Dymond et al. (1981) for Soutar cone.

[f] Dunbar and Berger (19S1).

[g] Based on data given in Dymond et al. (1981) for Gardner trap.

[h] Malouta et al. (1981).

[i] Huh et al. (1987) and Finney and Huh (1989).

[j] Jackson et al. (1989).

Sources of Organic Matter:
Use of Stable Isotope Ratios

The light elements S, O, C, H, N comprise the building blocks of all forms of life on Earth. Each of these elements exists as two or more stable isotopes whose physical properties differ from each other slightly because of differences in their atomic mass (Bigeleisen and Mayer 1947). These differences lead to measurable variations in the relative abundance of the isotopes which, in turn, reflect the origin(s) and processes occurring during cycling of the elements. Two general types "of isotope effects are observed: equilibrium and kinetic. These lead to isotopic fractionation (that is, changes in isotope ratios).

Isotopic composition is usually defined in terms of isotope ratios rather than absolute abundances. By convention, the measured isotope ratio is referred to that of an accepted standard (refere to Hoefs 1980), the results being presented in the familiar "del" notation whereby:

$$\delta \text{ in } {}^{0}/_{00} = (R_{sample} - R_{std})/R_{std} \times 1000$$

where: R is the isotopic ratio (heavy/light; for example, $^{13}C/^{12}C$)

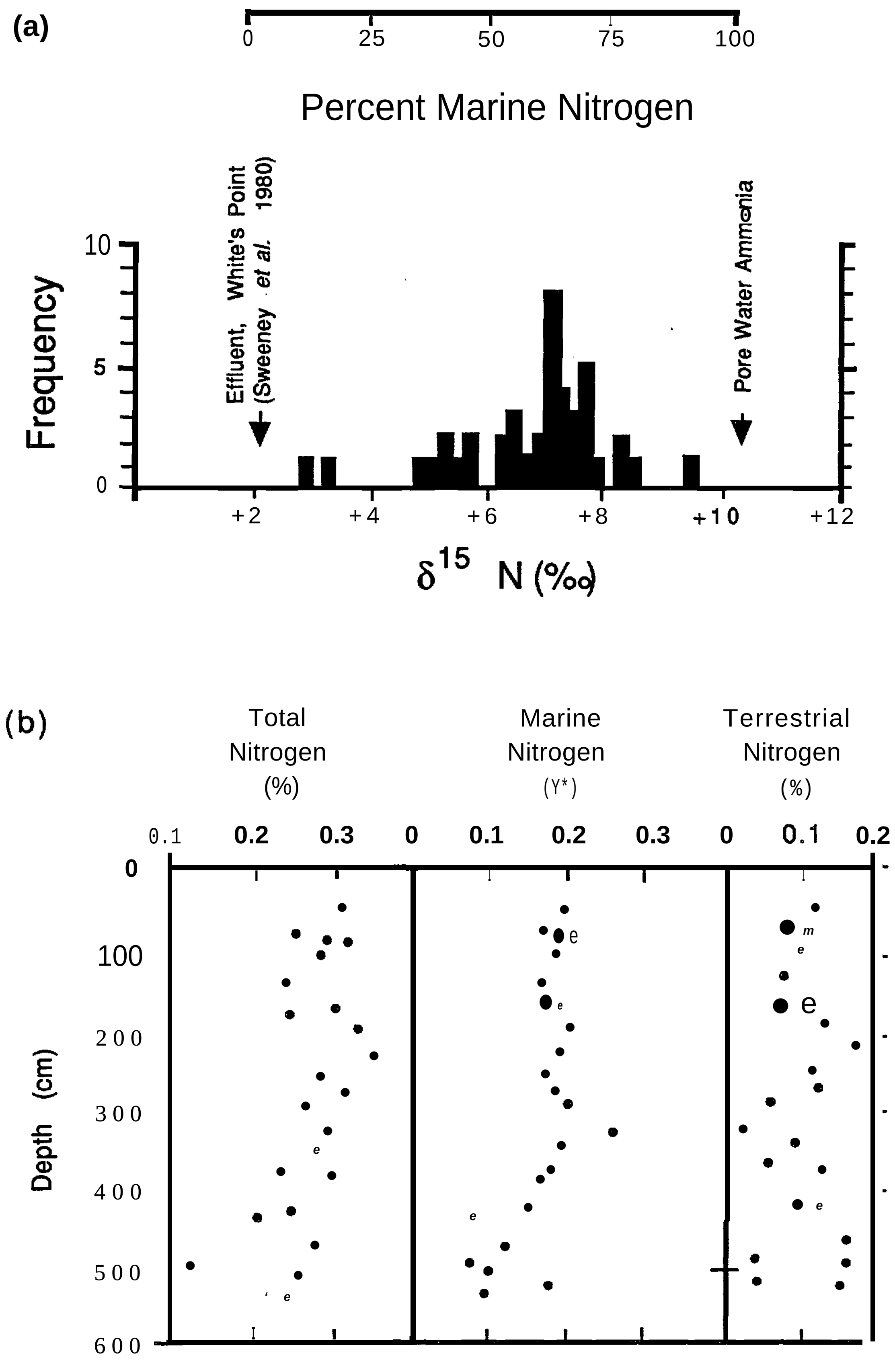
A complete discussion of the theory of isotope effects and the many applications of stable isotope geochemistry are beyond the scope of this section. The reader is, therefore, referred elsewhere for more extensive treatments of these subjects (Deines 1980; Garlick 1974; Hoefs 1980; Kaplan 1975). What follows Is a brief review of some of the most important geochemical studies that have been carried out in the SCB with the use of stable carbon and nitrogen isotopes.

Emery (1960) presented data on the stable isotopic composition of organic carbon in SCB basin sediments along with results for the continental slope and the deep sea floor. Most values fell within a range of

Figure 3.15. Distribution of stable nitrogen and carbon isotope ratios for marine and terrestrial inorganic substrates (NO_3^-, HCO_3^-; N_2, CO_2) and sedimentary organic matter from the Northeastern Pacific (after Peters et al. 197S).

line is nearly parallel to that connecting the isotopic compositions of the presumed inorganic precursors (that is, marine: HCO_3^-, NO_3^-; terrestrial: CO_2 , N_2) indicating that coastal sediments largely reflect the differences in isotopic composition of the corresponding source materials. This finding made it possible to use the isotopic composition of two of the most abundant elements in organic matter for purposes of source differentiation.

In a series of papers, Sweeney and coworkers (Sweeney and Kaplan 1980a,b; Sweeney et al. 1978; Sweeney et al. 1980) further described the application of nitrogen isotopes in measuring relative contributions of terrestrial and marine nitrogen to nearshore basin and shelf sediments. Sweeney and Kaplan (1980a) found the isotopic composition of porewater ammonia in Santa Barbara Basin sediments (mean: $+10.2^{o}/_{oo}$) to be similar to that of marine phytoplankton (mean: +8.90/00), suggesting that most of the diagenetic remineralization of nitrogen in these sediments involves marine, not terrestrial, organic matter (refer also to Doose 1980). The sediments exhibited isotope ratios of +2.8 to +9.4°/00 with most values falling above +6°/00 (Figure 3.16a). These were compared to ratios for marine phytoplankton (8.9 ± 1.8°/00) and a terrigenous endmember of +2°/00 in a simple two-source mixing model. (The lowest isotope ratio observed in the sediments, $+2.8^{o}/_{oo}$, corresponded to a "gray layer" commonly attributed to the rapid influx of terrigenous debris following flooding on land [Fleischer 1972].) Model calculations indicated that most of the nitrogen in Santa Barbara Basin sediments was of marine origin (Figure 3.16a). Thus, downcore variations in the nitrogen isotope ratios of the sediments were interpreted in terms of changing relative inputs of marine and terrestrial (organic) nitrogen as a function of time (Figure 3.16b). Sweeney and Kaplan (1980a) also noted a sudden and progressive decline in the fraction of marine


(a)
0
25
50
75
100
Percent Marine Nitrogen
Effluent, White's Point
(Sweeney et al. 1980)
Pore Water Ammonia
Frequency
10
5
0
+2
+4
+6
+8
+10
+12
δ15 N (‰)
(b)
Total
Nitrogen
(%)
Marine
Nitrogen
(Y*)
Terrestrial
Nitrogen
(%)
0.1
0.2
0.3
0
0.1
0.2
0.3
0
0.1
0.2
Depth (cm)
0
100
200
300
400
500
600

3.84b

The most recent work on the isotopic composition of basin sediments comes from Williams (1988) in the context of the CaBS project. In this investigation the organic carbon and nitrogen isotopic composition of suspended and sinking (sediment trap) particulate and sediments from Santa Monica Basin were measured and compared (see above). A discrepancy similar to that described above was found between nitrogen and carbon isotopic compositions in sediments and sediment trap particulate collected in Santa Monica Basin. In this case, first-order calculations Indicated that sinking particles collected on the basin slope were composed of 21-93% terrestrial material, whereas at the basin center the proportions ranged from **16-58%** (based on δ^{15}N measurements). In contrast, the corresponding slope and basin estimates, using stable carbon isotope ratios, were **5-14%** and and O-27$, respectively. The difference was interpreted as the result of incorporation of carbon-rich sedimentary marine material into sediment traps after downslope transport, although sediments from the basin are typically around -22°/00.

Williams (1988) found that **downcore** variations in the δ^{13}C and δ^{15}N values of total sedimentary organic matter in Santa **Monica** Basin were not strongly correlated. However, the distribution of δ^{13}C and δ^{15}N values falls close to the regression line presented by Peters et al. (1978) for northeast Pacific coastal sediments. Generally speaking, δ^{15}N values varied more than those for δ^{13}C, perhaps reflecting greater natural variation in the isotopic composition of seawater NO_3^--N, particularly where **denitrification** is an important, if variable, phenomenon (**Cline** and Kaplan 1975; Liu 1979). More important, the sediments differed markedly from the suspended and sinking particulate, the primary difference being that the suspended particulate typically are more depleted in ^{13}C than the

Calder 1976). Existing data in Southern California suggest that natural terrigenous carbon is rapidly diluted by autochthonous marine inputs, such that there is little evidence of it in the isotopic composition of the sedimentary organic matter, even in the inner basins (Emery 1960; Peters et al. 1978; Williams 1988). An important exception to this statement is the localized accumulation of anthropogenic (waste-derived) organic carbon and nitrogen in sediments of the San Pedro Shelf.

COMPOSITION OF SEDIMENTARY ORGANIC MATTER

Up to this point, discussion has focused on the distribution of total sedimentary organic matter and certain bulk properties of this material. Although the elemental and isotopic composition of sediments offer important information, detailed chemical analysis provides greater insight into the origins and history of this material. For this reason, we now turn to studies involving the examination of specific compound classes.

The organic matter of marine sediments comes from the products of photosynthesis in the ocean and on land. Although the basic molecular building blocks of **biopolymers** are universal, there are important differences between the chemical composition and specific molecular structures and distributions of **phytoplankton** and higher plants. To the extent that these cellular constituents survive, they provide clues to the original sources of the organic matter. However, the various components of cells differ in their susceptibility to biodegradation and reactivity. Consequently, sediment chemistry reflects the net result of input and biological recycling in the water column and sediments.

Figure 3.17 presents a schematic conceptualization of the transformations involved in early ***(organic)* diagenesis**. It is clear from this diagram that the chemical substances incorporated into sediments

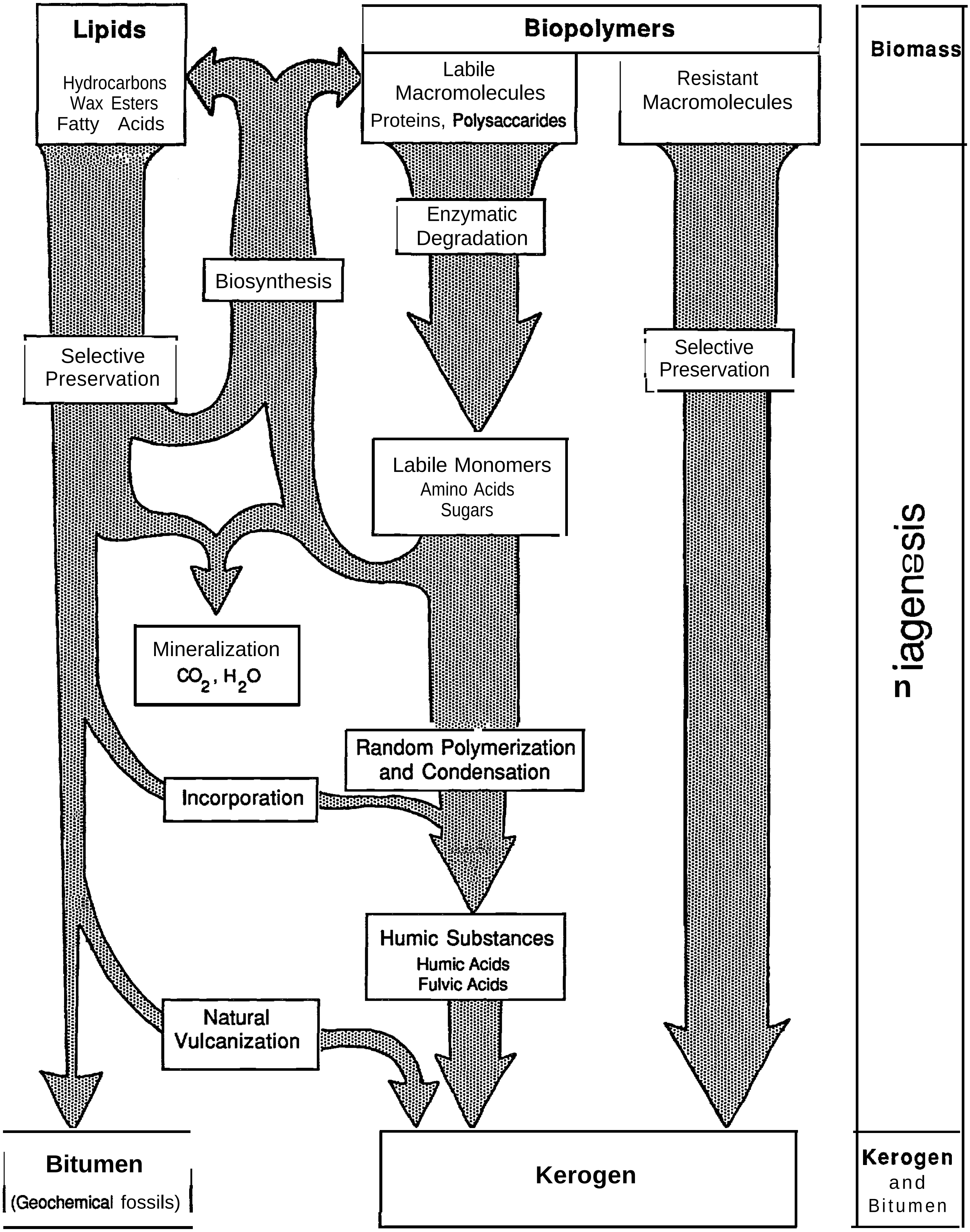

Lipids
Hydrocarbons
Wax Esters
Fatty Acids
Biopolymers
Labile Macromolecules
Proteins, Polysaccarides
Resistant Macromolecules
Biomass
Enzymatic Degradation
Biosynthesis
Selective Preservation
Selective Preservation
Labile Monomers
Amino Acids
Sugars
Diagenesis
Mineralization
CO_2, H_2O
Random Polymerization and Condensation
Incorporation
Humic Substances
Humic Acids
Fulvic Acids
Natural Vulcanization
Bitumen
(Geochemical fossils)
Kerogen
Kerogen and Bitumen

Table 3.11. Chemical composition of recent marine sediments from Santa Barbara Basin (from Emery 1960).

Organic fraction	% Total organic matter	
Ether extractable	1	
Alcohol extractable	5	
Hemicellulose	2	
Cellulose	1	
Nitrogenous compounds:	40	
Amino acids		1
Complex proteins		19
Resistant compounds		17
Water soluble, N-free	3	
Acid soluble, N-free	7	
Lignin-humus complexes	31	

50-100 ug g-l, whereas the highest concentrations (200-1350 ug g-l) were measured in Santa Monica and San Pedro basins or near Coal Oil Point (approximately 600 ug g-l) in the vicinity of known oil seeps. The aromatic hydrocarbons represented from 18-55% of the total hydrocarbons (mean=38.1%, n=11). These results are in reasonable agreement with data given earlier by Emery (1960) and others (Reed and Kaplan 1977; Simoneit and Kaplan 1980; Simoneit et al. 1979a,b; Venkatesan et al. 1980) in later reports.

Figure 3.18 shows the distribution of total hydrocarbons in surface sediments determined in the second year (1976-1977) of the BLM study, along with data from other sources. Here, concentrations are normalized to total organic carbon as a means of compensating for the effects of varying grain size. The strong gradient in hydrocarbon concentrations with radial distance from the Los Angeles Basin is evident. Highest concentrations (approximately 400 mg g^{-1} OC) have been found in sediments of the San Pedro Shelf (Eganhouse 1978). San Pedro and Santa Monica basin sediments exhibit concentrations in the range of 14 to 62 mg g^{-1} OC (Eganhouse 1978; Venkatesan et al. 1980). These shelf and inner basin sediment concentrations exceed (by 1 to >3 orders of magnitude) those found in surface sediments of the outer basin and bank environments (0.2 to 3.3 mg g OC^{-1} ; Mankiewicz 1981; Rapp and Kvenvolden 1982), sediments from the continental margin and rise (2.6-7.5 mg g OC^{-1}; Simoneit et al. 1979a), and deeper subsurface basin sediment horizons (1.8-13.4 ug g OC^{-1}; Simoneit and Kaplan 1980; Venkatesan et al. 1980). As will be shown, the enrichment of hydrocarbons in nearshore surface sediments of the northern SCB is related to the proximity of anthropogenic inputs (municipal wastewaters, storm runoff, atmospheric input). Concentrations in Santa Barbara Basin sediments are relatively elevated (approximately 6 mg g^{-1}OC) but still a factor of 3 less than the highest found in nearby shelf areas (Mankiewicz 1981). Reed

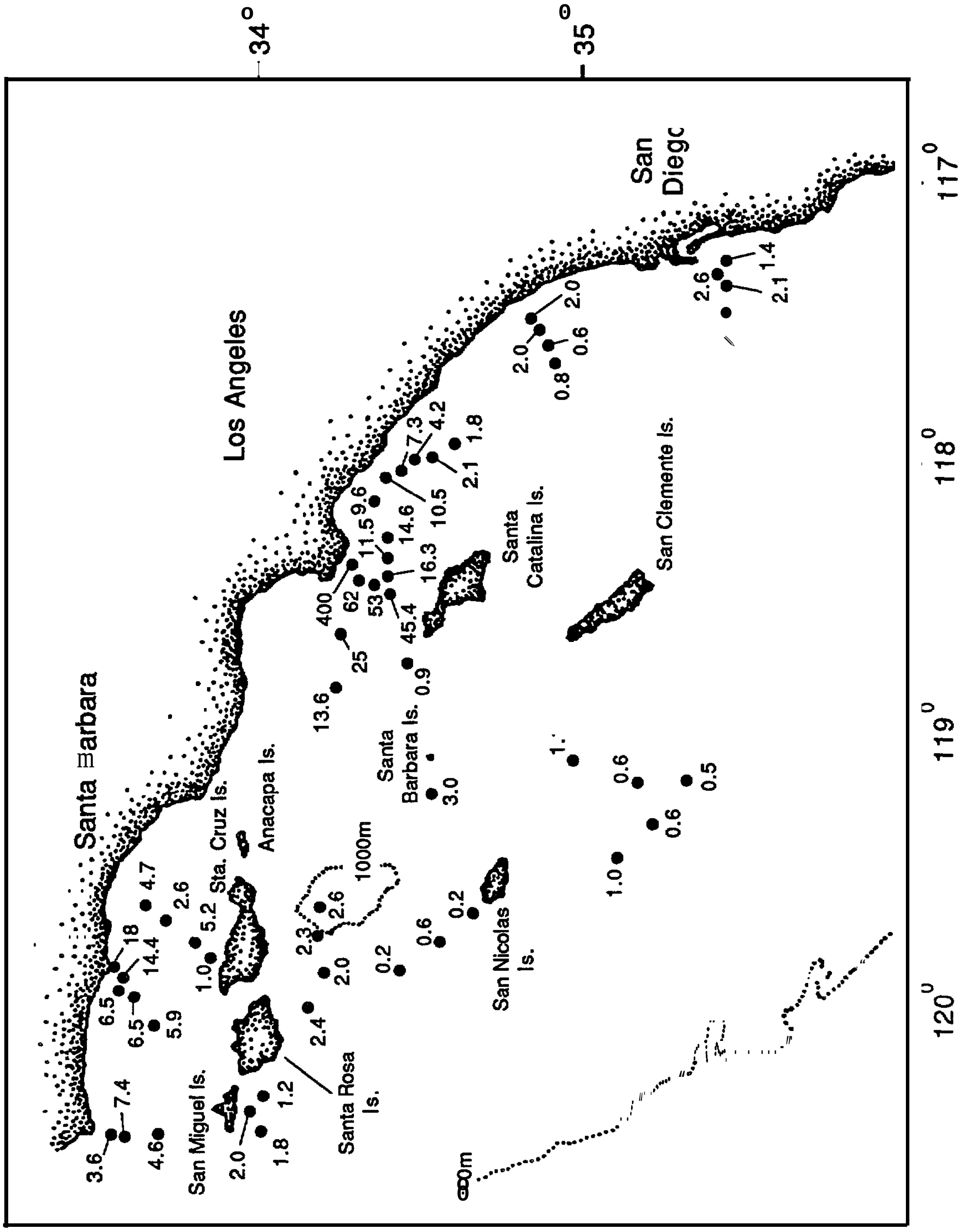

Santa Barbara
Los Angeles
San Diego
San Miguel Is.
Santa Rosa Is.
Sta. Cruz Is.
Anacapa Is.
Santa Barbara Is.
Santa Catalina Is.
San Clemente Is.
San Nicolas Is.
1000m
34°
35°
117°
118°
119°
120°
3.6
7.4
4.6
2.0
1.8
1.2
6.5
6.5
5.9
18
14.4
4.7
2.6
5.2
1.0
2.4
2.0
2.3
2.6
0.2
0.6
0.2
13.6
25
400
62
53
45.4
16.3
14.6
11.5
9.6
10.5
7.3
4.2
2.1
1.8
0.9
3.0
0.6
0.6
0.5
1.0
2.0
2.0
0.6
0.8
2.6
1.4
2.1

Figure 3.19. Gas chromatograms of saturated hydrocarbon fractions isolated from surface sediments collected along a cross-shelf transect in the SCB (after Reed et al. 1977).

1980; see discussion below). Further offshore, and especially to the south, saturated hydrocarbon compositions show increasing relative contributions of biogenic material from both autochthonous and allochthonous sources with lesser amounts of petroleum. However, the hydrocarbon mixtures are complex and their distribution really is quite heterogeneous.

The presence and distributions of unique "biomarker" compounds give further evidence of inputs from specific biogenic and petroleum sources. Figure 3.20 shows distributions of normal alkanes for selected sediments from the BLM studies reported by Simoneit and Kaplan (1980). These samples depict variations in the major features seen in sediments from different parts of the SCB. The n-alkane distributions show contributions of petroleum (n-C_{15}-C_{36}, with little or no odd-even predominance; CPI [carbon preference index] approximately 1.0), bacteria (n-C_{19}), bacterial resynthesis products (n-C_{18}-C_{25}, maximum at n-C_{22} or -C_{23}), algae (n-C_{15}-C_{19}, CPI >> 1.0), and higher plant epicuticular waxes (>n-C_{26}, max at n-C_{29}, C_{31}, CPI >> 1.0). In general, the higher plant wax n-alkanes are found throughout the SCB, indicating long range transport via the atmosphere or as suspended load. In the nearshore region, n-alkane patterns are sometimes dominated by petroleum or bacterial degradation products or, alternately, by terrigenous residues, depending upon the proximity of the sediments to sources of these materials.

A group of compounds commonly observed in upper sediment layers and presumed to be of marine biogenic origin are a series of C_{25} cyclic and acyclic olefins eluting between n-C_{20} and n-C_{22} (Venkatesan et al. 1980; Reed et al. 1977; Simoneit and Kaplan 1980). These compounds appear to be distributed differently from each other in the SCB, possibly in response to variations in grain size or oxygen levels (Mankiewicz 1981). Equally ubiquitous are the polycyclic diterpanes, triterpanes, and steranes. Of

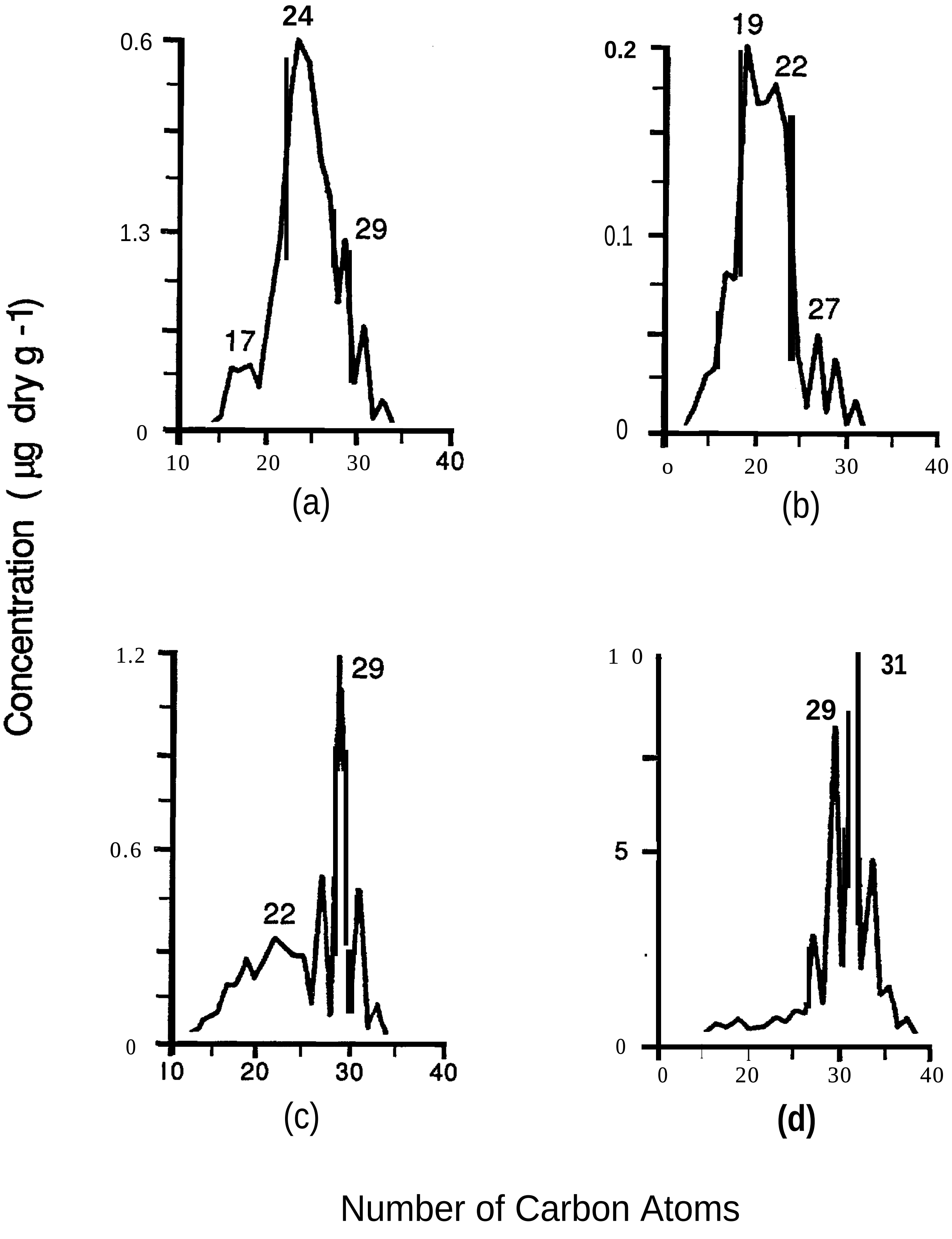

Concentration (µg dry g -1)
24
0.6
1.3
0
29
17
10
20
30
40
(a)
19
0.2
22
0.1
27
0
o
20
30
40
(b)
1.2
29
0.6
22
0
10
20
30
40
(c)
1 0
31
29
5
0
0
20
30
40
(d)
Number of Carbon Atoms

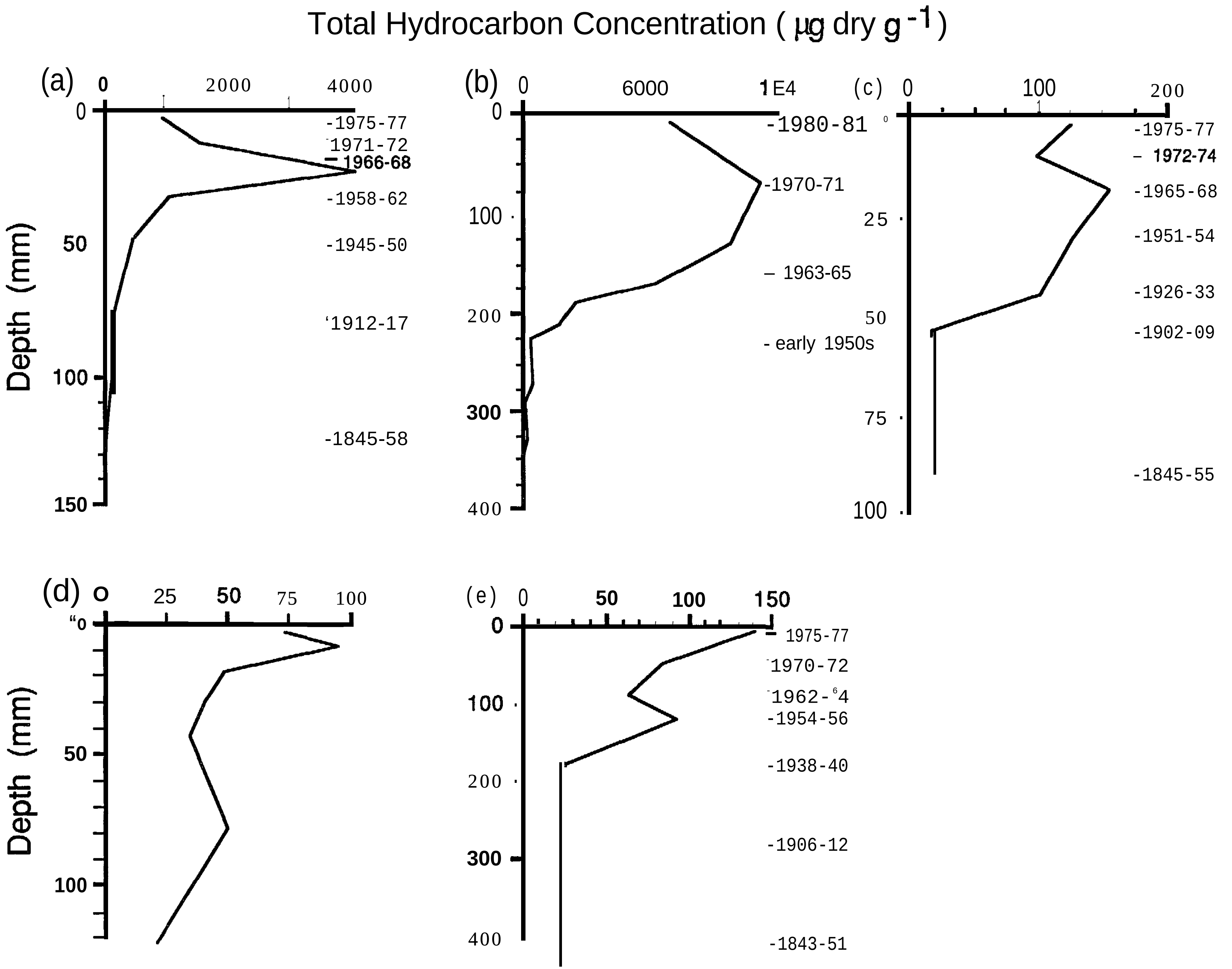
Table 3.12. Ratio of hopane (C_{30}) to 17α(H),18α (H),21β(H)-28,30-bisnorhopane (C_{28}) in sediments of the SCB.

Location	Sample Type[a]	Station/ Depth	C_{30}/C_{28} Ratio	Ref.[b]
Santa Barbara Basin	SED	193/(surface)	2.2	1
		193/(25-31cm)	0.80	1
	PIT		2.2	4
Santa Monica Basin	SED	380/(surface)	4.1	1
		380/(20-26 cm)	0.80	1
	PIT		5.2	4
San Pedro Basin	SED	823/(0-5mm)	5.1	2
		823/(20-25mm)	3.7	2
		823/(45-50mm)	2.9	2
		823/(75-80mm)	1.3	2
		823/(12-13cm)	0.6	2
		372/(28-30cm)	1.5	1
	PIT		5.2	4
San Pedro Shelf	SED	3C1/(0-2cm)	5.3	3
		3C1/(2-4cm)	5.0	3
		3C1/(4-6cm)	5.3	3
		3C1/(6-8cm)	5.3	3
		3C1/(8-10cm)	6.7	3
		3C1/(10-12cm)	5.0	3
		3C1/(12-14cm)	5.3	3
		3C1/(14-16cm)	6.7	3
		3C1/(16-18cm)	5.0	3
		3C1/(18-20cm)	4.8	3
		3C1/(20-22cm)	3.2	3
		3C1/(22-24cm)	2.4	3
		3C1/(24-26cm)	1.9	3
		3C1/(26-28cm)	2.4	3
		3C1/(28-30cm)	1.6	3
		3C1/(30-32cm)	1.6	3
		3C1/(32-34cm)	2.0	3
		3C1/(34-36cm)	0.4	3
San Nicolas Basin	SED	813/(15-20mm)	1.8	2
		813/(75-80mm)	0.5	2
		748/(28-32cm)	1.4	1
	PIT		4.7	4
Tanner Basin	SED	575/(25-31cm)	2.5	1
		YELS 5/(11-20cm)	1.2	6
		YELS 5/(291-300cm)	0.6	6
Outer Bank	SED	12G/(11-29cm)	0.6	5

seepage contribute greater than 95% of the sedimentary hydrocarbons, with the former dominating in the upper 34 cm at one site.

Surface sediments in Santa Barbara Basin and those presently being deposited in San Nicolas Basin (note PIT sample, San Nicolas Basin; Table 3.12) would also appear to contain detectable quantities of non-indigenous (anthropogenic) hydrocarbons. Results for sediments from the Patton Escarpment and Continental Rise (Simoneit et al. 1979a) suggest that little, if any, anthropogenic petroleum reaches the continental slope. Thus, petroleum introduced to coastal waters by humans heavily influences nearshore shelf and basin sediment chemistry but is not widely dispersed offshore.

Studies of the vertical distribution and rate of sedimentary accumulation of hydrocarbons in Southern California are limited (Eganhouse and Kaplan 1988; Emery 1960; Shokes and Mankiewicz 1979; Venkatesan et al. 1980; Venkatesan and Kaplan 1988). Recently, Venkatesan et al. (1980) presented geochemical data for box cores taken from San Pedro and San Nicolas basins and submitted to age-dating by ^{210}Pb (Figure 3.21). This was part of a larger study (Shokes and Mankiewicz 1979) which also included Santa Barbara and Santa Monica basin sediments. In the San Pedro Basin core (Figure 3.21a), the concentrations of total, aliphatic, and aromatic hydrocarbons exhibit a subsurface maximum (approximately 25 mm) and decrease continuously at greater depths, reaching apparent background levels at 12-13 cm, a depth estimated to correspond to the mid-1800s. Over this same depth interval, the percentage UCM, THC/OC (total hydrocarbons/organic carbon), hopane/bisnorhopane ratio, and the concentration of total DDT also decrease dramatically with the highest values confined to the upper 50 mm. The most rapid change in these parameters is observed at a depth dated circa 1945; the subsurface maximum in total hydrocarbon concentration occurs in the


Total Hydrocarbon Concentration (µg dry g -1)
(a)
0
2000
4000
0
50
100
150
Depth (mm)
-1975-77
1971-72
1966-68
-1958-62
-1945-50
1912-17
-1845-58
(b)
0
6000
1E4
0
100
200
300
400
-1980-81
-1970-71
– 1963-65
- early 1950s
(c)
0
100
200
0
25
50
75
100
-1975-77
– 1972-74
-1965-68
-1951-54
-1926-33
-1902-09
-1845-55
(d)
0
25
50
75
100
0
50
100
Depth (mm)
(e)
0
50
100
150
0
100
200
300
400
1975-77
1970-72
1962-64
-1954-56
-1938-40
-1906-12
-1843-51

3.94b

exponential decrease in total hydrocarbon concentration with depth (with the exception of the horizon corresponding to the 1954-1956 period). Although it is clear that a significant fraction of the hydrocarbons may be coming from anthropogenic sources (based on the hopane/bisnorhopane ratio; Table 3.12), the hydrocarbon profile does not appear to reflect the rapid changes in post-1971 anthropogenic hydrocarbon fluxes (such as the absence of a subsurface maximum) seen in other basin sediments.

The major sources of polynuclear aromatic hydrocarbons (PAH) are believed to be combustion of fossil fuels and petroleum or oil shales. The BLM and Department of Energy (DOE) studies revealed a complex array of sedimentary aromatic hydrocarbons that are generally present in lower abundance than the saturated hydrocarbons, except in the northern Channel Islands region (Amit et al. 1980; Reed et al. 1977; Shaltiel et al. 1979; Venkatesan et al. 19S0). Again, an unresolved complex mixture generally dominates the aromatic fraction in surface sediments, particularly in the nearshore zone. Examination of sediment cores from San Pedro and San Nicolas basins (Shokes and Mankiewicz 1979; Venkatesan et al. 1980) indicates that PAHs from both sources are present, and that the more recently deposited sediments (that is, post-1900) have been influenced to a greater extent than deeper sections by contributions of specific compounds of pyrolytic origin, including pyrene, benzopyrene, and benzofluoranthenes. Samples taken further offshore, from the Patton Escarpment and Continental Rise (Shaltiel et al. 1979), are dominated by phenanthrane, pyrene, and fluoranthene. Retene, an indicator of resinous higher plants (Simoneit and Kaplan 1980; Figure 3.21, structure III), has also been found. Lower molecular weight species (naphthalene, phenanthrene) are accompanied by significant amounts of higher alkylated homologs (that is, Cl-, C_2-, C_3-, etc.). However, distributions of PAHs having four or more fused rings are

The homolog distribution of g-fatty acids is always bimodal. Homologs $<C_{20}$ exhibiting a maximum at C_{16} originate from marine autochthonous sources, and those having carbon chains $>C_{20}$ with a maximum at C_{24} or C_{26} are derived from higher plant waxes. Monomethyl-branched fatty acids (iso- and <u>anteiso-)</u> having odd numbers of carbons from C_{13} to C_{19} are ubiquitous and reflect bacterial contributions. Isoprenoid acids with 15, 16, 17, 19, and 20 carbons have also been reported in Tanner Basin sediments (Hoering 1967a). These are most likely breakdown products of the phytol side chain of chlorophyll. Minor amounts of triterpenoidal acids--for example, 17β(H),21β(H)-bishomohopanoic acid; Figure 3.12, structure IV--presumably derived from bacterial cell membranes are typically observed, as are terpenoid acids indicative of terrestrial flora (for example, dehydroabietic acid; Figure 3.12, structure V). Because of their lability, only small amounts of unsaturated fatty acids are seen in surface sediments, the exception being sediments impacted by municipal wastes on the San Pedro Shelf (Eganhouse 1978).

Hoering (1967b) and Sever and Parker (1969) identified long-chain fatty alcohols in Recent sediments of Tanner and San Nicolas basins, respectively. These compounds range in chain length from C_{12} to C_{28} with a pronounced even-odd carbon chain length preference. In both of these studies, bimodal distributions with maxima at C_{16} and C_{22} were found. The primary sources of these compounds are probably the lipids of zooplankton, especially calanoid copepods (C_{12-22}; Boon and de Leeuw 1979; and Sargent et al. 1976, among others) and higher plant wax esters (Fukushima and Ishiwatari 1984; Tulloch 1976). Ikan et al. (1975b) reported both saturated and monounsaturated C_{22} and C_{24} n-alkanols in Tanner Basin sediments. They also found isoprenoid alcohols, phytol, and dihydrophytol, presumed to derive by hydrolysis of from 2 to 3%, of the total sedimentary organic carbon. Venkatesan and Kaplan (1990) demonstrated that the percentage of coprostanols [(coprostanol + epicoprostanol)/total sterols ″ 100] decreases with distance along a transect originating in Santa Monica Bay and terminating Santa Monica Basin. This suggests dilution of waste-derived particulate during offshore transport. Examination of sections from one age-dated Santa Monica Basin core revealed the existence of a subsurface maximum in the percentage of coprostanols content and rapidly diminishing concentrations at greater subbottom depths. The concentration maximum corresponded to a sediment horizon dated circa 1962, which suggests a relationship to the pattern of solids emissions for the LACSD outfall system off Pales Verdes (refer to Chapter 12).

More recently, Venkatesan (1989) and Venkatesan et al. (1990) reported the occurrence of several pentacyclic triterpenols in sediments and sinking particles from Santa Barbara and Santa Monica basins. A series of 17P(H), 21β(H)-hopanols (having 30, 31, and 32 carbons) probably originated diagenetically from bacteriohopanetetrol or they represent biosynthetic products of bacteria. Tetrahymanol would appear to be of microbiological origin and probably represents the biological precursor of gammacerane, a widespread constituent of oils and ancient sediments (Ten Haven et al. 1989; Venkatesan 1989).

Chlorinated Hydrocarbons

Polychlorinated biphenyls (PCB) are a group of halogenated hydrocarbons comprising up to 209 individual compounds (conveners). Individual PCB congeners differ in the numbers and positions of chlorines attached to a biphenyl nucleus (Ballschmiter and Zen 1980). Consequently, they have widely varying physico-chemical properties and toxicities. Owing to their

Figure 3.22. **Polychlorinated biphenyls.** (a) concentrations (ug dry g-l) in surface sediments along the 60-m isobath (Word and Mearns 1979); (b) vertical concentration profile in San Pedro Shelf sediments; and (c) mass emissions (metric tons yr^{-1}) from LACSD (b,c after Stun et al. 1988).

taken in 1971 from the San Pedro Shelf were highest within 2 cm of the surface (approximately 12 **ug** g-l) and declined precipitously with increasing depth in the core. At that time, the inventory of **ΣPCBs** in the San Pedro Shelf sediments was estimated at 6 mt. In a later study using cores collected in 1981, Stun et al. (1986) "and Stun et al. (1988) presented evidence that steady declines in PCB emissions from the **LACSD** waste treatment plant paralleled vertical PCB concentration profiles in nearby shelf sediments (refer to Figure **3.22b).** These changes have apparently resulted in the burial of the highly contaminated sediments (deposited in the early 1970s) at greater sub-bottom depths, such that there now exists a sub-surface maximum in **ΣPCB** (and other trace-contaminant) concentration approaching 40 **ug** g-l near the **outfalls.**

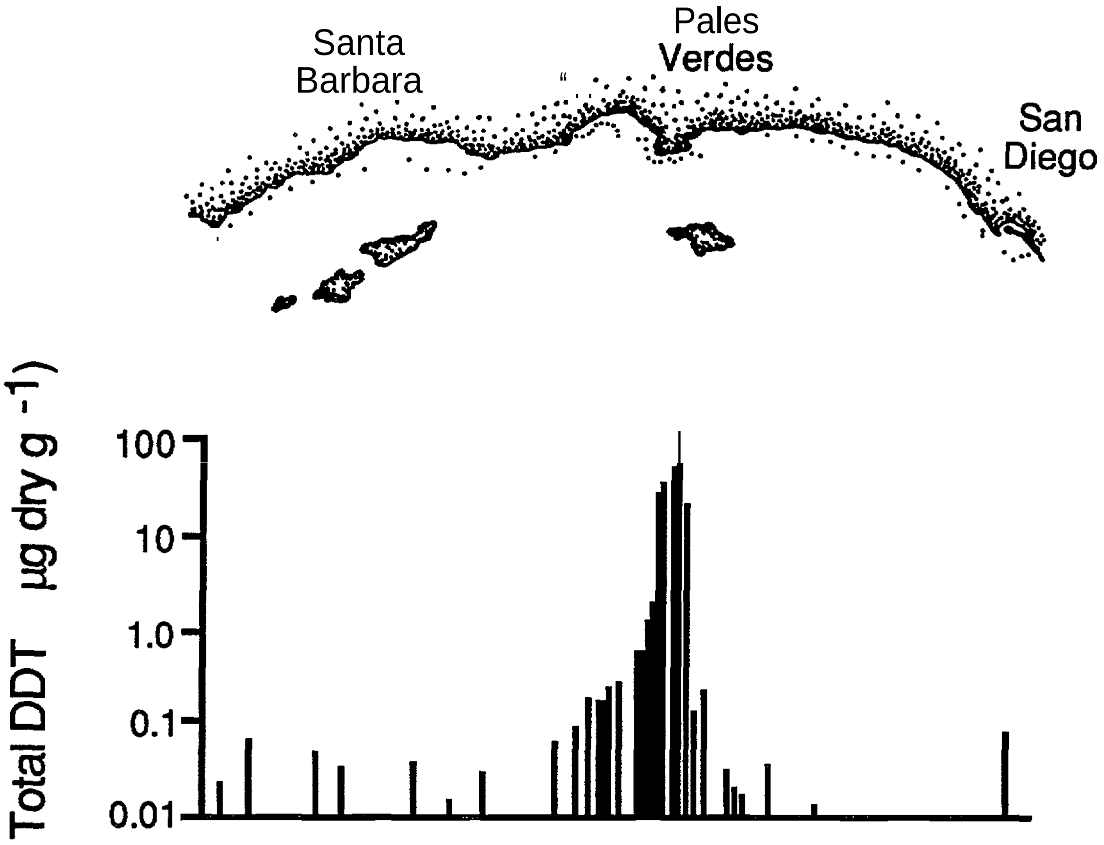
The only attempt to measure concentrations of PCBS in offshore basin sediments was made by Horn et al. (1974), who reported finding concentrations of **ΣPCB** of approximately 100 ng g'^{1}**in** surface sediments of Santa Barbara Basin dated circa 1967. Age-dating of the core by ^{210}**Pb** allowed Horn et al. (1974) to **establish** that PCBS began to accumulate in sediments around 1945 and continued to increase steadily with time to 1967. This agrees with national trends in the usage rates of PCBS (Summers et al. 1987) suggesting that peak accumulation rates probably occurred around 1970. Subsequently, Reed et al. (1977) and Venkatesan et al. (1980) **anecdotally** noted the presence of PCBS in sediments of San Pedro and San **Nicolas** basins. This indicates that PCBS are transported offshore **via** the atmosphere and ocean currents. Young et al. (1975) reported atmospheric depositional fluxes of **Aroclor** 1254 ranging from approximately 7 to >35 ng cm'^{2} yr^{-1} in the Los Angeles basin during 1974. This range compares favorably with the estimated flux to Santa Barbara basin sediments of approximately 12 ng cm^{-2} yr^{-1} as of 1967 (Hem et al. 1974), indicating that **aeolian** transport could play a

1971 were computed to be approximately 21.6 mt, but with elimination of the source of DDT to the plant, major reductions in effluent emissions were accomplished in succeeding years (Chapter 12; Smokier et al. 1979; Stun et al. 1988).

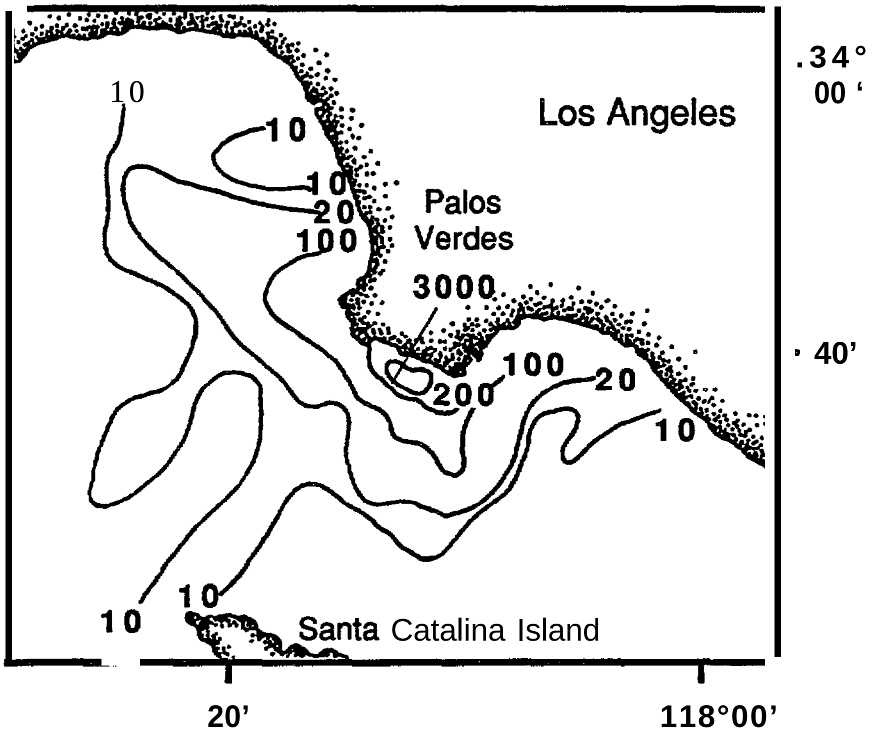
The discharge of these wastes led to the build-up of DDT residues in the sediments of San Pedro Shelf to such an extent that approximately 200-300 mt now reside in a thin layer (10 to 100 cm) of sediments overlying relatively clean deposits laid down prior to the discharge of wastes at this site (MacGregor 1976; McDermott 1974). Synoptic bight-wide surveys for DDT residues in surface sediments of the shelf (Thompson et al. 1987; Word and Mearns 1979: Mearns et al. in press; Figure 3.23a) consistently reveal that DDT contamination is widespread and that the concentration gradient is stronger to the south. This indicates that the dominant dispersal mechanism for effluent-derived DDT residues is advection by northward-flowing currents. Moreover, the distribution of contaminant isopleths in sediments on San Pedro Shelf and Slope indicates that the LACSD plant is the major source of DDT (compare Figure 3.23b from either Word and Mearns [1979] or Mearns et al. [in press]), although leakage of barged wastes in San Pedro Channel may be a possible second source (Chartrand 1988). In addition, it is clear that other municipal waste discharges have led to localized accumulations of DDT residues in sediments around the Los Angeles city (Santa Monica Bay), Orange County (Newport-Huntington Beach), and city of San Diego (Point Loma) submarine outfall systems (McDermott et al. 1974).

Sediments from the outer basins have not been examined for the presence of DDT metabolizes. However, o,p'-DDE and p,p'-DDE were observed in surface sediments of the Santa Barbara, Santa Cruz, and San Nicolas basins (Hem et al. 1974; Shokes and Mankiewicz 1979; Venkatesan et al. 1980), and shallower areas throughout most of the northern SCB (Mankiewicz 1981), reflecting its

(a)


Santa Barbara
Pales Verdes
San Diego
Total DDT µg dry g -1)
100
10
1.0
0.1
0.01

(b)


.34° 00 '
Los Angeles
Palos Verdes
3000
200
100
20
10
' 40'
Santa Catalina Island
20'
118°00'

Barbara Basin may have been dominated by advection of waste-derived particles.

MacGregor (1976), Venkatesan et al. (1980), and Eganhouse and Kaplan (1988) have also documented the contamination of San Pedro Basin sediments, where concentrations of ΣDDT reach 2-4 ug g^{-1} (approximately 70 ug g OC^{-1}) in surface layers. Recently it was determined that DDT production wastes (comprising approximately 350-700 mt of ΣDDT) were dumped into San Pedro Channel from 1947-1961 (Chartrand et al. 1985), indicating that emissions from the LACSD outfalls may not have been the only source of DDT residues to sediments of the San Pedro and Santa Monica basins. This may account for the observation of a second subsurface maximum in ΣDDT concentration in San Pedro Basin sediments dated at approximately 1958-1962 by Venkatesan et al. (1980). Moreover, because the acid wastes barged offshore contained significant quantities of undegraded DDT (as opposed to metabolizes such as DDE), the higher *p,p'*-DDT/*p,p'*-DDE ratios reported by MacGregor (1976) for San Pedro Basin sediments compared with those found on the nearby shelf may reflect contributions from dumped, as opposed to outfall-discharged, wastes. This hypothesis has been forwarded by Risebrough et al. (1989), who recently presented evidence of high DDT concentrations in tar balls and tar cakes taken from historic dumpsites in San Pedro Basin. In these samples, *o,p'*-DDT and *p,p'*-DDT isomers comprise from 44-98% of the total DDT (total DDT = ΣDDTs, DDEs, DDDs, *p,p'*-DDMU). Formerly, the abundance of undegraded DDT residues was attributed solely to differences in the availability of oxygen in shelf and basin environments.

Amino acids and lignin. Since Emery's (1960) anecdotal reference to amino acid analyses in sediments of Santa Cruz Basin, very little research on amino acids has been carried out. Degens et al. (1964) reported the occurrence of 17 essential amino acids in sediments near Guadalupe Island, oxidation products were detected (approximately 0.001 to 0.3 mg g-l organic carbon). This is consistent with the hemipelagic nature of these sediments (Ikan et al. 1975a; Sturmer et al. 1978).

Humic Substances and Kerogen. Humic substances include humic acids, fulvic acids, and humin. Humic acids are high molecular weight (2000 to $>10^6$ daltons) organic substances that form in both marine and terrestrial environments and are soluble in basic solution but are insoluble at pH <2. Fulvic acids are lower molecular weight (700 to 10^4 daltons), more highly functionalized compounds that are soluble in both acidic and basic solutions. Humin, sometimes referred to as protokerogen, is sedimentary organic matter that is insoluble in both basic and acidic media but has moieties that are hydrolyzable. It is considered to be an intermediate product of early diagenesis and an immature precursor to kerogen, a more highly aromatized, defunctionalized, refractory polymeric carbon-rich material. Kerogen is believed to be the main source of petroleum which is released upon further burial (and heating) of sediments (see Tissot and Welte 1981).

The procedures used to isolate kerogen involve solvent extraction (to remove lipids), base extraction (to remove humic and fulvic acids), and demineralization with HCl/HF (to remove silicate minerals). As noted earlier, these procedures may result in hydrolysis of some fraction of humin (or protokerogen), whereas the same is not believed to be true of kerogen (Tissot and Welte 19S1). However, attempts to distinguish between these two classes of insoluble material are often overlooked. For this reason, the following discussion will refer to those materials remaining after solvent, base, and HCl/HF extraction of sediments as kerogen, recognizing that some or all of the kerogen in Recent sediments may, in fact, be humin.

According to the nomenclature of Emery (1960), compounds represented by

Table 3.13. Elemental and stable isotopic composition of humic acids and kerogens isolated from sediments of the SCB.

		Elemental composition					Isotope ratios		
Location gms9m. fen;	%OC^a	%C	%N	%H	H/C	N/C	@font d^{13}C	δ ^{15}N	Ref^b
HUMIC ACIDS									
Santa Barbara Basin		54	4.5	6.5	1.6	0.14	-22.5	---	1
Santa Monica Basin	--	59	6.2	5.9	1.4	0.17	-27.4	---	1
San Pedro Basin	--	54	3.9	6.4	1.6	0.12	-22.7	---	1
San Pedro Basin		--	---	---	---	---	-22.4	8.1-10.2	2
Santa Cruz Basin	--	52	5.2	6.6	1.7	0.16	-21.8	---	1
San Nicolas Basin	--	--	---	---	---	---	-21.1	8.6-9.2	2
Tanner Basin	3	38	8.1	4.9	1.6	0.18	-20.6	+9.1	3
Tanner Basin	--	52	4.7	6.1	1.4	0.08	-22.0	---	1
Tanner Basin	7	51	7.1	5.2	1.2	0.12	-21.7	---	4
KEROGEN									
Santa Barbara Basin	--	--	---	---	---	---	-22.1, -22.3		6
Santa Barbara Basin	45	52	4.0	5.9	1.4	0.07	-.22.4	---	5
San Pedro Basin	--	--	---	---	---	---	-22.2	8.5-9.6	2
San Pedro Shelf	--	--	---	---	---	---	-23.3, -22.2	3.8-6.8	6
San Nicolas Basin	--	--	---	---	---	---	-21.5	8.9-10	2
Tanner Basin	36	48	5.1	5.3	1.3	0.09	-21.4	7.2	3
Tanner Basin	72	57	6.0	6.5	1.4	0.09	-22.4	---	4,5
Tanner Basin	--	47- 52	5.2- 5.5	---	---	0.08- 0.10	-21.5- -21.6	7.2- 7.3	7
Tanner Basin	--	--	---	---	---	---	-21.4- -22.3	5.7- 9.9	6
Tanner Basin	--	60	6.3	6.3	1.2	0.09	-21.5	8.1	8

[a] %OC = per cent of organic carbon made up by specific organic fraction (e. g., keragen or humic acids).

[b] References: 1--Nissenbaum and Kaplan 1972; 2--Venkatesan et al. 1980; 3--Stuermer et al. 1978; 4--Ishiwatari et al. 1977; 5--Ishiwatari et al. 1978; 6--Peters et al. 1978; 7--Minagawa et al. 1984; 8--Halpern 1981.

results of which are found in the final technical report (Chow and Earl 1979).

The reader should also be aware of two major reviews of this subject. Katz and Kaplan (1981) discussed the literature developed during the 1970s and attempted to synthesize information on sediment distributions and correlate them with the sources of various metals. More recently, Mearns et al. (in press) reviewed available data up to 1988 for the mainland shelf region and examined temporal trends for selected metals measured in various coastal surveys. In view of the enormous amount of information developed over the last two decades on heavy metal distributions in sediments, we here present results from only a small number of the investigations.

Establishing the "background" concentration of a given metal in sediments of the SCB is complicated by variations in the sediment grain size distribution and organic matter content of the sediments because these characteristics largely control metal content (Chow and Earl 1979; Thompson et al. 1987). Nevertheless, Katz and Kaplan (1981) attempted to estimate the "background" concentrations of heavy metals on the basis of measurements made on surface sediments from "clean" sites (Word and Mearns 1979; Chow and Earl 1979) and from deep sections-of basin and mainland shelf cores whose deposition was known to predate anthropogenic influences (Chow et al. 1973; Bruland et al. 1974; Galloway 1979; Kettering 1981; Shokes and Mankiewicz 1979). Table 3.14 summarizes these data and includes for comparison recent results presented by Thompson et al. (1987).

The data of Word and Means (1979), Thompson et al. (1987), and Chow and Earl (1979) compare well despite the fact that vastly different sample digestions were used in the first two studies. Sediments analyzed in the Word and Mearns (1979) study came from a survey of sites along the 60-m isobath, whereas the data of Chow and Earl (1979) represent sediments from the mainland shelf, inner and central basin, and outer bank and ridge environments. Data from Thompson et al. (1987) are for sediments taken at 13 of the same sites as Word and Mearns (1979) as well as 25 additional sites at shallower and deeper regions of the shelf (30 m and 150 m). It is noteworthy that the background concentrations developed from historical core sections are in all cases higher than those found in “clean” surface sediments. This development probably reflects the influence of finer grain size and higher organic matter content of the basin sediments (Chow and Earl 1979).

Numerous studies have documented the accumulation of heavy metals in sediments deposited near the major wastewater outfall systems (Eganhouse et al. 1976; Galloway 1979; Hershelman et al. 1981; and Stun and Baird 1985, among others). These investigations have shown that concentrations of many heavy metals in waste-affected sediments exceed “background” concentrations by 1-2 orders of magnitude. Nevertheless, only a small fraction of the metals discharged to the mainland shelf area from outfall systems appear to be stored in the sediments. Galloway (1979) and Hendricks and Young (1974) independently estimated that more than 90% of waste-associated metals escaped deposition on the Pales Verdes Shelf, either being released from particles into solution (Sweeney et al. 1980) or transported offshore in association with fine suspended matter.

The first evidence that inner basin sediments were also receiving significant amounts of trace metal contamination due to human activities came in 1973. Young et al. (1973) and Chow et al. (1973) reported increased rates of mercury and lead accumulation in age-dated sediments of the Santa Barbara, Santa Monica, and San Pedro basins. These authors noted a significant change in the flux of mercury at approximately the turn of the

Figure 3.24. Comparison of lead distributions in age-dated sediment cores collected from Santa Monica Basin. (a) 1971 (Bruland et al. 1974); b) 1977 (Ng and Patterson 1982); and (c) 19S6 (Finney and Huh 1989).

yields primarily anthropogenic metals, the remainder being largely incorporated into the crystalline lattice of detrital minerals. Ng and Patterson (19S2) demonstrated that stable Pb in leachates and leached residues of recent sediments from three basins (Santa Monica, Santa Barbara, San Pedro) are isotonically distinct. The leachates have ^{206}Pb/^{207}Pb ratios resembling those of atmospheric particles and tetraethyl lead, whereas the Pb isotopic ratios of leached residues are typical of Pb derived from marginal provenances in Southern California. Ng and Patterson (1982) further demonstrated downcore variations in the isotopic composition of leachate lead that paralleled those of tetraethyl lead used in the United States. Inspection of Figure 3.24b clearly indicates that the rise in Pb concentrations in Santa Monica Basin sediments through time is attributable to additions made to the leachable Pb pool. On the basis of differences between the historical lead flux rates and the assumption that atmospheric lead is removed to sediments via adsorption onto clay particles, Ng and Patterson (1982) calculated that the proportions of sewage-derived industrial lead being deposited in Santa Barbara, Santa Monica, and San Pedro Basin sediments were 0, 66, and 75%, respectively.

Table 3.8 provides estimates of the sedimentary fluxes of anthropogenic and natural lead, chromium, cadmium, copper, silver, and zinc to Santa Barbara, Santa Monica, and San Pedro basins. Natural fluxes of all elements to Santa Barbara Basin exceed those in other basins because of the higher sedimentation rate. Estimates for the natural fluxes of Cr, Zn, and Pb made by the various investigators are in reasonable agreement, and the anthropogenic fluxes to Santa Monica Basin in 1970-1971, as determined by Bruland et al. (1974), are within a factor of 2 of peak fluxes (approximately 1965-1970) reportedby Finney and Huh (1989). Data given by temporal changes may lead to apparent differences between (surface) sedimentary and effluent compositions.

Moreover, it has been observed that sedimentary compositions become increasingly dissimilar to the effluent pattern with distance from the outfall systems (Finney and Huh 19S9; Katz and Kaplan 1981). This phenomenon is attributed to differences in the distribution of elements between different particle sizes (that is, fractionation by settling of different size particles; Chen and Hendricks 1974; Katz and Kaplan 1981); differences in the rates and magnitude of mobilization of the elements from particles (Chen and Hendricks 1974; Faisst 1976; Finney and Huh 1989; Kettering 1981; Lu and Chen 1977; Sweeney et al. 1980); and mixing of effluent particles from different treatment plants and biological processes occurring in the water column or during early diagenesis following deposition in sediments (Finney and Huh 1989; Shaw 1988).

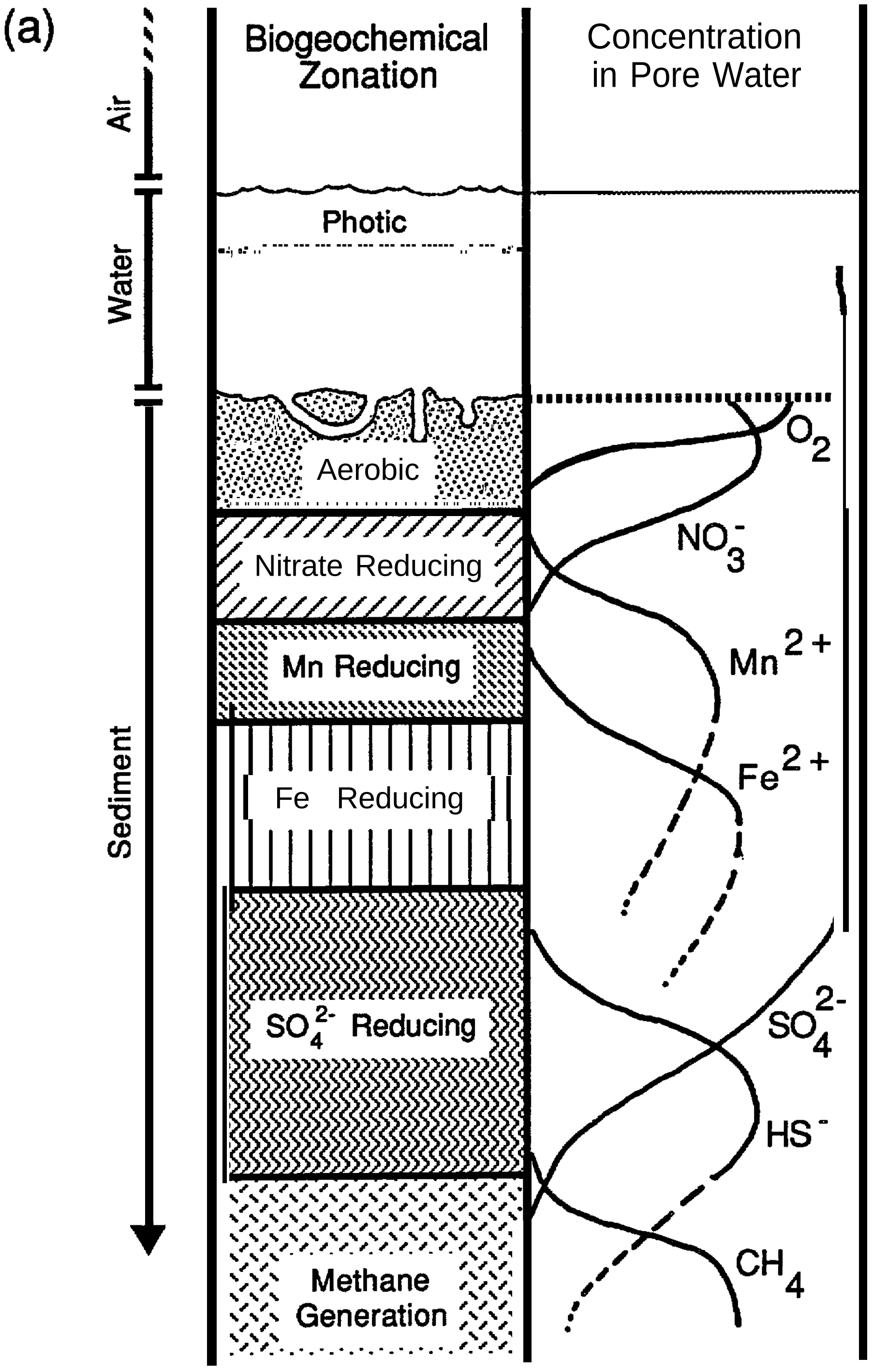
Recent work by Shaw (1988) shows that the post-depositional distribution and fate of several metals (Ni, Co, Cu, Mo, V, Cr) are determined by the redox-dependent cycling of manganese oxides. Manganese is mobilized under reducing conditions and reprecipitated in more oxidizing sediment horizons near the sediment-water interface (Froehlich et al. 1979). Under the strongly reducing conditions found in the inner basins, manganese does not appear to accumulate appreciably and is probably transported offshore. Cobalt behaves similarly to manganese, whereas nickel and copper cycling is controlled largely by the nature of the phases with which they associate during and after deposition. Chromium, vanadium, and molybdenum appear to reach the sediments in their reduced (insoluble) forms, perhaps in association with biogenic material. Of the three, only chromium is depleted in overlying basin waters, and this phenomenon is an indication that waters, and stable isotopic composition provides valuable clues to its origins.

EARLY DIAGENETIC PROCESSES

The inner basins in the northern portion of the SCB provide a nearly ideal setting for investigating early diagenetic transformations occurring in sediments. Suboxic conditions in deep bottom waters and the corresponding lack of significant bioturbation have led to conditions that approach steady-state diagenesis (Koide et al. 1972). At the same time, each basin environment is unique with regard to the types and amounts of inorganic and organic source materials being deposited in its sediments. Variations in physiography and oceanographic conditions also contribute to differences in biological activities in the sediments.

Following burial, sedimentary organic matter undergoes decomposition as a result of respiration by benthic fauna and heterotrophic microorganisms, primarily bacteria. When oxygen is available, aerobic respiration predominates, and benthic macrofauna may be abundant. When oxygen is absent or available in limited amounts (approximately <20 umoles kg‘1), as in the case of water at sub-sill depths in Santa Barbara, Santa Monica, and San Pedro basins (Emery 1960; Shaw 1988), bacterial degradation predominates, and metazoans are either not found or are present in small numbers.

Studies of the distribution of sediment bacteria and porewater profiles in cores from such environments have revealed vertical zonation of sediments which reflect specific diagenetic reactions (Figure 3.25). Such zonation represents the activities of a succession of bacterial communities utilizing different terminal electron acceptors at various depths in the sediments as the supply of each electron acceptor is exhausted. According to this scheme, the sequence of biologically mediated reactions proceeds in the



(a)
Air
Water
Sediment
Biogeochemical Zonation
Concentration in Pore Water
Photic
Aerobic
Nitrate Reducing
Mn Reducing
Fe Reducing
SO_4^{2-} Reducing
Methane Generation
O_2
NO_3^-
Mn^{2+}
Fe^{2+}
SO_4^{2-}
HS^-
CH_4

direction of increasingly smaller free energy yield (Aller 1982; Claypool and Kaplan 1974; Shaw 1988) and leads to the build-up of specific metabolizes in porewaters of different sediment layers (refer to Bender et al. 19S9, among others). In addition, changes in the redox potential facilitates mobilization of chemical species which reach the sediments in oxidized form but are soluble under reducing conditions (Fe^{+2}, Mn^{+2}, for example). The cycling of other species (for example, Co, Ni, Cu) is controlled by association with such oxide phases prior to or following sedimentation. The sequence is not always complete or fully developed as the dominance of one reaction at a given sediment horizon is determined by the overall sedimentation rate, biological and physical mixing rates, the porosity of the sediments, and the chemical composition of the overlying seawater. Nevertheless, it is a useful conceptual framework within which porewater profiles can be interpreted. Idealized reactions corresponding to these biogeochemical zones are shown in Figure 3.25.

The production of soluble metabolizes via decomposition of labile organic matter leads to measurable changes in the chemical composition of the interstitial waters (Brooks et al. 1968; Shaw 1988; Sholkovitz 1973, among others). If the sedimentation rate is constant over time scales longer than that required to establish steady-state diagenesis, the flux of any chemical species across the sediment-water interface can be determined from measured concentration gradients in porewaters, using suitable advection-diffusion-reaction models (for example, Berner 1980; and others). Knowledge of these fluxes is important to understanding the biological cycling of the elements and environmental controls on benthic respiration processes. Calculation of diffusive fluxes from porewater profiles is only one of several means by which fluxes of important chemical species (such as

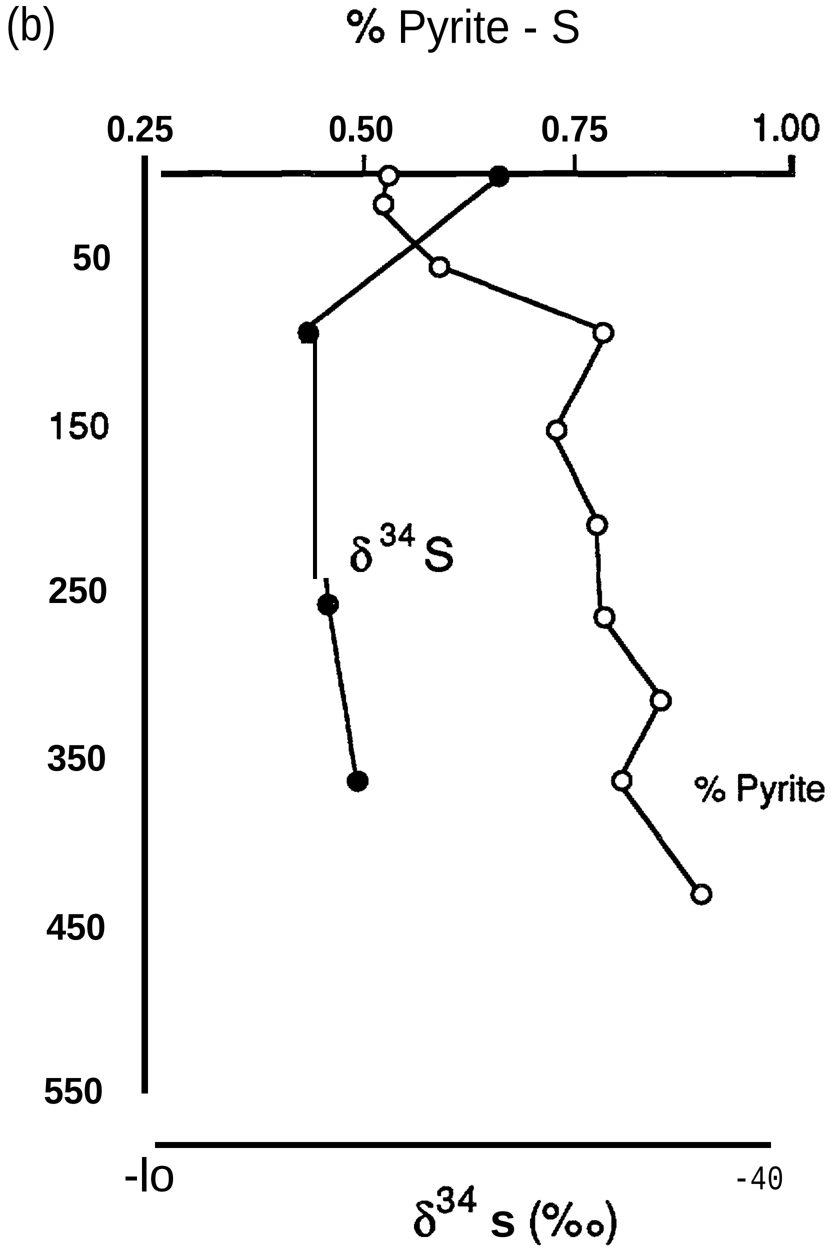
Table 3.15. Investigations of interstitial water chemistry in Southern California basins.

Investigation	Basins[a]	Porewater Constituents Analyzed[b]
Rittenberget al. (1955)	SBB,SMB,SCtB	pH,Eh,NH_3,NO_2^-,NO_3^-, PO_4^{-3},Si
Emery and Hoggan (1958)	SBB,SMB,SCtB	NH_3,N_2,Ar,CO_2,CH_4,VHC
Kaplan et al. (1963)	SBB,SMB,SCtB, SDT	Eh,pH,SO_4^{-2},H_2S,ΣS^{-2}
Brooks et al. (1968)	SBB,SCtB,TB SCZB	pH,Eh,PO_4^{-3},Na^+,K^+,Mg^{+2}, Ca^{+2} ,Sr^{+2},Cd,Co,Cu,Fe,Ni, Zn
Presley and Kaplan (1968)	SPB,SCtB	pH,Eh,Ca^{+2}, SO_4^{-2},ΣCO_2, $\delta^{13}C_{CO2}$,Fe,Zn,Co,Ni
Sholkovitz (.1973)	SBB	pH,NH_3,NO_2^-,NO_3^-,PO_4^{-3}, Si,Cl^-,HCO_3^-,TAlk, ΣS^{-2}, SO_4^{-2},K^+,Ca^{+2},Mg^{+2}
Barnes et al. (1975)	SBB	NO_2^-,NO_3^-,N_2,Ar ,CH_4
Bischoff et al. (1975)	SBB	Mg^{+2}
Kalil (1976)	SBB,SCtB,TB, ECB , SPS	pH,Eh,NH_3,PO_4^{-3},TAlk, SO_4^{-2}, Ca^{+2}, Mg^{+2}
Warford (1977)	SBB,SPS,SMBy	pH,Eh,Es,SO_4^{-2},H_2S,CH_4, CH_3COO^-,HCO_3^-

millimeters of the sediment surface (**Reimers pers. comm.** 1989).

Nitrate and nitrite typically present at concentrations of approximately 15-40 and 0.1-0.4 **umoles** kg^{-1}, respectively, in basin bottom waters (Barnes et al. 1975; Liu 1979; **Rittenberg** et al. 1955; **Sholkovitz** and **Gieskes** 1971; **Sholkovitz** 1973) were not found in basin sediments by **Rittenberg** et al. (1955). At the same time, porewater ammonia concentrations showed a consistent increase with depth (0.61-11.4 **mmoles** kg^{-1}, down to 200 cm, whereas sedimentary nitrogen decreased over the same interval. These observations led **Rittenberg** et al. (1955) to conclude that **denitrification** within the sediments was not occurring, and that deficits between the organic nitrogen lost **diagenetically** and ammonia accumulated in the porewaters could be accounted for by diffusion of ammonia from the sediments into the overlying waters. In a later study, **Sholkovitz** (1973) reported finding nitrate in the upper 1 cm of sediments. This is consistent with recent work (in which box cored sediments were extruded at in situ temperatures under an inert atmosphere) demonstrating that nitrate is, indeed, detectable within the upper 2 cm of the Santa Barbara Basin sediments, thus signaling the importance of **denitrification** as a pathway for oxidation of recently deposited organic carbon (**Reimers** pers. **comm.** 1989). The discrepancy between these studies can be explained by the fact that the early investigations employed gravity coring devices which disturb the uppermost layers of the sediments, where **denitrification** is most intense. **Reimers (pers. comm.** 1989) employed a box corer capable of recovering relatively undisturbed surface sediments. Barnes et al. (1975) also suggested that nitrate and nitrite (as **well** as excess N_2) were Present throughout the upper 10 cm of the Santa Barbara Basin sediments and that active **denitrification** accompanied by diffusion of nitrate into the sediments and N_2 out of the sediments was occurring. Based on the data of

Figure 3.26. Distribution of porewater and solid phase constituents in Santa Barbara Basin sediments. (a) concentrations of dissolved sulfate, sulfide, and methane in porewaters (after Doose 1980); (b) percent pyrite and $6^{34}S_{pyrite}$ (after Kaplan et al. 1963).


(b)
% Pyrite - S
0.25
0.50
0.75
1.00
50
150
250
350
450
550
δ^{34}S
% Pyrite
-lo
-40
δ^{34} s (‰)

reduction when a large pool of SO_4^{-2} is available (compare Figure **3.26b; Goldhaber** and Kaplan 1973). The isotopic composition of total sedimentary sulfur (-10 to -15°/00) is also significantly depleted in ^{32}S **relative** to seawater sulfate, further suggesting the importance of sulfate reduction at the sediment-water interface where large quantities of sulfate can be made available. Increasing concentrations of **pyrite** with depth indicate that continued pyrite formation occurs following **burial** (see Figure **3.26b).** At the same time, dissolved sulfide concentrations appear to reach **a peak at** approximately 250 cm below the sediment-water interface (Figure 3.26a). The decline, albeit irregular, in dissolved sulfide concentration with increasing depth signals further reaction of H_2S with iron in deeper sections where **a** supply of sulfate no longer exists'. The correspondence between declining sulfate concentrations and increasing dissolved sulfide and pyrite concentrations is indicated by the measurable enrichment of ^{34}S **in** the reduced sulfur species with increasing depth in the sediment column. For example, the Isotope ratios of the dissolved sulfide and pyrite increase from -26.5 to **+17.4°/oo** and -26.6 to -19.9°/00, respectively, reflecting contributions from the isotonically heavier residual sulfate pool (Figure **3.26b).**

As noted above, because the rate of sulfate reduction exceeds the supply of sulfate from overlying waters, dissolved $SO_4'^2$ **is** exhausted within 2 m of the sediment-water interface (that **is**, sulfate-reduction is essentially complete at this depth). **Methanogenesis** (see Figure **3.25b,** reaction 6) then becomes the thermodynamically favored metabolic process, whereby methane Is produced via reduction of either bicarbonate or **disproportionation** of acetate or both. Emery and **Hoggan** (1958) were first to report the occurrence of **biogenic** methane in subsurface sediments of appear to be the case according to the experiments of Warford et al. (1979), who incubated basin sediments with 2-^{14}C-acetate and $H^{14}CO_3^-$. Additional field and laboratory evidence for a bicarbonate source was provided by Doose (1980), who observed steadily increasing $\delta^{13}C$ values for methane and HCO_3^{-1} with depth throughout the zone of methanogenesis (150-500 cm; Figure 3.27). Isotopic fractionation results when methanogenic bacteria preferentially utilize $H^{12}CO_3^{-1}$, causing residual bicarbonate (and later-formed methane) to become increasingly heavy. Under these circumstances, the resulting isotope profiles exhibit the classical Rayleigh relationship (Hoefs 1980). The instantaneous fractionation factor (αmethane-bicarbonate) determined from the Santa Barbara Basin profiles, 1.07, was found to agree with measurements made with laboratory cultures of methanogenic bacteria from Santa Barbara Basin. Together, these facts would seem to indicate that substrate (that is, HCO_3^{-1}) limitation, rather than competition, is a more likely explanation for the reduced methane production rates observed by Warford et al. (1979) with increasing depth in the sulfate reducing zone.

Based on modeling of methane porewater profiles, Barnes and Goldberg (1976) concluded that consumption of methane in the sulfate reduction zone was occurring. This was later confirmed by Warford et al. (1979), who performed incubations of Santa Barbara Basin sediments with and without addition of ^{14}C-labeled substrates. They showed that methane production occurs at all depths in the sediments, whereas the rate of loss of methane (due to methane oxidation) is reduced in sediments below the sulfate reduction zone, where high concentrations of methane occur naturally (Kosiur and Warford 1979). Methane production rates were found to range from 5 to more than 40 umoles yr^{-1} with oxidation rates reaching a maximum of 360 umoles yr^{-1} in the sulfate reducing zone (30-35 cm). Doose (1980) provided

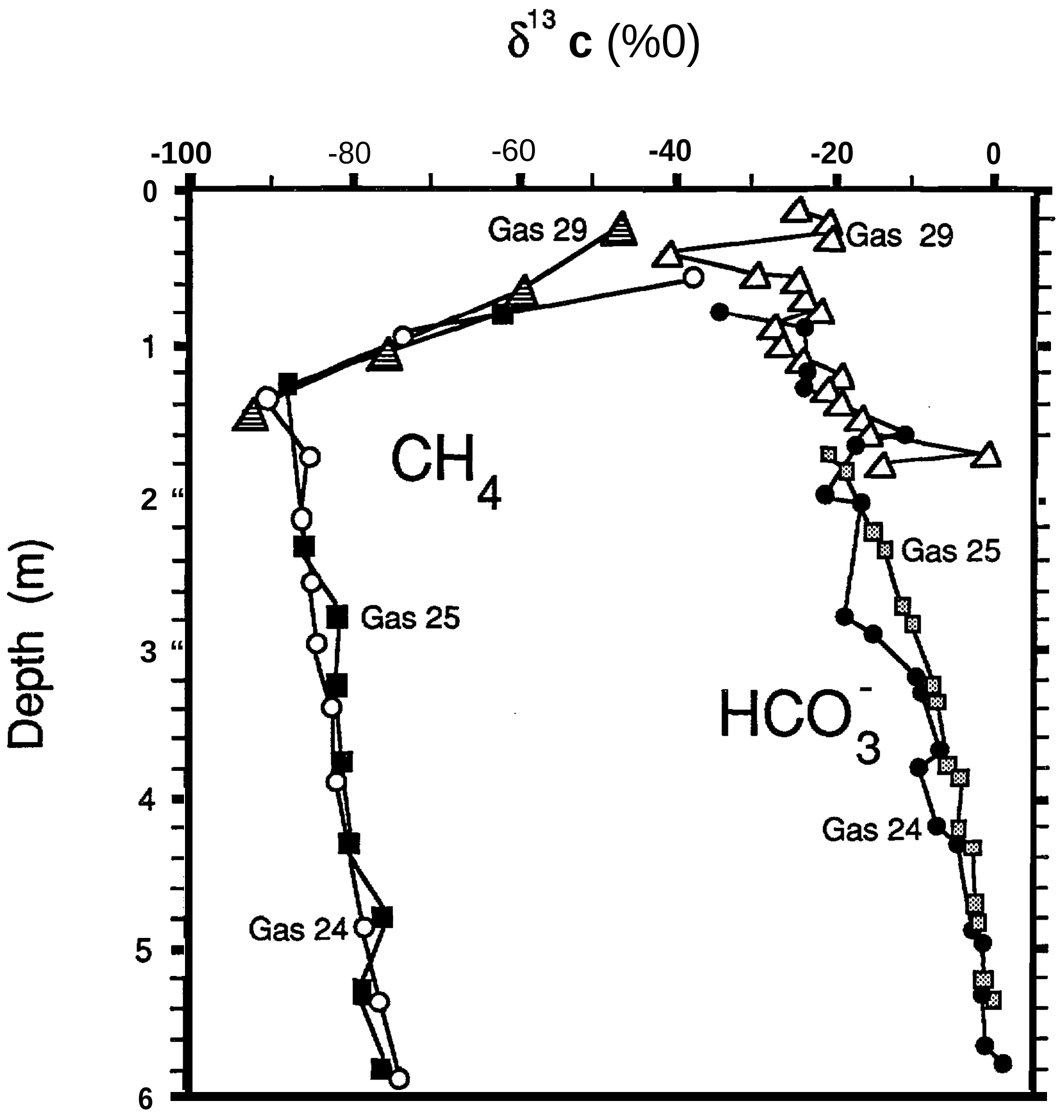

δ13 c (%0)
-100
-80
-60
-40
-20
0
0
1
2
3
4
5
6
Depth (m)
Gas 29
Gas 29
CH4
HCO3-
Gas 25
Gas 25
Gas 24
Gas 24

Figure 3.28. Distribution of inorganic porewater constituents in Santa Barbara Basin sediments (after Sholkovitz 1973).

reduction or other reactions strongly affecting alkalinity. **Sholkovitz** (1973) proposed that Mg^{+2} was removed via cation exchange at the surfaces of clay minerals whose exchange sites were exposed by dissolution of iron **oxide-hydroxy** coatings under the reducing conditions extant in Santa Barbara Basin sediments. This hypothesis was later tested by **Bischoff** et al. (1975), who performed cation exchange capacity **(CEC)** measurements on sediments from several basins in Southern California. These investigators found that the Santa Barbara Basin sediments had higher Mg^{+2} CEC values than sediments from the Santa Cruz, Santa Catalina, and San **Nicolas** basins. They postulated that the production of H_2S in Santa Barbara Basin sediments provided the necessary sink for Fe^{+2} mobilized under highly reducing conditions. A flux of Mg^{+2} into sediments of 10 **umoles** cm^{-2} yr^{-1} was proposed on the basis that changes in the exchangeable Mg^{+2} concentrations on the sediments greatly exceed the porewater supply.

Sediment-water Exchange

Table 3.16 presents published values for the exchange of nutrients and other chemical constituents between sediments and overlying waters for several offshore basins and the Patton Escarpment. The estimates come from studies which employed in situ **benthic** chambers, modeling of porewater concentration profiles, modeling of water column property gradients, sediment incubations, and basin-water mass balances. Only a small number of offshore basins have been studied, and estimates of **benthic** fluxes derived by more than one method exist only for Santa Monica, San Pedro, Santa Catalina, San **Clemente,** and San **Nicolas** basins.

From the limited data available it is clear that there is some variation (generally within a factor of 2-3) in the oxygen fluxes estimated for a given basin. This variability reflects uncertainties and differences in the analytical methods used by various investigators, possible difficulties with the assumptions and mixing coefficients employed in calculations for modeling of pore water and water column profiles, and temporal and spatial variations of measured fluxes. Work by Berelson et al. (1987) in San Nicolas Basin indicates that spatial and temporal variations in oxygen fluxes within a basin may be relatively small. They found good agreement between directly measured benthic fluxes (in situ chamber) and those estimated from water column properties (Table 3.16). Because the water column standing crop integrates over longer time periods and larger areas than waters enclosed in a benthic chamber (3-5 days; 730 cm^2), the similarity of the flux estimates determined by these two methods suggests that benthic oxygen exchange rates are not likely to have experienced large excursions with time. Likewise, Bender et al. (1989) found little difference between oxygen fluxes determined from benthic chamber experiments conducted in San Clemente Basin in January and April of 1986. In contrast, Smith and Baldwin (1984) report variations in benthic oxygen uptake for sediments from the base of the Patton Escarpment ranging up to a factor of 4 during different seasons. Reimers and Smith (1986) suggest that seasonal variations in the rate of oxygen consumption in sediments of the Patton Escarpment may be related to productivity of the overlying waters. (It is important to note that this site is not within a basin and may be subject to greater variation with respect to oxygen flux due to spatial heterogeneities [Reimers 1987]). In the course of more extensive investigations at five stations along a transect from the central Pacific to Santa Catalina Basin, Smith (1987) documented statistically significant temporal variations in benthic oxygen consumption. At the latter (basin) site, however, the maximum range of oxygen consumption rates was only 2.6-3.4 mmol $O_2 m^{-2}$ d-l.

basin-water oxygen content (Tables 3.16 and 3.17). The opposite conclusion was reached by Smith et al. (19S3) for a transect originating in the eastern Pacific and terminating in Santa Catalina Basin. Smith et al. (1983) developed an equation to describe benthic oxygen demand in which the dependent variables were water depth and macrofaunal abundance.

It is most likely that benthic oxygen flux is a complex function of organic matter supply and character (degradability), oxygen availability, sedimentation rate, and benthic community composition. The relative importance of these factors in controlling organic carbon remineralization, and hence oxygen utilization, are a subject of controversy (Emerson 1985; Reimers 1989).

Smith et al. (1987) attempted to estimate the contributions made by different groups of organisms to oxygen consumption in the benthic boundary layer (a region they defined as encompassing the overlying 100 m of seawater and basin sediments) of Santa Catalina Basin. They were able to demonstrate that approximately 90% of the oxygen demand could be accounted for by microorganisms inhabiting the sediments, particularly the near-surface layers. However, the flux of particulate organic carbon to deep basin waters as measured by sediment traps, accounted for only 17-43% of that estimated to be demineralized by the benthic boundary layer biological communities. Later work (Smith 1987) confirmed this deficit for five stations with periodic sampling over a time span of several years. The discrepancies suggest difficulties with the methods used to measure vertical fluxes or benthic respiration, or the existence of other, as yet unknown, sources of organic matter to the benthos.

Ultimately, the consumption of organic matter at the sea floor is reflected in the demand for all available electron acceptors under the

Table 3.17. Organic carbon remineralization rates (mmole C m^{-2} d^{-1}) for different metabolic pathways in sediments of Santa Monica, San Pedro, San Nicolas, and San Clemente basins.

	O_2 Cone.	OC Mineralization Rate[c]				Vert. Flux
Basin[a]	Basin H_2O[b]	O_2	NO_3^-	$S O_4^{-2}$	Total	Org. Carbon[g]
SMB[d]	13	-0.25 (lo)	-1.4 (57)	-0.8 (33)	-2.4	2.3-3.9
SPB[e]	9	-0.50 (27)	-0.88 (48)	-0.44 (24)	-1.82	3.0-3.6
SNB[e]	22	-1.0 (44)	-1.0 (44)	-0.26 (12)	-2.26	1.0-1.4
SClB[f]	56	-0.85 (70)	-0.2 (17)	-0.16 (13)	-1.21	ND[h]

[a] SMB--Santa Monica Basin; SPB--San Pedro Basin; SNB--San Nicolas Basin; SClB--San Clemente Basin.

[b] Concentration of oxygen (mmole kg‘^{1}) in deep basin (subsill depths) waters. Sources: Emery 1960; Bender et al. 1989.

[c] Organic carbon mineralization rates (mmol C m^{-2} d-l) for specific metabolic pathways: negative values indicate consumption of organic carbon. Stoichiometry given by reactions in Figure 3.25. Numbers in parentheses represent percentages of combined mineralization rates represented by individual pathways.

[d] Jahnke (1988).

[e] Berelson et al. (1987).

[f] Based on sediment trap data presented in Table 3.10.

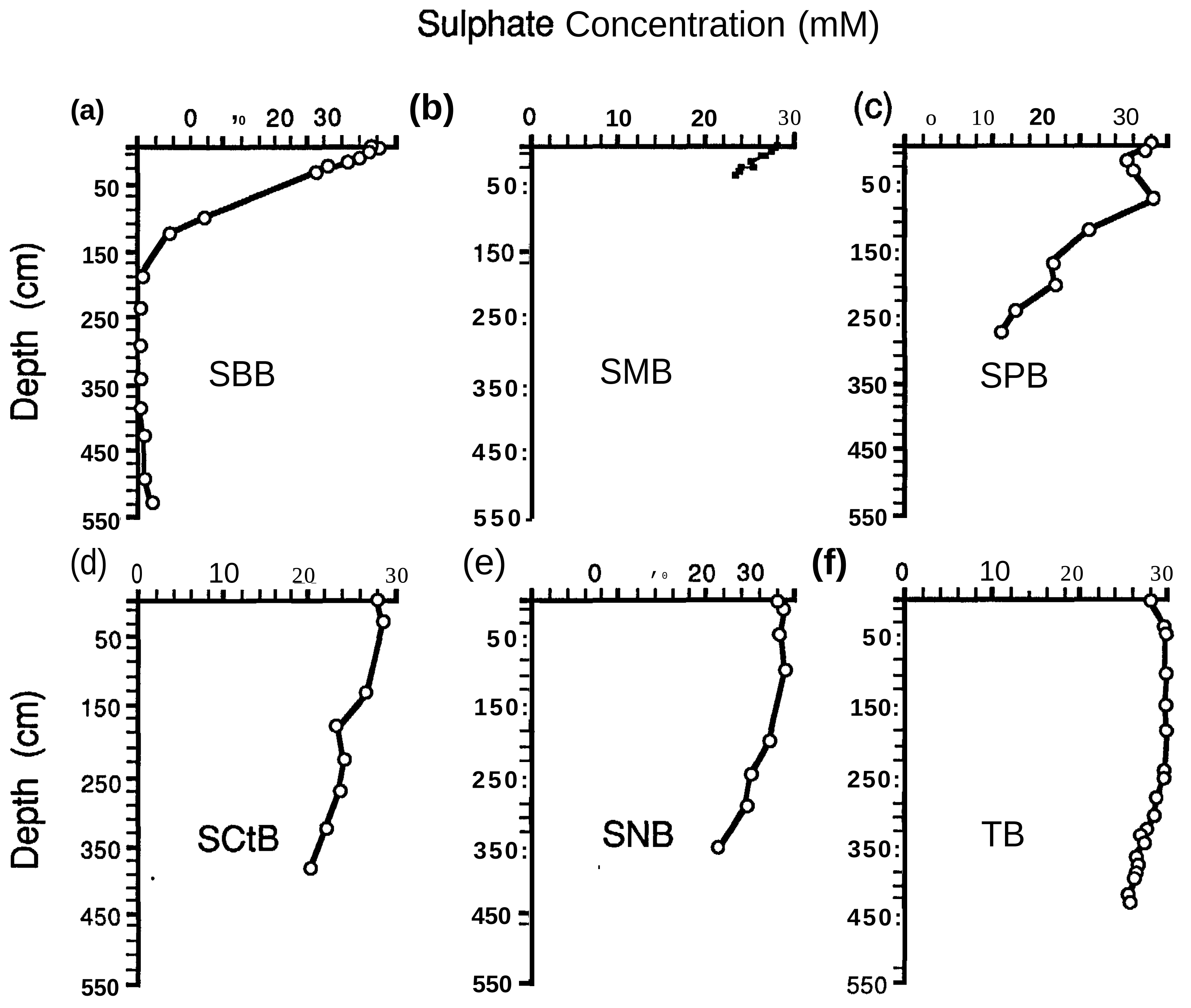
[g] Not determined.

conditions that exist at and below the sediment-water interface. Thus, the inner basins, whose waters are relatively oxygen-poor, sustain **benthic** metabolism to a significant extent under **suboxic** or **anoxic** conditions. Central and outer basin waters are deeper, more oxygenated, and their sediments are subject to **bioturbation (Berelson** et al. 1987; **Reimers** 1987; Smith and Hamilton 1983; Smith et al. 1987); the result is that organic remineralization in surface sediments is largely dominated by aerobic processes. Thus, the importance of nitrate reduction and sulfate reduction as metabolic pathways vs. aerobic destruction (or O_2 as electron acceptor) of sedimentary organic matter varies from basin to basin. (Methanogenesis has purposely been excluded from this discussion because, except in Santa Barbara Basin, early sediment **diagenesis** in the basins appears to be dominated by reduction of O_2, NO_3^-, and SO_4^{-2}, as shown below). Cycling of manganese is difficult to address quantitatively insofar as the identities of the oxidant(s) involved in reactions with Mn^{+2} are not known **(Shaw** 1988). Except for Santa Monica and Santa **Cruz** basins, however, basin sediments would appear to be closed with respect to manganese cycling. Computation of the excess inventory of dissolved and solid phase manganese in the manganese cycling zone of basin sediments **(Shaw** 1988) with the assumption of a **2:1 (Mn/C) stoichiometry** for oxidation of organic matter via manganese reduction (reaction 3, Figure 3.25) leads to the conclusion that under steady-state conditions, Mn^{+4} reduction plays a quantitatively insignificant role in **benthic** respiration in basin sediments. The same applies for iron. Similar conclusions were reached by Bender et al. (1989) and Bender and Heggie (1984), who estimated organic carbon oxidation rates for reduction of O_2, NO_3^-, Mn'', Fe^{+3}, and SO_4^{-2} in deep ocean sediments (including San Clemente Basin) by modeling porewater profiles.

For all basin sediments so far examined (except the San Diego Trough and one site in Santa Catalina Basin; Smith et al. 1983) there appears to be a measurable flux of nitrate and sulfate from overlying waters into the sediments in support of active nitrate and sulfate reduction (Table 3.16). In general, the magnitude of the fluxes of these two electron acceptors varies inversely with the oxygen concentrations in basin waters (compare Tables 3.16 and 3.17). Although one indication of the importance of nitrate reduction is the flux of nitrate into the sediments, the significance of measured (or estimated) nitrate fluxes is complicated by cycling of nitrogen within the near surface sediments wherein ammonia generated by oxidation of organic matter in the O_2 reduction zone is oxidized to nitrate (vitrification). By this mechanism a second source of nitrate becomes available for **denitrification** in microfiches or proximal **suboxic** layers (Bender et al. 1989; **Berelson** et al. 1987). In addition, nitrate is consumed by upward-diffusing ammonia (generated by sulfate reduction) as evidenced by the increasing ammonia concentrations at depths near or below that where nitrate concentrations approach zero (Bender et al. 1989). In outer basins and at the shelf break, the expansion of vitrification and **denitrification** zones is evidenced by the occurrence of a subsurface **maximum** in the NO_3^- profile, whereas these zones are compressed in inner and central basin sediments, and nitrate concentrations decline exponentially with increasing sub-bottom depth (**Shaw** 1988). For these reasons, sulfate profiles may provide the most reliable indicator of the intensity of anaerobic metabolism of organic matter in various basin environments.

The relative importance of sulfate reduction in different basins is indicated by the sub-bottom depths at which porewater sulfate concentrations begin to decline and by the magnitude of the observed concentration gradients (Figure 3.29). These depths increase and the magnitude of the

Figure 3.29. Vertical concentration profiles of dissolved sulfate in porewaters of offshore basin sediments. (a) Santa Barbara Basin (Doose 1980; Sholkovitz 1973); (b) Santa Monica Basin (Jahnke 198S); (c) San Pedro Basin (Berelson et al. 1987); (d) Santa Catalina Basin (Kalil 1976); (e) San Nicolas Basin (Berelson et al. 1987); (f) Tanner Basin (Kalil 1976).


Sulphate Concentration (mM)
(a)
0
,0
20
30
Depth (cm)
50
150
250
350
450
550
SBB
(b)
0
10
20
30
50
150
250
350
450
550
SMB
(c)
o
10
20
30
50
150
250
350
450
550
SPB
(d)
0
10
20
30
50
150
250
350
450
550
SCtB
(e)
0
,0
20
30
50
150
250
350
450
550
SNB
(f)
0
10
20
30
50
150
250
350
450
550
TB

gradients decreases in basins along north-to-south and east-to-west transects. Similar observations have been made by Shaw (1988) based on oxygen, nitrate, iron, and manganese porewater profiles. When the fluxes of oxygen, nitrate, and sulfate are converted to a molar carbon basis using the stoichiometries given by equations 1, 2, and 5 in Figure 3.25b, remineralization rates of organic carbon are obtained as shown in Table 3.17. (These rates do not include manganese, iron, or carbonate reduction, and, thus, must be regarded as first approximation estimates for the total flux of electrons. In addition, consumption of oxygen during vitrification and nitrate during reaction with ammonia cannot be explicitly separated.) The range in the total rate of sedimentary organic carbon remineralization among these basins is within a factor of 2 (1.2-2.4 mmol C m^{-2} d-l). Since the flux of particulate organic carbon to basin sediments generally decreases with distance offshore (Table 3.10), the similarity of the remineralization rates would lead one to predict that a higher percentage of the organic carbon being deposited in outer and central basin sediments is recycled when compared with the inner basins (all else being equal). If SO, this is probably related both to the higher oxygen concentrations of offshore basin waters, the lower sedimentation rates, and the greater lability of autochthonous organic matter, the relative abundance of which would be expected to Increase with distance from land. If the vertical flux of organic carbon, as determined by sediment trap data, is compared with the combined remineralization rates (Table 3.17), however, deficits in the carbon budget sometimes occur (that is, vertical $flux_{sed\ traps}$ < combined carbon mineralization rate). Such comparisons may suffer from the same difficulties described above for estimating sediment-water exchange rates. A more consistent qualitative pattern is observed when the carbon remineralization rates are partitioned between pathways associated with O_2,

NO_3^-, and SO_4^{-2} fluxes (Table 3.17). Here, differences in the importance of the metabolic pathways in the basins are revealed. As expected, oxygen and nitrate reduction account for increasingly greater proportions of benthic carbon recycling with distance offshore (and to the south) at the expense of sulfate reduction, an obligately anaerobic process. Although the data are limited, this trend generally appears to correlate with increasing water depth, bottom water oxygen content, and particulate carbon flux, making it difficult to ascertain the controlling factors (Reimers 1989).

There have been few attempts to construct carbon budgets for basins of the SCB. As noted earlier, Smith (1987) and Smith et al. (1983) were unable to account for the oxygen consumption in Santa Catalina Basin sediments from estimates of the vertical flux of particulate organic carbon based on the use of sediment traps.

Berelson et al. (1987) determined carbon and silica budgets for San Nicolas and San Pedro basins. They found that approximately 90% of the silica deposited on the basin floors was recycled and released to the overlying waters. Based on porewater profiles which show a shallow subsurface maximum in porewater silica content (approximately 5 cm; Berelson et al. 1987; Smith et al. 1987), much of the silica recycling appears to occur rapidly after sediment deposition. Comparison of sediment organic carbon fluxes (burial + sediment-water exchange) with primary productivity measured by Smith and Eppley (1982) indicates that approximately 10% of the POC formed in surface waters of San Nicolas Basin and San Pedro Basin actually reaches the sediment surface, and approximately 33-38$ of this carbon is recycled. Bender et al. (1989) reported that approximately 64% of the particulate organic carbon reaching San Clemente Basin sediments was recycled at the sea floor; they attributed the greater efficiency of POC degradation in San Clemente Basin (when compared to San Nicolas and San Pedro basins) to the higher oxygen content of its bottom waters.

Recent results developed by the CaBS group for Santa Monica Basin provide the most comprehensive data set for an inner basin (Jackson et al. 1989). Comparison of sediment trap fluxes, primary productivity measurements, sediment-water exchange, and burial flux estimates (Figure 3.30) indicate an approximate balance in the organic carbon budget for this basin. The long-term average flux of organic carbon to the sediments was found to be 1.72 mg C $\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ based on sediment trap data (Table 3.10). This represents approximately 4-11% of the primary production and approximately 9-26$ of the organic carbon exported from the euphotic zone. In comparison, the rate of sediment organic matter consumption estimated from porewater profiles and benthic flux measurements was 1.1 mg C cm-z yr^{-} 1, whereas the long-term sedimentary burial rate of organic carbon is 0.62 mg C $\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$. Thus, approximately 10% of photosynthetically fixed carbon reaches the floor of Santa Monica Basin and, of this, approximately two-thirds is recycled within the upper 40 cm of the sediment column. The turnover of organic carbon in the sediments appears to be approximately 10 times that accounted for by bacterial remineralization in the lower basin waters, again indicating the importance of diagenetic processes in bottom sediments.

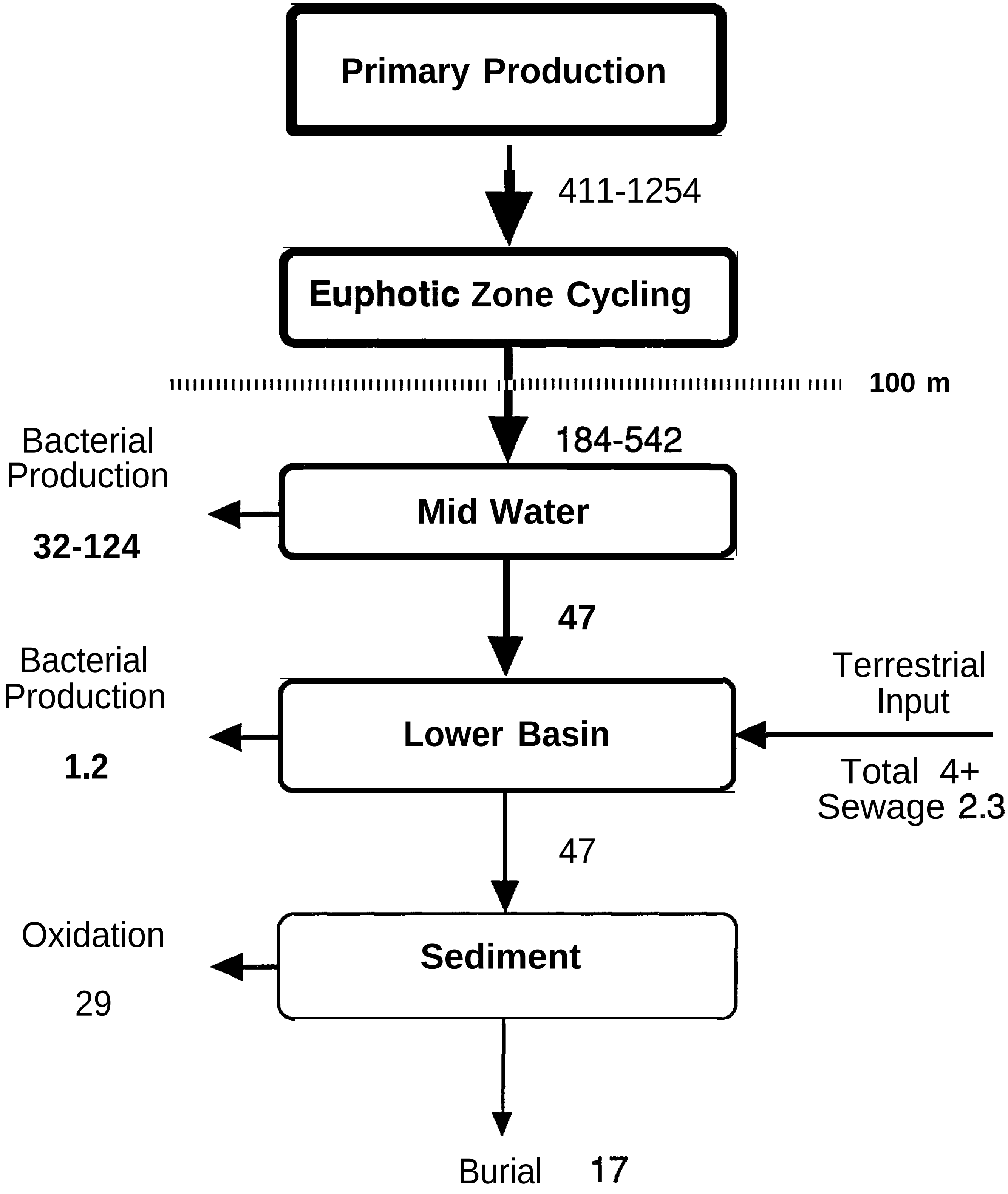
SUMMARY AND PROSPECTUS FOR FUTURE RESEARCH

The distribution of chemical substances in the SCB is determined by the fluxes of materials into the bight, processes occurring in the water column and sediments, and losses attributed to air-sea exchange and advection out of the bight. Because of the size of this region and the complexity of these processes, our understanding of bight-wide dynamics is still rather

Figure 3.30. Carbon budget for Santa Monica Basin (after Jackson et al. 1989).

Carbon Flow for the Santa Monica Basin

(mg Carbon $m^{-2}d^{-1}$)



poor. However, the development of more highly sophisticated monitoring techniques (for example, remote sensing) and the initiation of large multidisciplinary studies during the last decade offer new possibilities for understanding intra-bight dynamics and interactions between bight waters and larger-scale oceanic processes, such as El Nine.

When calculated on a mass flux basis, advection dominates the input of most constituents to the SCB. However, other inputs including those resulting from human activities (for example, the discharge of municipal wastes) are locally important and have led to the enrichment of many heavy metals and synthetic organic substances in sediments of the continental marginal shelf and inner basins. While impressive databases exist for historical emissions from waste treatment plants over the last two decades, information on inputs of contaminants from the atmosphere and surface runoff is scarce. In other cases (oil seepage and shale erosion, for example), estimates are based on extremely sketchy information. This makes the establishment of reliable budgets impossible at the present time.

The chemistry of the water column has been studied primarily in the context of ongoing efforts to understand controls on primary and secondary production within the SCB. Vertical profiles of most constituents of the dissolved and suspended particulate phases are largely inherited from the California Current with contributions from the Central Pacific and Equatorial Pacific. In addition, the water column is density stratified. As a consequence, vertical gradients in all properties greatly exceed horizontal variations. To the extent that the source waters experience changing relative contributions with time, the composition of SCB waters is variable both spatially and temporally. Within the bight, nutrients, particularly nitrate, are maintained at very low concentrations in surface waters. Primary productivity is high in the SCB relative to open ocean waters aided by mild seasonal upwelling. Most of this carbon is recycled in the upper 100 m of the water column. However, larger particles transport approximately 10-30% of photosynthetic organic carbon to deeper waters, where further bacterial decomposition leads to release of nitrogen and phosphorus. These nutrient-rich deeper waters represent the primary source of nitrogen (believed to be limiting) for “new production,” terrestrial inputs contributing only minor amounts of nitrogen because of the arid climate of the region. We are just beginning to understand the dynamics of carbon cycling within the inner basins.

In contrast, very little effort has been made to characterize the distribution and fate of synthetic organics and trace metals in waters of the SCB. Most of what is known about these substances is based on numerous sediment surveys conducted along the inner shelf, slope, and basin environments--particularly near urban centers. Here, evidence of historical contamination is recorded in basin sediments where benthic life forms are absent. Much of this contamination is attributable to the discharge of municipal wastes through deepwater outfalls, a practice established since the middle part of this century. Although extensive surveys of the outer continental shelf were initiated in the mid-1970s, the areal coverage was largely restricted to the northern portion of the SCB. Few measurements have been made on the outer edge of the continental shelf or to the south. The available evidence suggests that most of these anthropogenic materials are associated with particulate matter. Consequently, they are trapped on the inner shelves, slopes, and basins aided by entry into the biological cycle in association with fecal pellets and other rapidly settling particles. Evidence of offshore transport of contaminants can be found, but dispersion and effective trapping by the inner and central basins prevents the build-up of anything but traces of these substances in sediments of the outer continental shelf. The relative importance of aeolian and subaqueous transport mechanisms is unclear.

The topography of the SCB is highly irregular, having been formed by convergence of the Pacific and North American plates. A series of northwest-southeast trending basins, ridges, and islands form topographic features that not only influence water motions within the SCB, but also provide a range of environments for benthic organisms and sedimentation. The inner basins are shallower and have sills which Intersect the oceanic oxygen minimum zone. Consequently, deep basin waters are suboxic and sediments are anoxic, exhibiting varving due to the absence of burrowing benthic organisms. These sediments record depositional events and’ represent anoxic diagenetic environments where nitrate and sulfate reduction occur in surface layers of the sediment. The preservation of organic matter in basin sediments reflects a balance between productivity of surface waters, oxygen concentrations of basinal waters, and dilution by lithogenous material, most of which originates in the northern part of the SCB. With distance from land, basin sediments become increasingly oxidizing due to’ deeper sill depths and lower productivity (hence sedimentation) in overlying waters. The enhanced preservation of organic matter in inner basin sediments accounts for their status as modern-day analogs of petroleum-bearing onshore basins. Recent studies suggest that early diagenesis may result in recycling of as much as 50-60% of the particulate organic carbon reaching the bottom. Ultimately this accounts for <5$ of the photosynthetically fixed organic carbon in the euphotic zone.

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CHAPTER 4 MICROBIOLOGY

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INTRODUCTION

Microorganisms play an essential role in the maintenance of the waters of the Southern California Bight. The degrade not only decaying plant and animal remains produced in these waters, but also the anthropogenic matter introduced as sewage and industrial waste. Their degradative activities also result in the production of microbial biomass, which now is becoming recognized as a significant food source for other organisms in the water column and sediments. **Chroococcoid cyanobacteria** and vitrifying bacteria contribute to **autotrophic** processes in waters off Southern California.

Some microorganisms in marine waters off Southern California pose a risk to public health. Humans as well as marine species are susceptible to disease-causing microorganisms that are either indigenous to these waters or are introduced from other environments. In this chapter, a summary of the literature on the microbiology of the SCB is presented with the **goal** of identifying microbiological features and trends which may promote a more accurate understanding of ecological and **geochemical** processes within its boundaries. The result of this effort should help to identify specific areas of understanding, uncertainty, and ignorance.

MICROBIAL BIOMASS

WATER COLUMN

ZoBell and **Feltham** (1934) conducted some of the first detailed studies of bacterial concentrations in marine waters off Southern California. An enriched medium containing peptone, beef extract, and seawater yielded low numbers of colony-forming units **(cfu)** from water collected from the pier at Scripps Institution of Oceanography (S10) in La Jolla. No great difference in bacterial density was found in samples collected from the pier at a depth of 5 m and at the same depth 16.1 km offshore. The **ZoBell** and **Feltham** investigation included studies on the effect of tidal, diurnal, depth, and seasonal variations. After a comprehensive study of the cultural requirements of bacteria isolated from waters of the SCB and other locations, **ZoBell** developed the 2216 Medium which is now commercially marketed as Marine Broth or Marine Agar (ZoBell 1941a). Cultural methods were the primary approach for bacterial enumeration until the mid-1970s.

Non-Culture Methods of Estimating Microbial Biomass

Helm-Hansen and Booth (1966) described an adenosine triphosphate (ATP) assay for the determination of total biomass in seawater. The method has subsequently been adapted for evaluation of microbial biomass in the sea (Hamilton and Helm-Hansen 1967). ATP-based determinations of microbial biomass were presented by Sullivan et al. (1978). In their study, microbial biomass was operationally defined as ATP-derived carbon associated with material passing through a 203-um pore size filter, but retained by a 0.2-um pore size filter. This fraction contained a variety of living material including bacteria and phytoplankton.

Since the mid-1970s, microbial biomass has been determined by a direct enumeration approach, using epifluorescence microscopy. The fluorochrome acridine orange, 4'6-diamidino-2-phenylindole (DAPI), or a Hoechst dye, is used to stain cells trapped on a black polycarbonate membrane. Since acridine orange has become the fluorochrome of favor, the technique is now known as "acridine orange direct counts" (AODC). Electron microscopy has also been used to a limited extent to determine microbial sizes for biomass estimates. The direct microscopic methods have yielded biomass values that far surpass earlier estimates based on cultural methods.

Harbors

ZoBell and Feltham (1934) compared bacterial densities in Mission Bay and San Diego Bay with those obtained from oceanic samples. Bacterial densities in these harbors varied by over 2 orders of magnitude (Table 4.1). In Mission Bay, the lowest counts were recovered at the mouth of the bay

Table 4.1. **Bacterioplankton** standing stocks.

Location	Enumeration Method	**Bacterio-plankton** (cells 1^{-1})	**Autofluorescent cyanobacteria** (cells 1^{-1})	Reference
San Diego and Mission bays	culture	<5 x 10^5 to 4.8 X 10^8		ZoBell and Feltham 1934
Mission Bay				
flood tide	culture	1.47 x 10^6		ZoBell and Feltham 1934
ebb tide	culture	2.95 X 10^8		
Los Angeles-Long Beach harbors (mean)	AODC	1.6 X 10^8 to 5.5 x 10^8	0.2 x 10^7 to 6.3 X 10^7	Soule and Oguri 1979
Los Angeles Harbor near cannery effluent	AODC	1.0 x 10^{10} to 10 x 10^{10}		Sullivan et al. 1978
S10 Pier, La Jolla	AODC	0.66 x 10^9 to 2.9 X 10^9		Fuhrman and Azam 1980
S10 Pier, La Jolla	AODC	3.26 X 10^9		Fuhrman 1981
Del Mar nearshore	AODC	3 x 10^8		Fuhrman et al. 1980
1.5 km outside Los Angeles Harbor breakwater	AODC			
winter, 1978		0.4 x 10^9	0.1 x 10^7	Krempin et al. 1981 Krempin and Sullivan 1981
October 1978		2 x 10^9	2 x 10^7	
August 1979		4 x 10^9	7 x 10^7	
15 km offshore in San Pedro Channel	AODC			
surface		1.5 x 10^9	1*5 x 10^7	Krempin et al. 1981 Krempin and Sullivan 1981
30 m depth		1.7 x 10^9	3.0 x 10^7	
40 m depth		1.2 x 10^9	1.5 x 10^7	

Table 4.1.(continued) Bacterioplankton standing stocks in the SCB.

Location	Enumeration Method	Bacterio-plankton (cells 1^{-1})	Autofluorescent cyanobacteria (cells 1^{-1})	Reference
Santa Monica Basin, 1981	AODC			
surface		4×10^8		Carlucci et al. 1986
835 m depth		$<1 \times 10^8$		
Santa Monica Basin, 1982	AODC			Carlucci et al. 1986
surface		10×10^8		
800 m depth		1.5×10^8		
San Pedro Basin, 1983	AODC			Carlucci et al. 1986
surface		3×10^8		
800 m depth		$<1 \times 10^8$		
San Pedro Sill, 1982	AODC			Carlucci et al. 1986
surface		9×10^8		
700 m depth		1×10^8		
Offshore San Diego	culture	1×10^6		ZoBell and Feltham 1934
6 km off-shore from Dana Point	AODC			
May		3.7×10^8		Carlucci et al. 1984
October		4.5×10^8		
0.5 km off Santa Catalina Island	AODC			
Station 1				
surface		4×10^8	4×10^7	Krempin and Sullivan 1981
40 m depth		3×10^8	$<1 \times 10^7$	
Station 2				
surface		1.0×10^9		
30 m depth		1.5×10^9		

when the tide was flooding, and the highest in parts of the bay most influenced by land runoff (ZoBell 1941a). In a subsequent survey ZoBell and Feltham (1942) found the average bacterial densities from 34 sampling days in the water collected during flood tide to be significantly less than samples obtained during an ebbing tide (Table 4.1).

A number of stations were sampled by Sullivan et al. (1978) in Los Angeles-Long Beach harbors. Microbial biomass was highest near a cannery effluent outfall in the harbor (Table 4.2). Biomass was higher inside the harbor than outside the breakwater, with bacterial densities 1 to 2 orders of magnitude higher in the harbor than offshore. Biomass was higher in surface waters than near the bottom in the harbor, whereas outside the breakwater no significant difference in biomass was observed between surface and bottom water.

Plate counts performed in conjunction with the AODC bacterial enumeration method demonstrated that only 1-10% of the bacteria were culturable on marine agar. Highest plating efficiency was obtained from sites receiving the highest organic loading. These results were similar to those obtained by Juge and Griest (1973) by standard plate count of aerobic heterotrophic microorganisms in the harbor from 1973-1975. " A number of bacterial isolates (162) were recovered during the study, 17 of which were characterized. The low and variable recoveries of bacteria from these areas typify the inadequacy of culture methods for enumerating bacteria in natural waters. Nevertheless, much of the bacterial density data in the SCB to date is based on culture methods.

More recent determinations by AODC of microbial biomass in harbors yield higher estimates of bacterial densities than earlier cultural methods. A seasonal peak in bacterial densities within the Los Angeles-Long Beach harbors occurred in October (5×10^9 cells l^{-1}) one year (1978) and in

Table 4.2. **Planktonic** microbial biomass.

Location	Biomass (ug C l^{-1}) bacterio-plankton	cyanobacteria	References
Los Angeles-Long Beach harbors near cannery effluent			Sullivan et al. 1978
surface	406		
bottom	273		
Other harbor locations			
surface	178		
bottom	79		
Average of several harbor locations		0.09-2.87	**Soule** and **Oguri** 1979
Outside Los Angeles Harbor breakwater			Sullivan et al. 1978
surface	17.4		
bottom	16.5		
San Pedro Channel 15 km offshore			Krempin and Sullivan 1981
surface	12	0.12	
30m depth	13	0.23	
40m depth	9.4	0.12	
seasonal average	9	1.5	
0.5 km off Santa Catalina Island			**Krempin** and **Sullivan** 1981
site 1			
surface	3.5	0.3	
40m depth	2.3	<0.07	
site 2			**Krempin** and **Sullivan** 1981
surface	7.8	0.34	
30m depth	12	0.15	

August (4 x 10^9 cells l^{-1}) the following year (Krempin et al. 1981). McGrath and Sullivan (1981) reported the same peak bacterial densities in the harbor in October 1978. The bacterioplankton peaks occurred during or immediately after peaks in chlorophyll a concentration. During winter, bacterial densities ranged between 1-2 x 10^9 cells l^{-1}. The mean phytoplankton biomass was 24 times the mean bacterioplankton biomass. In spite of the larger biomass contributed by the phytoplankton, the mean surface area of the bacterioplankton was 168 times that of the phytoplankton cell surface area. The large catalytic surface area maintained by the bacterioplankton helps to explain how these microorganisms are able to have such a large impact in spite of their relatively small contribution to the total biomass.

Sullivan and co-workers determined densities and biomass of bacterioplankton and autofluorescent chroococoid cyanobacteria in Los Angeles Harbor and outside the harbor in the San Pedro Channel in 1978 (Soule and Oguri 1979). The annual bacterioplankton densities in the harbor were generally higher than those outside the harbor (Table 4.1). Monthly mean densities in the harbor were 2.5 times higher than those outside the harbor. Two blooms of bacterioplankton were observed: one in late spring and another in early fall. The cells in the harbor were generally larger than those found in coastal waters. A subsurface maximum (3 m depth) in bacterioplankton standing stock (14.8 ug C l^{-1}) was observed. It was estimated that bacterioplankton biomass contributed from 110-2610 kg C y-l "throughout the area of the harbor which was included in the sampling program.

Autofluorescent cyanobacteria were observed throughout the year in the harbor (Soule and Oguri 1979). Eighty-two percent of these cells fell within the size range of 0.6-1.0 um. Their standing stock was more than 1 order of magnitude less than the total bacterioplankton, contributing 0.09-2.87 ug C 1^{-1} (Tables 4.1, 4.2), or 7% of the total bacterial biomass in the harbor.

Discontinuation of cannery effluent discharge into the harbor led to a decrease in bacterial concentrations in the water near the outfall from 237-1648 x 10^8 to 35-43 x 10^8 cells 1^{-1} over a 9-month period in 1977-1978 (Soule and Oguri 1979). A thirtyfold drop in total microheterotrophs occurred with the transition from primary to secondary waste effluents. This also resulted in a reduction in the difference in bacterial densities inside and outside the harbor. A tenfold increase in marine bacterial standing stock in the harbor during the summer of 1978 coincided with a malfunction in the Terminal Island Water Treatment facility. It was not clear, however, whether the two events were related, since high bacterial counts also occurred outside the harbor upcurrent from the harbor plume. A treatment plant upset between April and June in 1979 led to an increase in the biological oxygen demand (BOD) in the harbor water which was subsequently followed by a peak in bacterial density in August (McGrath and Sullivan 1981). These data demonstrate the positive correlation between the levels of utilizable organic matter in the water and the densities of bacteria. The organic matter appears to be derived from sewage and phytoplankton sources in harbors and bays of the SCB.

Coastal Waters

Samples collected from the pier at S10 at six different times yielded AODC-based bacterioplankton densities that varied from 0.66 to 2.9 x 10^9 cells 1^{-1} (Fuhrman and Azam 1980). Estimates of bacterial cell carbon, based on size measurements obtained by scanning electron microscopy (SEM), ranged from 4.6 to 39 **femtogram** C cell-l. The **bacterioplankton** biomass at this nearshore site thus ranged from 3 to 113 **ug** C 1-1. A single biomass estimate based on size measurements made by **epifluorescence** microscopy fell within this range.

In another study of water samples collected off the S10 pier, Fuhrman (1981) determined a mean **AODC-based** bacterial density of 3.26 x 10^9 cells 1^{-1} and a mean cell volume of 0.145 um^3 based on size determinations made by **epifluorescence** microscopy. Using the carbon-to-volume ratio of 0.2 pg **C** urn-3 recommended by Kogure and **Kioke** (1987) for natural populations of bacteria in nearshore waters, calculations yield a bacterioplankton biomass estimate of 95 ug C 1^{-1} of seawater at this site.

Fuhrman et al. (1980) determined mean **bacterioplankton** densities throughout the water column at a nearshore station off Del Mar (Table 4.1). **Bacterioplankton** biomass was estimated from volume measurements (mean of 0.046 **um**^{3}) based on size determinations made by SEM. Biomass increased from **4 ug C** 1^{-1} at the surface to 12 ug C 1^{-1} at 15 m and then declined to 2 ug C 1^{-1} at 30 m. **Bacterioplankton** biomass contributed from 3.6 to 8.8% of the total plankton biomass at this nearshore station.

Bacterioplankton densities in water 6 km off Dana Point were similar to those obtained off the S10 pier in La Jolla (**Carlucci** et al. 1984). Samples collected at different times of the year showed no significant differences in **bacterioplankton** density (Table 4.1).

San Pedro Channel

Surface waters of the **San-Pedro** Channel exhibited trends in **bacterioplankton** densities that were similar to those observed in the waters of the Los Angeles-Long Beach Harbors (**Krempin** et al. 1981). A seasonal peak in **bacterioplankton** densities was observed during October in 1978 and in August of 1979 (Table 4.1). The lowest densities occurred during the winter and spring months. The bacterioplankton averaged 5% of the total carbon biomass within the size range of 0.2-203 um.

The density (Table 4.1) and size range (0.6-1.0 m) of autofluorescent chroococcoid cyanobacteria in the San Pedro Channel 1.5 km outside the Los Angeles Harbor, upcurrent of the harbor excurrent plume, was similar to the density and size range of these microorganisms in the harbor (Soule and Oguri 1979; Krempin and Sullivan 1981). Although the density of the autofluorescent cells was nearly 2 orders of magnitude lower than that of the total bacterioplankton, the seasonal trends of the two populations were similar: low in winter, increasing through the spring and summer, and peaking in early fall (Table 4.1). Bacterioplankton densities were determined at different depth intervals at one station 15 km offshore in the San Pedro Channel in 1979 (Krempin and Sullivan 1981). A subsurface maximum was observed at a depth of 30 m (Table 4.1).

Bacterioplankton densities in Santa Monica and San Pedro Basin water were determined during 1981-1983, using the AODC technique (Carlucci et al. 1986). San Pedro sill water contained higher densities in 1982 than water in either basin in 1981 or 1983 (Table 4.1). Yearly variations were observed in bottom water of the Santa Monica Basin. The bacterioplankton population density in the basin water reflected no apparent effects of the 1983 El Nino event. Distribution of bacteria and total free amino acid concentrations were well correlated.

Offshore

The mean bacterioplankton biomass estimated on a cruise in which a total of 6 stations, including inshore and offshore stations, were sampled was 4.6% (range of 1.7 to 16.7%) of the total plankton biomass (Fuhrman et al. 1980). On another cruise, which sampled 11 stations throughout the SCB, the mean bacterial biomass was 3.3$ (range of 0.4 to 12.8%) of the total plankton biomass. Bacterial biomass tended to decrease with distance from shore. A subsurface maximum was common.

Bacterioplankton densities in the channel near Santa Catalina Island were lower than in Los Angeles-Long Beach Harbors (Krempin and Sullivan 1981; Krempin et al. 1981). At one station 0.5 km off the island, the density decreased slightly with depth within the top 40 m (Table 4.1).

Carlucci et al. (1985) compared bacterioplankton densities in surface films (neuston layer) with those in underlying water at several stations off San Clemente Island and Santa Catalina Island. Surface-film densities averaged 4.4 x 10^8 cells l^{-1}, which were more than two times higher than the corresponding bacterioplankton densities in water collected at a depth of 10 cm.

In summary, bacterioplankton represents a very small fraction of the total plankton biomass. The standing stock is controlled by the availability of usable dissolved organic carbon. Higher bacterioplankton standing stocks occur in harbors, bays, and nearshore waters than in offshore waters. Maximum bacterioplankton biomass occurs in the surface film, and a submaximum occurs at subsurface depths ‘in the water column.

Particle-Associated Microbial Biomass

Suspended particles in the water column harbor populations of microorganisms. Macroscopic particles composed primarily of discarded appendicularian “houses" and found in samples collected at depths of 7-10 m in the Santa Barbara Channel, 5 km from shore at the leading edge of an upwelling plume, contained bacterial densities that were 3 orders of magnitude higher than that in the surrounding water (Prezelin and Alldredge

1983). Seventy-eight percent of the total bacterial population resided on the discarded particles. During **non-upwelling** conditions, aggregates of a different origin were found. These particles contained 7$ of the total bacterial population.

The densities of bacteria on macroscopic aggregates collected 2 km south of Santa Cruz Island during July ranged from 12.5 to 16.9 x 10^5 bacteria per aggregate (**Alldredge** et al. 1986). These densities were lower than those observed on particles collected in the Atlantic Ocean. The authors of this 1986 study postulated that the El Nino event may have contributed to the low observed bacterial densities. Less than 3$ of the total number of bacteria in the water column occurred in association with aggregates in samples collected from the SCB. Bacteria on macroscopic aggregates were significantly larger than free-living, **planktonic** bacteria. The average volume of bacteria on aggregates was 1.02 **um^3**, five times greater than that of free-living bacteria in the surrounding water. The contribution of particle-associated bacteria to the total water column bacterial standing stock thus appears to depend on local conditions within the water mass.

Microzooplankton

Taylor et al. (1985) determined the abundance of **microzooplankton** in waters of the SCB. **Microzooplankton** in Los Angeles Harbor was dominated by the **ciliates** **Strombidium** sp., **Euplotes** sp., and **Uronema** **sp., which had a** combined biomass of 1.0 **ug** C 1-1. In the San Pedro Channel, 19 km offshore, **Strombidium** sp. and six species of **tintinnids** were observed contributing a biomass of 1.1 **ug** C 1-1. More studies need to be conducted to relate the standing stocks of these microorganisms to the **bacterioplankton** standing stocks in waters of the SCB.

SEDIMENTS

The earliest enumeration studies were carried out using cultural methods. **ZoBell** and **Feltham** (1934) analyzed bottom deposits from 28 stations and found from 1.2 x 10^3 to 3.8 x 10^7 viable **aerobes** per gram wet mud; they obtained the highest counts from shallow bottoms. Anaerobic bacterial counts were only **5%** of the **aerobes** in these sediments, but the proportion of anaerobes increased **with** depth in the sediment. **At** three stations in coastal waters off San Diego, **ZoBell** and Anderson (1936) found between 10^5-10^7 bacteria per gram sediment. Sediments off the Channel Islands in 1000 to 2000 m of water yielded highest bacterial densities (8-35 x 10^6 bacteria g-l) in the top 5 cm of sediment, with densities decreasing to 1-41 x 10^3 bacteria per gram sediment at depths below 40 cm. Aerobes predominated throughout these depth intervals. The ratio of anaerobes to **aerobes** increased from **1:64** in surface sediments to **1:2** at 66-68 cm depths.

ZoBell (1942) presented data showing a decrease in bacterial densities with depth in bottom deposits collected off Southern California. Although the cultural methods employed in the studies described above grossly underestimate the total microbial densities in the sediment, they provide data that describe trends in microbial biomass and which, for the most part, have been confirmed by more modern techniques. Cultural techniques are still used to a great extent to evaluate the abundance of specific physiological groups of microbes present in aquatic habitats. In many instances, the only bacterial density data available for some areas of the **SCB** is derived from cultural methods.

Harbors and Estuaries

The most extensive studies published on the microbial biomass of sediments in protected bodies of water within the SCB are those of **ZoBell** and **Feltham** (1942). Large variations in cfu were obtained from different cores collected within a 1 m^2 area in Mission Bay. Densities in Mission Bay sediments varied from 1.72 to 4.60 x 10^5 cfu g-l dry wt sediment at the surface to 8.2 to 62 x 10^3 cfu g^{-1} dry wt at a depth interval of 85-90 cm below the sediment surface. Most of the bacteria were in the top 25 cm of sediment. Mud flats contained more bacteria than oceanic bottom mud.

Bacterial densities in the top 1 cm of bottom deposits in harbors and estuaries (as based on AODC) range from 1 x 10^9 to 5 x 10^{10} **cells** g-l **drywt** sediment. Using the value 1 x 10^{10} as the mean bacterial cell density, the value 0.29 **um**^{3} as the mean cell volume of sediment bacteria (Newell and Fallen 1982), and the value 0.2 pg C ur^{n-}3 for the carbon-to-volume ratio (**Kogure** and **Koike** 1987), bacterial biomass in harbor deposits is estimated to be 580 **ug** C g-l dry wt sediment.

Coastal Waters and Offshore Waters

Sediment bacterial densities were determined at different distances from sewage **outfalls** along a 60 m depth survey in Santa Monica Bay and off the Pales Verdes Peninsula (Laughlin 1982). Bacterial densities, based on the AODC method, increased from 0.25 x 10^9 to 30 x 10^9 cells g-l sediment as the **infaunal** index (degree of pollution based on **macrofaunal** populations) decreased from 77 (near-ambient) to 6.8 (highly organically enriched). These data, like those for water column bacterial populations, suggest that sediment bacterial biomass is controlled by the availability of usable organic matter.

Rittenberg (1940) sampled green clay and silt bottom deposits between the coastline of north San Diego County and San **Clemente** Island at water depths ranging from 450 to 1100 m. The aerobic microbial densities, determined by a cultural method, decreased rapidly with depth over the top

20 cm (Table 4.3). At all levels, the aerobes outnumbered anaerobes. Within some cores, the vertical distribution of bacteria departed from the general decrease in numbers with depth. These differences were thought to be due to extreme lateral and vertical variability in the bottom material. Depths as great as 355 cm still contained viable bacteria. It remains to be determined whether bacteria recovered from these depths in the sediment are active in situ.

Sediment bacterial densities were determined off Orange County on the slope where overlying water ranged from 300 to 600 m in depth (Thompson et al. 1984a). Bacterial densities based on direct ‘enumeration epiflourescent microscopy, using the stain DAPI, ranged from 7×10^8 to 12×10^8 cells cm^{-3} sediment (Table 4.3). No trend was observed between bacterial densities in the sediment and water-column depth or between bacterial densities and sediment grain size. Using the factors described above to convert sediment bacterial densities to sediment bacterial biomass, a value of 58 ug C cm^{-3} sediment is obtained. It was estimated that 10-36% of the total microbial carbon was contributed by bacteria, and the remainder by protozoans and meiofaunal metazoans.

Sediment bacterial densities were determined on the upper and lower slope off Newport Beach (Thompson et al. 1984b). No significant differences were detected from a sample size of four. Upper- and lower-slope sediments also contained similar organic carbon content. Bacterial densities based on direct enumeration epifluorescence microscopy using DAPI ranged from 7×10^8 to 9×10^8 cells cm^{-3} in sediments which contained 2-4% organic matter. Using the conversion factors above, this equates to 46 ug bacterial C cm^{-3} sediment.

Carlucci et al. (1976) studied the forms of bacteria that exist in

Table 4.3. Sediment bacterial standing stocks.

Location	Method	Density	Reference
offshore San Diego to San Clemente Island	culture		Rittenberg 1940
surface			
aerobes		1×10^6 to 8×10^6 cells g^{-1} wet weight sediment	
anaerobes		1.5×10^3 cells g^{-1} wet weight sediment	
20 cm depth			
aerobes		1×10^4 cells g-l wet weight sediment	
anaerobes		<500 cells g-l wet weight sediment	
upper slope off Newport Beach	(DAPI)DC		
300m depth		12×10^8 cells cm^{-3}	Thompson et al. 1984a
380m depth		7×10^8 cells cm^{-3}	
480m depth		9×10^8 cells cm^{-3}	
620m depth		7×10^8 cells cm^{-3}	

sediments of the San Diego Trough. Most bacteria were found to be rod-shaped, less than 0.4 um in diameter, and most occurred in aggregates or attached to particles. No bacterial biomass estimates were presented in this study.

Burnett (1979, 1981) determined the biomass in sediments contributed by nanobiota, defined as organisms in the size range between bacteria and meiofauna (2-50 urn), at a station sampled approximately 24 km west of San Diego in the San Diego Trough at a depth of 1200 m. Density of organisms and biovolume were determined for six depth intervals ranging from 0-5 mm to 89-98 mm below the sediment-water interface. There appeared to be no decrease in biovolume with increasing depth. A subsurface maximum of nanobiota volume occurred at a depth of 5-10 mm. Yeast-like cells outweighed both protozoans and procaryotes, typically constituting over 70% of the nanobiota volume. Burnett's work suggested that the yeast-like cells formed a major part of the food web in these sediments. Among the protozoans, flagellates predominated in the majority of samples. However, amoebae constituted a larger fraction of the protozoans in deeper parts of the sediment (23% at the top vs. 43% in the 10-16 mm interval). Testate cells of Foraminifera and testacids fluctuated around 10%. Nanobiota contributed from 2.5 to 5.1 g m^{-2} biomass in the sediment.

Studies such as these by Burnett need to be extended to other areas of the SCB.

BACTERIAL POPULATION STRUCTURE

Virtually nothing is known of community structure at the microbial level in the SCB. Relatively few of the total number of species present have been identified. Differences between bacterial densities estimated by cultural methods and those obtained by direct microscopic techniques suggest that the vast majority of the species in marine waters have not been cultured. Characterization of the different types of microorganisms present in various water masses will be an exciting challenge to future marine microbiologists. This information is essential for understanding the role of microorganisms in the sea. Where studies have focused on specific physiological types of microorganisms, the results generally reveal that the bacteria serve a function that is important to other trophic levels and to the successful operation of the ecosystem as a whole.

DISTRIBUTION OF AEROBIC AND ANAEROBIC BACTERIA IN SEDIMENTS

One of the earliest studies to address the question of microbial population structures was an investigation of the distribution of aerobic and anaerobic bacteria in sediments of San Diego Bay (ZoBell and Anderson 1936). Aerobes were more abundant than anaerobes in the top 3 cm of sediment, but the ratio of aerobes to anaerobes decreased from 74 at the surface to 2 at a depth of 66 cm.. The ratio of aerobes to anaerobes in surface sediments near the Channel Islands was lower (10-14) than that in San Diego Bay. Sediments 50 km offshore from San Diego contained surface aerobic bacterial densities ranging from 1.8 to 7.5 x 10^6 cfu g-l and only 1.5-7.5 x 10^3 anaerobes g-l (Rittenberg 1940) (Table 4.3). The sediments were green clays or silts derived from terrigenous sources. ZoBell and Anderson (1936) concluded that the distribution of aerobic and anaerobic bacteria was governed primarily by the type and quantity of organic matter rather than by distance from shore, depth of overlying water, and temperature.

LUMINOUS BACTERIA

Marine luminous bacteria comprise four species in two genera. They exist in a variety of niches and can be found as commensal, parasitic, saprophytic, and free-living forms. Water samples from the entrance of Mission Bay were collected at 3-to-4 week intervals over a 23-month period to evaluate seasonal variations in free-living luminous bacteria (Ruby and Nealson 1978). The total concentration of luminous bacteria varied from 1.5 to 7.5 ml-l with the highest concentrations in late spring and the lowest in winter. *Beneckea harveyi* and *Photobacterium fischeri* together contributed 99% of the strains isolated in the study. *P. phosphoreum* never contributed more than 14% of the total luminous bacteria. *P. leiognathi* was not detected by the culture procedures employed in the study. In the summer, *B. harveyi* contributed 60-70% of the total population, while in the winter it disappeared. *P. fischeri* varied inversely with *B. harveyi*. The abundance of *B. harveyi* was highly correlated with ambient surface water temperature.

Three taxa of luminous bacteria (*P. fischeri*, *P. phosphoreum*, and *Beneckea* spp.) were found to contribute to the enteric microbial populations of 22 species of surface- and midwater-dwelling fish inhabiting waters of La Jolla kelp beds, subtidal areas of Santa Catalina Island, and Santa Barbara Basin (Ruby and Morin 1979). High densities of luminous bacteria (10^5 to 10^7 cfu ml-l of gut contents) were associated with many of the fish. The luminous bacteria enter the fish during ingestion of seawater or particles, traverse the alimentary tract, and survive the digestion process. They proliferate in the fecal material and then are redistributed in the surrounding seawater. The study suggested that the enteric habitat of fish serves these bacteria as a site of enrichment.

BACTERIAL PRODUCTION

Production of microbial biomass is one of several pathways through which energy may flow in waters and sediments of the SCB. Estimates of the flux of energy through the microbial component of pelagic and benthic food webs must take into account that which is utilized for the production of microbial cells. Knowledge of microbial production is of particular significance in instances where microbial biomass serves as an important food resource for other trophic levels.

Zobell (1939) made the earliest bacterial production estimates in the SCB. On the basis of biochemical oxygen demand, sediment bacterial production was suggested to be as high as "several" milligrams carbon per square meter per day in the top 5 cm. Unfortunately, no follow-up studies have been performed to verify or refine the results of this early work. Consequently, understanding of benthic bacterial production in the SCB is very limited.

In recent years, bacterioplankton production has been based on rates of thymidine incorporation into DNA. Thymidine incorporation is determined as the amount of all cold trichloroacetic acid-insoluble material produced from the addition of tritiated thymidine to water samples containing populations of planktonic microorganisms. It was shown that virtually all bacteria which utilized glucose and amino acids (active bacteria) could utilize exogenous thymidine (Fuhrman and Azam 1982). For nearshore waters (S10 pier), 45-55% of the bacteria were active.

The success of the thymidine incorporation approach depends on the validity of several assumptions, some of which have not yet been tested under conditions characteristic of natural waters. Recognizing these limitations, Fuhrman and Azam (1980) converted moles of thymidine incorporated per liter per day to cells per liter per day by multiplying by 0.2×10^{18} and 1.3×10^{18} to provide a range that reflects the uncertainty in the amount of DNA per cell. After more detailed studies, Fuhrman and Azam (1982) determined that the most realistic factors for conversion of moles of thymidine incorporated to cells produced are 1.7×10^{18} for nearshore populations and 2.4×10^{18} for offshore (>10 km) bacterioplankton populations. Results from thymidine uptake studies provide some of the best estimates currently available for bacterioplankton production in waters of the SCB.

NEARSHORE

Studies with water samples collected from the S10 pier demonstrated that the majority (93%) of total thymidine uptake occurred in particles that passed through a l-urn pore-size filter (Fuhrman and Azam 1980). This indicated that thymidine incorporation was primarily a measurement of free-living bacterioplankton production in the sea. Most of the bacterial growth occurred in the absence of particles >3 um. In view of these results it was suggested that most of the bacterial growth occurred at the expense of dissolved organic carbon (DOC) rather than particulate organic carbon (POC).

Natural assemblages of marine bacteria grew as a continuous culture when maintained in nearshore water (S10 pier) that was filtered through a 0.22-um pore-size membrane (Hagstrom et al. 19S4). Bacteria grew at generation times of 6-39 h. These data suggested that at least some bacteria in the sea can grow rapidly at the expense of ambient levels of dissolved organic matter (DOM).

Production rates of bacterioplankton in water collected from the S10 pier at six different sampling times varied from 0.13×10^8 to 8.8×10^8 cells 1^{-1} d-l on one day to 0.46×10^9 to 3.0×10^9 cells 1^{-1} d-l on another day (Fuhrman and Azam 1980). This equated to a microbial biomass production rate of from 0.26 to 14 ug C 1^{-1} d-l when based on an average carbon content of 16 fg cell-l (estimated by epifluorescence photomicroscopy) and 2.1 to 13 ug C 1^{-1} d-l when based on an average carbon content of 4.6 fg cell-l (estimatedby **SEM)**, from the two different sampling periods, respectively (Table 4.4).

On the basis of **thymidine** incorporation rates that yielded a realistic bacterial production rate of between 8.91 x 10^8 to 2.51 x 10^9 cells 1^{-1} d-l, **Fuhrman** and **Azam** (1982) estimated bacteria doubling times of 1-4 days in **nearshore** waters. The ratio of **bacterioplankton** secondary production to total primary production in **nearshore** waters of the SCB were comparable to the ratios obtained for coastal waters of British Columbia and **Antartica** (15-25%).

OFFSHORE

Bacterial abundance and **thymidine** incorporation in the SCB both declined progressively with distance from shore to 100 km (**Fuhrman** et al. 1980). This trend paralleled that for phytoplankton. In offshore waters of the SCB, doubling times were estimated to be as long as a week or more. At one station in **oligotrophic** waters 50 km offshore, doubling times as short as 1 day were obtained, however (**Fuhrman** and **Azam** 1982). The fastest growth rates occur at depths just below the depths of greatest **phytoplankton** abundance (**Fuhrman** and Azam 1982). Bacterial production in offshore waters is approximately 5-25% of primary production.

Thymidine incorporation rates were determined in samples collected at various stations in the SCB during March 1979 (**Fuhrman** et al. 1980). Using the conversion factors presented by Fuhrman and **Azam** (1980) and an average cell volume of 0.046 um^3, **bacterioplankton** production is estimated to be from 0.1 to 0.8 **ug** C 1^{-1} d-l (Table 4.4). Similar values were obtained from samples collected in August 1979.

RELATIONSHIP OF BACTERIOPLANKTON PRODUCTION TO OTHER FACTORS

Bacterial abundance, **thymidine** incorporation, and **thymidine** and glucose

Table 4.4. **Bacterioplankton** production.

Location	male **thymidine** liter^{-1} day^{-1}	cells **produced/** male **thymidine** incorporated	cell volume **(um^{3})**	fg C ur^{n-} 3	fg C cell"	cells liter^{-1} day^{-1}	ug C **liter**$^{-1}$ day-'	Reference
S10 Pier								
18 May 1979	**6.5x10^{-10}** **or** **6.8x10^{-10}**	**2.0x10^{17}** **to** **1.3x10^{18}**			16	0.13x10^{8} to 8.8x10^{8}	0.26 to 14	**Fuhrman** and **Azam** 1980
16 May 1979	2.3x10-g	2.0x10^{17} **to** **1.3x10^{18}**			4.6	**0.46x10^{9}** to **3.0x10^{9}**	2.1 to 13	**Fuhrman** and Azam 1980
16 May 7979	2.3x10^{-9}	1.7x10^{18}			4.6	3.9x10^{9}	18	**Fuhrman** and Azam 1980; **Fuhrman** and Azom 1982
SCB								
March 1979	**10.8x10^{-11}**	1.7x10^{18}	0.046	121		1.8x108	1	**Fuhrman** et al. 1980; **Fuhrman** and Azam 1982
August 1979	10.35x10^{-11}	1.7x10^{18}	0.046	121		1.8x108	1	**Fuhrman** et al. 1980; **Fuhrman** and Azam 1982
Nearshore summer							6 **to** 69	**Fuhrman** and Azam 1980; Azam and **Fuhrman** 1981
2 km south **of** Santa Cruz Island								All dredge et al. 1986
particle- associated bacteria		**1.4x10^{18}**	1.02	120	122	0.48x10^{6} to **6.2x10^{6}**	0.48 to 0.74	
free- living bacteria		1.4x10^{18}	0.18	120	**0.02**	**2.1x10^{7}** to 2.5x10^{8}	0.46 to 5.4	

turnover rates were all significantly correlated (Fuhrman et al. 1980). Thymidine incorporation per cell, which is an indicator of specific growth rate, did not correlat with bacterial abundance. Bacterioplankton growth rate was influenced more by the standing stock of the phytoplankton than by primary production of the phytoplankton. It was suggested that bacterial growth results more from DOM released by phytoplankton that has been disrupted and incompletely digested during predation by zooplankton and nekton than by leakage from healthy phytoplankton.

Fuhrman and Azam (1982) estimated that bacterioplankton consume 10-50% of the total fixed carbon. This relationship apprears to be valid for inshore mesotrophic waters as well as oligotrophic offshore waters of the SCB . The conservative estimates of bacterial secondary production presented above demonstrate that bacterial utilization of organic matter is an important pathway for energy passage through pelagic food webs. Based on thymidine incorporation results obtained in the SCB, Azam and Fuhrman (1984) suggested that this pathway is comparable in magnitude to the energy transfer between phytoplankton and macrozooplankton.

PARTICLE-ASSOCIATEB BACTERIAL PRODUCTION

Thymidine incorporation experiments were performed with water samples containing macroscopic aggregates of particulate matter collected at a station 2 km south of Santa Cruz Island at depths of 7-15 m (Alldredge et al. 1986). Thymidine incorporation by microorganisms on aggregates varied by more than an order of magnitude over a 6-day period. Rates of incorporation into the particles were 3-95 times higher than in surrounding seawater. Despite this high rate, less than 3% of the total thymidine incorporation in surface waters was on aggregates. Thymidine incorporation per bacterium was 1.1 to 30 times lower on aggregates than in surrounding seawater. Carbon production on particles, based on the thymidine incorporation rate, ranged from 7.2 to 744 x 10^{-3} ug C 1^{-1} d-l (Table 4.4). One to 13% of total bacterial production occurred on the particles collected from the waters off Southern California as compared to 3.5-26% in waters of the Atlantic Ocean.

BACTERIA AS FOOD FOR HIGHER ORGANISMS

Microbial food webs have been shown to act both as a sink for organic carbon by serving as the terminal element in the detrital food chain (Ducklow et al. 1986) and as a link in the food web through the conversion of DOC to nutritional particles which serve as food for other trophic levels (Fuhrman and Azam 1980). The functional significance of the microbial component in marine waters therefore rests on the relative importance of these two pathways.

Bacteria are a rich source of proteins, phosphates (nucleic acids and polyphosphates), carbohydrates (polysaccharides), fatty acids (lipids), and growth factors (vitamins or ectocrine compounds). Consequently, bacteria represent an important source of energy to animals in the sea.

ZoBell and Feltham (1937) were among the first to show that marine bacteria were consumed by the mussel Mytilus californianus. Digestive enzymes which lyse bacteria were recovered from the viscera of mussels. Mussels fed a bacterial diet demonstrated a 10-12% weight gain over a 9-month period. The same investigators showed that bacteria were ingested by the sand crab Emerita analoga, a detritus-feeding crustacean. The ingested bacteria were readily digested, but it was difficult to determine whether they provided nutritional value to the crab. Evidence was also presented for bacterial consumption by the sipunculid worm, Dendrostroma zostericola. ZoBell and Feltham concluded that at least some bacteria are assimilated as food, but it seems doubtful that bacteria are sufficiently abundant in seawater to constitute an appreciable component of the diet of these marine animals. It is also doubtful whether **macrofauna** play a significant role in controlling **bacterioplankton** populations on a large scale.

Bacteria appear to play a major role in the diet of **polychaetes** and amphipods living in sediments of the SCB (Laughlin 1982). ***Capitella capitata*** removed large amounts of bacteria from the *sediments ingested. Concentrations of bacteria, measured by the AODC method, were 10,000 times higher in the gut of the worms than in the surface sediments where they fed. Concentrations of bacteria in the gut of the **polychaete** ***Cistena californiensis*** were 2 orders of magnitude higher than their densities in the sediment. As the sediments became more contaminated with sewage effluent, the densities of bacteria in the gut decreased even though the bacterial concentrations in the sediment increased.

Filamentous sulfur oxidizing bacteria which develop around sub-tidal sulfur springs near Whites Point off the Pales Verdes Peninsula are ingested by the black abalone ***Haliotis cracherodii*** (Stein 1984). Foraging vent abalones actively consume the bacteria and restrict their nightly feeding activities to the bacterial mats surrounding the springs. Since microbial biomass produced through sulfur oxidation in morphologically similar bacteria around deep-sea hydrothermal vents is a form of **chemosynthetic** production, that portion of the nutrition of invertebrates foraging around the shallow vents in the SCB that is derived from the sulfur bacteria may reflect a source of energy based on **chemosynthesis** rather than photosynthesis.

Dense populations of **oligochaetes** and the **maldanid polychaete** ***Paraxillella affinis pacifica*** in an area of the Santa Barbara Channel that contain a natural oil seep were thought to be attributable to an abundant supply of food in the form of H_2S-oxidizing Beggiatoa mats and hydrocarbon-degrading bacteria which occurred in the sediments in the vicinity of the seeps (Spies and Davis 1979). A consistently larger but fluctuating density of invertebrates was noted in areas containing seeps than in otherwise similar areas without seeps. However, infaunal benthic invertebrate diversity in seep areas appeared similar to that in areas without seeps (Davis and Spies 1980). Sulfur isotope data were consistent with a pathway beginning with petroleum degradation via sulfate-reducing bacteria with the production of H_2S. The sulfide is subsequently oxidized to S^0 via chemosynthetic Beggiatoa. The Beggiatoa biomass produced is then consumed by nematodes and other infauna (Spies and DesMarais 1983). Approximately 14% more carbon is available through this chemosynthetic pathway, one that appears to be energized initially by hydrocarbon degradation.

Two species of clams Lucinoma annalata and Calyptogena elongata, which inhabit sulfide-rich sediments in the Santa Barbara Basin, harbor symbiotic sulfur-oxidizing bacteria in their gills (Vetter 1985). The bacteria appear to provide the mollusc with chemosynthetically-fixed carbon via aerobic oxidation of sulfide in return for a stable environment in the gills.

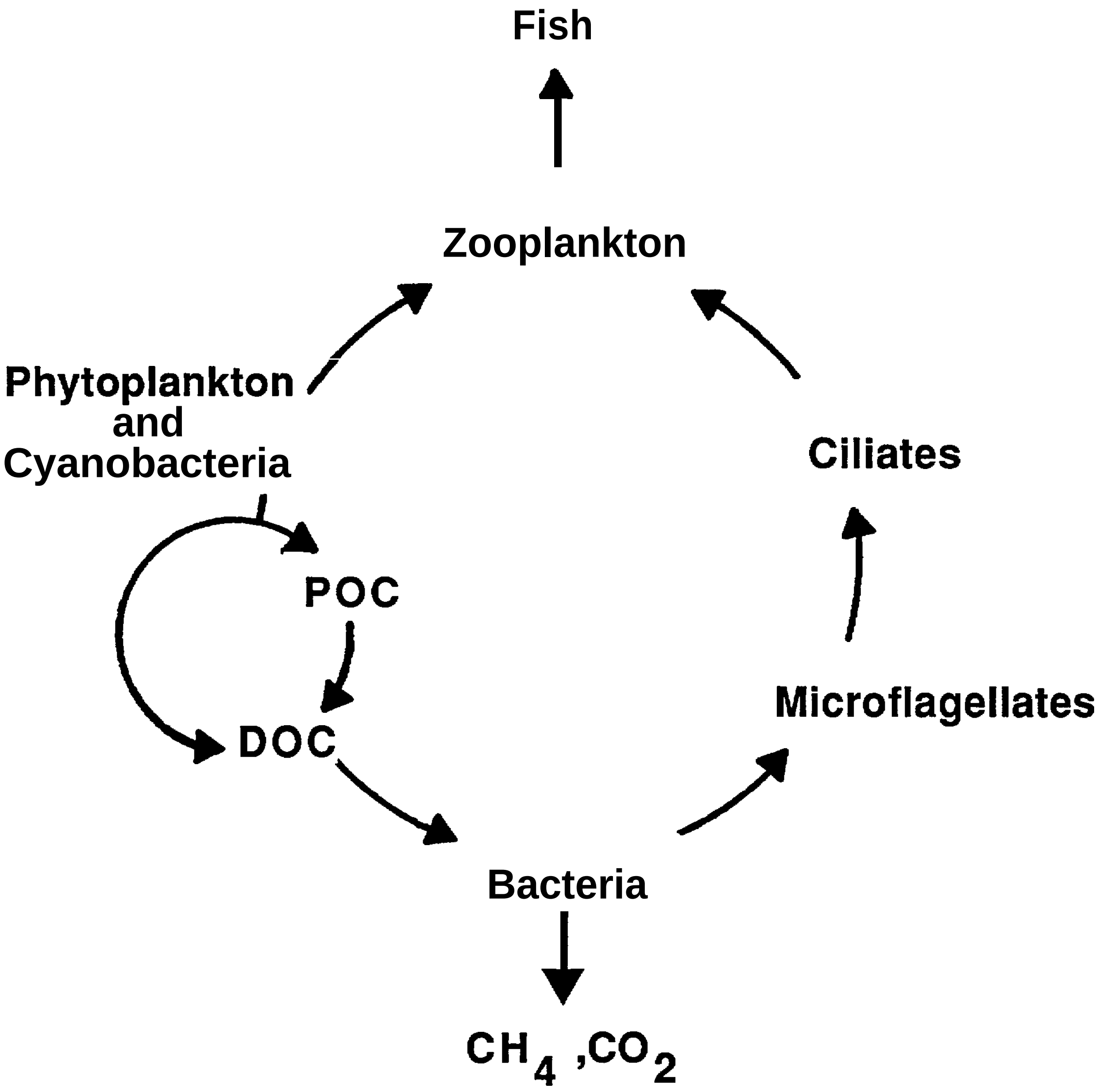
The above examples suggest that a portion of the sessile bacterial production in sulfide-rich bottom deposits of the SCB is due to chemosynthetic primary production rather than photosynthetic primary production and secondary production. Bacterial production in nearly all other marine waters considered to date, with the exception of regions of the deep sea that contain hydrothermal vents, is based solely on secondary production and photosynthetic primary production (cyanobacteria) estimates. Unfortunately, no estimates of the extent of bacterial chemosynthetic production in the SCB have been made, but recent evidence suggests that it may be wide-spread in bottom deposits of the Santa Barbara Basin (R. Francis pers. comm.). It is also not known to what extent the grazing activities of benthic organisms control production of the sessile bacterial populations in these habitats.

Thymidine incorporation studies suggest that secondary production of bacterioplankton is utilized by microflagellates (Fuhrman and Azam 1980). A "microbial loop" which returns energy released as DOM and POC from phytoplankton to the main food chain has been proposed (Figure 4.1).

Bactivory (ingestion of bacteria) by phagocytic protozoa (microflagellates) appears to have a significant impact on standing stocks and metabolic activities of bacterioplankton in many marine habitats. Heterotrophic microflagellates are now recognized as the main grazers of bacterioplankton (Fenchel 1986). Microflagellates in the size range from 3-10 um are capable of filtering 10-70% of the water column per day (Fenchel 1986). Bacterial densities which support flagellate feeding activity range from 0.5 to 2×10^{9} cells 1-1. It has been estimated that the ratio of microflagellates to bacteria is approximately 1:1000. Oscillations have been observed in the densities of the two populations, however. There is often a 3-to-4 day lag between the peaks that occur in the densities of the bacterioplankton and microflagellates (Fenchel 1986). This indicates that grazing is important in eutrophic waters such as in harbors and estuaries. Whether microflagellate grazing of bacterioplankton is significant in coastal and offshore waters of the SCB where bacterial densities are on the order of 1×10^{6} cells 1^{-1} remains to be determined.

Bactivory by microzooplankton and nanoplankton may regulate standing stocks , species composition, and metabolic activity of bacterioplankton.

Figure 4.1. Microbial loop **showing** the utilization of bacteria as a food source for **microflagellates.** Bacterial biomass is derived from dissolved organic carbon **(DOC)** and particulate organic carbon **(POC)** from primary producers.


Fish
Zooplankton
Phytoplankton and Cyanobacteria
Ciliates
POC
DOC
Microflagellates
Bacteria
CH_4, CO_2

Taylor et al. (1985) determined the importance of bacterioplankton as food for microzooplankton in water samples collected from Mugu Lagoon, Los Angeles Harbor, and San Pedro Channel. Rates of bacteria consumption were 7.05, 0.14, and 0.003 x 10^7 bacteria 1^{-1} h-l, respectively. The microzooplankton population in the harbor was dominated by the ciliates Strombidium sp., Euplotes sp., and Uronema sp. Strombidium sp. and tintinnids were observed in channel samples.

Bactivory by microzooplankton enhanced release of DOM by 487±354, 2±0, and 1±0 ng C l^{-1} h-l in lagoon, harbor, and channel samples, respectively (Taylor et al. 1985). The presence of bactivores appeared to alter the DOM pool quantitatively and qualitatively. Grazing activities contributed organic compounds of molecular weights less than 500 da and between 1,000-10,000 da. It was suggested that bactivore grazing stimulates production of biologically available DOM which, in turn, enhances heterotrophic activities and bacterial production. Bacterial ingestion by bactivorous plankton may be at steady state with bacterial production (Soule and Oguri 1979). A significant amount of the ingested bacterial biomass is used in energy metabolism.

Grazing on bacteria by bactivorous microzooplankton was suggested as the major pathway for the loss of adenylates from bacterioplankton (Taylor and Sullivan 1979). The turnover time of the bacterioplankton population by bactivory was estimated to be 12-29 h in the Los Angeles Harbor. Grazing of bacterioplankton was also suggested to be a mechanism of phosphate transfer to other consumers within the food web. These data suggest that secondary production of microbial biomass in harbors and nearshore waters of the SCB is an important source of energy for higher trophic levels.

DECOMPOSITION OF ORGANIC MATTER

One of the most important functions of bacteria in the sea is to recycle nutrients that are retained in dead plant and animal biomass. Essential elements such as carbon, nitrogen, sulfur, and phosphorus that are complexed in organic molecules are metabolized by heterotrophic microorganisms to the inorganic compounds required by phytoplankton and macroalgae for primary production. Marine microorganisms contribute to the carbon cycle by converting organic matter that exists in particulate and water-insoluble forms to dissolved compounds of a suitable size range that can be transported into the cell, where biochemical pathways convert the organic compounds into inorganic forms (Figure 4.1).

In offshore waters, high and low molecular weight organic compounds are derived from particulate matter, primarily in the form of phytoplankton. The compounds may be released directly from algal cells as DOC as a result of leakage and cell disruption or indirectly through the hydrolytic activities of microorganisms attached to the senescent algal cells. The organic matter in nearshore waters of the SCB is derived not only from phytoplankton but terrestrial sources as well.

Most of the studies on the degradative activities of microorganisms in the SCB have been concerned with the dissolved, labile, low molecular weight products derived from phytoplankton. Little information exists on the degradative activities of microorganisms in the SCB with respect to the other forms of organic carbon that are present. Sewage is a major contributor of particulate and dissolved organic carbon derived from land-based activities for which degradation rates in the SCB are largely unknown. Hydrocarbons in the form of crude oil and refinery products represent another significant source of organic carbon in the SCB. Hydrocarbons are sparingly soluble in seawater. Consequently, microorganisms must first dissolve the hydrocarbon compounds before they can be degraded. Oil from natural seeps in the Santa Barbara Basin as well as shipping and land-based industrial activities are the main sources of this form of organic carbon. Our understanding of pathways and rates of microbial degradation of hydrocarbons in marine environments, however, come from studies outside the SCB . Some of the organic matter introduced to the SCB from terrestrial sources, such as plastics and pesticides, are exceedingly resistant to microbial degradation and have a high likelihood of accumulating in the sediments or food chain. At present there are no good estimates of microbial degradation of these compounds in the **SCB.**

Characterization of the mechanisms by which different forms of organic matter are degraded by microorganisms in the sea is also an area that deserves greater attention than that given in the past. Most of what we know is based on the use of sugars. and amino acids by **enteric** bacteria from humans. More effort needs to be directed toward understanding the mechanisms by which POC, hydrocarbons, and pesticides are degraded by marine microbial populations.

HYDROCARBONS

The SCB contains as many as 60 zones of natural oil seepage. Seepage rate estimates range from <16 to >160 m^{-3} d-l (Reed et al. 1977). In addition, **anthropogenic** input of hydrocarbons to the SCB is estimated to be at least as important as that which is introduced through natural seeps.

ZoBell et al. (1943) first demonstrated hydrocarbon-utilizing bacteria in seawater collected in the La Jolla region. All 60 ml samples that were examined contained microorganisms that utilized kerosene, paraffin oil, crude oil, and petroleum ether. Hydrocarbon-utilizing bacteria were most abundant at the mud-water interface, where from 10^2 to 10^5 g-l wet wt sediment were detected by cultural methods. Their density decreased exponentially with depth in the sediment. However, one sample collected from an area near the Channel Islands contained hydrocarbon-utilizing bacteria at the bottom of a 5 m core.

Oil-oxidizing bacteria are most abundant in coastal waters and mud that are chronically exposed to oil. Five to 50% of the culturable bacteria are able to make use of one or more hydrocarbons in such areas (ZoBell 1969). Along the coast of Southern California, oil-oxidizing bacteria range in concentrations from <1 cfu per 10 ml to $>10^8$ cfu ml^{-1} mud (ZoBell 1969). The highest densities occurred in Los Angeles and Long Beach Harbors. Samples of beach sand and coastal seawater rarely contained $>10^4$ oil-oxidizing bacteria ml^{-1}. The populations of oil-oxidizing bacteria fluctuated dramatically from month to month at a single station. Densities varied by 4 to 5 orders of magnitude.

Hydrocarbon oxidation in marine systems requires the presence of free O_2 (ZoBell et al. 1943). Hydrocarbon oxidation was inhibited where oxygen concentrations were reduced to a level that permitted sulfide production by sulfate-reducing bacteria.

Surfaces in the form of combusted sediments promoted hydrocarbon oxidation by marine bacteria (ZoBell et al. 1943). It was proposed that the sediment aided in dispersion of the hydrocarbons, which increased the surface area of the hydrocarbons and their accessibility to bacteria. Under well-oxygenated conditions, hydrocarbons may be oxidized at rates ranging from 0.02 to 2 g m^{-2} sediment d^{-1} at 20-30°C (ZoBell 1969). The end products of hydrocarbon (paraffin oils) oxidation are CO_2 and water, although intermediate products may also accumulate.

CHITIN

One of the most abundant forms of polymeric organic matter in the sea is chitin, which is produced by many marine species and incorporated into their skeletal structure. It is estimated that several billion tons of chitin are produced annually (ZoBell and Rittenberg 1938). If chitin were not decomposed by microorganisms, there would be a serious loss of usable carbon and nitrogen in the sea. Because of chitin's water-insoluble nature, microorganisms must rely on exoenzymes to break down the molecules into usable subunits.

Samples of (5-6 g portions) bottom sediments from beaches and shallow water along the Southern California coast and in deep water nearly 320 km off the coast all demonstrated the presence of chitin-degrading bacteria (ZoBell and Rittenberg 1938). The distribution of chitinoclastic bacteria in sediments varied greatly within any given area. Chitinoclastic bacteria were most abundant in the topmost layers of the mud, where as many as 1000 g^{-1} were recovered. Between 0.1 and 1.0% of the bacteria recovered from seawater by cultural methods are chitinoclastic to some degree. From 100 to >1000 chitinoclastic bacteria were found per milliliter of stomach contents of squid and other cephalopods which digest chitinous food. This suggests that chitin-digesting bacteria may exist as endosymbionts which aid in the digestion of chitin in these organisms.

Many chitinoclastic bacteria derive their complete carbon, or energy, and nitrogen requirements from chitin (ZoBell and Rittenberg 1938). They also liberate ammonia and acetic acid from chitin. Reducing sugars have been detected as products of chitin digestion in some cultures of isolated bacteria. Although there is ample evidence to suggest that chitin degradation via microorganisms occurs in the SCB, no rates are available at this time.

PROTEIN

Protein is one of the most labile polymeric forms of organic carbon in the sea. Protease enzymes are produced by microorganisms which hydrolyze proteins into free amino acids. Hollibaugh and Azam (1983) determined protein degradation rates by natural populations of bacteria in the SCB. Protein as hemoglobin was degraded at a constant rate of 4% h-l by natural microbial populations in water samples collected near Santa Catalina Island. The protein was respired as CO_2 at a conservative rate of 0.2% h-l. The rate of degradation increased with increased protein concentration. A biphasic Wolff plot of the reaction suggested that more than one degradative enzyme was active over the added protein concentration range of 1 to 1000 ug 1-1. The fraction of degraded protein that was respired ranged from 8 to 10%.

The rate of protein, as bovine serum albumin, degradation by nearshore microbial populations at the S10 pier increased from 0.06% to a maximum of 0.8% h-l as the temperature of incubation increased from zero degrees to 25°C (Hollibaugh and Azam 1983). Essentially all of the protein degradation activity was associated with particles >0.2 um in size. In nearshore waters, approximately 40% of the degradative activity was associated with particles equal to or less than 1.0 um in size (primarily bacteria and small algae), whereas in offshore waters near Santa Barbara, approximately 80% of the activity was associated with particles in this size range.

Accumulation of protein degradation products in the microbial population was not greatly inhibited by exogenously supplied free amino acids (Hollibaugh and Azam 1983). It was concluded that the amino acids from proteins are utilized preferentially over free amino acids present in surrounding seawater. The advantage of this strategy to the microorganisms remains to be determined, since one would predict that it is energetically more expensive for the microbes to hydrolyze the protein to gain access to the amino acids than to make use of amino acids that already exist in a free state. It was also concluded that dissolved enzymes are not important in protein degradation in natural seawater. Statistical analysis of data collected from water taken nearshore showed that hemoglobin turnover rates correlated significantly with bacterial abundance and biomass, L-leucine turnover rates, chlorophyll concentration, and primary productivity.

PHYTOPLANKTON EXUDATES

Iturriaga (1981) determined that 18-19% of the carbon assimilated by phytoplankton in coastal waters of Southern California is released into the surrounding seawater. It was estimated that this exudate is turned over at a rate of 2% h-l. More than 49?6 of the exudate was composed of compounds with a molecular weight less than 1000. The low molecular weight fraction was taken up and respired faster than larger-size fractions of phytoplankton extracellular products.

AMINO ACIDS

Degradation of amino acids leads to the liberation of CO_2 and ammonia, which are required for phytoplankton growth. Amino acids are also metabolized into proteins and other cellular components that contribute to microbial biomass.

Sullivan et al. (1978) determined dissolved free amino acid (DFAA) usage by microbial populations in Los Angeles Harbor. A mixture of ^{14}C-amino acids was rapidly taken up by the microbial community in bottom waters of the harbor near a cannery effluent outfall. As much as 33% of the carbon taken up in the form of amino acids was respired as CO_2. Uptake of the amino acid mixture occurred at a greater rate in bottom-water microbial populations than in surface water populations even though total microbial biomass and bacterial densities were two to threefold higher in surface waters. Most (72-94%) of the amino acid uptake was mediated by microorganisms in the size range of 0.2-1.0 um. The size fraction vs. amino acid uptake rate was similar to that reported by Azam and Hodson (1977a).

Turnover times of amino acids by microorganisms in harbor water (<25 h) were among the highest reported in marine systems (Sullivan et al. 1978). These results suggest that the heterotrophic microbial population is adapted to degrade the protein-rich cannery wastes discharged into the harbor at this location. Outside the harbor in the San Pedro Channel, turnover times ranged from 15 to 100 h. Turnover times of amino acids by the size fraction 0.2-1.0 um were found to be as much as 75 times faster than the size fraction 5-203 um.

Williams et al. (1976) determined amino acid concentrations and heterotrophic turnover of amino acids at a station 6 miles off the California coast. The turnover rate ranged from undetectable to 1.2 ug 1^{-1} d-l , with serine, aspartate, alanine, and glutamate having the highest rates. The highest turnover rates were obtained from samples collected at a depth of 25 m. Rates at this depth were 15-20 times higher than at a depth of 100 m. It was estimated that the flux of the amino acids studied amounted to a rate that was 1-10% of the photosynthetic carbon dioxide fixation rate.

Size fractionation studies demonstrated that the majority of leucine uptake in surface waters collected from a variety of stations in the SCB is mediated by particles <1 um in size, a fraction which is considered to consist of free-living bacteria (Fuhrman and Azam 1983). Only 4.9$ of the total uptake was contributed by >1 um size particles.

Bacterial activities in subsurface waters of the SCB appear to be dominated by locally adapted, free-living microbial populations. Bacteria attached to sinking particles with temperature optima characteristic of surface populations contributed only a small part of the leucine uptake at depths of 100-200 m (Fuhrman and Azam 1983). In subsurface waters, the >1 um size fraction averaged 4.1% of the total leucine uptake. It is possible, therefore, that decomposition of dissolved organic matter in subsurface waters of the SCB does not depend on bacteria descending from the surface.

Carlucci et al. (1984) determined the uptake of dissolved free amino acids (DFAA) by natural microbial populations in the waters 6 km off the coast of Newport Beach. Their diel studies revealed that maximum rates of DFAA uptake occurred between midmorning to midafternoon and minimum uptake rates occurred during late evening. The turnover time for DFAA pools ranged from 6 to 48 h. Turnover times for the DFAA pools were longest at night and shortest in the early morning. Seasonal differences were observed in the daytime and nighttime turnover times.

Glutamic acid utilization was threefold faster in May than in October (Carlucci et al. 1984). The DFAA utilized by the microbial population was believed to have been derived from the DOC exudate from phytoplankton. The study suggested that there is a coupling between primary production and amino acid flux through the microbial population. Microbial utilization, or production of total protein amino acids, was estimated to be 3.6 ug C l-id-i in spring and about one-half that rate in fall. Assimilation efficiency for DFAA averaged 65% for marine microbial populations.

Rates of heterotrophic utilization of amino acids were determined in seawater surface films (neuston layer) off the east coast of San Clemente Island and the southwest tip of Santa Catalina Island during November 1982 (Carlucci et al. 1985). Glutamic acid utilization rates at all stations ranged from 0.03 to 0.13 **nmol** 1^{-1}h-l. With one exception, there was no evidence of **higher** utilization rates of this amino acid in surface films than in water at a depth of 10 cm. The percentage of glutamate taken up that was respired to **CO_2** varied from 8 to 41$. Respiration rates in the surface film were highest at night. Turnover times for **glutamic** acid varied from 91 to 174 h in the **neuston** layer; these rates were generally equal to or longer than values obtained at the 10 cm depth. Surface-film **microheterotrophs** had an average of **63%** amino acid carbon assimilation efficiency, which was similar to **euphotic-zone** heterotrophic populations.

Amino acid utilization by **microheterotrophs** was studied **in** waters of Santa Monica and San Pedro basins (**Carlucci** et al. 1986): The effect of different concentrations of **glutamic** acid on its use by **microheterotrophs** in **euphotic** (50 m) water with high concentrations of total free amino acids **(TFAA)** and in deep (500 m) water containing low TFAA concentrations was determined. The populations in the upper water layer did not respond to increases in amino acid concentrations over the range of 0.15-15 mM. Populations in the deeper water layer did respond to enrichments of the amino acid at concentrations between 7 and 15 nM. It was determined that **DFAA** additions must be kept below 2 **nM** to simulate "natural" amino acid uptake rates.

DFAA utilization rates decreased from **1 nmol** 1^{-1}h-l at the surface to 0.001 **nmol** 1^{-1}h-l at a depth of 800 m (**Carlucci** et al. 1986). The absorption rate per cell was nearly an order of magnitude higher in **euphotic-zone** water than in deep water. Bacterial cells in **midwaters** absorbed the lower levels of DOC more efficiently than the **euphotic** zone bacterial cells. Both shallow and deep water populations consumed **glutamic** acid at a slower rate in 1982 and 1983 than in 1981. During an El Nino event which occurred in 1983 and was characterized by warm water and low productivity, substantial differences in glutamate consumption were noted between the different basins. DFAA uptake was similar in San Pedro Basin and sill waters. The fraction of the amino acids taken up that was respired as CO_2 ranged from 10 to 38$ in shallow (0-30 m) water (Carlucci et al. 1986).

Turnover times for amino acids was shortest in subsurface euphotic zone waters, while the longest turnover times were recorded at midwater depths (Carlucci et al. 1986). These turnover times were within the range of turnover times for euphotic zone DFAA pools determined by other researchers. TFAA utilization represented approximately 2-11% of primary production in the study areas. The higher values were measured during periods of relatively low primary productivity.

GLUCOSE

Complete degradation of glucose results in the formation of CO_2. Like amino acids, sugars such as glucose are also metabolized to other compounds which contribute to microbial biomass. Glucose is one of the most common sugars in coastal seawater, since it is the structural subunit of plant cellulose.

Glucose consumption by the microbial population in surface waters of Los Angeles Harbor was studied by Sullivan et al. (1978). The glucose uptake rate near a cannery waste outfall was estimated to be 42 ug glucose l^{-1} d^{-1}. Approximately 25$ of the glucose taken up by the microorganisms was oxidized to CO_2. The bulk of the glucose taken up (88%) occurred in a size fraction (<1.0 and >0.2 um) that contained mainly bacteria.

Nearshore and Offshore Waters

Azam and Helm-Hansen (1973) indicated that usable organic compounds in the sea are generally in the order of 10^{-9} to 10^{-8} M. To evaluate heterotrophic activity in marine waters off Southern California, they used ^{3}H-labeled glucose added at concentrations which did not significantly alter the ambient substrate concentration. At one station in offshore waters, most of the heterotrophic activity (86%) at a depth of 10 m appeared to be due to cells that passed through a 3-urn pore-size membrane. At 50 m, the portion of the total heterotrophic activity associated with <3 um particles decreased to approximately 66%. The total heterotrophic activity at this depth was approximately twice that at 10 m. Approximately one-third of the heterotrophic activity was associated with particles greater than 3 um in size.

Another study on the distribution of ^{3}H-glucose assimilation by various plankton size fractions was performed by Azam and Hodson (1977a). Depth profiles in the SCB 100 km offshore showed very little variation in the particle size fraction responsible for ^{3}H-glucose assimilation from the surface to 45 m (1% surface irradiance depth) at one station and from the surface to 150 m depth at another station. The <l-urn size fraction contained most of the glucose assimilation activity. Ten to 15% of the particulate chlorophyll passed through the l-urn filter in nearshore samples collected from the S10 pier, while 20-40% passed through the filters in samples taken offshore in the SCB. Microflagellates were suggested as the possible source of the particulate chlorophyll in the l-urn filtrates of the nearshore samples. The majority (70%) of the assimilation was due to particles in the size range of 0.4-0.6 um. No significant amount of chlorophyll was detected in this size fraction. ATP determinations suggested that this size fraction contained 33 ug of living bacterial biomass, which is equivalent to about 1 x 10^8 cells 1^{-1}, based on an ATP:C ratio of 250

obtained from laboratory cultures. It was concluded that roughly 90% of the microbial heterotrophic activity is due to free-living organisms, presumably bacteria.

Bacteria associated with particles exhibited D-glucose utilization rates that were 1 order of magnitude less than that of the free-living bacteria (Azam and Hodson 1977a). Variations in D-glucose concentration from 5×10^{-9} to 1×10^{-3} M did not appreciably change the fraction of heterotrophic activity ascribed to free bacteria. The results support the contention that bacteria are responsible for most of the microbial heterotrophic activity in the SCB, even though this size fraction comprises only 5-15% of the total biomass. The smallest bacteria are most active in utilization of D-glucose.

According to Fuhrman (1981), the uptake of radio-labeled organic compounds more closely follows bacterial numbers than bacterial volume. The various sizes of bacteria have roughly the same activity on a per-cell basis. Their evidence suggests that the smaller marine bacterioplankton are as active as larger bacteria.

Glucose uptake kinetics of natural marine microbial populations in the waters of the SCB were studied by Azam and Hodson (1981). Wright-Hobbie plots of t/f vs. A, where t/f is the reciprocal of the tracer uptake rate and A is the amount of tracer added to the sample, were non-linear for a large number of seawater samples. This was interpreted as the existence of multiple transport systems with different transport constants (K_t) within the population. This is reasonable considering the variety of microbial species likely to be present. As the ambient glucose concentration increased, systems with lower affinity for glucose were employed in place of high-affinity systems. Multiphasic kinetics were observed for size fractions greater than 0.6 um and less than 0.6 um. Only 5-9% of the total glucose uptake was contributed by organisms in the larger-size fraction. The size fraction containing small, free-living bacteria accounts for the vast majority of the glucose uptake at glucose concentrations ranging from 2 x 10^{-9} to 6 X 10^{-4} M. **Multiphasic** kinetics were.observed in nearshore waters as well as in waters 10 km offshore (**Azam** and Hodson 1981). Although actual transport constants were not determined because of difficulties in determining the natural substrate concentration, **linear** glucose uptake kinetics over the glucose concentration range of 9.8 x 10^{-11} to 1 x 10^{-8} M suggested that **subnanomolar** K_t glucose uptake systems were not present and that glucose uptake was unlikely in the **picomolar** range.

The maximum rate of glucose uptake increased as the exogenous glucose concentration was increased (**Azam** and Hodson 19S1). Even with the greater capacity to take up this compound, turnover times increased from 9.5 h after enrichments of 2.5 x 10^{-9} M glucose to over 6000 h after enrichments of 10^{-3} M glucose. Respiration of glucose was low when exogenous concentrations of this substrate were in the **nanomolar** range (17-18% of the total glucose taken up) and increased at higher exogenous glucose concentrations until a maximum (25-28$) was obtained at 5 x 10^{-8} M glucose concentrations.

These results demonstrate that the ambient glucose concentration has a significant impact on the regeneration of glucose carbon in waters off Southern California. The glucose turnover rate, which is the percentage of glucose in the water sample that is assimilated each hour, was found to average 1.23 h^{-1} over 11 stations which included nearshore and offshore sites (**Fuhrman** et al. 1980).

SEDIMENT MICROBIAL ACTIVITIES

Sediment particles offer an abundance of surface areas for sessile microbial colonization and growth. These surfaces provide the opportunity for the development of structured microbial communities. Immobilized sediment bacteria have a greater chance to interact and cooperate in the metabolism of various compounds than do free-living pelagic microbial populations. Consequently, microbial consortia can bring about biochemical transformations that are not normally favored in the water column.

Although sediment particles provide a large surface area for microbially catalyzed reactions, their spacing impedes the diffusion of substances to and from the surface. Diffusion processes, therefore, often limit microbial activities and growth in the sediment environment. Oxygen depletion and hydrogen accumulation commonly occur during microbial decomposition of reduced organic matter in sediments, frequently leading to the establishment of highly reduced anaerobic conditions.

Oxygen

During degradation of organic matter in sediments, oxygen is consumed by aerobic microorganisms. Oxygen consumption studies in sediments on the continental slope off Newport Beach yielded an average of 5.32 ml $O_2 m^{-3}$ h-l from 18 different measurements (Thompson et al. 1984b). A high coefficient of variation (61%) was obtained, which suggested heterogeneity due to differences in the organic carbon content, microbial densities, and infauna distribution. Values of 2.31 ml $O_2 m^{-3}$ h-l were reported from the floor of the San Diego Trough (Smith 1974).

Hydrogen

Microbially mediated H_2 evolution was demonstrated during organic enrichment of mud from various estuaries, bays, and coastal and offshore sites in marine waters off Southern California (ZoBell 1947). The gas evolved was a mixture of H_2 (1.5-3.5%), CO_2 (6-36%), and CH_4 (60-90%). Un-enriched mud containing 3.8% organic matter also contained active H_2-evolving bacteria. Up to 10^4 H_2-producing bacteria were detected per gram of sediment based on the minimum dilution method. H_2 producers decreased in abundance with depth in the sediment.

Hydrogen lyase is the microbial enzyme most commonly responsible for the liberation of H_2 from organic matter (ZoBell 1947). Hydrogen production in sediments is most easily demonstrated by inhibiting hydrogen-oxidizing bacteria. These reactions are closely coupled in marine sediments. In one experiment, Mission Bay mud microorganisms consumed from 20-65 ml of hydrogen per 20 g mud at 27°C over a period of 6 weeks. A variety of organic compounds were shown to promote hydrogen utilization in muds suspended in seawater medium. Muds obtained from various estuaries were shown to produce H_2S at the expense of H_2. Part of the H_2 appeared to be used for reduction reactions besides sulfate reduction.

Methane Production

Methane.formation is considered to be the final step in anaerobic bacterial degradation of organic carbon. Most methanogenic bacteria grow optimally in pure cultures at an Eh less than -330 mV and within a pH range of 6 to 8. Claypool and Kaplan (1974) have proposed that bicarbonate is the primary precursor of methane in marine sediments. In sediments of the Santa Barbara Basin, methanogenesis is thought to be most prevalent at depths below the sulfate-reducing zone (150-200 cm depth) (Kaplan et al. 1963).

Warford et al. (1979) found that methane concentrations increase with depth from approximately 1 mM at 150 cm to 10 mM at 250 cm in Santa Barbara Basin sediments. Methane was produced from substrates that occurred naturally in the sediments. Production rates determined at different depth intervals demonstrated a submaximum at the surface (0-25 cm) of 0.442 nmol

g^{-1} d^{-1}, a minimum of 0.016 nmol g-l d-l at a depth of 110-120 cm, and a maximum of 0.767 nmol g^{-1} d-l at a depth of 300 cm. In the sulfate-reducing zone, the rate of methane production decreased with depth. The absence of methane production in the presence of carbon tetrachloride indicated that the methane formed was the result of microbial action rather than sediment outgassing. Rates of methane production did not appear to be limited by hydrogen. The Warford study proposed that the relatively low levels of methane in the sulfate-reducing zone were caused by rapid methane consumption rather than the absence of methanogenesis.

Radioisotope studies suggested that 70-85% of the methane produced in the sediments was derived from bicarbonate with only 2-11% derived from acetate (Warford et al. 1979). It was further demonstrated that some of the $C0_2$ evolved by sulfate-reducing bacteria during lactate oxidation was subsequently metabolized to methane by methogens. Addition of sulfate appeared to stimulate the conversion of lactate to methane. These results suggest that some form of syntrophic relationship exists between the sulfate-reducing bacteria and the methanogens and that the sulfate-reducing bacteria are capable of providing substrates for methane-producing bacteria. Although it has been suggested that the activities of sulfate-reducing bacteria and methanogens are mutually exclusive, since they both compete for the same reductants and substrates, the results of Warford et al. (1979) suggest that substrate availability, not competition for substrates, controls methane production in the sulfate-reducing zone.

Methane recycling in sediments receiving sewage discharged from the Avalon outfall off Santa Catalina Island was determined by Warford and Kosiur (1979). The rate of methane production was 30.3 nmol g-l d-l during a period when raw sewage (1100 m^3 d-l) was discharged. The density of methanogens estimated by culture method was 1 x 10^5 cfu ml^{-1} sediment. The rate of methanogenesis decreased by a factor of 30 and the density of methanogens in the sediment decreased by a factor of 20 after the sewage was treated with extended aeration and secondary clarification before discharge. Sulfate was reduced to sulfide during methane production, suggesting that the two reactions are not mutually exclusive. On the basis of this study, it was estimated that prior to wastewater treatment, only 0.13% of the sedimentary organic carbon was recycled annually. Following sewage treatment, less than **0.001%** was recycled by methanogenesis.

Methane oxidation

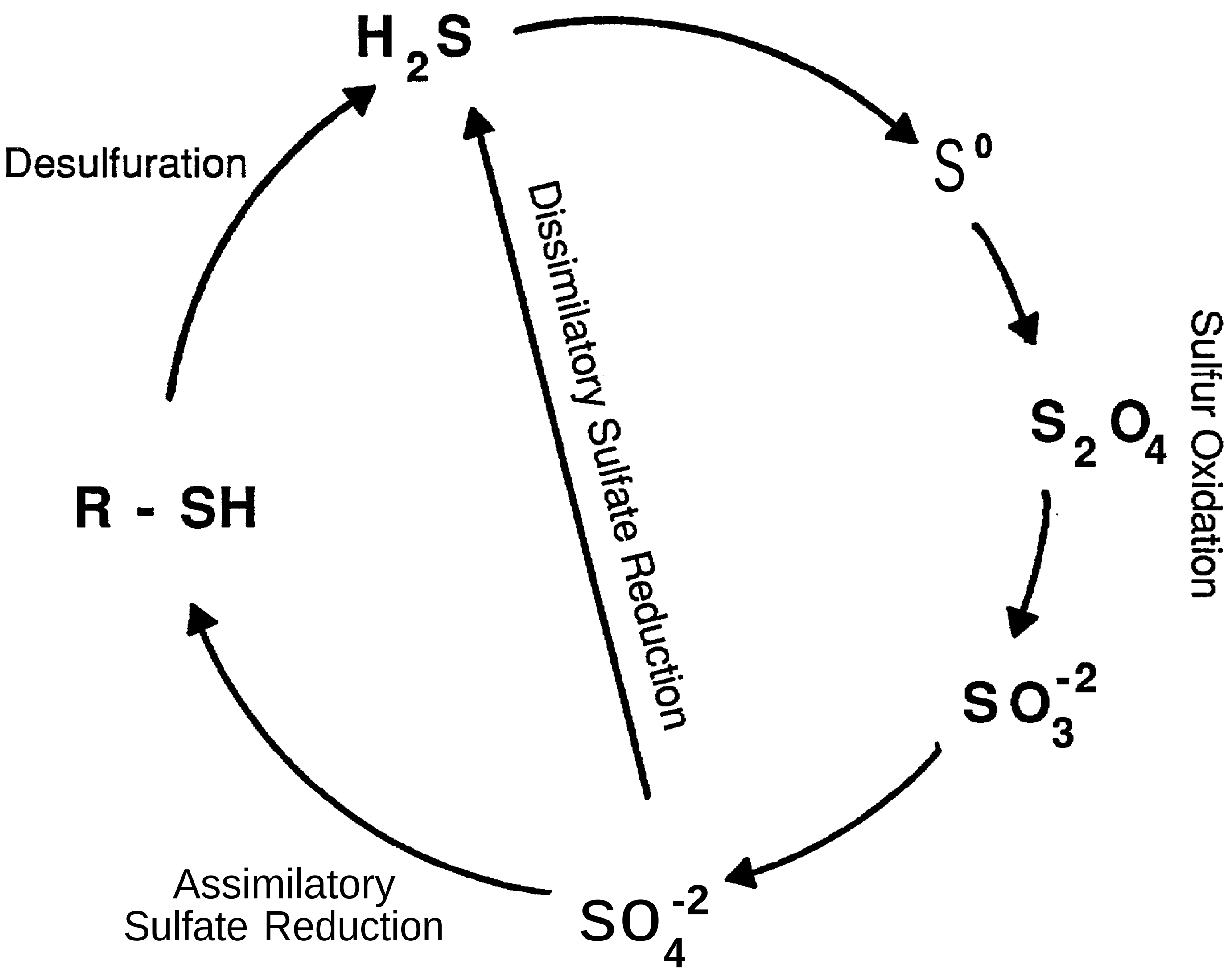
Kosiur and Warford (1979) proposed that methane oxidation occurred at the same sediment depths in the Santa Barbara Basin as methane production. The highest oxidation rate (357.6 **umol** 1^{-1} Y-l) was observed near the sediment surface (30-35 cm) and decreased with depth, yielding values of approximately 8 **umol** 1^{-1} y-l at depths below 130 cm.

Methane oxidation occurred in zones containing high- and low-sulfate pore water concentrations **(Kosiur** and Warford 1979). It was estimated that the energy yield from methane oxidation was not sufficient to support bacterial growth. It was proposed that other substrates are put to use as energy sources during methane oxidation, using sulfate as the oxidant.

SULFUR CYCLING

Marine microorganisms are **important** in the cycling of sulfur. Although sulfur is rarely considered a limiting element in the marine environment because of the abundance of magnesium sulfate in seawater, microbes are needed to oxidize reduced organic forms of the element--as it exists in living and dead material--to the sulfate form required by primary producers and many microorganisms (Figure 4.2). Sulfur-oxidizing bacteria also

Figure 4.2. Involvement of marine bacteria in the cycling of sulfur. Microorganisms catalyze the reactions in each of the steps shown above. H_2S, hydrogen sulfide; SO, elemental sulfur; S_20_4, **hyposulfite;** $S0_3$, sulfite; $S0_4$, sulfate; R-SH, organic sulfide.


H2S
S0
S2O4
SO3-2
SO4-2
R - SH
Desulfuration
Dissimilatory Sulfate Reduction
Sulfur Oxidation
Assimilatory Sulfate Reduction

catalyze the oxidation of mineral sulfides which are common in reduced marine sediments. Sulfate-reducing bacteria impact the sulfur cycle, since they convert biologically available sulfate-S to non-metabolizable, toxic H_2S.

SULFATE REDUCTION

In recent marine sediments rich in organic matter, the major process affecting sulfur geochemistry is bacterial reduction of sulfate to sulfide. Kaplan et al. (1963) presented evidence that bacterial reduction of sulfate is the single most important process in the sulfur cycle. Evaluation of cores from the Santa Barbara Basin, Santa Monica Basin, Santa Catalina Basin, San Diego Trough, and a Newport Bay marsh showed that sulfate concentration decreased markedly with depth in the sediments and was significantly less than that in seawater. This finding indicated that sulfate was reduced in the sediments. Sulfate reduction occurred mainly in the upper 1-1.5 m of sediment. The rate of sulfate reduction in sediments of the Santa Barbara Basin was calculated to be 7×10^{-6} mg S^{2-} cm^{-3} h-l.

ZoBell (1938) found from 10^3 to 10^4 sulfate reducing bacteria (SRB) g-l sediment in reducing areas. However, Kaplan et al. (1963) estimated densities of 3.5×10^7 SRB cm^{-3} using sulfur isotope values and rates of sulfide production in the laboratory which yielded isotope values found in sulfides in surface sediments. Sulfate reduction was suggested to be a major pathway for sediment organic carbon oxidation in oxygen-depleted sediments such as the Santa Barbara Basin. It was estimated that approximately 16% of the initial organic carbon in the surface sediment is oxidized via the sulfate reduction pathway.

Sulfide levels in Los Angeles Harbor water were high due to the large amounts of organic matter discharged from canneries (Soule and Soule 1981).

Treatment of the waste before discharge resulted in reduced BOD levels and a reduction in sulfide levels by as much as an order of magnitude between the year 1974 and 1978. These observations suggest that in anaerobic marine environments, where sulfate ions are not limiting, sulfide production is controlled by the availability of organic carbon, which serves as an electron donor for sulfate reduction to sulfide.

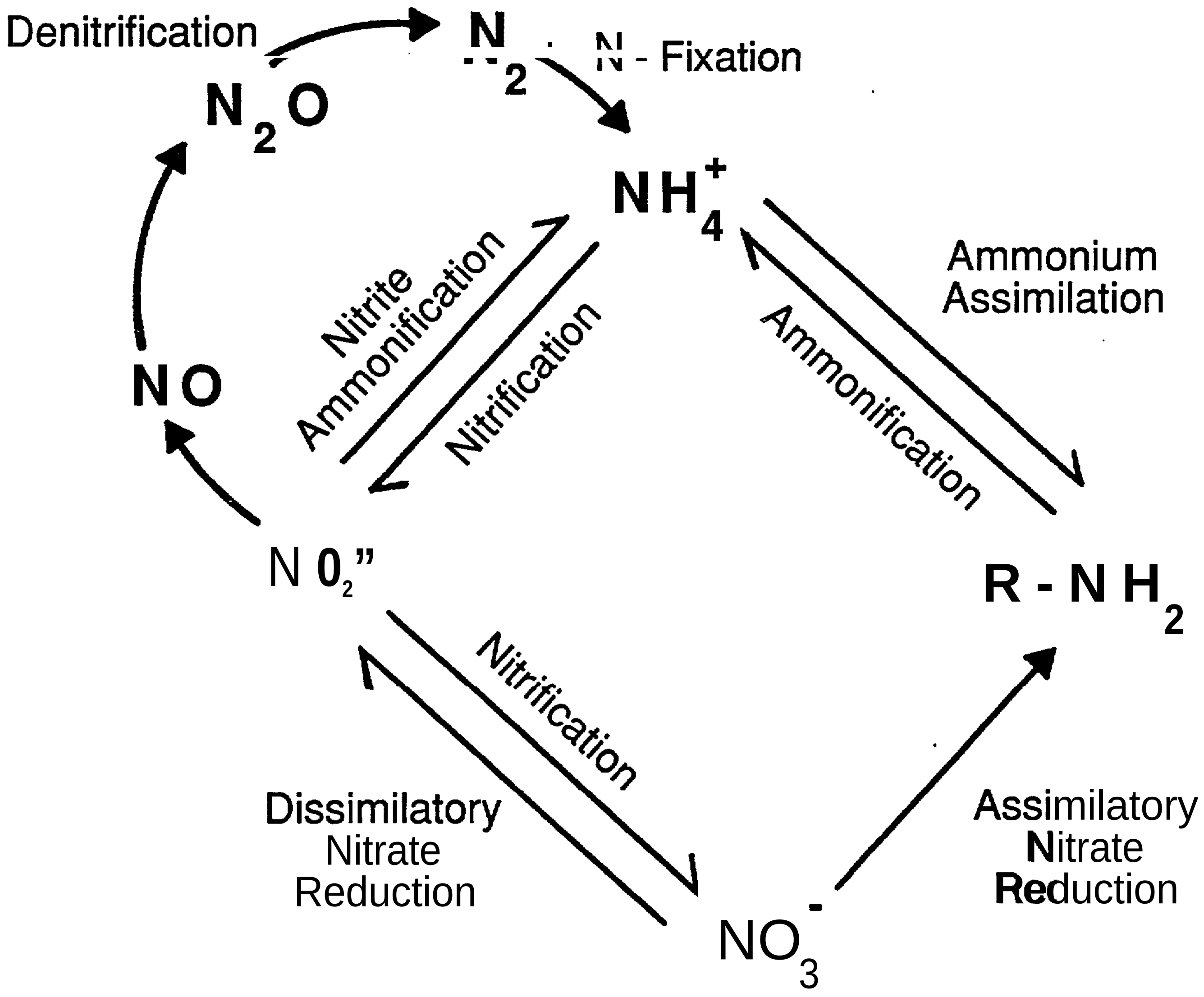
SULFUR OXIDATION

Filamentous sulfur oxidizing bacteria have been shown to exist around intertidal and subtidal sulfur springs near Whites Point off the Pales Verdes Peninsula and around oil seeps in the Santa Barbara Channel (Spies and Davis 1979; Stein 19S4). Stein (1984) indicated that these bacteria grow as a sessile mat around the point of discharge. Evidence suggests that the bacteria oxidize hydrogen sulfide to elemental sulfur (Jacq et al. 1989). The energy derived from this process led to very high densities of bacterial biomass in localized areas on the bottom. The large biomass of filamentous bacteria around oil seeps in the Santa Barbara Channel was also thought to lead to the high benthic invertebrate biomass at these locations (Spies and Davis 1979).

NITROGEN CYCLING

Plants, animals, and most microorganisms require combined forms of nitrogen for incorporation into cellular biomass; thus, the availability of combined nitrogen limits primary production in many marine ecosystems. Nitrogen in living and dead biomass occurs predominantly in the reduced amino form. During microbially mediated decomposition ammonium is liberated via a process known as ammonification (Figure 4.3). Oxidation of ammonium to nitrite and nitrate is then carried out by a limited number of autotrophic vitrifying bacteria by the process of vitrification.

Figure 4.3. Involvement of marine bacteria in the cycling of nitrogen. Microorganisms catalyze the reactions in each step of the nitrogen cycle shown above. N_2, gaseous nitrogen; NH_4^+, ammonium; R-NHz, organic nitrogen; NO_2 , nitrite; NO, nitric oxide; N_2O, nitrous oxide; NO_3 , nitrate.


Denitrification
N_2
N - Fixation
N_2O
NH_4^+
Nitrite Ammonification
Nitrification
Ammonium Assimilation
Ammonification
NO
NO_2^-
R - N H_2
Nitrification
Dissimilatory Nitrate Reduction
Assimilatory Nitrate Reduction
NO_3^-

Vitrification occurs exclusively in aerobic environments.

Ammonium, nitrite, and nitrate salts serve as small reservoirs of rapidly cycled nitrogen. Nitrate is reduced via assimilatory and dissimilatory reactions. Assimilatory nitrate reduction results in the incorporation of nitrogen into organic compounds needed for the production of cell biomass. The dissimilatory reactions can lead to the formation of free ammonia (nitrate ammonification) or, through a more complete reduction pathway, to the conversion of nitrate through nitrite to nitric oxide (NO) and nitrous oxide (N_2O) to molecular nitrogen. Denitrification occurs under strictly anaerobic conditions or conditions of reduced oxygen concentration. Atmospheric (molecular) nitrogen is the largest and most slowly cycled reservoir of nitrogen. Biological fixation of atmospheric nitrogen is mediated by a diverse number of procaryotes. Microbially mediated nitrogen fixation in the world's oceans is estimated to be 40 mt Y-l, or about 23% of the total annual global fixation (Atlas and Bartha 1987). The biogeochemical cycling of nitrogen is thus highly dependent on the activities of microorganisms.

The participation of microorganisms in ammonification and vitrification has been demonstrated in the SCB. Other segments of the nitrogen cycle, such as denitrification and nitrogen fixation, need to be assessed in future studies of the area.

AMMONIFICATION

Nitrogen isotope studies suggest that the dissolved ammonium in pore water of sediments from the Santa Barbara Basin is produced from bacterial degradation of marine organic matter (Sweeney and Kaplan 1980). Bacterial degradation of marine planktonic organic matter was determined to be the main source of ammonia in sediment pore water. Only organic matter from marine sources is degraded to any extent by bacteria in the basin sediment. The zone of most rapid ammonia generation is the surface 2 m of sediment. **Ammonification** is also likely to occur in the water column. However, no information is available on the microbial participation in this process in waters of the SCB.

VITRIFICATION

Primary production in the SCB appears to be driven by the rate of nitrogen input to the **euphotic** zone. Although there are numerous sources of nitrogen, the most significant is the ocean itself. The process of vitrification is critical to the replenishment of nitrate-N in **euphotic** waters of the SCB.

Stations sampled from Santa Monica Bay to 98 km offshore near the Channel Islands showed a typical nitrite maximum near the **1%** light level which coincided with the upper part of the nitrate gradient (Olson 1981). Seasonal variations in the depth of the nitrite maximum were observed at a station in the San Pedro Channel. The maximum decreased from a depth of 35 m in March to 60 m in October. Highest nitrite concentrations were measured in June.

Olson (1981) used an ^{15}N-tracer technique to determine microbial ammonia oxidation rates in the SCB. The microorganisms responsible for ammonia oxidation at various stations in the SCB exhibited a very high affinity for ammonia (Ks of 0.1 **uM** or less). No consistent increase in the rate of ammonia oxidation was observed over the ammonia concentration range of 0.1-20 UM. Ammonia appeared to be the main source of nitrite in the nitrite maximum. At depths above the maximum, nitrate reduction becomes a more important source of nitrite.

Carlucci et al. (1970) determined that the high nitrite concentrations in the secondary nitrite maximum (generally below 150 m) in oxygen-depleted waters of the eastern tropical Pacific Ocean arise from nitrate reduction. The energy for bacterial nitrate reduction originates from the biochemical oxidation of organic matter. Some nitrite in the secondary nitrite maximum may arise from oxidation of ammonia by vitrifying bacteria. Concentrations of ammonia found in seawater indicate that nitrite production by vitrifying bacteria is very slow.

The mean turnover time for nitrite in the nitrite maximum layer was 12.5 days in Southern California coastal waters as compared to 25 days in the central north Pacific gyre (Olson 1981). Size fractionation experiments indicated that vitrifying bacteria mediated the observed ammonia-oxidizing activity. A large portion of the activity passed through a 0.6-um pore size filter, but was retained by a 0.2-um pore size filter. Chemical inhibitors of vitrifying bacterial activity also inhibited ammonia oxidation when added to samples.

In these waters, ammonium oxidation rates were comparable to ammonium uptake rates. At the nitrite maximum, ammonium uptake by bacteria was comparable to that by phytoplankton.

Studies in water collected from S10 pier and from the San Clemente Basin showed that nitrate reduction increases with light intensity while ammonia oxidation decreases (Olson 1981). The threshold for inhibition of ammonia oxidation is between 0.2-2% of sunlight.

Nitrite and nitrate uptake appear to be competitive processes (Olson 1981). ‘Unlike ammonia oxidation, nitrite oxidation showed a marked dependence on nitrite concentration. A Lineweaver-Burk plot of the data obtained from water samples taken 3 miles off S10 pier at a depth of 60 m resulted in a half-saturation constant value of 0.07 uM nitrite. This value is similar to many natural nitrite concentrations in the marine environment. The highest nitrite oxidation potential was found below the nitrite maximum layer, while the ammonia oxidation activity was highest within the nitrite layer. The relatively low nitrite oxidation rate within the nitrite maximum is likely due to inhibition by light similar to that demonstrated for ammonia oxidation. Nitrite oxidation exceeded nitrite production at all depths except at the nitrite maximum. It was concluded that the main source of nitrite in oxygenated water is ammonia oxidation and that there is a gradual switch from nitrate reduction to ammonia oxidation as light intensity decreases.

The abundance of Nitrosomonas and Nitrosococcus was measured at five stations in the SCB, using an immunofluorescent assay (Ward 1982). Cell concentrations were fairly constant with depth. For Nitrosococcus, densities of 4×10^3 cells 1^{-1} in November and 3×10^4 cells 1^{-1} in July were obtained. Nitrosomonas densities were 4.6×10^4 cells 1^{-1} in July. Nitrifiers were more abundant in bottom water samples than in surface samples, suggesting a sediment origin for part of the water column population.

Nitrifiers were found to constitute a very small portion of the total bacterial population in seawater (Ward and Carlucci 1985). Antisera developed against ammonium-oxidizing bacteria did not cross react with nitrite-oxidizing bacteria and vice versa. Not all of the ammonium- and nitrite-oxidizing isolates reacted with antisera produced against genera of their respective physiological group. There was no significant difference in the distribution pattern of total ammonium-oxidizing and total nitrite-oxidizing bacteria in the water column of a station off the eastern tip of Santa Catalina Island. Most cells occurred singly. The total abundance of ammonium-oxidizing cells (Nitrosococcus + Nitrosomonas) averaged 3.5×10^5

cells l^{-1}. Total cell concentration was highest in surface water. Total nitrite-oxidizing cells (**Nitrobacter** + **Nitrococcus**) averaged 2.8 x 10^{5} cells 1-1. Maximum concentration occurred at 9 m depth. Abundance at 700 m was greater than at 150 m. Vitrifying bacterial densities at this station were higher than those reported for another station in the SCB (Ward 1982).

Vitrifying bacteria densities were also determined in the water column 5 km off the S10 pier and 5 km off Del Mar (Ward 1982). The mean bacterial counts (over the upper 100 m), based on **immunofluorescent** assay for two species of ammonium-oxidizing bacteria, yielded 5.2 x 10^{4} cells l^{-1} in July and 4.7 X 10^{4} cells l^{-1} in November. Nitrosomonas **marinus** was always more abundant than **Nitrosococcus oceanus.**

Although ammonium concentrations were quite variable with depth and a well-defined nitrite maximum was present at the bottom of the **thermocline,** no significant difference in density was observed with depth in the upper 100 m for either species (Ward et al. 1982). ^{15}**N-tracer** studies ***were*** performed to relate ammonia oxidation rates to vitrifying bacterial densities. Rates of ammonia oxidation were low at the surface and generally increased to a maximum in the nitrite maximum layer. Ammonia oxidation rates on a per-cell basis increased 2 orders of magnitude from the surface to the nitrite maximum layer and below. The mean nitrite production rate was estimated to be 1.9 x 10^{-8} mol cell^{-1} d-l over the upper 100 m of the water column in July and 1.6 x 10^{-8} **mol** cell-l d-l in November. The data suggest that ammonia concentrations do not control ammonia oxidation rates. The results report for the first **time** the presence of vitrifying bacterial populations of sufficient size to **account** for the high in situ rates of ammonia oxidation.

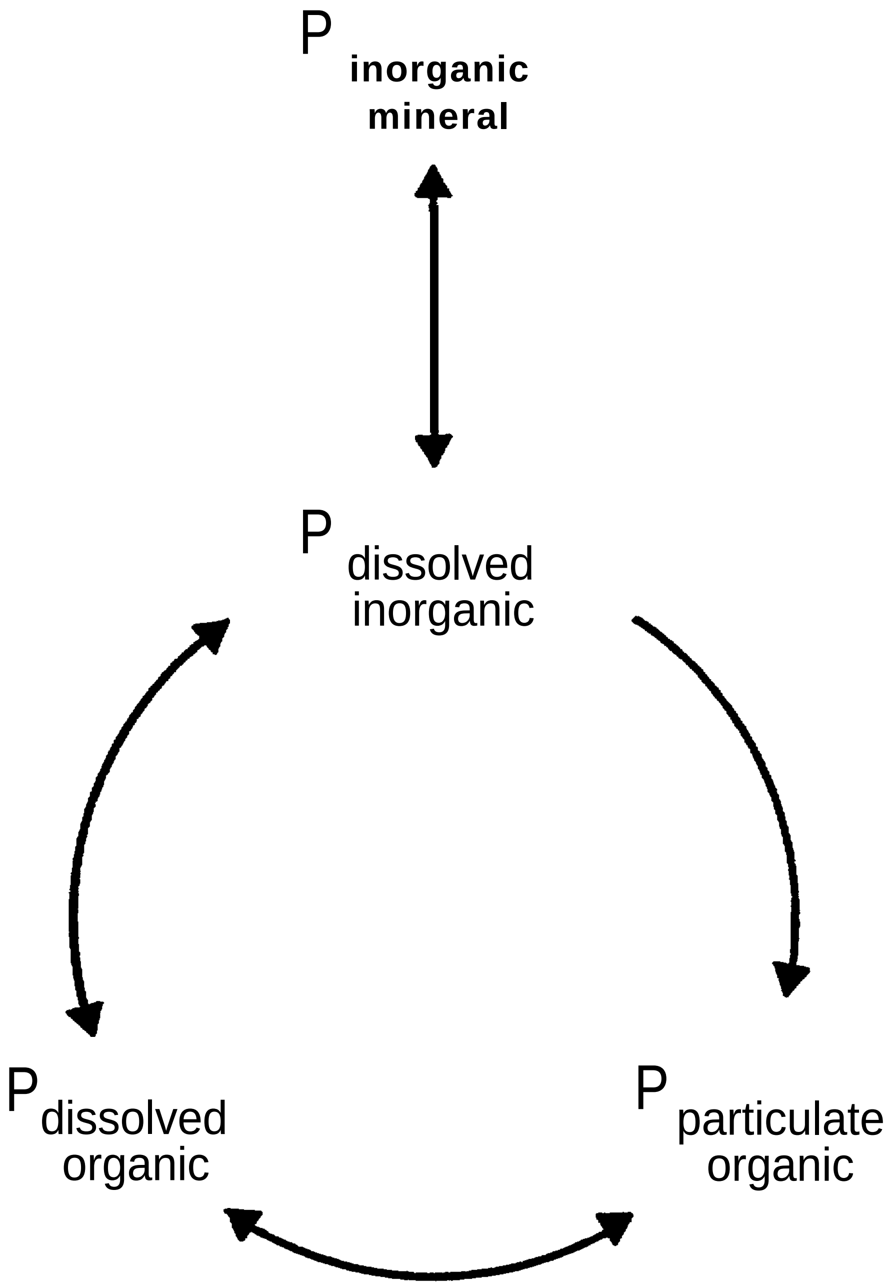
Virtually all the ammonia in water samples collected at depths of 7-10 m in the Santa Barbara Channel, 5 km from shore and at the leading edge of an upwelling plume, was associated with suspended macroscopic particles, which were composed primarily of discarded appendicularian houses (Prezelin and Alldredge 1983). Nitrate and nitrite were undetectable in the aggregates. Since ribulose-l,5-biphosphate carboxylase activity was high in photosynthetically suppressed aggregates, it was suggested that the enzyme activity was due to chemoautotrophic vitrifying bacteria. It was further suggested that the surfaces of aggregates are favorable environments for vitrifying bacteria. Such observations help to explain the consistent, but low densities of these bacteria in pelagic waters.

PHOSPHORUS CYCLING

Phosphorus exists mainly as ortho-phosphate in the marine environment. Phosphate is cycled between particulate organic forms to soluble inorganic forms, the latter being the preferred source of phosphorus by phytoplankton (Figure 4.4).

Marine microorganisms have been shown to utilize dissolved phosphorylated organic compounds in seawater. Azam and Hodson (1977b) determined that dissolved adenosine triphosphate (DATP) in surface waters of the SCB varied from an average high value of 218 ng 1^{-1} off the S10 pier to an average low value of 65 ng 1^{-1} 4 miles offshore from Point Loma, San Diego. Turnover rates of DATP, defined as the fraction of the total DATP in the sample that is assimilated per hour, were determined from measurements of assimilation of 2,8-^{3}H-ATP by natural microbial populations in water samples. The turnover rates were indicated to be quite high (>0.59% h-l), although actual rates were not presented. Using ^{14}C-DATP as a tracer, it was determined that greater than 98% of the ^{14}C taken up was assimilated by the microbial population with insignificant amounts being respired.

Figure 4.4. Involvement of marine bacteria in the cycling of phosphorus. Microorganisms catalyze the reactions that convert particulate inorganic phosphorus (P inorganic material) to dissolved inorganic phosphorus (P dissolved inorganic) and vice versa. They also catalyze the conversion of dissolved inorganic phosphorus to particulate dissolved organic phosphorus (P dissolved organic) and particulate organic phosphorus (P particulate organic) and catalyze reactions that lead to interconversion between the two latter forms of phosphorus.


P inorganic mineral
P dissolved inorganic
P dissolved organic
P particulate organic

Bacteria accounted for approximately 80% of the DATP assimilated.

Natural populations of microorganisms in nearshore and offshore waters of the SCB readily take up cyclic adenosine monophosphate (cAMP) (Ammerman and Azam 1981, 1982). Uptake occurred predominantly by microorganisms (bacteria and some cyanobacteria) which passed through a 0.6-um pore size filter. Rates of dissolved cAMP (DcAMP) turnover were approximately 1% h-l within 6 km of shore and approximately 0.1$ h-l in water 100 km offshore.

It was proposed that DcAMP was taken up by specific, energy-dependent, high-affinity transport systems with measured transport constants (K_m) of 10 to 1000 pM (Ammerman and Azam 19S1). The DcAMP concentrations in nearshore waters (S10 pier) ranged from 2 to 30 PM, and DcAMP concentrations in the relatively oligotrophic waters 41 km offshore in the SCB varied from less than 1 to 3 pM. These concentrations appear too low for the transport systems to operate effectively. Only in the pore water of the sediments, where DcAMP concentrations were 1 to 3 orders of magnitude higher than water column concentrations, would these high-affinity bacterial transport systems be functional. Neither algal nor bacterial uptake of DcAMP could account for a sharp diurnal drop in the concentration of this compound in the water column between midnight and dawn. Since both (^{32}P)-DcAMP and (2,8-^{3}H)-DcAMP were taken up in the presence of excess 5’AMP and inorganic phosphate (Pi), it was suggested that DcAMP was taken up intact.

McGrath and Sullivan (1981) determined the rate of total adenylates (ATP + ADP + AMP) uptake in waters of Los Angeles Harbor and the San Pedro Channel. Four stations within the harbor and one station 1.5 km outside the breakwater were sampled on a monthly to quarterly basis. The rate of total adenylate uptake was approximately equal to that which was incorporated, indicating that soluble intracellular pools were small and turned over rapidly. The uptake rate of adenylates in harbor water equalled or was slightly greater than that in channel water. Uptake kinetic analysis suggested that the transport systems for adenylates were always undersaturated. There were no significant differences in the natural velocity of uptake or the turnover time between the **bacterioplankton** of harbor water and channel water for **adenylate** uptake. The plankton community in channel water had lower transport constants than in harbor water, indicating that the channel populations were adapted to lower total **adenylate** concentrations in the surrounding seawater. Uptake was due almost entirely to bacterial-sized rather than algal-sized organisms. These data thus demonstrate that bacteria in the SCB are important in converting dissolved organic phosphate into particulate organic phosphate.

Microorganisms in marine waters off the Southern California coast release some of the P taken up in an organic form as free Pi. **Picoplankton** (organisms less than 1 **um** in diameter) have a cell-surface enzyme, **5'-nucleotidase,** that rapidly hydrolyzes 5**'-nucleotides** and regenerates P_i (**Ammerman** and **Azam** 1985). Substrate specificity was not repressed by Pi concentrations (100 **uM** or less) that normally exist in the sea. Hydrolysis of organic P and uptake of the hydrolyzed P_i were coupled. High enzyme activity was detected in nearshore waters (S10 pier) and those collected 3 km offshore. Activity was detected through the water column down to 50 m at **a** station 100 km offshore. Little activity was due to enzymes free in solution. The enzyme exhibited high affinity for **5'-nucleotides,** with **Michaelis** constants of 3 and 67 nM, depending on the **5'-nucleotide** concentration. In California coastal water, a typical rate of Pi consumption is 1-2 nmol 1^{-1}h-l. The rate of P_i release by the microbial enzyme was estimated to be 1 **nmol** 1^{-1}h-l. Thus, microbial **5'-nucleotidase** accounts for **50-100%** of the total P_i consumption rate in the sea. Ten to

15% of the Pi generated by the enzymatic **activity** was **taken** up by the bacteria. As Pi is depleted in the seawater, the **amount** of pi incorporated by the microorganisms increases to around 50$.

Microorganisms also take up Pi from marine waters. A **phytoplankton**-enriched size fraction (1-203 um) and bacteria-enriched size fraction (0.2-1.0 **um)** accounted for 47 and **53%** of the microbial pi **uptake** in Los **Angeles** Harbor and San Pedro Channel water **(Krempin** et al. 1981). Although the mean **phytoplankton** biomass was 24 times the mean **bacterioplankton** biomass, the two populations took up Pi at comparable rates (7 **nmol** P 1^{-1} h-l) and turned ***over*** the P_i in the harbor water in similar time periods (140-150 h). Rates of Pi uptake by microbial populations in channel water were lower than in harbor water. Turnover times of phosphorus by the bacteria fraction in the channel were similar to that in the harbor. Microbial biomass and P_i uptake rates were significantly correlated **(r=0.89)** among samples collected at a station inside and outside the harbor.

Phosphate uptake at different depths In the harbor correlated with chlorophyll *a*, **bacterioplankton,** and *in situ* soluble reactive P_i **(Krempin** et al. 1981). The greatest uptake occurred at a depth of 3 m, where chlorophyll *a* and bacterial biomass peaked. In the channel, P_i uptake rates varied with microbial biomass above and below the **thermocline.**

Maximum velocity of P_i uptake by combined **phytoplankton** and **bacterioplankton** fractions was estimated to be 1.23 nmol P 1^{-1} h-l, while that of the **bacterioplankton** fraction alone was 5.17 nmol P 1^{-1} h-l in surface water 0.5 km north of Isthmus Cove, Santa Catalina Island **(Krempin** et al. 1981). Transport constants (K_t) for the combined plankton fractions and the **bacterioplankton** fraction alone were estimated to be 5.93 and 112 **nmol** P 1^{-1}.

Krempin et al. (1981) suggested that if the flow of energy is more rapid through the detrital food web than through the phytoplankton, the bacterioplankton could be dominant in Pi uptake, while phytoplankton dominate biomass. Krempin's group concluded that although bacterioplankton may constitute a relatively small (10-20%) part of the total microbial biomass, they are a functionally significant part of the pelagic ecosystem and are responsible for the majority of orthophosphate assimilation in the outer Los Angeles Harbor.

HUMAN PATHOGENS AND FECAL INDICATORS

Most bathing beaches in Southern California are located on the ocean and are used year around. Shellfish are harvested in tidal areas and eaten by the population. Since sewage is also discharged into these coastal waters, it is necessary to closely monitor the water for infectious microbes. Because concentrations of pathogens are usually very low, indicator organisms, which reflect the presence of pathogens but which are present in greater concentrations than the pathogens and are, therefore, easier to detect, are generally used as monitors of fecal pollution. Total coliforms (TC), fecal coliforms (FC), and fecal streptococci (FS) are usually employed to indicate the possible presence of enteropathogens such as Salmonella and Shigella. (In reality, there is no universal indicator organism for determining water quality.)

According to a California State Department of Public Health report (1942), no epidemic disease traceable to use of Santa Monica Bay beaches for bathing was reported prior to the period of rapid population growth that occurred in the Los Angeles area after World War II, in spite of heavy pollution in which coliform counts exceeded 11,000 coliform MPN (most probable number) per 100 ml in surf near the Hyperion Wastewater Plant discharge area. More recently, however, there have been reports of increased incidence of sickness among lifeguards at beaches in Santa Monica Bay. Furthermore, beach closures are now common during and immediately following rainy periods, when coliform counts rise above acceptable levels as a result of the diversion of raw sewage to storm drains which empty into coastal waters of Los Angeles and Orange Counties.

OCCURRENCE OF INDICATOR MICROORGANISMS

After a survey involving 961 samples of seawater and 387 marine fishes, ZoBell (1941b) concluded that coliform bacteria were not present in the ocean at places remote from sewage outfalls. Escherichia coli was found in the intestines of only a few fish that were taken near land. Enterobacter and Citrobacter were much more abundant than E. coli in the intestinal contents of fish. In bays, estuaries, and in the vicinity of outfall sewers, as few as 1 coliform 1^{-1} often gave a presumptive test. The abundance of these organisms decreases rapidly with distance from the outfall.

ZoBell (1960) presented evidence that in the open ocean only 12 of 1468 1 ml samples of seawater yielded positive presumptive tests. The presence of E. coli was confirmed in none. One ml volumes of the intestinal contents of fish yielded 206 presumptive positive tests from a total of 630 tests. Only 9% were confirmed positive for E. coli. Approximately 75% of the gas producers were Aeromonas spp. In general, it is difficult to estimate bacterial pollution on the basis of these presumptive tests.

Rittenberg et al. (1958) determined the numbers of TC in sediments in the vicinity of sewage outfalls in Orange County (Santa Ana River mouth), White's Point, and Santa Monica Bay. High numbers of presumptive positive tests were obtained within a radius of a few thousand feet of the outfalls off Orange County and in Santa Monica Bay. Sediments in an extensive area around the Orange County and Los Angeles County outfalls, which discharged unchlorinated sewage, contained as many as 25,000 and 92,000 coliforms cm^{-2}. Samples collected around the Santa Monica Bay outfall, which discharged chlorinated sewage, contained much lower (250 coliforms cm^{-2}) levels of contamination. Like the pelagic population, the large majority of presumptive coliform positive samples from sediments failed to confirm on EMB agar. At least some of the false positive presumptive results were due to the presence of lactose-fermenting, anaerobic, spore-forming bacteria. Results with brilliant green bile broth suggested that this medium should not be used for the confirmed test when using marine sediments.

In 1972, the California State Water Quality Board established criteria for limits on total coliforms in waters along the shore and in areas where shellfish may be harvested for human consumption. Monthly monitoring of TC, standard plate counts, and BOD were Instituted in 1972 in Los Angeles Harbor in response to discharges of cannery wastes (Soule and Oguri 1975). Mean standard plate counts showed considerable variation between yearly means in 1973 and 1974. Outfall areas were high, as was the Los Angeles River channel. Increases In TC generally occurred after storms. A three-year investigation of microbial activity in the harbor showed that deviation from normal marine bacterial flora reflects the nature of non-marine or mixed waters introduced into the harbor. No one variable, with the possible exception of FC, could be used to estimate the presence or levels of microbial pollution.

Bacterial pollution did not appear to exhibit a seasonal pattern in San Diego Bay (Nusbaum and Garver 1955). Coliforms disappeared rapidly in the large shallow south section of the bay, where the heaviest sources of pollution exist. At low tide, coliforms were detected as far as 6 miles from the sewage outfall, whereas at high tide coliforms were not detected further than 2 miles from the outfall.

Newport Bay has experienced increasing bacterial pollution since 1976 (Skinner 1984). San Diego Creek discharges approximately 16 million gallons of water each day into the bay with coliform counts as high as 240,000 per 100 ml. The percent of water samples collected from the cleanest areas of the lower bay with coliform counts over 100 per 100 ml increased from 5% in 1976 to 53% in 1983.

Olson (1978) conducted a study of the effectiveness of the most-probable-number (MPN) method to enumerate coliforms in marine waters of Newport Beach. False negatives were found in approximately one-half of the 270 samples tested. More than 50% of the isolates giving false negatives were Ecoli_. Inclusion of the false-negative tubes into the data resulted in the discovery of increased violation of the California ocean-water contact sports standard at all sites. More than 20% of the samples collected were in violation of this standard. It was suggested that the MPN method be modified to detect coliforms in the marine environment. No suitable modifications have been adopted yet in the standard methods for bacteriological examination of recreation waters.

Coliform concentrations were reported for waters in the Point Loma wastewater discharge area in waters off San Diego (Bascom 1973). At all but one of the stations, concentrations of 1000 MPN per 100 ml or less were recovered 86% or more of the time from 1963 to 1970.

Since 1960, the City of Los Angeles has monitored coliform concentrations along the shoreline between Malibu Canyon and Pales Verdes Point and around a 5-mile outfall (Bascom 1973). Between 1960 and 1970, coliform concentrations averaged 0.6 MPN per 100 ml at the offshore stations. Coliform concentrations varied with season and tended to decrease in surface and subsurface waters with increasing distance from shore. Coliform concentrations greater than 1000 MPN per 100 ml occurred from nearly zero to 15% of the time.

An intensive study was conducted in 1966 and 1967 at five major storm drain discharge areas (Bascom 1973). Coliform concentrations were significantly higher (23,000-230,000 MPN per 100 ml) in storm flows than in dry periods (62-6200 MPN per 100 ml). The north shoreline of Santa Monica Bay often had higher coliform counts after storms than did other shoreline areas.

A study of coliform concentrations in the surf near municipal discharges in Orange and San Diego Counties revealed that the levels were within state standards for bathing beaches (Bascom 1973). Samples collected near storm drains had consistently higher coliform concentrations than samples from other areas, and the frequency of occurrence of samples containing greater than 1000 MPN per 100 ml was higher during the winter months than summer months. The high values in the winter may have resulted from storm sewer discharge. In a study of waters near Orange County Sanitation District outfalls, Fay (1966) found that offshore subsurface (6 m depth) water contained higher coliform concentrations than corresponding offshore and surf waters. Subsurface concentrations of 10,000-50,000 per 100 ml were often observed. Some surf stations appeared to be contaminated by the coliforms from subsurface offshore waters.

Coliforms were found in seawater surface films (neuston layer) in areas around sewage outfalls (Hyperion and Pales Verdes) at concentrations of approximately 300 cfu per 100 ml (Bascom 1973). Coliform concentrations in surface films in outer areas of Santa Monica Bay and around Santa Catalina Island were less than 2 cfu per 100 ml.

Coliforms were found on wastewater **macroparticles** at outfall sites (**Bascom** 1973). Particles in the vicinity of outfall sites contained **coliform** concentrations of 3500-21,000 cfu per particle. No **coliforms** were found on particles recovered from **unimpacted** seawater around Santa Catalina Island. These data suggest that **coliforms** are not a part of the normal particle-associated **microfauna** in waters of the SCB, but that particles do serve as a vehicle of entry into these waters for these microorganisms.

Kenis et al. (1972) evaluated bacteriological water quality in waters which received sewage effluent off San **Clemente** Island. The initial concentrations and dieoff rates of TC, FC, and FS were determined at 4, 12, and **25°C.** The TC group was found to be more abundant than the FC and FS groups at time zero and at subsequent samplings. **Dieoff** of the TC group was slower at 4°C than at 25°C. TC abundance decreased rapidly with distance from the outfall.

The densities of TC were also determined on surfaces of kelp and rocks in the vicinity of the outfall (Kenis et al. 1972). Slime masses on submerged rocks around sources of raw sewage discharge concentrated TC by factors of >1000 relative to the surrounding seawater. Kelp concentrated TC by a factor of 40-60 relative to the surrounding water. Sewage dilution in the water column was generally in excess of 1000 times in water 30 m from the point of discharge. Seawater outside of a radius of several hundred feet from a discharge pipe releasing 95,000 1 d-l generally met bacteriological health standards for swimming beaches. It was concluded that it was unnecessary to treat the sewage from human wastes generated on the island.

The results of the above study were also used to predict the impact of sewage discharge from a middle-class Navy ship with a similar number of inhabitants and from larger vessels, such as aircraft carriers, which carry approximately 10 times more people. It was concluded that even with large ships, the biochemical oxygen demand by microorganisms degrading the sewage would not significantly alter the oxygen concentration more than 30 m from the point of discharge.

DILUTION AND DIEOFF OF SEWAGE MICROORGANISMS

Dye and radioactive tracers were used in conjunction with MPN coliform enumeration by Rittenberg (1956) to estimate the dieoff and dilution of sewage microorganisms. The average time required for a 90% reduction in the MPN of coliform bacteria (T_{90}) from the Hyperion primary effluent in Santa Monica Bay was 3 h. Nine hours after discharge, the T_{90} increased to 15 h. This difference was attributed to either a greater resistance of the bacteria that survived the initial exposure to seawater or to disaggregation of bacterial clumps.

Indicator bacteria from sewage effluents discharged into coastal waters near Santa Barbara, Ventura, and Oxnard were monitored by Foxworthy and Kneeling (1969). Coliform counts decreased from 5050 per 100 ml at the outfall to 0 per 100 ml at a distance 1170 m from the outfall. The decrease in counts was due to both dilution and dieoff. Little or no tendency for sedimentation of coliforms occurred except in the immediate vicinity of the outfall. Maximum coliform counts usually occurred at the surface.

An equation was described which predicted the concentration of coliform bacteria anywhere along the discharge plume:

$$c/c. \text{ (dieoff)} = ae \exp -k_1 t + (100-a)\ e \exp -k_2 t$$

where c and co are coliform concentrations at the source and at any point along the longitudinal axis of the plume, k_1 and k_2 have units of l/t and are constants, and a is a constant. The rate of dieoff was high near the source and decreased with time. After 1 h of exposure to seawater, dieoff was nearly constant. On another day, however, the rate of dieoff was low at the source and increased with time, becoming nearly constant after 125 min. There was no evidence of growth of coliforms in the plume. However, within the first few minutes of contact with seawater, a significant increase in counts was observed in about 50% of the samples. In the majority of samples, maximum coliform density occurred within a few feet of the water surface all along the plume.

A parallel study showed that FS dieoff could also be adequately described by the equation. In one experiment, the initial FS density was about 2 orders of magnitude less than the coliform density. Although the experiments suggested that FS are better indicators of enteric bacterial pollution in the sea, since they exhibited the highest overall resistance to adverse effects of the marine environment, other studies suggest that this conclusion was erroneous. FS densities decreased initially after exposure to the seawater and then increased to a concentration greater than the initial maximum concentration. This contrasts with the coliform density which decreased continuously along the plume. It was concluded that the growth/mortality characteristics of FS are highly unpredictable.

The factors that contributed to coliform dieoff were evaluated. Since there was good correlation between the distribution of Rhodamine B dye and coliform densities in the plume, it was concluded that sedimentation was not a factor. Dieoff rates varied significantly with season. There was a greater tendency for dieoff in spring and summer and regrowth in winter. Although the influencing factors were not identified, this tendency did not appear to be due to consequences of phytoplankton growth. The rate of dieoff did not vary directly with temperature; rather, a complex relationship with temperature was observed. There was a tendency for higher plume regrowth at lower (<15°C) temperatures.

SURVIVAL OF INDICATOR MICROORGANISMS IN SEAWATER

Several studies have addressed the survival of coliforms in marine waters of the SCB. ZoBell (1936) determined viability in filtered and autoclave water samples. The most significant destructive agent(s) of coliform bacteria in seawater were suggested to be biological in nature, heat labile, and related to the normal population of organisms indigenous to the water masses. Inactivation of coliform bacteria is caused by adsorption and sedimentation processes, sunlight ultraviolet irradiation inactivation, lack of nutrients, toxic substances, bacteriophages, predation by protozoans and nematodes, and antagonism by other microorganisms such as *Bdellovibrio* and *Pseudomonas* sp. (Carlucci and Pramer 1959; Foxworthy and Kneeling 1969). Carlucci and Silbernagel (1965) later concluded that seawater toxicity is not controlled by the physical and biological properties of a particular water mass, but, rather, the same factors may be responsible for the rapid death of bacteria in all waters.

Nusbaum and Garver (1955) studied the effects of seawater from San Diego Bay on the survival of laboratory cultures of *E. coli* and coliforms in raw sewage. Viability was evaluated by the presumptive 3-tube MPN method. The death rate of *E. coli* at an initial concentration of 10^7 cells ml-l was about 2 times that of a population with an initial cell concentration of 5 x 10^3 cells ml-l. The period of time over which the coliform population remained relatively stable before the effects of seawater inactivation occurred varied from less than 24 h to 4 days. This variation appeared to be seasonal. In one experiment, the coliform density decreased from 4.9 x

10^5 to 330 per 100 ml over a 9-day period. It appears from the studies conducted to date that the factors which control survival of sewage microorganisms are rather complex and not yet understood.

MICROORGANISMS THAT CAUSE DISEASE IN MARINE SPECIES

Microorganisms have been implicated in several diseases of marine species in the SCB. Two common sea stars, Patiria miniata and Henricia leviuscula, suffered heavy mortalities in 1978 and from 1981-1983. The highest mortalities coincided with the warming trend associated with the 1982-1984 El Nine. The causative agent of the disease appears to be a previously-undescribed marine bacterial species tentatively referred to as Vibrio patiria (Schroeter et al. in press). V. patiria is o-nitrophenyl-B-D-galactopyranoside (ONPG) positive and, unlike Vibrio vulnificus, a human pathogen, and other reported ONPG-positive marine isolates, is sucrose-positive. Since other bacteria were also isolated from the lesions, the possibility of a multi-organismal infection cannot be ruled out. The disease virtually eliminates populations of these common sea stars in the shallow subtidal waters along the Southern California coastline. It appears, therefore, that the epizootics are a major perturbation to community structure since these sea stars are an important benthic predator.

An infectious fin rot disease in Dover sole (Microstomus Pacificus) and other bottom fish occurred at a higher incidence around wastewater discharges on the Pales Verdes shelf than in other areas (Sherwood 1978). Ten percent of all fishes collected from the shelf had fin erosion; 99% of the fish showing the symptoms were flatfish or rockfish. No systemic infectious agent has been identified. However, the total number and diversity of bacteria were greater on specimens from the shelf than in other areas. The presence of the disease in the environment has been correlated with high sediment bacterial densities (Mahoney et al. 1973). In the laboratory, fin erosion has been induced in fish exposed to bacteria (Oppenheimer 1958). Most recently, the etiological agent of the disease has been suggested to be a unicellular protozoan parasite or X-cell which resembles a parasitic amoeba (Cross 1984). Amoebae that are morphologically similar to the X-cell are common in marine sediments and sewage sludge.

A new species, *Vibrio damsela,* was identified as the causative agent of skin ulcers in the blacksmith, *Chromis punctipinnis* (Love et al. 1981). Infected fish have been observed in King Harbor, Redondo Beach, and off Santa Catalina Island during the summer and fall spawning season. Ulceration rates are generally around 10%, although some aggregations of fish exhibited incidence of infection as high as 70%. Scarification of the skin with 10^7-10^8 viable cells of the bacterium produced large ulcers within three days and death in all infected fish within four days. The disease was never observed in other species although it could be artificially induced in the garibaldi (*Hypsypops rubicund*). The disease could also be induced in blue and brown *Chromis* spp. found in the Caribbean (Geesey, unpubl. results). Since *V. damsela* was also isolated from marine algae, it is likely indigenous to SCB waters.

Strains of *V. damsela* have been isolated from human wounds obtained in Florida, the Gulf coast, the Bahamas, and Hawaii. In all but one case, wounds had been incurred in seawater or brackish water. Wounds were described as being erythematous, indurated, and had purulent drainage (Morris et al. 1982). In all cases, the wounds were self-limiting and the patients recovered fully. Infections also developed through the consumption of raw shellfish. No human infections have yet been reported in Southern California.

A systematic search demonstrated the occurrence of *Vibrio cholerae* in water, sediment, and shellfish of the SCB as well as in other West Coast regions (Kaysner et al. 1987a). Samples from San Diego Bay, Mission Bay, San Diego River, and Tijuana Slough all contained *V. cholerae*. The vast majority were non-01 strains. *V. cholerae* were isolated from shellfish beds that were considered safe by coliform standards. The bacterium occurred in lower incidence in West Coast marine environments than those in the East Coast and Gulf Coast.

Virulent strains of *V. vulnificus* were isolated from sediments of Mission Bay in 1984 (Kaysner et al. 1987b). Samples of water and shellfish from Mission Bay tested negative for this organism. Since all strains isolated hybridized with cytotoxin-hemolysin gene probe, they likely produced cytotoxin. *V. vulnificus* can cause fatal septicemia in patients with liver disease, and may be responsible for necrotic wound infections in otherwise healthy individuals. There was a lower incidence of this bacterium in Southern California waters than in Northern California waters. In general, West Coast waters exhibited a lower incidence of *V. vulnificus* than East Coast or Gulf Coast waters.

SUMMARY AND PROSPECTUS FOR FUTURE RESEARCH

Some of the earliest studies in marine microbiology were conducted in waters of the SCB. It was in these waters and underlying sediments that a fundamental understanding of microbial distribution and activities developed. In the past decade, detailed studies have provided an understanding of utilization of DOC by bacterioplankton and bacterioplankton production in the SCB. There is now wide agreement that bacterioplankton biomass, production, and heterotrophic activities in coastal and offshore waters are closely coupled to the phytoplankton. In harbors and estuaries, bacterioplankton activities are also influenced by terrestrial organic input. **Bacterioplankton** production and biomass in the Los Angeles-Long Beach harbors appear to be sufficient to serve as an important energy source for **microzooplankton.** Whether this holds true for coastal and offshore waters remains to be determined.

Bacteria play an important role in the cycling of nitrogen, sulfur, and phosphorus in the SCB. **Planktonic** vitrifying bacteria exist in sufficient numbers to account for the high in situ rates of ammonia oxidation. Macroscopic particles appear to be active sites of vitrification. In recent marine sediments of the SCB, the major process affecting sulfur geochemistry is bacterial reduction of sulfate to sulfide. Sulfate reduction is likely to be the major pathway for organic carbon oxidation in oxygen-depleted sediments. **Bacterioplankton** are the main means for making phosphate that is present in very dilute concentrations of DOC available to higher organisms in the food web. Microorganisms also compete with the **phytoplankton** for inorganic phosphate and are responsible for the majority of inorganic phosphate assimilation in parts of Los Angeles Harbor.

The impact of sewage and other forms of organic point-source pollution on the microbiology of receiving waters in Southern California coastal waters has been widely studied over the past several decades. Monitoring infectious microorganisms has become a routine practice in Southern California coastal city and county agencies.

The role of microorganisms in maintaining the stability of marine ecosystems such as the SCB is only now beginning to be appreciated. As additional work is carried out in marine microbial ecology, we will discover new pathways **in** food webs that depend on microorganisms, and we will obtain reaction rates for microbial-driven processes that we can now assign to microorganisms only as **"uncertain** involvement.”

One of the most critical areas where we lack information in the SCB is in sediment microbiology. We need comprehensive studies on microbial biomass, production, and degradation of particulate organic matter. Although vast quantities of anthropogenic solid waste are discharged into the SCB, little is known about the microbiological processing of these wastes in bottom deposits where they accumulate. This information is needed because microbial action plays a major role in the fate of this material. We also need to determine denitrification, sulfate reduction, sulfide oxidation, and mineral transformation rates in bottom deposits. Studies performed in other marine areas comparable to the SCB suggest that microorganisms play a major role in these reactions.

Another area that deserves attention is the autotrophic activity of microorganisms in the SCB. With the exception of the vitrifying bacteria, little effort has been directed toward the study of microorganisms that produce biomass from CO_2. The activities of chroococcoid cyanobacteria are likely to dominate primary production In some areas of the SCB, but these prokaryotic organisms are generally overlooked during studies of primary production.

Finally, it should be emphasized that work must be initiated in the area of marine virology. Efforts should be increased to obtain a better understanding of the fate of pathogenic viral agents such as infectious hepatitis, polio, and viral gastroenteritis. Virus recovery, cultivation, and enumeration needs further scientific progress before wide-scale monitoring in marine waters can be undertaken.

The SCB is adjacent to a population center that is growing faster than any other metropolitan area in the United States. As in the past, we will continue to depend on the marine waters off Southern California for many purposes. After all, it is the mild Mediterranean climate afforded by the

SCB that makes its shoreline and inland areas so desirable a place to live. We must, therefore, continue to improve our analytical techniques to assess the microbiology of the SCB so that we can detect changes brought about by either natural or human causes and--we hope--prevent unnecessary deterioration of this valuable marine habitat.

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CHAPTER 5 PHYTOPLANKTON

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INTRODUCTION

THE IMPORTANCE OF PHYTOPLANKTON

The vast majority of life in the world's oceans depends, either directly or indirectly, on phytoplankton, tiny unicellular or colonial algae. These plants of the sea utilize carbon dioxide, present as dissolved bicarbonate In sea water, and light energy, and--through photosynthesis--convert the inorganic carbon to cellular material. **Phytoplankton** form the base of the food web; the support grazing zooplankton, fish, and, through their decay, large quantities of marine bacteria. The success of zooplankton depends upon both the quantity and quality of their **phytoplankton** food supply. For example, in the Southern California Bight, the fecundity (egg production) of zooplankton depends upon the nutritive value (nitrogen content) of the **phytoplankton** on which they feed **(Checkley 1980a,b).**

Fish production, in turn, is highly dependent on the growth and productivity of **phytoplankton** and zooplankton **(Ryther** 1969). Empirical indices indicate that fishery yield increases exponentially with increasing primary production In a variety of marine and freshwater environments (Hanson and Leggett 1982; Nixon 1988). Furthermore, spatial and temporal patterns of **phytoplankton** occurrence are important to fisheries. The success of larval fish and their subsequent recruitment into the adult fish population often depend upon spatial and temporal co-occurrence of fish larvae with an abundance of their plankton food source **(Lasker 1975; Cushing** 1982; **Mullin** et al. 1985).

SYSTEMATIC OF **PHYTOPLANKTON**

The algae are an extremely diverse group of organisms. Their systematic classification Is based on evolutionary relationships, using criteria based on the structure of the flagella, pigment composition, structure of the **chloroplast,** and the relationship between the **chloroplast** and the nuclear envelope. The taxonomy and biology of algae have been discussed in a number of standard texts **(Fritsch 1935;** Prescott 1968; Bold techniques. These techniques have evolved and improved over many years. They include: sampling design, use of sampling apparatus such as water bottles and nets, preservation and storage, concentrating and subsampling populations, taxonomic identifications, estimation of cell numbers, special microscopic techniques (including scanning electron microscopy), electronic cell-counting, culturing, statistical methods of data analysis, and, finally, interpretation.

A particularly useful and comprehensive manual on methodology for phytoplankton study was prepared by the United Nations Educational, Scientific and Cultural Organization (UNESCO) (Sournia 1978). It remains the best overall treatment of methodology, from initial sampling to final data interpretation. Specific methods for measuring biomass and primary productivity are found in Parsons et al. (1984) and Vollenweider (1974). Culture techniques for phytoplankton are described in Stein (1973). In addition, new innovations in methodology are reported regularly in the journals Limnology and Oceanography, Phycologia, and Journal of Phycology.

SPECIES COMPOSITION

SIZE DISTRIBUTION

The size distribution of phytoplankton species populations determines several important characteristics of the community. Phytoplankton are typically divided into two size classes based on their retention in plankton nets. The larger phytoplankton, retained in nets of mesh size 20 to 90 um, are commonly called "net plankton," while those that pass through such nets are called "nanoplankton." The ecological significance of cell size lies in the surface area-to-volume ratio, which affects the dynamics of phytoplankton productivity and energy flow through the food web.

Typically, more than half of the phytoplankton biomass in the Santa

Monica Basin passes through a 5-urn sieve, and, therefore, is of a size which can be grazed by protozoans (Small et al. 1989). Small cells generally have shorter generation times and higher growth rates in a given environment than do larger cells (Eppley et al. 1969). For nitrate and ammonium, uptake rates increase with increasing cell size, so larger "net plankton" are favored when nitrate concentrations are high, while nanoplankton are favored when nitrate concentrations are low (Eppley et al. 1969).

Sinking rates generally increase as cell size increases. Larger cells have shorter residence times in the photic zone under stratified conditions and tend to be concentrated in regions of upward water flow.

Cell size also determines the distribution and abundance of herbivores which graze selectively on the basis of preferred food size. Plankton-feeding larvae and microzooplankton generally prefer small phytoplankton as food, whereas larger herbivorous copepods actively select larger planktonic species (Thorson 1950; Richman and Rodgers 1969). Phytoplankton cell size also can affect the efficiency of energy transfer to large predators since nanoplankton-based food chains appear to require one or two more energy transfers to reach a given size consumer than do larger net plankton- based food chains (Ryther 1969; Parsons and LeBrasseur 1970).

Many species of phytoplankton inhabit the SCB. Their relative abundance in terms of numbers, biomass, and production varies greatly both spatially and temporally. The two most abundant and important components of the phytoplankton community are generally the diatoms (bacillariophytes) and the dinoflagellates (pyrrophytes). The size range of individual species of both groups is great--from a few micrometers to a few hundred micrometers.

The community of larger (>50 um) net phytoplankton in the SCB includes a broad *range* of temperate water forms as well as forms that characteristically occur in either warmer or colder water. This diversity reflects the general transitional nature of the SCB'S flora, which results from the physical oceanographic and mixing characteristics of the region. For example, incursions of exceptionally warm water currents in the area generally bring with them warm water species (Balech 1960).

The species composition and distribution of the smaller micro-, nano-, and picoplanktonic autotrophs is less well known, although data suggest that nanoplankton are generally extremely important contributors to primary productivity in both nearshore and offshore areas. For example, in Monterey Bay and in the California Current system, nanoplankton accounted for 60 to 99% of the observed productivity and standing crop.

Seasonal and geographic variations in nanoplankton are remarkably stable, and variations in plankton productivity are due primarily to the net plankton. Malone (1971) found that (1) the nanoplankton fraction varied within narrow limits compared with fractions of the net plankton, (2) the nanoplankton assimilation ratios were consistently high and twice those of the net plankton, and (3) the net plankton productivity and standing crop increased relative to the nanoplankton during periods of upwelling. The most abundant components of the biomass, integrated over the euphotic zone, at sites from 1.4 to 12.1 km off La Jolla were often small dinoflagellates, monads, and flagellates (Reid et al. 1970). Studies that have included data on the nano- and small picoplanktonic components of the SCB indicated that they commonly include the diatoms *Cylindrotheca closterium*, the dinoflagellates *Scrippsiella trochoidea* and *Prorocentrum vaginulum*, and the coccolithophorid *Emiliania* (= *Coccolithus*) *huxleyi* (Briand 1976; Reid et al. 1970).

As in other marine environments, recent data from Southern California coastal waters suggest the importance of small photosynthetic prokaryotic chroococcoid cyanophytes (blue-green algae). For example, at a depth of 1 m in the San Pedro Channel, outside of Los Angeles Harbor, cyanobacteria abundances were relatively low in winter, and increased throughout the spring, reaching a peak in late summer (Krempin and Sullivan 1981).

SPECIES ASSEMBLAGES

Phytoplankton assemblages in the SCB exist in great variety, richness, and complexity, and have not been adequately characterized. In general, phytoplankton community organization has been described in terms of two opposing hypotheses. One, the equilibrium view, treats gradients of environmental conditions as essentially accessible to all species; the gradients simply define the differentiation of the resources available. The community composition at any place and time is determined by the interplay of intrinsic biological properties of the species as modulated by local conditions. Coexistence of competitors is thought to depend on quantitative conditions and the extent of overlap of resource utilization (Allen 1977). The second, or non-equilibrium, hypothesis treats the separation of species and resources in time and space as virtual. Observed overlap in occurrence is interpreted merely as spillover of respective species centers of abundance--a coincidental phenomenon contingent on spatial and temporal transients. In this model the persistence of a community depends very much on scale. This non-equilibrium view suggests that the community at any given place and time is importantly influenced by past environmental conditions and spatially distant events that are not necessarily reconstructible from information about the present local state of the environment.

Computerized statistical analyses of community species composition have shed new light on the temporal pattern of phytoplankton species assemblages in the SCB and its relationship to environmental variables. Goodman et al. (1984) demonstrated that the community off La Jolla can be separated into three species groups. They described the phytoplankton assemblages and changes in community composition over a 21-week period from mid-April to mid-September 1967 at three stations north of La Jolla. The stations were located 1.4, 4.6, and 12.1 km from shore at depths of 21, 175, and 175 m, respectively. The authors identified 147 phytoplankton taxa present in 63 samples with 114 of the taxa present in more than 10% of the samples; 29.8% were centric diatoms, 16.7$ pennate diatoms, 43.9% dinoflagellates, 4.4% coccolithophorids, 3.5$ flagellates, and 1.8% silicoflagellates. Canonical correlation was used to associate 25 taxa and 13 physical and chemical variables.

Goodman et al. (1984) also found that assemblages tended to persist at a given location for periods of 1-4 weeks. One assemblage (component I) was a typical warm-water upwelling group dominated by *Skeletonema costatum* present at the inception of the spring bloom. A second component (II) was dominated by *Chaetoceros radicans* (also a temperate upwelling species), along with *Eucampia zoodicus* and two coccolithophorids, *Emiliania* (. *Coccolithus) huxleyi* and *Cyclococcolithus leptoporus*. Component III, which was dominated by *Gonyaulax polyedra*, did not show a marked agreement between stations except for a peak in week 20.

Phytoplankton component I showed very strong positive correlations with conditions characteristic of upwelling: a shallow pigment layer at which *in vivo* chlorophyll fluorescence dropped to near zero, low surface temperature, and high salinity and density at the pigment layer depth. Phytoplankton component II was highly correlated with a high concentration of nitrate relative to silicate at the pigment-layer depth, again indicating an association with upwelling. Phytoplankton component III, dominated by

Gonyaulax polyedra, was not an upwelling assemblage and was correlated with a shallow pigment layer, low silicate at the pigment-layer depth, and high temperatures at both the surface and pigment-layer depth (Goodman et al. 1984).

Reid et al. (1978) studied the vertical distribution of plankton assemblages in the nearshore part of the SCB during March 1976. By using three vessels, they were able to sample simultaneously at three locations: one north of the Pales Verdes Peninsula, another near Dana Point, and a third between Oceanside and La Jolla. Finding 20 species to be most abundant in the 58 samples (Table 5.1), the authors of this study used a percent-similarity index and principal-component analysis to investigate station-to-station differences among the 20 species. This method led to the separation of the species into three groups (Figure 5.1). The most abundant species in the chlorophyll-maximum layer (CML) were Exuviaella sp. and Mesodinium rubrum.

Reid et al. (1978) found only partial support for their hypothesis that the species assemblage is more similar in samples from the CML at nearby stations than between the CML and surface samples at the same station. A second hypothesis, that the species assemblage is more similar between stations of the CML than between the surface layer and CML, was not verified. A third hypothesis, that spatial differences in the phytoplankton assemblage are more abrupt in the offshore direction than in the longshore direction, was supported by the similarity analysis, but not by the principal component analysis. Distribution patterns were coherent over many kilometers in the longshore direction, while abrupt changes were evident in the offshore direction.

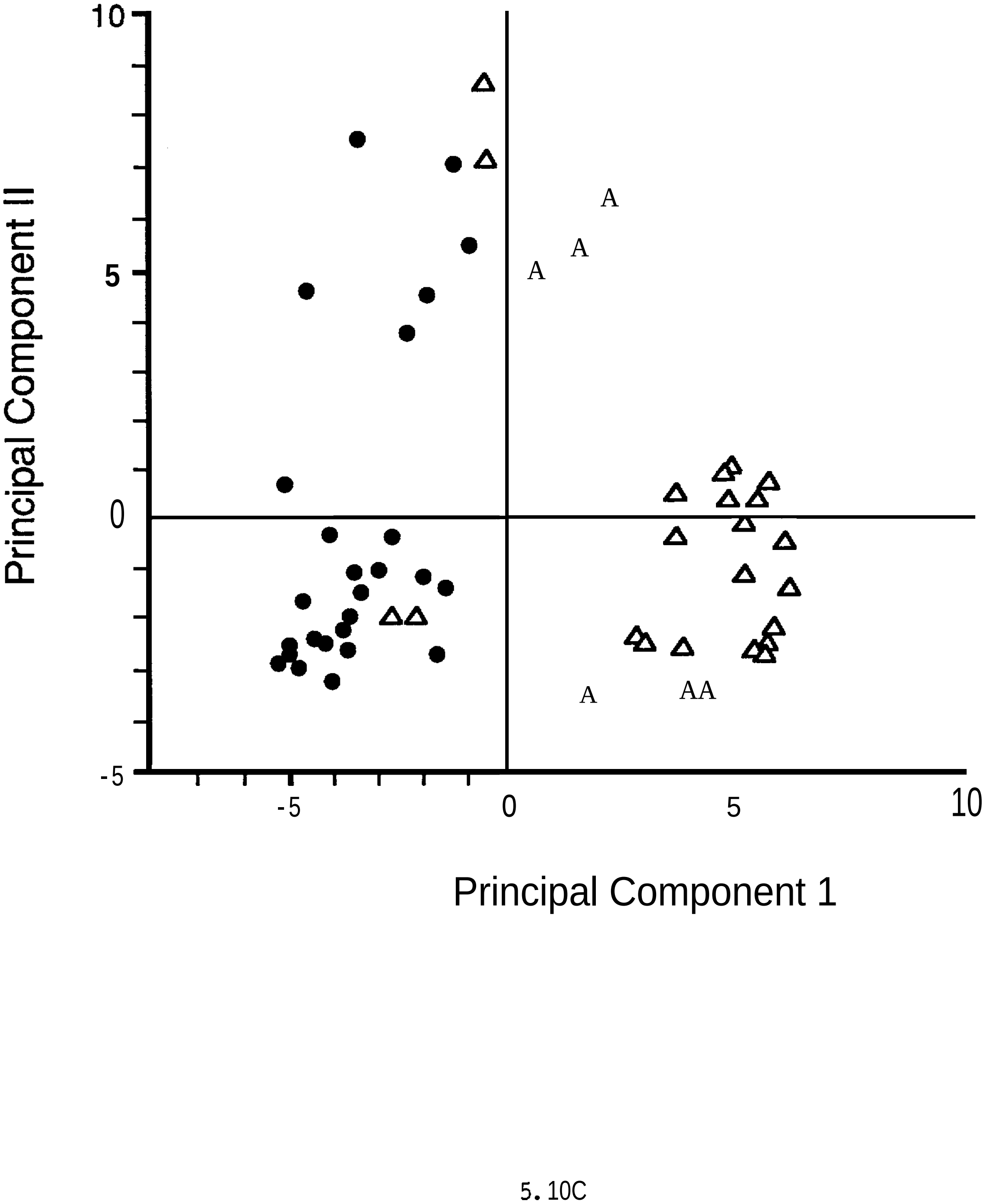
Winter (1985) reported finding four separate species assemblages of coccolithophores

Table 5.1. **Phytoplankton** species. First 20 **taxa** listed in order of average abundance in 58 samples (from Reid et al. 1978).

---

1. **Exuviaella** sp.
2. **Scrippsiella sp./Peridinium trochoideum** (Stein) **Lemm.**
3. **Skeletonema costatum (Grev.) Cleve**
4. **Eucampia zodiacus Ehrenberg**
5. **Prorocentrum gracile Schutt**
6. **Calciosolenia murrayi Schlauder**
7. **Thalassiothrix fruenfeldii (Grun.) Grunow**
8. **Gymnodinium** sp. A
9. **Gymnodinium splendens** Lebour
10. **Mesodinium rubrum Lohmann**
11. **Rhizosolenia fragilissima** Bergen (small form)
12. **Eutrptiella gymnastica** Throndsen
13. **Hemiaulus sinensis** Grev.
14. **Ceratium kofoidii** Jorgensen
15. **Torodinium robustum Kofoid** & Swezy
16. Gymnodinium sp. S.
17. **Leptocylindrus danicus Cleve**
18. **Cochlodinium** catenatum **Okamura**
19. **Peridinium minutum Kofoid**
20. **Gonyaulax polyedra** Stein

Figure 5.1. Principal=component analysis of phytoplankton species assemblages collected in March 1976 between La Jolla and Santa Monica Bay. Triangles are samples from the chlorophyll=maximum layer. Open circles represent surface samples. The species assemblages feel into three clusters. The cluster at the lower left includes primarily surface samples taken between La Jolla and Dana Point. The cluster at the lower right includes most of the chlorophyll=maximum samples from the same stations, although three of those appear in the first cluster. The upper, looser cluster includes all the samples from Santa Monica Bay, both from the surface and the chlorophyll maximum. The most important species for component I were the dinoflagellates, *Exuviaella* sp., *Gymnodinium* sp., and *Ceratium kofoidii*. Those most important for component II were the diatoms, *Hemiaulus sinensis* and *Skeletonema costatum*, and the protozoan *Mesodinium rubrum* (from Reid et al. 1978).


10
5
0
-5
-5
0
5
10
Principal Component II
Principal Component 1
A
A
A
A
AA

occurring during March in the SCB, each correlated with distinct water masses in (1) the California CUrrent, (2) the Southern California Countercurrent, (3) the transitional zone, and (4) the nearshore. Coccolithophore assemblages were more uniform in June, indicating that the SCB was experiencing more stable conditions than were prevalent during March.

Species assemblages differ temporally and spatially. Near the thermocline, for example, an area of elevated chlorophyll concentration often occurs with a vertical species assemblage that is different from that of the surface layer. When the onshore-offshore gradient of abundance for individual species was examined, 20 of 44 taxa were found in significantly greater numbers horizontally onshore (notably <u>Nitzschia</u> sp., <u>Ceratium tripes</u>, and <u>Emiliania</u> [= <u>Coccolithus] huxleyi)</u>, and 4 appeared in significantly greater abundance offshore (notably <u>Prorocentrum balticum</u>). Other data show dominant species changes in onshore-offshore gradients (Reid et al. 1970). But when the same data are analyzed by multivariate techniques, temporal changes between stratified and upwelling conditions were more significant than were the persistent onshore-offshore floral changes (Goodman et al. 1984). Furthermore, offshore net-caught diatoms of several species are often dominant (Sargent and Walker 1948).

The midsummer phytoplankton, sampled at five stations along each of six lines extending seaward from the coast at approximately 8 km intervals between Encinitas and San Onofre, indicated significant differences in the spatial patterns of species. In terms of relative species composition, populations separated by vertical distances of a few tens of meters can be as different as, or greater than, populations separated by tens of kilometers in the horizontal dimension. Horizontal variation was generally greater at the surface than at the depth of chlorophyll maximum (Cullen et al. 1982a). The residence time of water near the coast was of great importance in determining the abundance and taxonomic composition of phytoplankton; advection of offshore water toward the coast was a major determinant of the pattern (Cullen et al. 1982a).

PHYTONEUSTON

The sea surface microlayer (upper 50 um) is a habitat populated by dense populations of microorganisms. A number of studies document enrichments in the concentration of microorganisms in the microlayer that are often several orders of magnitude greater than that occurring in subsurface waters (Hardy 1982).

Phytoneuston are the microalgae inhabiting the surface microlayer. Their existence has been recognized since early in this century (Naumann 1917), and their importance as a food source for surface-feeding zooplankton and fish larvae is well documented (Hardy 1982; Zaitsev 1971). Abundant populations of numerous species inhabit this layer. Research has not yet addressed the role of phytoneuston in the SCB, but studies in Puget Sound indicate that primary productivity within the microlayer is 2-53 times greater than in the subsurface water only a few centimeters below (Hardy and Apts 1989).

STANDING STOCK

PARTICULATE ORGANIC CARBON

Particulate organic carbon (POC) is a heterogeneous mixture of small particles in sea water. It includes living plankton, organic detritus such as fecal material, crustacean molts, and mucus material from gelatinous plankton and fish. Living plankton usually accounts for less than half the total POC, but in blooms it may comprise 70% or more of the measured POC.

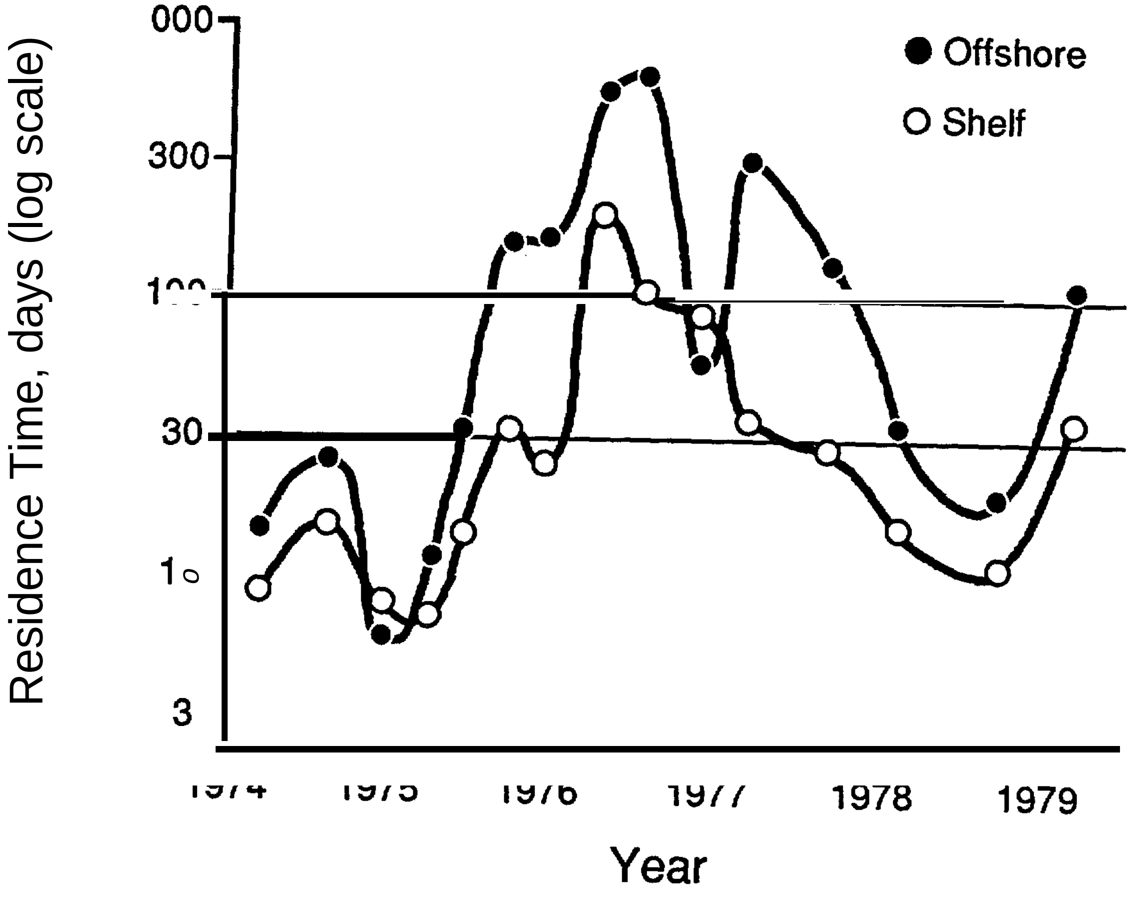
Approximately one-third of the particulate organic matter produced by primary production sinks through the euphotic zone into deep water and settles on the sediments. The rate of sedimentation, as measured in sediment traps, is greatest during times of high surface production (Honjo 1982). Several studies have examined the residence time of particulate organic carbon (the quantity present in the water divided by its rate of input or removal). In general, the residence time of POC varies from 3 to more than 100 days between seasons and years (Figure 5.2) (Eppley et al. 1983). Eppley et al. (1977, 1983) considered POC as the total mass of particulate carbon in the euphotic zone and assumed a steady state--that is, that the sinking flux out of the photic zone was equal to the production rate within the photic zone. They found that the residence time of POC decreased as a power function with increasing total carbon productivity. They suggested that this relationship provides a general guide to POC residence times in the surface layers of other oceanic regions of similar temperature and illumination.

A series of cruises spanning more than 5 years showed a marked temporal variability in both POC and ^{14}C primary production in the surface layer of the SCB. The area fluctuated between states of high production and short POC residence time and low production and long POC residence time, or between relatively eutrophic and oligotrophic states. These rates were correlated with anomalies in sea-surface temperature, reflecting both low frequency changes in ocean climate and episodic upwelling.

The number of times an atom recycles before sinking is the rate of regenerated production divided by the rate of new production. This parameter varied in the SCB from a low of 1 to 3 during the seasonal maximum of upwelling in April and June 1975, a year of high production, to nearly 20 during the most oligotrophic periods in 1976 and 1977.

What proportion of the standing stock particulate organic matter is

Figure 5.2. Residence time of particulate organic carbon (POC) in the euphotic zone from 1974 to 1979 in the SCB. Separate estimates are provided for shelf waters, <100 m depth, and offshore waters. The horizontal lines at 30 and 100 days correspond to minimum and mean estimates of the residence time of surface waters in the SCB from Hendricks (1979). When values lie above the lines, as in 1976, the surface circulation would carry organic particles out of the region before they settled out of the euphotic zone to deep water (from Eppley et al. 1983).


Residence Time, days (log scale)
000
300
100
30
10
3
● Offshore
○ Shelf
1974
1975
1976
1977
1978
1979
Year

5.13b

composed of phytoplankton? Eppley et al. (1977) found that POC was positively correlated with particulate organic nitrogen (PON), chlorophyll a, adenosine 5 '-triphosphate (ATP), and total particulate volume, with 59-83% of the variation in one variable explainable by its correlation with the other. These correlations suggest that much of the POC is of biogenic origin. Forty percent of the POC was associated with particles of less than 5 Um. Like POC, chlorophyll a, PON, ATP, and total particle volume in the chlorophyll maximum layers were higher onshore than offshore by a factor of 2 to 3. During blooms of chain-forming diatoms the particle size distribution was rather broad, whereas during blooms of dinoflagellates specific particle-size peaks were seen. For example, as much as 70% of the particulate carbon was associated with a single-size distribution peak of Prorocentrum micans. Based on decomposition experiments conducted by others, Eppley et al. (1977) concluded that only about 10-20% of the measured POC was refractory. Thus, the observed distribution of particulate matter reflected primary production and the standing stock of phytoplankton. Loss rates were density dependent, as would be expected if losses resulted from either grazing or sinking.

Small et al. (19S9) examined the dynamics and fate of POC in the photic zone overlying the Santa Monica Basin during spring and fall seasons. The major analyses centered on five cruises (October 1985, 1986, 1987; May 1986; and April 1987). Particulate carbon fluxes (PCF) during the five periods ranged from 184 to 542 mg m^{-2} d-l. When anomalies were ignored, carbon flux rates during spring were twice those of fall. Particulate carbon and nitrogen residence times in the photic zone averaged about 20 days and 39 days respectively, with no seasonality. Rapidly sinking marine snow aggregates, invested with zooplankton fecal debris, probably represent a major part of the downward flux (Alldredge and Silver 1988).

CHLOROPHYLL

Measurements of the biomass of phytoplankton have been facilitated by techniques of *in vivo* chlorophyll fluorescence (Lorenzen 1966), the measurement of ATP (Helm-Hansen and Booth 1966), and satellite remote sensing (Pelaez and McGowan 1986). One hundred and forty-three vertical profiles of *in vivo* fluorescence taken from 1974 to 1979 indicated that a subsurface chlorophyll maximum layer (CML) is generally present in the SCB. The CML is generally located well above the 1$ light level in the vicinity of the nitracline, and it is also a biomass maxima. Although the CML occurs often where light and nutrient conditions are favorable for growth, the CML depth does not usually coincide with the depth of maximum productivity (Cullen and Eppley 1981).

Cullen et al. (1982a) sampled 30 stations in a 25 by 40 km grid close to the Southern California coast and found that chlorophyll and phytoplankton biomass were higher nearshore and to the south, where relatively large dinoflagellates dominated. At each station the CML was near the nitracline and 10% light level. At some stations the CML resulted from higher levels of phytoplankton biomass, and at other stations from increases in the chlorophyll content of small flagellated phytoplankton.

REMOTE SENSING

The coastal-zone color scanner (CZCS) on the Nimbus 7 satellite has provided useful information on the distribution of phytoplankton by measuring chlorophyll over extensive areas of the SCB. Such data provide us with synoptic views of complex oceanographic regions which are impractical to obtain from ships alone (Figure 5.3). Satellite imagery has also allowed the identification of persistent and striking biological features. Many of

Figure 5.3. Phytoplankton pigment image off California derived from Nimbus-7 CZCS imagery. Red represents areas that were richest in plant pigment. A May-June cruise to the area had relatively few stations within these red areas (6), but those had 10 m chlorophyll values ranging from 2 to 8 mg m^{-3}. There were 28 stations within the yellow area with a range of 10 m chlorophyll values >0.5 to <4 mg m^{-3}. The pale blue had values >0.06, but <0.5 mg m^{-3} (from Pelaez and McGowan 1986).

5.15b

these recurring large-scale patterns were either unknown or only dimly perceived prior to the advent of satellite imagery. For example, Nimbus 7 CZCS imagery (Figure 5.3) revealed the occurrence far offshore of a large region of high phytoplankton pigment, a biological hotspot that loosely overlies a system of submarine ridges, banks, and basins that make up the Southern California Borderland. Also, shallow basins and enclosed shallow areas like the Santa Barbara Channel consistently show high pigment content, with an approximately threefold change in phytoplankton pigment content over a distance of a few kilometers. These large-scale structures undergo significant monthly, seasonal, and annual changes, although the large-scale pigment patterns for a given season tend to reappear from one year to another (Pelaez and McGowan 1986).

A longitudinally oriented meandering boundary 200-500 km offshore and several hundreds of kilometers long occurs. The inner side of this longitudinal boundary has high-pigment content interwoven with lower-pigment structures located immediately offshore. A region of low-pigment content usually overlies the deep troughs and basins that characterize most of the SCB. This low-pigment area is a recurrent feature of the region. It is immediately offshore of a narrow coastal band of high-pigment content, and is usually continuous with the low-pigment region south of the latitudinal boundary.

Surface chlorophyll, depth-integrated chlorophyll, and primary production may or may not be closely correlated, and there is considerable variance in the relationships. In some areas, such as the Central North Pacific, surface chlorophyll is not correlated with either depth-integrated chlorophyll or integrated primary production, whereas good correlations have been found in the California Current. Therefore, the use of surface chlorophyll as an indicator of the total integrated water column biomass or production must be applied with caution (Hayward and **Venrick** 1982).

Data have been gathered concurrently by ships and satellite in order to calibrate satellite measurements against actual <u>in</u> <u>situ</u> measurements of chlorophyll. A general algorithm relating satellite chlorophyll measurements to shipboard measurements agreed within **±40%.** Satellite images recorded between late February and mid-March 1979 revealed complex and changing chlorophyll patterns, including a significant decline in the mean chlorophyll concentration during the period of study. In addition, fair agreement was obtained between shipboard production estimates (554 mg m^{-2} d^{-1}, and satellite estimates (403 **mg** m^{-2} d-l) when averaged for the entire **SCB** during this period (Smith and Baker 19S2; Smith et 'al. 1982).

Pelaez and McGowan (1986) used a 34-month **CZCS** data set to describe the major **phytoplankton** pigment patterns in the California Current over space and time. Measurements were complicated because of the variability in the depth of penetration of the signals received. During June 1971, they used empirical ground **truthing** and compared independent shipboard measurements of surface chlorophyll (estimated by a flow-through **fluorometer)** with measurements from the CZCS on a 200-km transect. They found a highly significant (correlation coefficient of 0.92) relationship between the satellite and shipboard measurements. Further measurements in the California Current indicated that the surface chlorophyll concentrations correlated well with the integrated overall water column chlorophyll.

Remotely sensed near-surface chlorophyll data produce regular patterns in time and space, especially on the larger scales. These are consistent with measurements of other variables such as currents and temperature; therefore, they can yield information that will lead to an increased understanding of the distribution and patchiness of productivity. However, chlorophyll often proves to be only a crude predictor of water column biomass. Until more is known about the relationship of surface chlorophyll to the state of the phytoplankton in the rest of the water column, and until confidence limits can be placed on satellite-derived estimates, caution must be used in interpreting such measures in terms of population biology or production.

GROWTH AND PRODUCTIVITY

GROWTH

Phytoplankton "grow" by cell division and increase in cell number rather than by size. As noted above, the rate of cell division varies, according to both the natural intrinsic capability of the species and environmental conditions, from about one division per day to less than one division per week. One must be clear in distinguishing between changes in algal biomass and changes in the turnover rate of that biomass. The increase in algal biomass over a period of time may be referred to as "growth" or "new production." Thus, growth is the increase in the pool size of biomass as represented, for example, by particulate organic carbon. "Specific growth," or "regenerated production," refers to the rate of flux of carbon through that pool. Short-term measurements of carbon or nitrogen uptake are really measurements of "specific growth" since it is the turnover rate that is being measured. It is possible for high "specific growth" rates to occur simultaneously with low "growth rates" if the phytoplankton particulate carbon pool turns over rapidly but does not get any larger because of grazing by zooplankton or other factors.

Maximum phytoplankton growth, or cell division, is frequently synchronized to occur (depending on the species) at a particular time of day. For example, some dinoflagellates show maximum cell division in the early morning hours (Weiler and Chisholm 1976). Division rates for dinoflagellates have been found to be about 0.16-0.5 d-l, corresponding to doubling times of 1.4-4.4 days, respectively.

PHYTOPLANKTON PRODUCTION

Numerous measurements of primary production, the photosynthetic conversion of inorganic carbon to organic cellular material by phytoplankton, have been conducted in the SCB. The efficiency of conversion of solar energy into organic matter in the SCB has been estimated to be well under 1% (Eppley and Helm-Hansen 1986). Most measurements have been made by the classical radioactive carbon incubation technique (Steemann-Nielsen 1952). Briefly, samples of seawater containing phytoplankton are collected from depth, inoculated with a known activity of ^{14}C, and then incubated either in a shipboard deck incubator or while resuspended <u>in situ</u>. After a period of time, the samples are collected, and the now-particulate ^{14}c collected on a filter. The radioactivity is counted and is proportional to the amount of Inorganic carbon fixed to organic carbon. Early measurements of primary production indicated values, integrated over the water column, of about 0.5 g C m'^{2} of sea surface per day (Holmes 1958). Data from more than 20 cruises, with more than 220 stations sampled since 1974, indicate that the average primary production in the inner and southern portions of the SCB is 0.39 g C m^{-2} d-l over an area of approximately 30,000 km^{2}. The total production over this area is 4.3 x 10^{6} of carbon per year, or roughly 1.7 times more production per unit area than the average ocean value (Eppley et al. 1970; Owen 1974).

Small et al. (1989) summarized both historical data and the results of their own measurements of primary production for the Santa Monica Basin. Their summary indicates mean rates in spring (March-May) of 1.050 g C m^{-2} d^{-}

^{1} (range 0.411-1.254) and in fall (September-November) of 0.531 mg C m^{-2} d-l (range 0.213-0.800).

PHOTOSYNTHESIS AND CHLOROPHYLL

The efficiency of photosynthesis, often called the photosynthetic assimilation number, can be represented as micrograms of carbon assimilated per microgram chlorophyll a. In the SCB, as in many areas, the photosynthetic assimilation number increases during bloom formation or when ample light and nutrients become available during the spring, then decreases as factors limit production.

Phytoplankton show evidence of adaptation to available light quality and quantity, including a shift in pigment composition. The photosynthetic action spectrum, or photosynthetic activity at different specific wavelengths, has not been measured routinely at sea. However, measurements have been made of the action spectra of chlorophyll a fluorescence. These chlorophyll a fluorescence action spectra have been used to study the light adaptation of phytoplankton, including species in the SCB (Neori et al. 1984). Comparisons of absorption spectra with fluorescence excitation spectra indicate an apparent increase in efficiency of sensitization of chlorophyll a fluorescence in the blue and green spectral regions for low-light populations (Neori et al. 1984). In samples from deeper waters, both absorption of chlorophyll a and fluorescence excitation spectra showed enhancement in the blue to green portion of the spectrum from 700 to 560 nm, relative to that at 440 nm. The data indicated that, in the natural population studied, shade adaptation caused increases in the concentration of photosynthetic accessory pigments relative to chlorophyll a. Changes in pigment concentration occurred over periods of less than one day.

FACTORS AFFECTING PRODUCTION

Currents and Upwelling

Primary production in the SCB is regulated by basic physical processes, including wind, which affect the stability of the water column and subsequent mixing and nutrient input to the euphotic zone. These processes change on a variety of temporal and spatial scales. An important controlling process is the advection of nutrient-rich, low-salinity water from the north in the offshore flow of “the California Current. Time series data indicate that the strength of this cold-current flow is positively correlated with increasing plankton biomass. For example, the anomalistic warm years, 1957 to 1960, were correlated with low biological production, while the cold years of 1953 and 1956 were associated with high production (Bernal and McGowan 1981).

Coastal upwelling is the vertical advection of water along the coast when previous surface waters are displaced offshore. Upwelling events are indicated by sudden declines of sea surface temperature, the shoaling of the nitracline, and the appearance of nitrate at the surface. Upwelling is usually driven by local winds blowing parallel to the shoreline and has been documented in the San Diego area (Dorman and Palmer 1981). At the Scripps Institution of Oceanography (S10) pier, low temperature anomalies corresponding to such upwelling episodes are accompanied by a rapid growth of phytoplanktonic diatoms (Tent 1981). Small-scale mixing processes are important to the nutrient input across the nitracline into the nutrient-depleted surface waters. Relatively short-term tidal and internal wave frequencies bring nitrate rich water into the surface layer over short-term intervals (Cullen et al. 1983; Armstrong and LaFond 1966).

The upward transport of the denser subsurface water during upwelling brings nutrient-rich cold water to the surface. Satellite imagery, remote temperature sensing, and ship-based temperature sampling show that coastal upwelling in the SCB occurs within a few kilometers of shore, with exceptions at Point Conception, Pales Verdes Peninsula, and Point Loma. Water south of these points frequently has a clear visible cold phase that extends for many kilometers. In general, upwelling is only a weak summer phenomenon in Southern California, although May and June appear to be times of maximum upwelling in the vicinity of the S10 pier. In short, upwelling in the SCB is generally of short duration (a week or less), and generally occurs less frequently and less intensely than in other places along the coast north of Point Conception.

Water Temperature

In the SCB, average seasonal temperatures range from a minimum of about 12°C to a maximum of about 24°C. As with biological processes in other organisms, temperature has a major influence on the growth and physiology of phytoplankton. Each species generally displays its own specific temperature optimum for growth (Smayda 1980) and for primary production (Eppley 1972).

The initial photochemical reactions of photosynthesis are not temperature dependent, but the subsequent enzymatic carbon transformation reactions are generally described by the Van't Hoff equation (that is, an approximate doubling with a 10°C rise in temperature). Most marine phytoplankton have growth rates of about 1 to 2 doublings per day at 20-25°C, whereas the fastest-growing species approach 3 to 4 doublings per day at those temperatures. In the SCB, doublings are generally less than 1 per day, averaged over the euphotic zone (Eppley 1972).

Nutrients

Many of the micronutrients required by phytoplankton for growth, including Ca, K, S, B, and others, are believed to be present in sufficient concentration in seawater to meet or exceed the growth requirements of phytoplankton. Others, such as N, P, and trace metals (for example, Fe, Mn, Co, Cu, Z, and others), are in low concentrations and are potentially limiting to growth. Vitamins such as B_1, B_{12}, or biotin are also required by many species for growth. Data on the vitamin requirements of phytoplankton are extremely limited, but some studies indicate that populations in the SCB do require sufficient vitamin B_{12} to grow normally (Carlucci 1970).

Considerable stimulation in phytoplankton growth can be obtained in surface-water samples from the SCB when they are experimentally enriched with nitrogen, phosphorus, and silicon, indicating that these three elements are most likely to limit phytoplankton growth in the SCB (Eppley 1968). Evidence suggests that nitrogen is the most common limiting nutrient. Uptake rates of nitrogen-15, ammonium, and urea have been measured at different concentration levels. In general, these uptake rates increase hyperbolically with increasing nutrient concentration. Such data suggest that increases in ambient nitrogen, for example, from coastal wastewater outfalls, will lead to increasing primary production (Eppley et al. 1979a,b).

Nitrate enters the euphotic zone from deep water, rain, and river and coastal wastewater discharges. The resulting production based on this nitrogen is termed “new” production in contrast to the “regenerated” production that results from utilization by the phytoplankton of ammonium, urea, and other forms of recycled nitrogen produced in the euphotic zone. The rates of utilization and regeneration of nitrogen in the SCB have been examined in some detail (McCarthy 1972; Eppley et al. 1979a,b; Harrison 1978; Redalje 1983). About two-thirds of the nitrogen demand is provided by recycled nitrogen (that is, ammonium and urea produced within the **euphotic** zone by the metabolism of animals and bacteria) and about one-third by nitrate via physical transport from deeper water. The physical processes that bring nitrate into the **euphotic** zone are, along with seasonal changes in light intensity and temperature, the driving forces for primary production. Nitrogen is recycled from ammonium to particulate organic nitrogen and back to ammonium over a time scale of approximately two weeks (**Eppley** et al. 1983). Thus, regenerated production is generally proportional to new production (**Eppley** 1979a; **Eppley** et al. 19S3).

Sewage **outfalls** in Southern California provide a source of nutrients, primarily nitrogen, which stimulate **phytoplankton** primary production. The combined flow of sewage **outfalls** in the SCB is large--about 4 x 10^9 l of primary and secondary effluent per day. Studies of the assimilation of ammonium, nitrate, and urea were conducted at outfall sites in the SCB (Institute of Marine Resources 1971; Thomas **and Seibert** 1974). Nutrient bioassays, that is, measurements of phytoplankton growth in response to different additions of nutrients, were performed on samples taken above major sewage **outfalls.** Assimilation of nitrogen versus increasing concentrations of nitrogen fit the **Michaelis-Menten** kinetics and indicated that the maximum growth rate increased with the concentration of nitrogen, while the saturation constant was uniform over a range of dilution rates. In general, these studies showed that nitrogen was the principal nutrient limiting **phytoplankton** growth and that nitrogen inputs from **outfalls** stimulated **phytoplankton** growth.

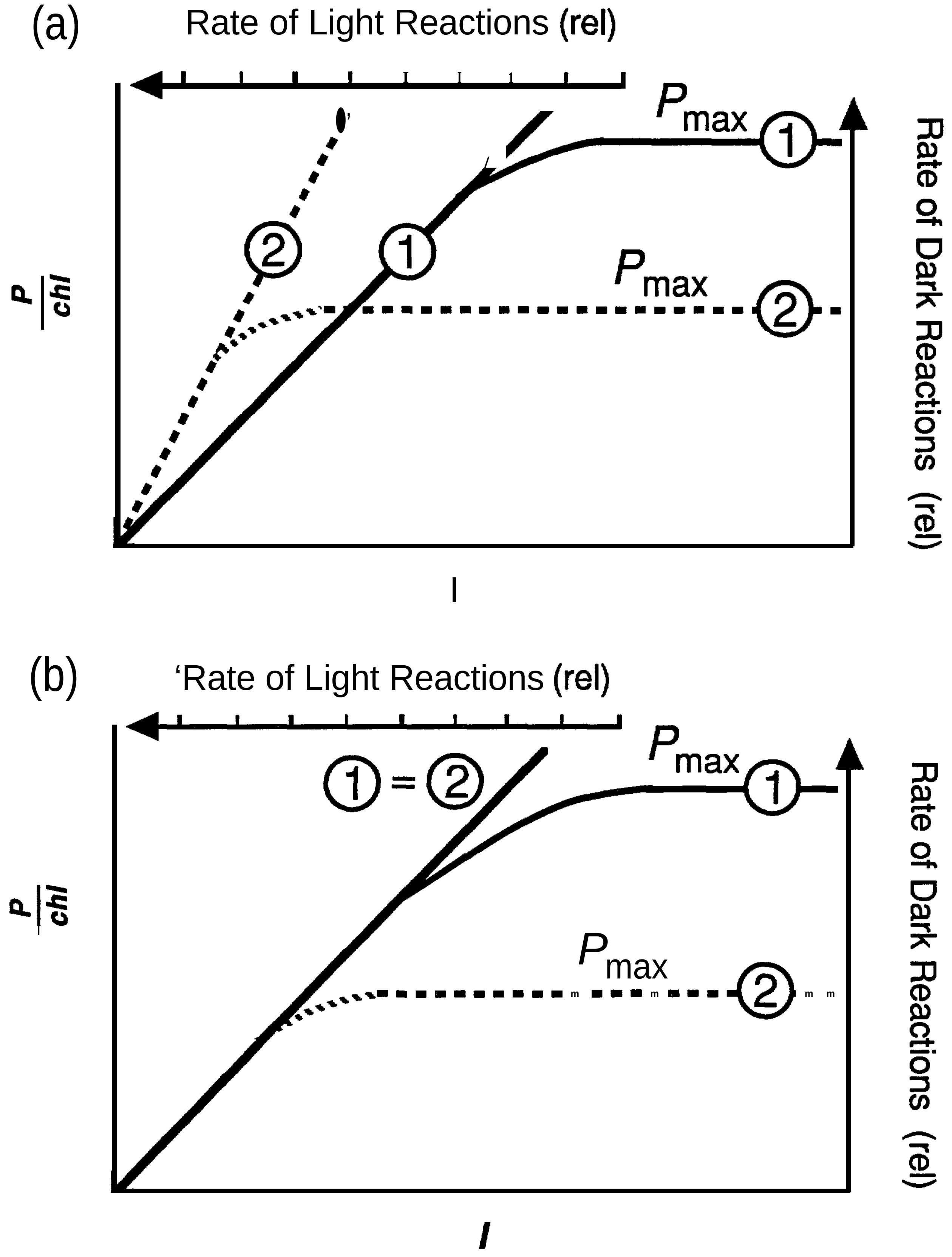
Light

The quality (spectral distribution of wavelengths) and quantity (**irradiance**) of solar energy differ both spatially and temporally according to depth in the photic zone, cloud cover, day length, and seasonal sun angle. The portion of the solar spectrum which is utilized for photosynthesis, the so-called photosynthetically active radiation (PAR), is confined to the spectral region 350-700 nm. The amount of energy penetrating the water column increases with decreasing angle to the solar zenith. Long wavelengths and very short wavelengths are absorbed relatively rapidly, with the least absorption at approximately 490 nm in blue ocean water. In greener coastal water, rich with phytoplankton, wave lengths of maximum penetration are shifted to about 550 nm.

General responses of phytoplankton photosynthetic rate to light intensity and quality have been discussed in detail elsewhere (Harris 1980). When phytoplankton are incubated at different light intensities, photosynthesis generally increases with increasing light intensities until a point of light saturation is reached, where further increases in intensity generally result in very little or no increase, or even a decrease, in photosynthesis. This point of light saturation typically occurs at lower light levels for populations occurring deep in the euphotic zone and occurs at higher light intensities for populations near the surface (Figure 5.4). Such data indicate that phytoplankton are typically adapted to the incident levels of light where they occur; that is, so-called light or shade species occur, just as they do in terrestrial forest ecosystems. The compensation light intensity (that is, where photosynthesis and respiration balance each other in regard to oxygen exchange) occurs at approximately .1$ of surface irradiance (Platt and Jassby 1976).

Unlike high-latitude boreal "areas where light levels can be limiting to production, evidence suggests that in the SCB light intensity does not normally limit primary production. However, beyond saturation light levels,

Figure 5.4. The effects of high- and low-light conditions on photosynthetic responses in phytoplankton. Population (1) is located at the top of the euphotic zone, population (2) at the bottom. Situation (a) reflects the response of increased chlorophyll content of population (2); that is, the light reaction rate is higher in (2) than in (l). Situation (b) reflects the response of the light reactions being equal (from Yentsch 1980).


(a)
Rate of Light Reactions (rel)
P_{max} ①
② ①
P_{max} ②
$\frac{P}{chl}$
Rate of Dark Reactions (rel)
I
(b)
'Rate of Light Reactions (rel)
① = ②
P_{max} ①
P_{max} ②
$\frac{P}{chl}$
Rate of Dark Reactions (rel)
I

5.25b

photoinhibition can occur, and near-surface populations may be photoinhibited by high summer light intensities (Hardy and Apts 19S9).

Both light-limited and light-saturated photosynthesis typically exhibit diel periodicity which is not uniform. An endogenous biological rhythm, the underlying basis of which has not been completely defined, may partially control these diel oscillations of photosynthesis. Studies in the Santa Barbara Channel, from north of Anacapa Island to south of Point Conception between May and August 1980, confirmed the presence of diel oscillations in the photosynthesis-irradiance (P-I) relationships. The initial slopes (alpha) and asymptote (P_{max}) of the P-I curve change significantly over the day and the oscillations appeared unrelated to changes in chlorophyll a concentrations. Amplitudes of the daily variations in photosynthesis ranged from approximately 3 to 9 as measured by the maximum to minimum ratio for P_{max}, Diatom rich samples collected during an upwelling event and those dominated by dinoflagellates both have midday to early afternoon maxima in alpha and P_{max}. Samples from other locations had peak photosynthetic activity later in the afternoon. Results indicated that the photosynthesis-irradiance relationship is time dependent and, moreover, that changes in alpha and P_{max} are closely coupled for a variety of natural phytoplankton assemblages (Harding et al. 1982).

Ultraviolet-B radiation (280-320 nm) penetrates approximately 20 m through the water column in clear oceanic water. Evidence suggests that UV-B radiation inhibits photosynthesis in the upper water column (Smith et al. 1980). Many earlier measurements probably overestimated primary production to some extent because they were conducted in glass bottles or containers which filtered out the inhibiting UV-B component of the solar spectrum (Worrest 1983). Concerns are growing regarding the global stratospheric ozone depletion, resultant increases in UV-B radiation, and potential detrimental effects on marine ecosystems (Hardy and Gucinski in press).

Grazing

Most zooplankton depend to a large degree on phytoplankton as a food source; therefore, one might expect to find increases in zooplankton abundance correlated with increases in phytoplankton abundance. However, because of differences in generation time between phytoplankton and the "response time" of zooplankton, one actually finds an alteration of Positive and negative correlations in space and time (Harvey et al. 1935). The abundance of feeding juvenile stages of the copepod *Callinus pacificus* was positively correlated with the horizontal and vertical biomass of phytoplankton (Mullen and Brooks 1972). However, in another study, utilizing concurrent phyto- and zooplankton sampling, no correlation was found between phytoplankton biomass estimated microscopically and the biomass of protozoa, micrometazoa, or total microzooplankton (Beers et al. 1980).

Differences In reproduction rates between unicellular plants and metazoan animals cause correlations to occur with a time lag. The maximum concentration of phytoplankton tends to occur in spring, while the macrozooplankton maximum generally occurs in summer. When estimated on a quarterly basis, macrozooplankton biomass was positively correlated with primary production over the past 30 years (Smith and Eppley 1982).

MODELING PHYTOPLANKTON PRODUCTION

The Food Chain Research Group of Scripps Institution of Oceanography (S10) developed an empirical algorithm to predict primary production in the SCB from daylength and the temperature anomaly (departure from the long-term mean temperature) for sea-surface temperature recorded at the S10 pier.

$$P = \exp(-3.78 - 0.372\,T + 0.227\,D)$$

The mean production, P, can be calculated from this equation by setting daylength (D = 12 hours) and temperature anomaly (T = 0) to give 0.392 g C m^{-2} d ‘l.

This algorithm explains, in a statistical sense, about 60% of the between-cruises variability in primary production measurements. It has been used to reconstruct the history of primary production back to 1920. Nitrate is believed to drive production, and the temperature anomaly explained about 65$ of the variability in nitracline depth on the shelf, but only about 25% at offshore stations.

Satellite imagery has provided valuable information on the spatial and temporal distribution of chlorophyll biomass and its relationship to primary productivity. Using measurements of surface chlorophyll, measured from the coastal-zone color scanner aboard the Nimbus 7 satellite, along with measurements of photosynthetic primary production during simultaneous oceanographic cruises, the relationship between surface chlorophyll and productivity over large areas has begun to emerge. These measurements indicate that productivity in the SCB is intermediate compared to other areas of the Pacific (greater than the subtropical Pacific gyre), but less than the Peru upwelling region. For example, aerial average productivity over the SCB between 17 February and 11 March 1979 was about 461-564 mg C m^{-2} d-l (Smith and Baker 1982). Satellite chlorophyll-images (1260 km on a side) showed a high degree of heterogeneity in chlorophyll distribution patterns at all scales and revealed recurrent chlorophyll features in the California Current (Pelaez and Guan 1982).

Obtaining accurate measures of primary productivity from satellite imagery can be a difficult and complex task. First, only approximately the upper one-fifth of the euphotic zone chlorophyll is registered by satellite images, and the vertical distribution of chlorophyll and photosynthesis is not uniform. To estimate primary productivity from satellite imagery one must derive an accurate proportionality estimate (f) relating the satellite-measured chlorophyll concentration to actual *in situ* chlorophyll concentration and *in situ* primary productivity (milligrams of carbon per square meter per day). This proportionality often has a large variance. In the richest waters f approaches a minimum limit value of about 100 mg C m^{-2} ″ d-l mg^{-1} chlorophyll pigment m^{-3}. In the simplest systems f is proportional to insolation (solar irradiance) (Eppley et al. 1985). However, much of the variability in the relationship between time and space in the SCB is related to environmental variables.

SPATIAL AND TEMPORAL PATTERN

GENERAL PATTERN

Spatial and temporal patterns occur over a wide range of scales, complicating interpretations of the distribution and abundance of plankton. Environmental factors regulating growth lead to a complex spatial and temporal pattern of phytoplankton and productivity in the SCB. Every point in the water column is basically unique with regard to such variables as light intensity, nutrient mixture and concentration, and temperature. Small-scale biomass patchiness occurs even on scales of less than a meter. For example, high chlorophyll concentrations are associated with mucilaginous aggregates of a few millimeters In size (Alldredge and Cox 1982). Physical factors of mixing and currents also determine the distribution of phytoplankton. Each species differs in its unique physiological requirements and optima for both light and nutrients. Topographic features of the SCB such as the complex of offshore islands and banks, which run from Santa Rosa and San Nicolas south to Tanner and Cortes banks, impose additional heterogeneity.

Santa Monica Bay, in the central part of the SCB, reflects in its geographic features, nutrients, and plankton populations an entity that is distinguishable from other nearshore sites (Reid et al. 1978). The bay generally has more dominant dinoflagellate populations, higher concentrations of ammonium, and proximity of the euphotic zone to nutrient regeneration at the bottom, as well as considerable anthropogenic inputs (Eppley et al. 1979a).

ONSHORE-OFFSHORE PATTERN

The terms "nearshore" and “offshore” are used rather loosely by different authors; so, for this reason, "nearshore" may include an area extending out to 5 km in one study and as far out as 100 km in another study . In terms of the nutrient regime over the entire euphotic zone in general, ammonia increases curvilinearly with distance from shore, silicate declines slightly, but phosphate and nitrate show no consistent gradient. This is because the euphotic depth increases offshore in somewhat the same way as does the nitracline. Less is known concerning gradients of other dissolved materials. Dissolved organic carbon shows little pattern in surface waters within 10 km of shore. The concentrations of organic nitrogen, phosphorus, vitamin B_{12}, and thiamine generally decrease offshore (Strickland et al. 1970; Carlucci 1970).

In the SCB, as is typical of the West Coast, plankton abundance and primary production are generally higher nearshore than offshore. Since the continental shelf is only a few kilometers wide, internal waves from deep water typically move shoreward, injecting nutrient-rich water onto the shelf area (Cooper 1947). Also, episodic sediment disturbance and suspension are important mechanisms of nutrient regeneration in the shallow nearshore area

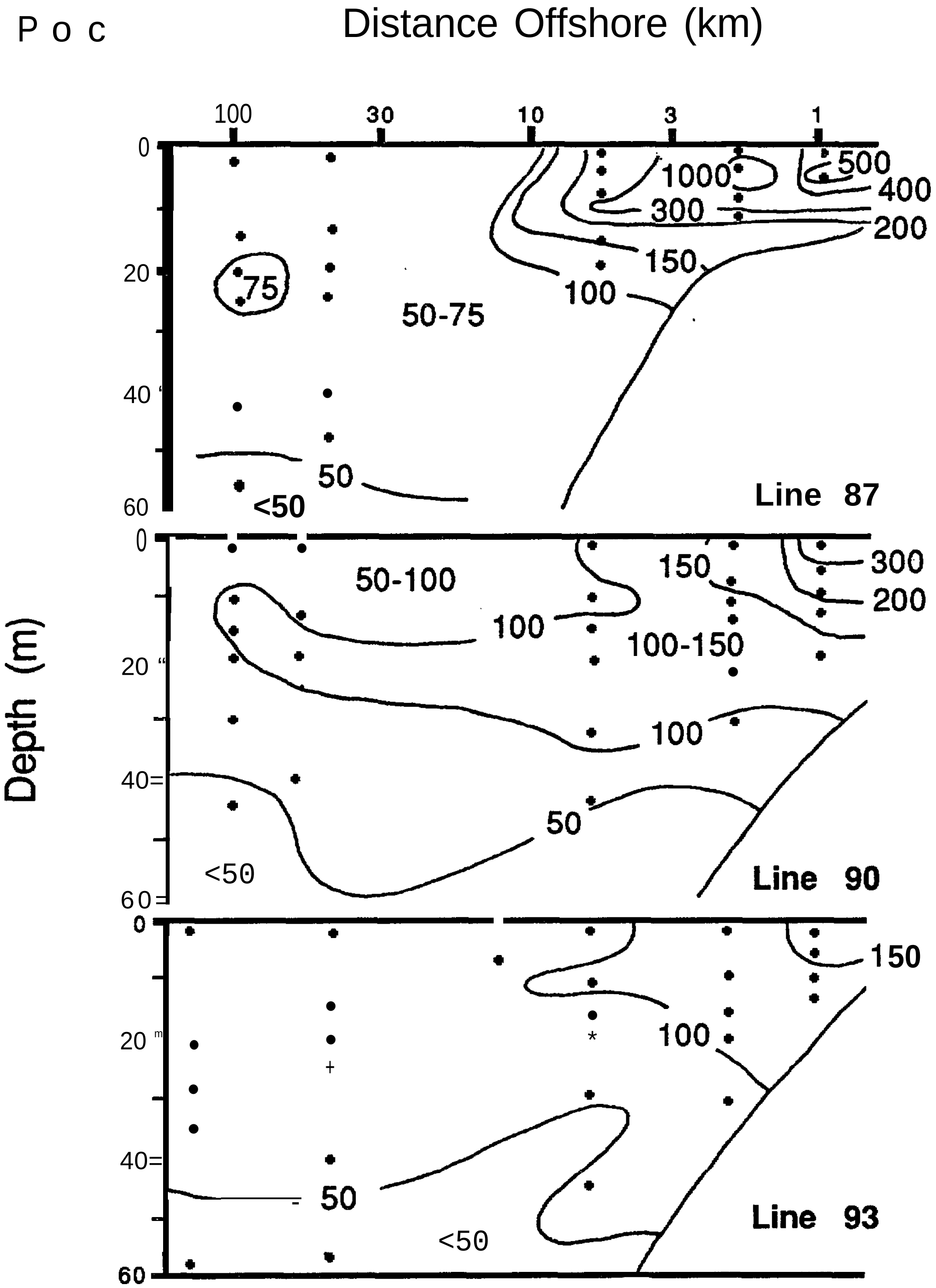
(Fanning et al. 1982). **Eppley** et al. (1977) collected samples during quarterly cruises along three transects approximately perpendicular to shore from: (1) Santa Monica Bay, (2) near Dana Point, and (3) Del Mar. These samples were taken from six depths in the **euphotic** zone, which varied from 20 m nearshore to 50-70 m offshore. The three transects extended as far as ***96-107 km*** offshore. They found that particulate organic carbon decreased along a gradient from onshore to offshore and decreased with increasing depth, although subsurface maxima were often present. The highest POC values were found in Santa Monica Bay (Figure 5.5).

The biomass of **phytoplankton** either per-unit surface area or per-unit volume decreases with Increasing distance from shore within the first 10 km offshore **(Eppley** et al. 1970). This general pattern holds off Point Loma **(Kiefer** 1973) and off **La Jolla (Barnett** 1974). The coastal-zone color scanner satellite images confirm the decreasing biomass as one moves offshore, although offshore eddies and swirls exist that also contain quite high concentrations of **phytoplankton** (Smith and Baker 1982; **Pelaez** and Guan 1982). Most data indicate that primary production also decreases in the offshore direction. Because of the greater supply of nutrients nearshore, a unit of chlorophyll is more productive nearshore than offshore **(Cullen** and Renger 1979).

LONGSHORE PATTERN

Statistical comparison of pairs of stations located at equal distances from shore revealed no significant **longshore** trends in nitrate, silicate, or phosphate in the upper 50 m **(Mullin 1986).** However, the lack of a **longshore** trend in nutrients may apply only to the portion of the SCB from Santa Monica Bay southward. The northern half of the nearshore SCB has not been studied. Unpublished data (Brewer and Brewer) that encompass the entire SCB

Figure 5.5. Vertical sections of particulate organic carbon (POC, expressed as mg 1^{-1}) during 6-17 September 1975. Distance offshore is shown on a logarithmic scale. Line 87 from Santa Monica Bay, Line 90 from Dana Point, Line 93 from Del Mar (from Eppley et al. 1977).


P o c
Distance Offshore (km)
100
30
10
3
1
Depth (m)
0
20
40
60
75
50-75
1000
500
400
300
200
150
100
50
<50
Line 87
50-100
100
150
300
200
100-150
100
50
<50
Line 90
150
100
50
<50
Line 93

do, in fact, show a significant trend in nitrate that increases from Santa Monica Bay to Point Conception. Evidence also points to small-scale longshore patchiness of phytoplankton biomass on scales between 0.1 and 10 km (Mullin 1979). Measurements based on *in vivo* fluorescence of chlorophyll at a single depth show predominant variability on scales exceeding 600 m (Star and Mullin 1979; Fiedler 1982a).

Significant differences in longshore abundances of phytoplankton species occurred between the north and south parts of the SCB. out of 45 cases tested, 19 had greater abundances in the south--notably *Nitzschia sicula*, *Ceratium tripes*, and *Emiliania* (=*Coccolithus*) *huxleyi*. Only three species had greater abundances to the north (Cullen et al. 1982a). Surface phytoplankton occurring from Dana Point to San Diego were clearly divided into three distinct floral groups based on the 54 most abundant species. These "assemblage patches" had approximate longshore dimensions of 22-27 km (similar to the length of so-called coherent currents in the same area), suggesting that current patterns are important in determining the longshore distribution of these species assemblages (Eppley et al. 1984b).

Phytoplankton species assemblages also differ in longshore transects between La Jolla and Santa Monica Bay (Reid et al. 1978). Comparison of the longshore- and offshore-directed transects indicates that, at both the chlorophyll-maximum layer and at the surface, species composition varied more in the offshore than in the longshore direction.

VERTICAL PATTERN AND VERTICAL MIGRATION

In addition to horizontal patterns, the abundance of individual species, total biomass, and productivity of phytoplankton generally show marked differences vertically through the water column. Differences in biomass occur at the same depth from stations sampled within a few kilometers of each other and only a few days apart.

The use of in vivo fluorescence to measure biomass by either pumping samples from depth to a sensing instrument on deck or by using submersible detectors has led to a recognition of the importance of fine-scale vertical distribution in the SCB. Biomass, as measured by chlorophyll fluorescence, is generally maximum below the surface, often occurring at a depth of about 20 m. The maximum may become more intense and shallower as one moves closer to shore, generally following the nutricline (Cullen and Eppley 1981; Cullen et al. 1982a). Other measures, including microscopic phytoplankton abundance, ATP, and bacterial biomass are often also positively correlated with the vertical distribution of chlorophyll in the euphotic zone (Fuhrman et al. 1980; Cullen and Eppley 1981).

The depth of maximum abundance usually differs between individual species. Differences in the vertical distribution of individual species result from differences in physiology with respect to light, nutrients, buoyancy, and motility. Often large dinoflagellates are plentiful near the surface, whereas the numerically dominant diatoms are most numerous at or below 20 m.

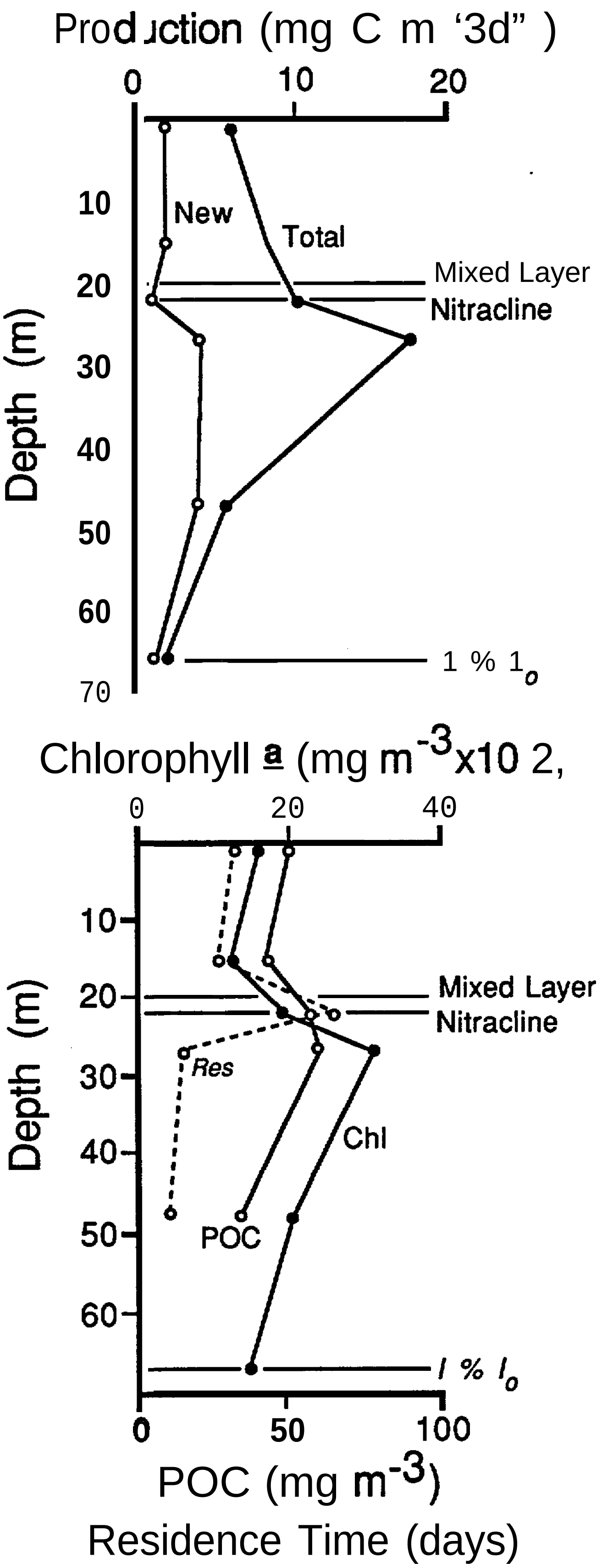
Primary production depends largely on the presence of light and chlorophyll and less directly on nutrients. It generally shows a subsurface maximum at both nearshore and offshore stations of the SCB, and tends to be shallower than the chlorophyll maximum layer (Cullen and Eppley 1981). In Santa Monica Bay, maximum production is at the surface, as is the greatest concentration of chlorophyll. At nearshore stations, production per unit of chlorophyll is maximum at subsurface depths, probably because of the favorable nutrient supply there, and perhaps also because of photoinhibition occurring at the surface. Recent data by Small et al. (1989) confirm a subsurface maximum of both chlorophyll and primary production in the Santa Monica Basin (Figure 5.6).

In the SCB, as in many other coastal areas, dinoflagellates migrate vertically through the water column with a recurring diel pattern. For example, Gonyaulax polyedra was found to migrate downward in the evening and then re-form in surface patches in the morning (Holmes et al. 1967). A layer of dinoflagellates dominated by Prorocentrum micans, Perirdinium depressum, and Ceratium furca migrates downward in the evening (Eppley et al. 1968). Many studies have described particular patterns of depth distribution for different species (Allen 1928; Cullen et al. 1982a; Kimor 1981; Reid et al. 1978). Several studies have suggested that the relative species composition and abundances were more similar to each other in samples from the surface than in samples from the deep chlorophyll maximum. In these studies the horizontal separation between stations was tens of kilometers and the vertical separation was only tens of meters (Reid et al. 1978; Cullen et al. 1982a).

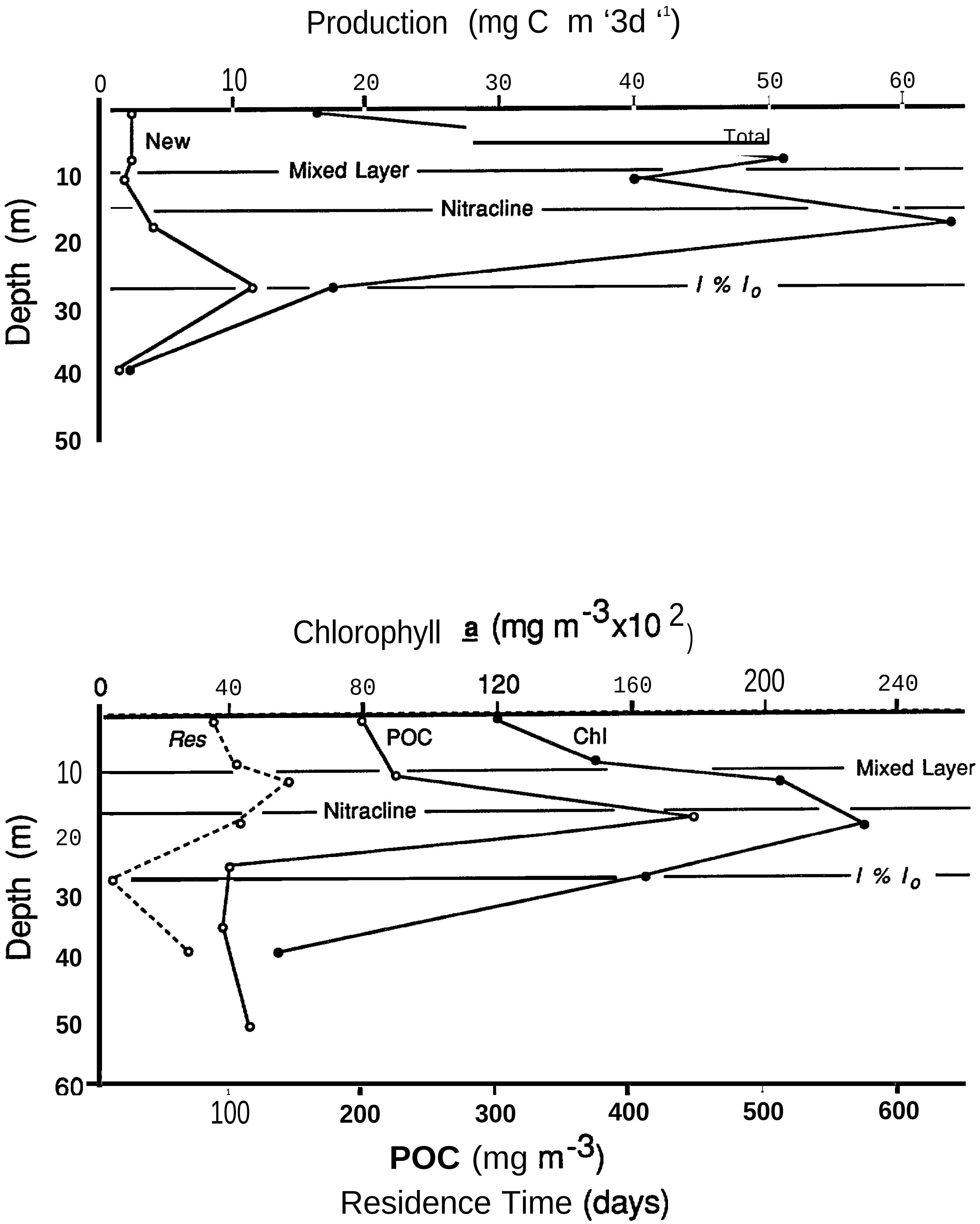
LONG-TERM TEMPORAL PATTERN

Temporal patterns can be divided into short-term “events” on a scale of hours, days, or a few months (discussed below) and longer-term seasonal or recurring annual trends. Long-term trends in species composition and population fluctuations are available from a few sites, including Santa Monica Bay from 1957 to 1972 (Kleppel 1980) and the S10 pier from 1920 to 1939 (Allen 1936, 1941). In general, diatoms have several major peaks of abundance 5 to 6 weeks in duration, usually during the first half (occasionally the latter half) of each summer (Tent 1976, 1981; Tent and Platt 1979). A high correlation in the occurrence of blooms was generally observed between San Diego and Port Hueneme, although the dominant species

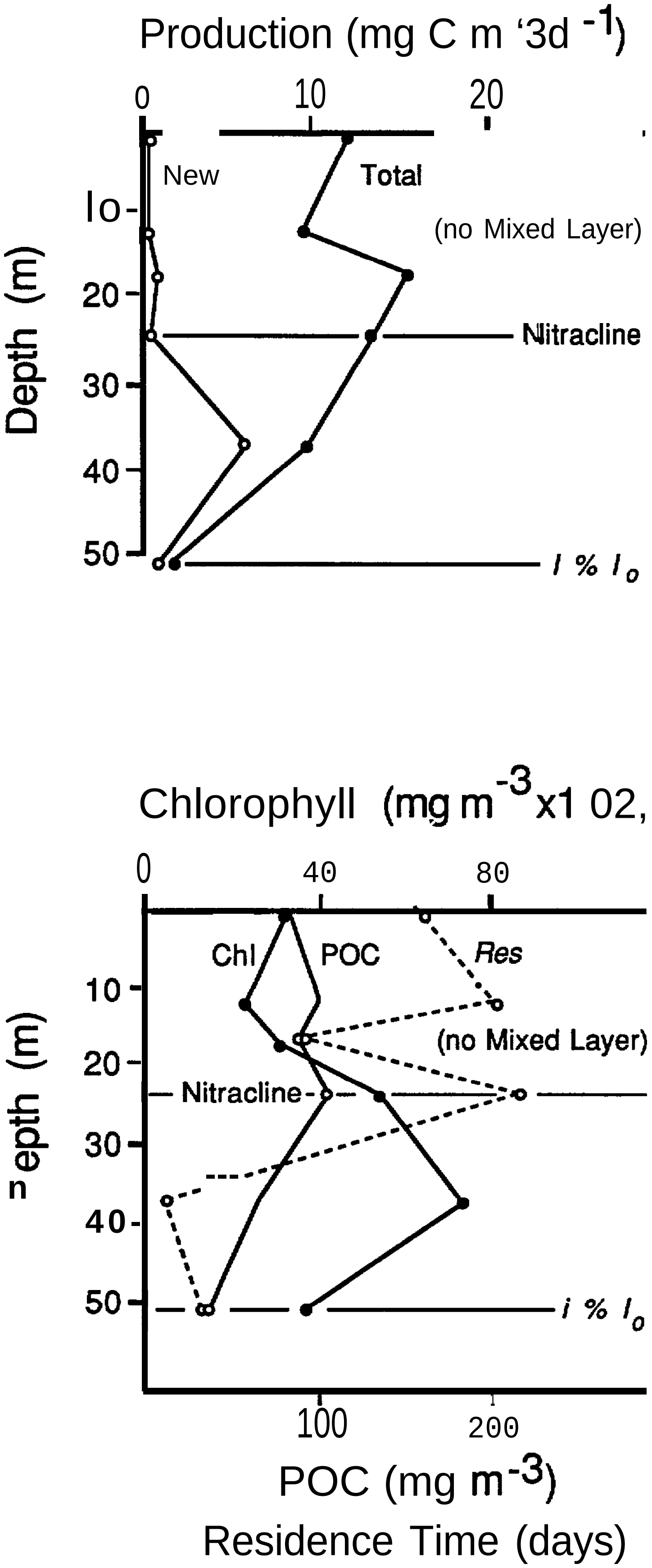
Figure 5.6. Vertical profiles of primary and new production, chlorophyll, POC, and particle residence time in the Santa Monica Basin. A=October 1986, B=May 1986, C=April 1987 (from Small et al. 1989).


Production (mg C m-3d-1)
0
10
20
Depth (m)
10
20
30
40
50
60
70
New
Total
Mixed Layer
Nitracline
1 % I0
Chlorophyll a (mg m-3x10 2,
0
20
40
Depth (m)
10
20
30
40
50
60
Mixed Layer
Nitracline
Res
Chl
POC
1 % I0
0
50
100
POC (mg m-3)
Residence Time (days)

(a)


Production (mg C m ‘3d ‘1)
0
10
20
30
40
50
60
New
Total
Mixed Layer
Nitracline
I % I0
Depth (m)
10
20
30
40
50
Chlorophyll a (mg m-3x10 2)
0
40
80
120
160
200
240
Res
POC
Chl
Mixed Layer
Nitracline
I % I0
Depth (m)
10
20
30
40
50
60
100
200
300
400
500
600
POC (mg m-3)
Residence Time (days)

(b)


Production (mg C m ‘3d -1)
0
10
20
New
Total
(no Mixed Layer)
Nitracline
I % Io
Depth (m)
lo-
20
30
40
50
Chlorophyll (mg m-3 x1 02,
0
40
80
Chl
POC
Res
(no Mixed Layer)
Nitracline
i % Io
ⁿepth (m)
10
20
30
40
50
100
200
POC (mg m-3)
Residence Time (days)

(c)

in the two locales were frequently different. The majority of these blooms occurred in conjunction with upwelling events. Sea surface temperature decreases of 2.5°C, indicating upwelling, were often associated with diatom standing-stock increases of 4 orders of magnitude.

The biomass of the larger net-caught diatoms tends to be maximal in late winter or spring, although fall blooms also occur (Allen 1936). Large dinoflagellates tend to bloom in summer and slightly earlier at La Jolla than at Point Hueneme, but winter blooms are also known (Allen 1941). Unlike La Jolla, phytoplankton densities at Point Hueneme show seasonal variations that exceed the variability on shorter time scales (Tent and Platt 1979). Dinoflagellate abundances fluctuate with some peaks continuing to appear in the fall (Reid et al. 1970). Weekly samples at a depth of 2 m off the end of the Seal Beach Pier over a period of a year indicated abundant populations of diatoms or dinoflagellates (or both) blooming in the spring, followed by a second pulse of diatoms appearing in late summer. *Asterionella japonica* was an important component, succeeded later by *Skeletonema costatum*. The numbers of these major groups of phytoplankton remained low throughout the winter while nanoplanktonic flagellates such as the chrysophytes and cryptophytes showed an increased relative and absolute abundance.

Patterns of species abundance in the SCB phytoplankton also differ from year to year (Esterly 1928; Sleggs 1927; Allen 1941; Goodman et al. 1984). The year-to-year differences in the size of coastal diatom blooms are believed to be related to the timing and intensity of local coastal upwelling and interannual changes in the flow of the California Current (Tent 1976, 1981).

RELATION BETWEEN LARGE- AND SMALL-SCALE PATTERN

Persistent large scale patterns such as onshore-offshore or gross vertical gradients of biomass do exist. There are also climatic changes on interannual and interdecadal scales as well as small-scale spatial and temporal variability that affect the patterns of phytoplankton distribution. However, the coupling between these scales is not well understood. Also, for the most part, the time scale of phytoplankton patches and possible interannual changes in the supply of food for grazing animals remain unknown.

ENCLOSED EMBAYMENTS

Studies of phytoplankton communities in harbors of Southern California indicate general patterns of seasonal variation similar to those occurring nearshore; that is, low winter productivity starting in December followed by a spring bloom in April, a minor drop in productivity in May, and secondary summer and fall blooms which are localized and sporadic. In Marina Del Rey, phytoplankton productivity and chlorophyll values decreased from the marina entrance inward. In Long Beach Harbor, on the other hand, both productivity and chlorophyll values were consistently greater inside the harbor than outside, and productivity and chlorophyll were higher than that in Marina del Rey by a factor of 2 to 3 (Soule and Oguri 1977).

The diatom flora of California lagoons has been classified into six categories (Carpelan 1978). Categories were defined on the basis of tolerance to many factors in addition to salinity. Stenotypic species were limited to environments with slow, small, and predictable changes. Species within other categories can tolerate rapid, large, and random changes in the environment.

SHALLOW WATER BENTHIC MICROFLORA

Benthic microflora represent important contributors to primary productivity in shallow water intertidal habitats from the tropics to the Arctic . The productivity of such **benthic microflora** differs greatly, both spatially and temporally. **Shaffer** and Onuf (1983) studied Mugu Lagoon in order to determine the factors that contributed to the heterogeneity of the **benthic microflora.** Over a l-year period, duplicate monthly determinations of **benthic microflora** production were made at different locations along six parallel transects located at different distances from the mouth of Mugu Lagoon so that the spatial, temporal, sediment, and tidal height relationships could be examined. Multiple-regression analysis indicated that chlorophyll a, solar radiation, water temperature, community respiration, sediment composition, and initial dissolved oxygen accounted for little of the observed variation. But, when samples were analyzed separately for each month, the **individual** categories explained much of the variance. In the monthly categorization, each of the six independent variables was most important during at least one month. Light or chlorophyll was most important in 5 of 14 months. Gross primary production did not vary according to sediment type.

PHYTOPLANKTON BLOOMS

GENERAL

The **SCB,** like other coastal areas, can experience blooms, that is, dense growths and accumulations of phytoplankton. Short-term blooms of diatoms and other phytoplankton, associated with **upwelling** events, often occur in winter or spring and last for a few days to a few weeks. A typical year has three such blooms, each lasting 5 to 6 weeks (Tent 1976). The variance in abundance of phytoplankton between bloom and non-bloom periods can be almost as great as the annual variation in abundance (Tent and **Platt** 1979).

Under certain oceanographic conditions blooms are dense enough to alter the color of the water to red, yellow, green, or brown (Oguri et al. 1975). Although these blooms can be caused by different groups of organisms, including diatoms, the most common are caused by dinoflagellates.

RED TIDE

Although not related to the tidal cycle, blooms of red-pigmented dinoflagellates are called "red tide." Red tides can occur in the SCB almost any month of the year and are generally most pronounced nearshore (Oguri et al. 1975). Spring red-tide blooms are dominated by Prorocentrum micans, while the more intensive and frequent blooms during July through October are dominated by Gonyaulax polyedra (Sweeney 1975).

Dinoflagellate blooms in the La Jolla region between May 1964 and December 1966, as well as blooms in previous years, were dominated by Gymnodinium polyedra. In the same region Prorocentrum micans was responsible for red tides in 1924, 1933, 1939 (Allen 1941), and in April 1965 (Holmes et al. 1967). A bloom of the dinoflagellate Gymnodinium splendins (=G. sanguineum) occurred between March and July as a subsurface phenomenon extending in a band as far as 100 km along the Southern California coast (Kiefer and Lasker 1975).

Mesodinium rubrum, a ciliated protozoan that Is autotrophic because of its algal endosymbionts, also produces red tides in the SCB (Taylor 1982).

Red-tide outbreaks have been attributed to a variety of causes, including upwelling, heated effluents, reduced salinity, high levels of water runoff, sewage wastewater, nutrient enrichment, general inshore eutrophication, and the presence of a specific unknown growth factor (Clendenning 1959; Oguri et al. 1975; Pra Kash 1975; Sweeney 1979). However, none of these conditions has been identified definitively as the sole causative factor of an outbreak of red tide. Initial introduction of bloom-forming dinoflagellates may result from transport of dormant resting-stage cysts. For example, cysts of *Gonyaulax polyedra* are found on the surface of sediments where they could be carried upward into the photic zone by upwelling. Species which do not produce cysts, such as *Prorocentrum micans*, may be introduced by lateral transport of the water mass. In either case, light, temperature, salinity, and nutrient supply must be at or near optimal conditions for the species to flourish (Taylor and Pollingher 1987). Such conditions generally occur in the late spring, after the spring diatom bloom, and through the summer months. Depletion of nutrients, especially nitrates, as a result of the diatom spring bloom as well as a more stable water column, probably favor the build-up of dinoflagellates.

OTHER COLORED BLOOMS

Other colored phytoplankton blooms occur less frequently. The most common, "yellow water," is due to the non-thecate dinoflagellate *Gymnodinium flavum* (Kofoid and Swezy 1921; Lackey and Clendenning 1963; Cullen et al. 1982b). Yellow tides caused by this organism occurred off La Jolla during the summers of 1914, 1961, and 1980, with organism densities reaching 6.2 x 10^6 cells 1^{-1} (Cullen et al. 1982b). *G. flavum* was also responsible for an extensive yellow tide that was documented by satellite imagery in July 1980 over the Coronado shelf south of San Diego (Palaez-Hudlet 1984).

Green tides in the SCB have resulted from blooms of the chlorophyte algae *Staurastrum* and *Halosphaera* in Santa Monica Bay in September 1980 (Kleppel et al. 1982) and the euglenoid *Eutreptia* sp. in Los Angeles Harbor (Harbor Environmental Project 1975). Brown tides are usually caused by diatom blooms in the spring.

DIEL MIGRATION OF BLOOMS

The historical record for dinoflagellate blooms in the La Jolla region, as well as a summary of blooms occurring in other areas of the SCB, was provided by Eppley and Harrison (1975). They noted that bloom-forming dinoflagellates, particularly Gonyaulax polyedra, undergo diel vertical migrations to depths at which nutrients are high. This may be the reason why dinoflagellates, rather than the less motile diatoms, are the primary bloom formers. A fall bloom of the dinoflagellate Ceratium furca occurred off Seal Beach from a surface band in the upper 2 m, the cells migrated to a depth of 5 m within two hours after sunset, and had dispersed over the approximate depth interval of 5-16 m 4.5 hours after the onset of darkness.

NEGATIVE EFFECTS OF BLOOMS

Some species of dinoflagellates contain toxins and, in coastal areas elsewhere, are responsible for paralytic shellfish poisoning, making shellfish unfit for human consumption. In Southern California, toxic species are rare, but depletion of oxygen from decay of the abundant biomass shortly after blooms in semi-enclosed basins can have negative impacts (Oguri et al. 1975). For example, oxygen depletion has caused extensive fish kills in Santa Monica Bay (Sommer and Clark 1946), Alamitos Bay (Reish 1963), Huntington Harbour (Reish pers. comm.), and Los Angeles Harbor (Oguri et al. 1975).

Bloom-forming dinoflagellate species are believed to be less useful as food for herbivores than other phytoplankton (Huntley 1982; Fiedler 1982b). However, red-tide dinoflagellate blooms apparently provided an abundant food source for grazing crustaceans in Los Angeles-Long Beach Harbor (Morey-Gaines 1979) as well as for phagotrophic dinoflagellates in the La Jolla area (Holmes et al. 1967).

BIOLUMINESCENCE

Many marine organisms, including **dinoflagellates,** display bioluminescence. Studies of the vertical distribution of bioluminescence in the California Current indicated a nighttime maximum at the surface and a daytime maximum at 30 to 40 m depth. Furthermore, day-to-night differences in the color spectrum at the depth of maximum bioluminescence suggested that the type of luminescent organisms differed from day to night (**Greenblatt** et al. 1984).

SUMMARY AND PROSPECTUS FOR FUTURE RESEARCH

SUMMARY

Phytoplankton represent an important part of the SCB ecosystem. The conversion of solar energy to organic carbon through photosynthesis is the basic process upon which virtually all marine **life** depends. The **phytoplankton** community of the **SCB** consists of a great diversity of unicellular and colonial algal species covering a size range of several orders of magnitude. Work on phytoplankton of the SCB has accelerated and shifted focus over the past three decades from descriptive to quantitative and process-oriented research. New sampling and measurement techniques have been essential to the progress of our understanding.

The success of each species depends on water currents, zooplankton grazing, competitive interactions with other species, and optimum levels of available light and ***nutrients.*** Differences In these environmental variables lead to unique assemblages of species which differ both spatially and temporally. The standing stock of phytoplankton has been quantified on the basis of particulate organic carbon and chlorophyll as well as **cell** numbers (abundance). It generally has a subsurface maximum and decreases in the offshore direction. However, satellite remote-sensing of chlorophyll has revealed that the actual pattern is extremely complex, with many changing eddies.

The growth and productivity of SCB phytoplankton is intermediate when compared to other areas of the world's oceans. It is greater than that in the central ocean gyres, but less than that in many of the estuarine or nutrient-rich upwelling regions. Nitrogen availability is probably a critical factor controlling the growth of many species. Recent models provide a very approximate way of predicting temporal changes in productivity.

The abundance of phytoplankton in the SCB varies. Populations are generally more abundant in the spring and--to a lesser extent--in the fall than at other times. Vertically, they are frequently most abundant near the nitracline. Differences in abundance are generally greater in the vertical, offshore, and longshore directions, in that order. In enclosed embayments, shallow-water benthic microflora is important to the system.

Very abundant growths or blooms occur frequently. They tend to be associated with stable water conditions and warm temperatures and are generally dominated by dinoflagellate species. Red-tide blooms can have detrimental effects through subsequent oxygen depletion of the water.

PROSPECTUS FOR FUTURE RESEARCH

Our current understanding of the ecology of phytoplankton of the SCB remains inadequate in many ways. We need models to predict the effects of changing conditions on phytoplankton and subsequent effects on higher levels of the food web. The predictive capability of such models will only be as good as the data upon which they are built. To reduce the uncertainty of our predictions, we need new information in several important areas. These areas include:

- The **taxonomy** and role of picoplankton in the food web. Some evidence suggests that these minute organisms, because of their high turnover rate, may be more important than previously believed.

- Food web relationships that support higher organisms. What species of **phytoplankton** are most important in supporting zooplankton and fish populations?

- Species-specific productivity. Techniques are now available to determine what fraction of the total productivity at any time is due to individual species in the community.

- Total productivity by remote sensing. Methods are needed for determining not only surface chlorophyll, but total water column productivity from satellite observations.

- The role of surface **microlayer** (phytoneuston) populations. Do such dense film communities occur in the SCB? How important are they in the near-surface food web, in binding surface-active materials, or in affecting the transfer of gases across the air-water interface?

- The impacts of contaminants. What are the effects of sewage nutrient enrichment, toxic chemical effluents, or deposition of air toxics on **phytoplankton** growth or community diversity?

- The effects of global climate change. What will be the effects of increased water temperatures from global "greenhouse" warming or increased ultraviolet radiation from stratospheric ozone depletion on the **phytoplankton** community?

Only when these questions can be answered with some degree of certainty will we have the ability to predict the results of natural or human-induced environmental change on the ecology of the Southern California Bight.

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CHAPTER 6 ZOOPLANKTON

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INTRODUCTION

The zooplankton of the Southern California Bight comprise a large and diverse group of organisms. The focus of this review will be on the interrelationships between the distribution and abundance of these organisms and on the oceanography which influences these distributions.

Temporal and spatial variability in both the oceanography and zooplankton are the first and most important factors to consider in studying the zooplankton of the SCB. Oceanographically, the area is a boundary region between sub-Arctic, Central, and Equatorial water masses. It is also a transition zone between the cold, nutrient-rich waters of the California

Current and the warm, nutrient-poor waters of the California Countercurrent and Undercurrent. The physical morphology of the SCB is complex and includes unique circulation patterns caused by the influence of headlands, submarine canyons, semi-enclosed bays (Santa Monica Bay), harbors, offshore islands, and 12 major offshore basins (Chapter 2). Excellent reviews and listings of books on the oceanography of the SCB can be found in Sverdrup et al. (1942), Emery (1960), and **Eppley** (1986).

The literature on zooplankton in the SCB is extensive. Many studies have originated from local colleges, universities, and fisheries laboratories. For example, the California Cooperative Oceanic Fisheries Investigations **(CalCOFI)** database is probably one of the largest, long **time**-series of data found anywhere. Numerous studies and reports have also been completed on harbors, enclosed bays, and nearshore zooplankton. While some of these later studies have been reported in the **"hard"** literature, many are the result of environmental impact studies which remain unpublished.

Any understanding of zooplankton ecology of the SCB must be tied to an understanding of the oceanographic variability. Excellent reviews on the zooplankton (as well as on the oceanography) of the SCB are found in the books referenced above. The SCB also represents **a** variable boundary (and mixture) of assemblages of zooplankton and their corresponding oceanic ecosystems which are comparable to--and related to--water mass variability (McGowan 1974). Steele (1978) and **Haury** and Pieper (1988) discuss the importance of understanding spatial and temporal heterogeneity, variability, and patchiness.

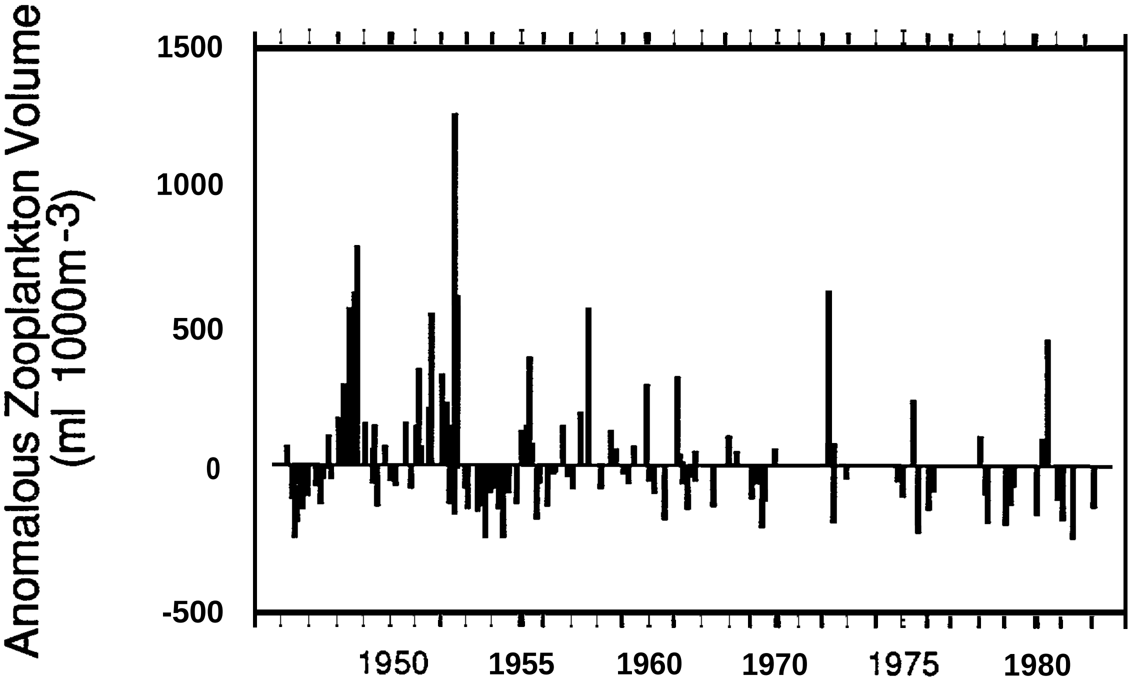
The importance of zooplankton variability in the SCB is also discussed by Roesler and **Chelton** (1987), who summarized **CalCOFI** zooplankton data (displacement volumes) over a 32-year period ranging from 1951 to 1982.

They note that non-seasonal zooplankton currents variability was dominated by a very low-frequency pattern during periods of 3-5 years that were associated with variations in large-scale equatorward transport of the California Current (Figure 6.1). Years of higher than normal California Current flow were associated with larger zooplankton volumes. Episodic bursts of zooplankton biomass of 3-4 month duration were also observed, superimposed on the low-frequency pattern.

The interannual variability discussed above should be considered the baseline for understanding higher-frequency events and processes, including biological interactions. These smaller-scale, higher-frequency processes include seasonal changes and localized events such as coastal upwelling, eddies, plumes, tidal oscillations, bottom processes, diel cycles, wind stress, and turbulence. The extent to which these physical events control or modify zooplankton ecology is a function of the particular organism, including its size, swimming ability, reproductive state, food needs, and other requirements.

A wide variety of sampling devices and preservation techniques are available for zooplankton population assessment. Each must be selected for particular organisms of interest, and to best obtain data at the appropriate scale and data rate for the specific study. Sampling, fixation, and preservation techniques are reviewed in two United Nations Educational, Scientific and Cultural Organization (UNESCO) monographs on oceanographic methodology (UNESCO 196S, 1976). The macrozooplankton in the CalCOFI program discussed above, for example, are sampled with bongo nets (505-um mesh) towed obliquely from a depth of 140 m. Covering a large spatial grid, the CalCOFI data set is long enough (32 years) in duration and large enough in number of samples to detect the interannual patterns of macrozooplankton biomass.

Figure 6.1. Seasonally corrected zooplankton biomass deviations from the mean over 32 years in the SCB. From Roesler and Chelton (1987).


Anomalous Zooplankton Volume
(ml 1000m-3)
1500
1000
500
0
-500
1950
1955
1960
1970
1975
1980

6.3b

Selection of sampling gear and the design of the sampling protocol are critical for obtaining data pertinent to a given study. For example, smaller mesh nets, sampling bottles, or pumps might be used to sample microzooplankton, while larger nets or trawls might be needed to collect the larger macrozooplankton, such as euphausiids or sergestid shrimps. Manned submersibles or SCUBA divers are used to observe and collect fragile, gelatinous organisms. Similarly, studies of vertical or horizontal patterns would necessitate the use of discrete collection techniques. Particle counters or acoustic techniques might be needed to obtain an adequate number of samples to map small-scale patterns of distributions. In addition, given the known heterogeneity of the system, concurrent measurements of both biotic and abiotic parameters, on the same scale, should be attempted. All data and conclusions must be considered with respect to the sampling methodologies used, including their advantages and limitations.

Three oceanographic zones will be discussed separately in the body of this chapter: harbor and bay zooplankton, nearshore zooplankton (shelf and shelf-break), and offshore zooplankton (open ocean and basins). Emphasis is placed on field observations and results. Additional reviews of zooplankton trophic structure and spatial and temporal patterns in the SCB can be found in Beers (1986) and Mullin (1986), and both in Eppley (1986).

HARBOR AND BAY ZOOPLANKTON

The SCB contains three major ports serving the import-export needs of the southwestern United States. These are the port of San Diego in San Diego Bay and the ports of Los Angeles and Long Beach, both located in San Pedro Bay.

While there has been little zooplankton work done in San Diego Bay, several studies have been conducted in San Pedro Bay. These studies were the result of environmental impact report requirements (Allan Hancock Foundation 1976), as well as impact of pollution (Environmental Quality Analysts, Inc. and Marine Biological Consultants, Inc. 1976) and pollution abatement investigations (Soule and Oguri 1979).

Numerous secondary harbors and marinas also exist in the SCB (Table 8.1). Of these, Marina del Rey Harbor has been the most studied. Soule and Oguri (1977) reported on a year of investigation in Marina del Rey which was conducted to determine the causes of poor water quality in the marina. Studies of zooplankton abundance and distribution were a part of this study.

Copepods of the genus *Acartia* generally dominate the zooplankton in the SCB harbors. We (the authors) believe that much of the taxonomic work on this genus is actually a mixture of the two species *A. tonsa* and *A. californiensis*. Since we do not wish to change the words of cited references, where a reference refers to *A. tonsa*, but we believe it to be a mixture of *A. tonsa* and *A. californiensis*, we will append an asterisk (as in *A. tonsa**).

LOS ANGELES-LONG BEACH HARBORS

In order to help assess the environmental impacts of a proposed U.S. Army Corps of Engineers dredge and landfill of outer Los Angeles and Long Beach Harbors, the Harbors Environmental Projects of the University of Southern California conducted an extensive sampling program from 1972 through 1974 of the outer and inner Los Angeles-Long Beach Harbors (Allan Hancock Foundation 1976).

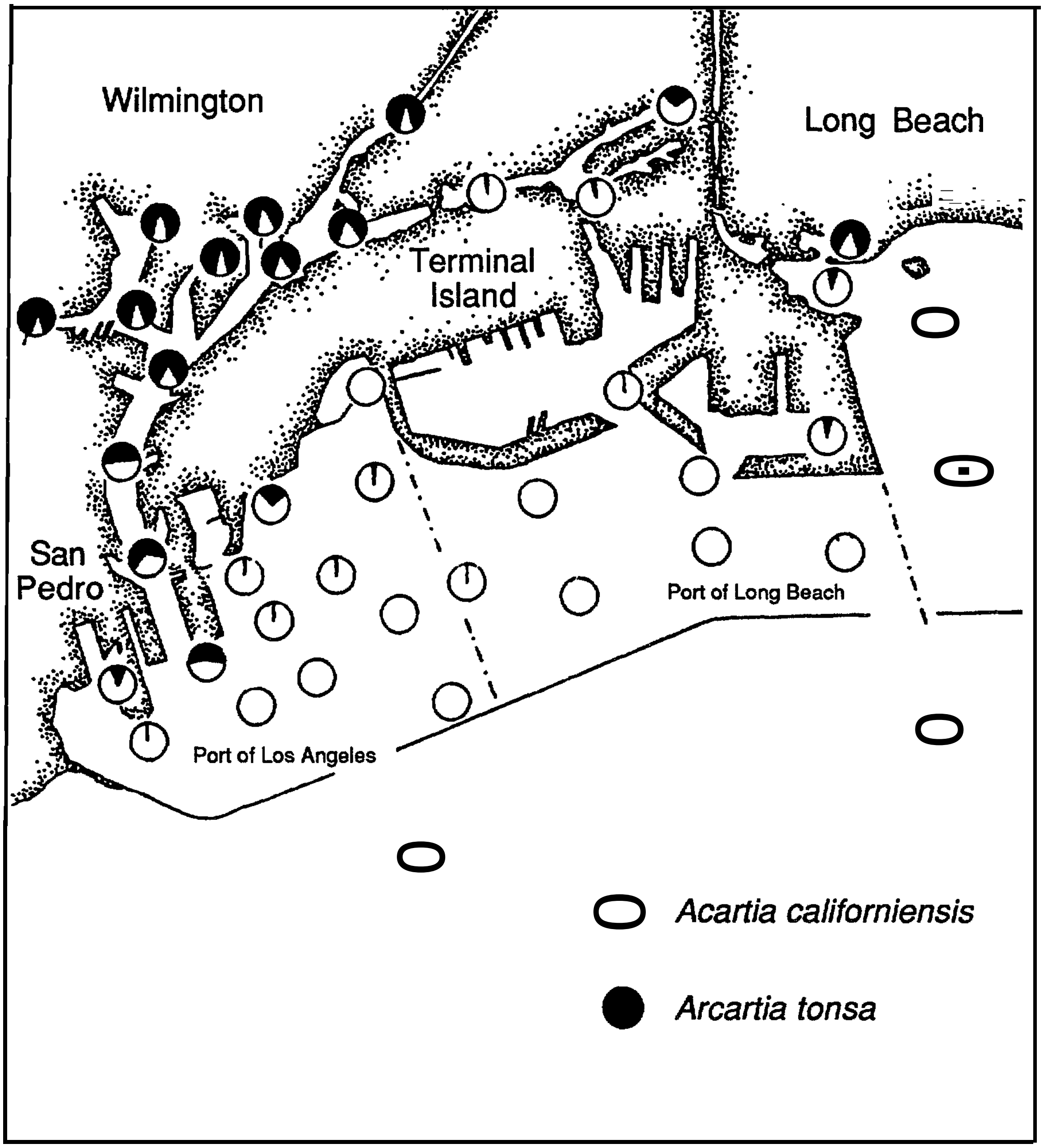
The dominant zooplankton species in the harbor included the calanoid copepods *Acartia tonsa** (57.9%) and *Paracalanus parvus* (10$), the cladocerans *Podon polyphemoides* (11%) and *Evadne nordmanni* (4.7$), and the cyclopoid copepod *Corycaeus anglicus* (1.6%). Other abundant organisms, which may be composed of one or more species, included larvaceans and cirripedia nauplii (approximately 5$ each).

The spatial distribution of the dominant zooplankton reflected the environmental characteristics of the harbor's waters. The zooplankton of the inner harbor channels was characterized by high concentrations of the copepod A. tonsa* and Oithona oculata, accompanied by a notable low abundance of other zooplanktonic species. The main decrease was in the three cladoceran species Podon polyphemoides, Evadne nordmanni, and Penilia avirostris which were 1, 2, and 3 orders of magnitude lower, respectively, in concentration in the inner harbor. The inner harbor channel was dominated by more than 75% A. tonsa*.

Perhaps the most enlightening zooplankton distribution regarding the environmental conditions of the harbor was the distribution of the congeneric copepods Acartia tonsa and A. californiensis. It was believed that what had been called Acartia tonsa exclusively was actually a mixture of the above two species. Dawson (1979) made a l-month (November 1978) zooplankton study in the harbor aimed at resolving the distribution of these very closely related species of Acartia. Figure 6.2 shows the relative percentage distribution of these two species. A. californiensis dominated most of the inner harbor channels and A. tonsa predominated in the outer harbor. There appeared to be mixing of the two species, perhaps by tidal action, at stations A8, Cl and C2. The small baylet at D10 was 85% A. californiensis, while the A. californiensis present at nearby D2 may have represented "spill out" from D10.

The lower concentrations of A. californiensis at the inner B stations (B5, B6, B7) appeared anomalous when viewed with the rest of the inner harbor stations. This area, however, was found by Allan Hancock Foundation

Figure 6.2. Distribution of *Acartia californiensis* and *A. tonsa* in Los Angeles-Long Beach harbors, California, November 197S (from Dawson 1979).


Wilmington
Long Beach
Terminal Island
San Pedro
Port of Los Angeles
Port of Long Beach
Acartia californiensis
Arcartia tonsa

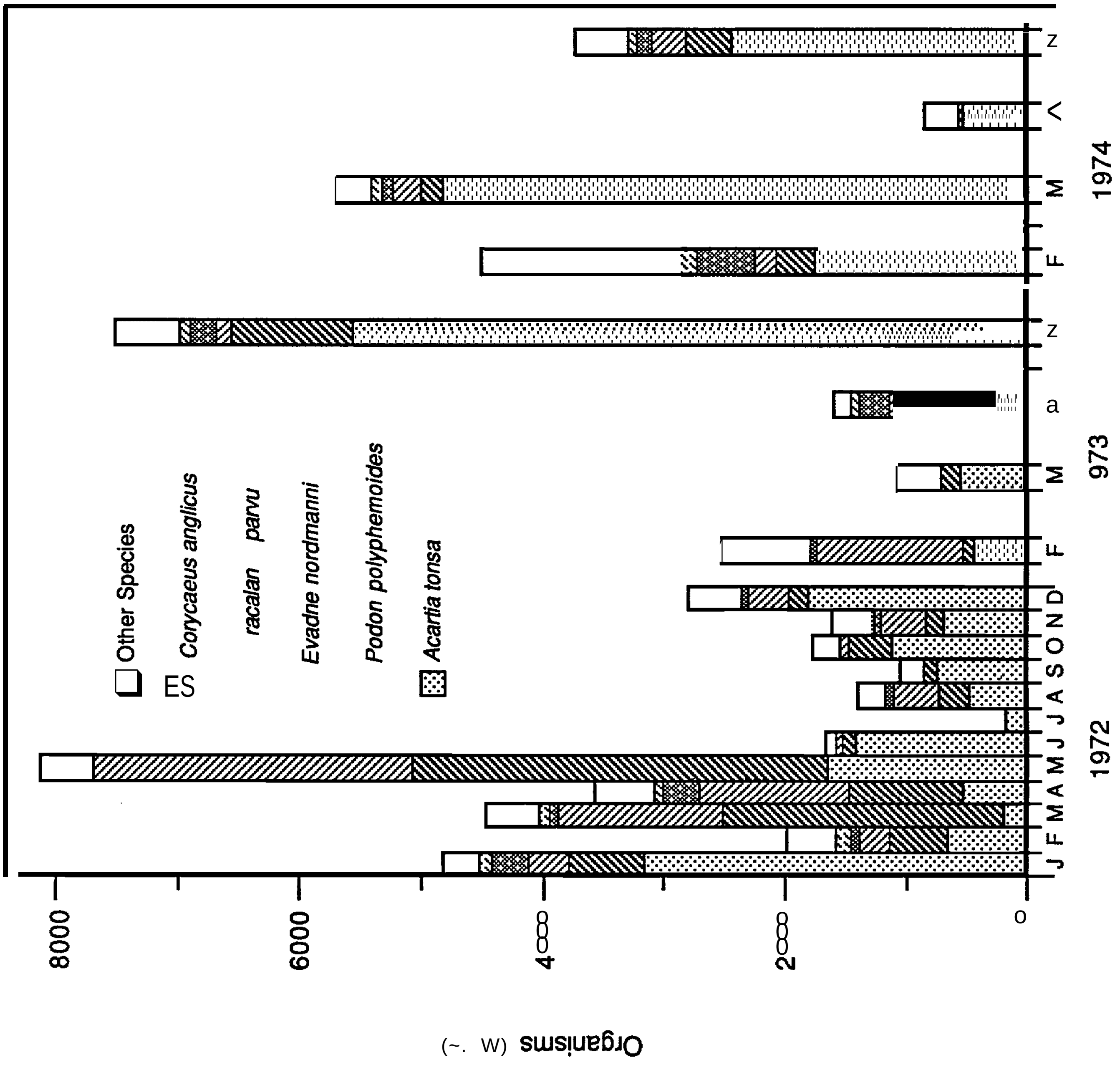
(1976) to be one of overlapping characteristics of inner- and outer-harbor planktonic fauna. Typically, outer harbor cladocerans, fish eggs and larvae were present in equally large numbers, while other copepod species such as Oithona oculata and Acartia spp., present only in larger numbers in the inner harbor, were also similarly present in large numbers at these inner B stations.

The total zooplankton distributions within the inner and outer harbor were roughly similar (Allan Hancock Foundation 1976). It appeared that the near exclusion of Cladocera from the inner harbor and the increased abundance of Acartia tonsa* were compensatory. Only the "B" stations were markedly higher in zooplankton, which may be credited to the overlapping of inner and outer zooplanktonic fauna in the area of stations B4 through B7.

Segregation of species between the inner and outer harbor may result from environmental conditions imposed on each and the competitive behavior between them. Allan Hancock Foundation (1976) has shown that the strongest and most consistent abiotic differences between the inner and outer harbor are pH and dissolved oxygen. The inner harbor pH (7.75) was lower than that of the outer harbor (8.02); the area also had a lower dissolved oxygen concentration (6.1 ppm) than the outer harbor (8.02 ppm). Whether or not such abiotic characteristics are responsible for the observed distribution of these species is unknown.

The seasonal distribution of the five dominant zooplankton species throughout the Los Angeles-Long Beach Harbors is shown in Figure 6.3 (Allan Hancock Foundation 1976). The three dominant copepods--Acartia tonsa*, Paracalanus parvus, and Corycaeus anglicus--show the same general seasonal pattern: Increased abundance in the winter months and a decrease in the summer, with irregular spring peaks. These data conflict with that of Environmental Quality Analysts Inc. and Marine Biological Consultants Inc.

Figure 6.3. Mean temporal abundance of zooplankton and major component species in Los Angeles-Long Beach harbors (from Allan Hancock Foundation 1976).


Other Species
ES
Corycaeus anglicus
racalan parvu
Evadne nordmanni
Podon polyphemoides
Acartia tonsa
Organisms (M -~)
8000
6000
4000
2000
0
J F M A M J J A S O N D
1972
F
M
a
Z
973
F
M
A
Z
1974

6.7b

(1978), which showed somewhat dissimilar monthly abundance highs and lows among the three species in Long Beach Harbor. A. tonsa* and P. parvus both showed peaks in May and July, with the latter species having additional peaks in December, February, and March. The low concentration of A. tonsa* occurred in January to April, while P. parvus had low abundances in August to November. Corycaeus anglicus showed peak concentrations in the spring and fall, with a yearly low in summer.

Environmental Quality Analysts Inc. and Marine Biological Consultants Inc. (1978) also determined the vertical preferences of the major copepod species by daytime sampling at three depths (2, 6, and 12 m). A. tonsa* showed a distinct preference for the upper 6 m of water, and from December through May more than 50% of the population was located at 2 m. P. parvus concentrations increased with depth, the greatest concentration occurring at 12 m, and C. anglicus showed distinct preference for 6 and 12 m.

The two dominant cladocerans, Podon polyphemoides and Evadne nordmanni, showed a seasonal pattern similar to the copepods (Allan Hancock Foundation 1976): low abundance in summer. Both species showed unusually high concentrations in the spring of 1972, but were never again sampled in such abundance.

In summary, copepods dominated the zooplankton in Los Angeles-Long Beach Harbors, and Acartia spp. were the dominant copepods. The distributions of A. tonsa and A. californiensis were important indicators, respectively, of outer and inner harbor environments. The inability to separate A. tonsa and A. californiensis in the early studies represents a loss of valuable information regarding the harbors. This emphasizes the importance of accurate identification of closely related taxa in ecological studies.

MARINA DEL REY HARBOR

Soule and Oguri (1977) reported on a l-year study conducted in Marina del Rey, although sampling actually continued for an additional two years. The information on the latter two years was drawn from unpublished data, and results of all three years (July 1976 to June 1979) of these zooplankton investigations will be summarized here.

The zooplankton of Marina del Rey were dominated by copepods, which comprised over 98.5% of the zooplankton; cladocerans contributed 0.84%. Other less significant groups included larvaceans (0.34%), brachyura zoea (0.14%), cirripedia nauplii (0.12%), and fish eggs and larvae (0.04%). Among the copepods, *Acartia* spp. dominated with 97.4% of the total zooplankton. This genus was composed mainly of *A. californiensis* (94.7%) and *A. tonsa* (2.7%). Other numerically less important copepods included *Paracalanus parvus* (1.0%) and *Corycaeus anglicus* (0.1%). Four species of cladocerans occurred; *Evadne nordmanni* was the most common (0.29$) followed by *Penilia avirostris* (0.22%), *Podon polyphemoides* (0.21%), and *E. spinifera* (0.12%).

While zooplankton diversity was much less in Marina del Rey than was found in Los Angeles-Long Beach Harbors, the areal "distribution of *A. tonsa* and *A. californiensis* followed a similar pattern. *A. californiensis* was most abundant in the inner main channel and slips while *A. tonsa* was found primarily in the entrance channel and mouth of the harbor.

NEWPORT BAY

Trinast (1976) described *Acartia californiensis* as a new species while studying the influence of tidal exchange on the population of *Acartia* spp. in Upper Newport Bay (Trinast 1975). She found that *A. californiensis* was the numerically dominant zooplankter, and the loss of this copepod from the bay due to tidal exchange was minimized by its behavioral tendency to congregate in deeper water during ebb tide. The life cycle was studied in detail by Trujillo-Ortez (1986), who considered it to be endemic to the northeastern Pacific and apparently restricted to estuaries and coastal lagoons. Additional reported SCB locations of A. californiensis are Laguna Penasquitos (Trujillo-Ortez 1986) and Mission Bay in San Diego (A. Fleminger pers. comm.).

NEARSHORE ZOOPLANKTON

Seaward of the harbors and estuaries, oceanographers typically separate the coastal longshore regions of open water on the basis of bottom topography. The nearshore region encompasses those' waters shoreward of the continental shelf-slope break, or approximately the 200-m depth contour. This is a useful demarcation since the water over the continental shelf tends to be an area of high productivity. This augmented region of productivity (Ryther 1969) is usually associated with increased vertical mixing and, thus, greater nutrient recycling and upwelling, both of which are wind-forced phenomena.

The maintenance of a shelf zooplankton assemblage is, to a large extent, dependent on the physical width of the shelf as well as the frequency of offshore advection over the shelf. The presence of a wide continental shelf off the east coast of the United States has been shown to support distinct zooplankton assemblages (Grice and Hart 1962; Bowman 1971). Only occasional intrusions of Gulf Stream water disturbs this relatively stable zooplankton ecosystem. The relatively narrow shelf of the western United States has also been shown to support persistent zooplankton assemblages (Peterson and Miller 1975, 1977).

MICROZOOPLANKTON

The microzooplankton were ignored by early oceanographers due to their tendency to pass through typically sized plankton nets (250-300 urn). The study of the microzooplankton as a food web component was an early objective of the Food Chain Research Group at the Scripps Institution of Oceanography (S10). Microzooplankton are now recognized as an important part of the consumer zooplankton, and this component of the plankton has been intensively studied in the SCB.

Microzooplankton are those animals feeding on particulate organic sources; they are comprised of protozoans as well as juvenile stages of metazoan zooplankters such as copepod nauplii and some early copepodites. Protozoans account for the greatest percent of the microzooplankton numerically, while the micrometazoans dominate the biomass (Beers and Stewart 1967, 1969a,b, 1970). Because of their high reproductive capacities relative to the metazoans, protozoans have a markedly more important effect on the dynamics of the pelagic trophic web. Since protozooplankton can reproduce by simple asexual binary fission, they are able to respond rapidly to a changing environment. In addition, because generally higher physiological rates are found among smaller organisms, they are considered by Beers (1986) to be among the most important pelagic herbivores, a role generally reserved for copepods in the past. Beers and Stewart (1969b, 1970) have shown that the biomass of the microzooplankton was generally 20-25$ of the total larger macrozooplankton, both inshore and offshore in the SCB .

In the SCB, Beers and Stewart (1970) made a weekly sampling study of the microzooplankton off La Jolla from April through September 1967. They sampled from the ‘pigment layer" at three stations (1, 1.4 km; 2, 4.6 km; 3, 12.1 km from shore) off La Jolla and from the bottom of the “pigment layer" to 100 m at the furthest offshore locations. The pigment layer was defined as that region from the surface to a depth of no significant chlorophyll fluorescence, averaging 50 m (Strickland et al. 1970). The average biomass, expressed as organic carbon, decreased from onshore to offshore in the pigment layer: 5.9, 3.0, and 2.4 mg C m^{-3} at stations 1, 2, and 3, respectively. Protozoans, dominated by ciliates, accounted for 32, 24, and 23% of the microzooplankton biomass at these stations. Copepod nauplii accounted for 59-65% of the total metazoan organic carbon at all stations. At stations 2 and 3, microzooplankton organic carbon accounted for 17 and 21%, respectively, of the total zooplankton organic carbon in the upper 100 m.

Variability in the microzooplankton over the 5-month period was generally attributed to periods of upwelling in the early part of the study and offshore advection later in the study. Periods delimited were approximately a month in length; the greatest temporal microzooplankton variation was between the initial period (first month of sampling) and the remainder of the study at station 1. At this station, the mean microzooplankton organic carbon per cubic meter in the first month was 375% of the rest of the values. Station 2 showed a 50% increase during the remaining periods. Station 3 showed a reversal of this trend; the remaining periods were 50% greater than the initial period.

While the Beers and Stewart (1970) study evaluated the cross-shelf and temporal variability of microzooplankton biomass, Beers et al. (1980) sampled the microzooplankton in small (5 m) increments to 50 m at several stations over the continental slope during a period of several days in late May and early June 1970. Their findings point out the extreme variability both vertically (up to 120-fold difference) and horizontally (greater than 2 orders of magnitude) in the areas off La Jolla. They suggest that this variability results from the effects of upwelling and advection from offshore.

A number of studies (Brewer et al. 1981; Brewer and Smith 1982) have established the importance of the nearshore ecosystem to the early development of fish. The role of the microzooplankton in ichthyoplankton development was studied by Brewer and Kleppel (1986) in Santa Monica Bay. Gut analysis of fish larvae showed they were feeding on a variety of microzooplankton. Copepod nauplii and copepodites were found in 34% of the northern anchovy and 43% of the white croaker that contained food. Copepod eggs were also commonly found in the guts of these species of ichthyoplankton. Bivalve veligers and tintinnids were more frequently found in the white croaker than the northern anchovy. While this may reflect selective feeding among the ichthyoplankton, it could also result from the integration of each species' micro-habitat. Densities of microzooplankton in the water column were found to vary significantly over depth, with the highest concentration in samples near the bottom. The single highest fish larvae concentration was found in a bottom sample over the 22 m isobath. This was commensurate with the highest densities of copepod nauplii and copepodites, invertebrate eggs, tintinnids, bivalve veligers, and total microzooplankton.

Owen (1981) has shown that the microzooplankters such as tintinnids, Noctiluca, and copepod nauplii are distributed both horizontally and vertically in microscale patches of less than 2 m. He concluded that since the microscale patches of food and non-food items did not usually coincide, the strike success of fish larvae within food patches may be augmented.

The impact of microzooplankton on primary production in the nearshore environment of the SCB can be significant. Heinbokel and Beers (1979) estimated that generally less than 4$, but, in some cases, greater than 20% of the total phytoplankton could be consumed by tintinnids. Since other ciliates are frequently more numerous than tintinnids and are mainly herbivorous, they concluded that ciliates can have a significant impact on phytoplankton production. Azam et al. (1983) also found that the protozooplankton are the chief consumers of the autotrophic pico- and nanoplankton, as well as of the bacteria. This makes them important contributors to the "microbial loop". A potential impact of microzooplankton on macrozooplankton populations may also exist. Kimor (1979) described predation by the dinoflagellate *Noctiluca miliaris* on the eggs of *Acartia tonsa* in samples off Del Mar. He concluded that this dinoflagellate may have a considerable influence on *Acartia* population abundance. Torrey (1902) also described *Noctiluca* to be a consumer of *Gonyaulax* sp. during a red-tide bloom in the SCB.

MACROZOOPLANKTON

Just as the microzooplankton are characterized by their size and ability to pass through most plankton nets, the macrozooplankton are similarly characterized, except that they are retained by the typical size (250-300-um mesh) plankton nets. When free-swimming animals become large enough to avoid being collected by plankton nets, they are generally termed micronekton and may or may not be considered a part of the zooplankton. Examples of this category are the adult mysids and euphausiids. Although both groups are found in both the nearshore and offshore realms, mysids are found in higher numbers nearshore, while euphausiids are in high concentrations in the offshore mesopelagic zone.

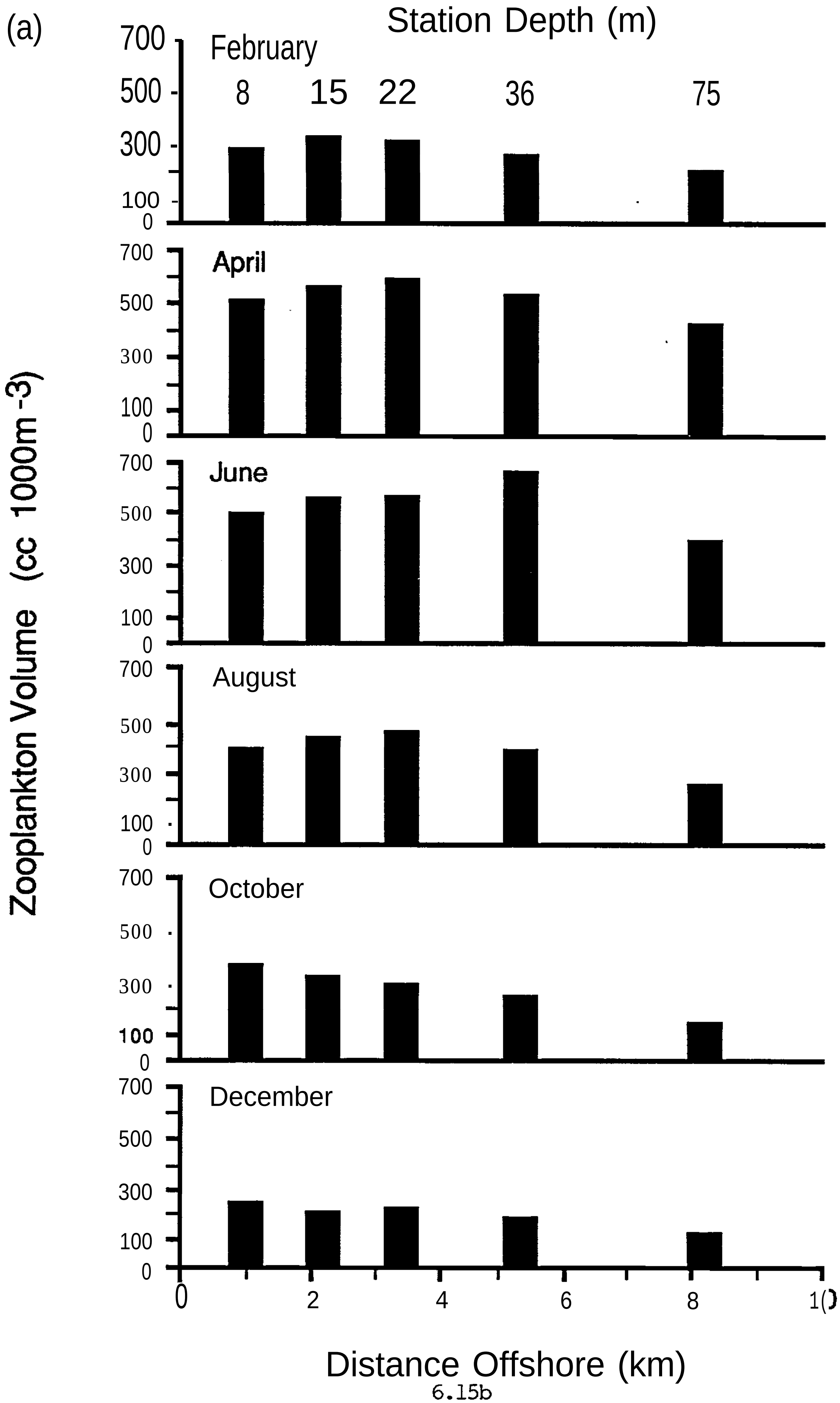
The macrozooplankton are a diverse group of animals composed of a number of major taxonomic categories. The medusae, ctenophores, and planktonic molluscs and tunicates are sometimes grouped into what are commonly termed gelatinous zooplankton. Planktonic tunicates include the thaliaceans, generally composed locally of salps and doliolids, and the larvaceans, which are exemplified by the very common genus Oikopleura. The chaetognaths (arrowworms) are important carnivorous zooplankters, but the majority of the zooplankton are made up of crustaceans. While cladocerans and ostracods are common, most of the crustaceans collected by net and pump are copepods. Planktonic copepods are primarily calanoids, but the cyclopoids and harpacticoids can sometimes be important contributors to the copepod fauna. Of the calanoid copepods, Acartia, Paracalanus, Labidocera, and Calanus are the most common genera collected nearshore in the SCB (Barnett and Jahn 1987).

Abundance and Distribution

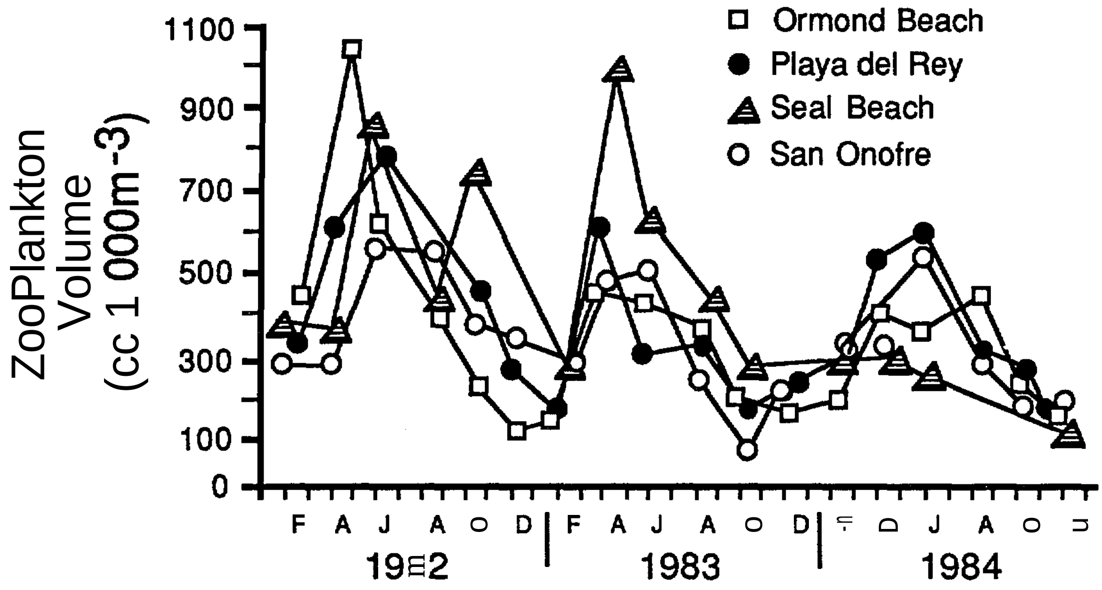
Peterson et al. (1986) examined the nearshore nutrients and zooplankton biomass of transects sampled bimonthly from Ormond Beach, Playa del Rey, Seal Beach, and San Onofre during the years 1982 through 1984. Clear seasonality was shown in zooplankton volumes (Figure 6.4.a) with a zooplankton maximum during the period April through June and a minimum from December through February. A plot of the mean cross-shelf zooplankton biomass for all transects (Figure 6.4.b) shows that the station further offshore (75-m isobath) always had a lower biomass than the inshore stations. During the February to June period of increasing zooplankton biomass, the maximum zooplankton biomass shifted from inshore to mid-transect depth (36 m), suggesting that the area of highest zooplankton production-survivorship gradually shifted from nearshore to offshore as the season progressed.

The source of nutrients (nitrate) which could stimulate primary

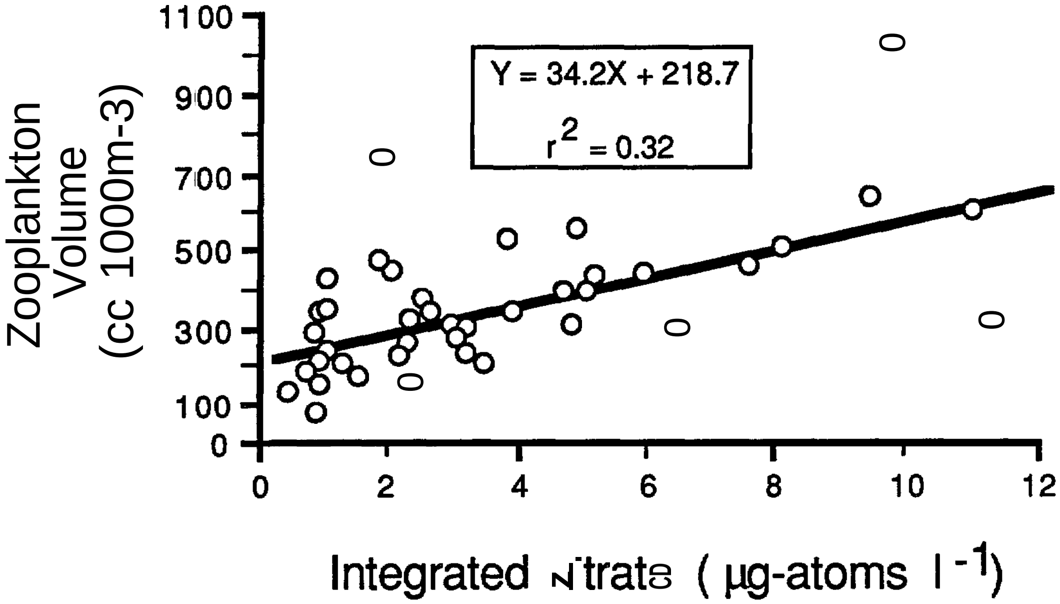
Figure 6.4. A. Mean zooplankton biomass from four major transects. B. Mean monthly zooplankton biomass from four major transects during 1982-1984. C. 75-m nitrate and zooplankton biomass regression (all from Peterson et al. 1986).


(a)
Station Depth (m)
8
15
22
36
75
February
April
June
August
October
December
700
500
300
100
0
Zooplankton Volume (cc 1000m -3)
0
2
4
6
8
10
Distance Offshore (km)

(b)


ZooPlankton Volume (cc 1 000m-3)
1100
900
700
500
300
100
0
F A J A O D F A J A O D F D J A O U
19E2
1983
1984
□ Ormond Beach
● Playa del Rey
▲ Seal Beach
○ San Onofre

(c)


Zooplankton Volume (cc 1000m-3)
1100
900
700
500
300
100
0
Y = 34.2X + 218.7
$r^2 = 0.32$
0
2
4
6
8
10
12
Integrated Nitrate (µg-atoms l -1)

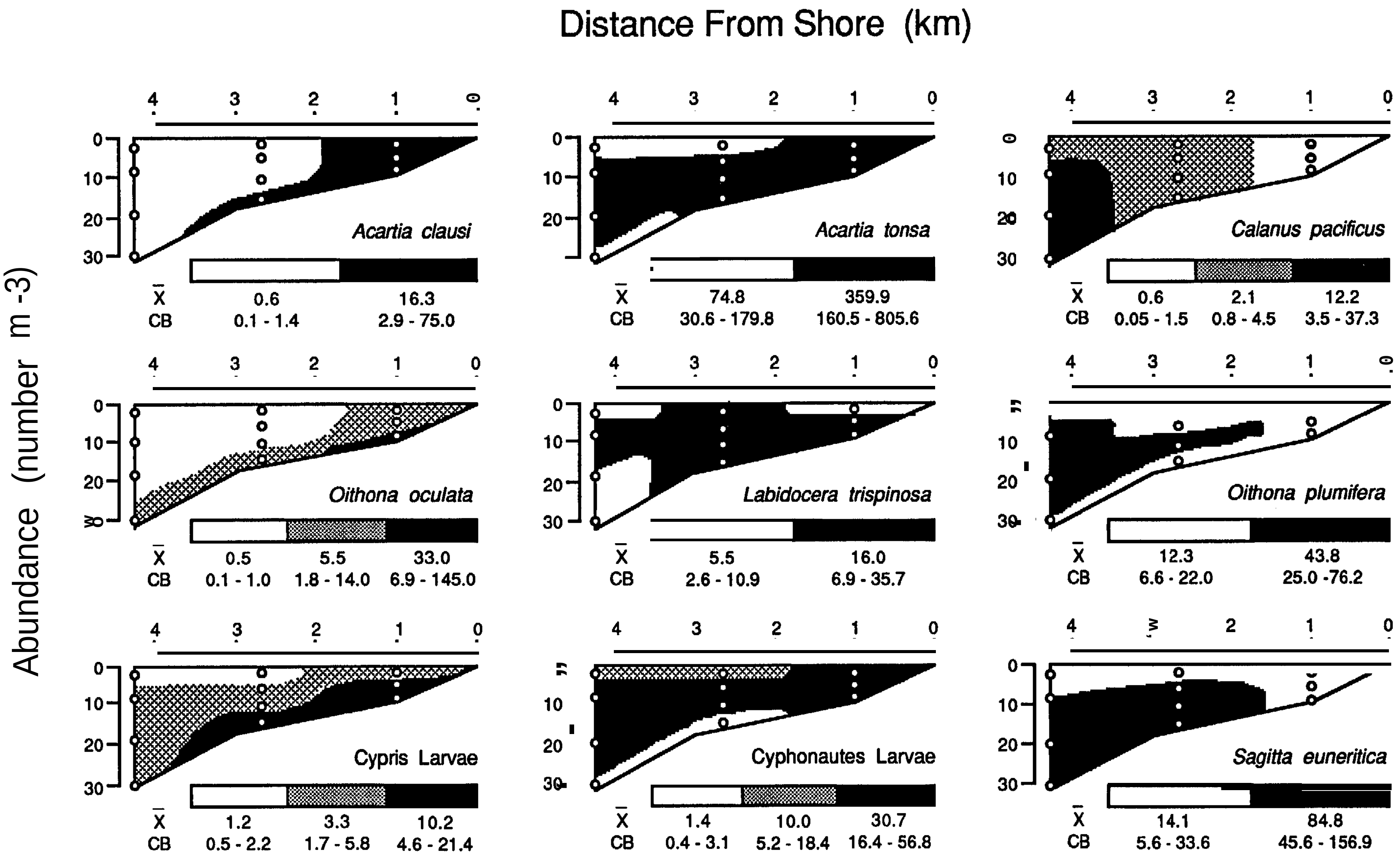
production and, thus, secondary production (zooplankton) was significantly correlated with zooplankton biomass at the 36-m and 75-m isobaths (Figure 6.4.c). Processes such as tidal mixing, internal waves, and local upwelling were thought to be important in mixing outer-shelf nutrient-rich water with the shallow nearshore waters.

Barnett and Jahn (1987) described the cross-shelf and some longshore differences in zooplankton gradients and addressed the 'persistence of these gradients over time. Their sampling covered the years 1976 to 1980 off the coast in the general vicinity of San Onofre, and they believed it to generally represent the over-shelf zooplankton dynamics of the southern half of the SCB.

The average cross-shelf abundance patterns of the nine most important zooplankton taxa found by Barnett and Jahn (1987) are shown in Figure 6.5. The centers of distribution for three groups, Acartia clausi, Oithona oculata, and cypris larvae, show similar patterns. These zooplankton taxa have highest concentrations near the bottom and nearest shore, reflecting perhaps a near-bottom rich layer of phytoplankton. They also reside in waters least likely to be dispersed offshore by intrusive advection because of reduced water velocity near the bottom. A second group of zooplankton species, Calanus pacificus, Oithona plumifera, and the chaetognath, Sagitta euneritica, are concentrated on the offshore end of the transect. The third Set of taxa, Acartia tonsa, Labidocera trispinosa, and bryozoan larvae (cyphonautes) show a distribution covering both inshore and offshore areas. A similar transect 12 km to the south showed no observable differences of cross-shelf species distributions; however, this distance may be too short to conclude an absence of SCB longshore differences in nearshore species.

Barnett and Jahn (1987) used clustering statistics to determine

Figure 6.5 Mean cross-shelf abundance profiles of nine zooplankton taxa based on surveys taken between 1976 and 1980. Abundances are in number m^{-3} (from Barnett and Jahn 1987).


Distance From Shore (km)
Abundance (number m -3)
4
3
2
1
0
0
10
20
30
Acartia clausi
X̄ 0.6 16.3
CB 0.1 - 1.4 2.9 - 75.0
Acartia tonsa
X̄ 74.8 359.9
CB 30.6 - 179.8 160.5 - 805.6
Calanus pacificus
X̄ 0.6 2.1 12.2
CB 0.05 - 1.5 0.8 - 4.5 3.5 - 37.3
Oithona oculata
X̄ 0.5 5.5 33.0
CB 0.1 - 1.0 1.8 - 14.0 6.9 - 145.0
Labidocera trispinosa
X̄ 5.5 16.0
CB 2.6 - 10.9 6.9 - 35.7
Oithona plumifera
X̄ 12.3 43.8
CB 6.6 - 22.0 25.0 -76.2
Cypris Larvae
X̄ 1.2 3.3 10.2
CB 0.5 - 2.2 1.7 - 5.8 4.6 - 21.4
Cyphonautes Larvae
X̄ 1.4 10.0 30.7
CB 0.4 - 3.1 5.2 - 18.4 16.4 - 56.8
Sagitta euneritica
X̄ 14.1 84.8
CB 5.6 - 33.6 45.6 - 156.9

6.16b

assemblages of zooplankton groups that occupied various cross-shelf positions at different times during the year of biweekly sampling (24 biweekly cruises). The 23 taxa used In this clustering analysis represented forms which were present during at least 17 of the 24 samplings. Five distinct groupings of zooplankton taxa were identified. Two groups (Groups I and II) were classified as the nearshore and offshore assemblages in the fall and winter, and three groups (Groups III, IV, and V) made up the nearshore, transitional, and offshore assemblages in the spring-summer period. These group associations are shown in Table 6.1.

Several species had single group associations: **Penilia avirostris** and Evadne **nordmanni** nearshore and **Calanus pacificus** and **Rhincalanus nasutus** offshore in the fall-winter period. Other taxa showed little temporal change (**Eucalanus californicus** offshore and Podon **polyphemoides** nearshore). A number of species (**Acartia** tonsa, **Corycaeus anglicus, Paracalanus parvus, Labidocera trispinosa, Oithona plumifera**, and **Sagitta euneritica**) showed a definite seaward shift In their distribution from winter to summer.

Zooplankton size was also clustered by shelf position and season. Results showed that smaller species dominated nearshore with the smallest crustaceans in the nearshore group of spring-summer and the largest species in the two offshore groups. Of the four taxa in which life stages were separated (**A.** tonsa, **L. trispinosa, P. parvus,** and barnacle larvae), the more immature stages showed a more nearshore distribution. Possible explanations for this were a shoreward transport of eggs and larvae, offshore movement of more mature stages, and a more fecund nearshore population (**Barnett** and Jahn 1987).

To further substantiate seasonal cross-shelf gradients and to reveal shorter-term fluctuations or stability, an analysis independent of the above cluster analysis was completed. Variations of each taxa's position relative

Table 6.1. Mean abundance (no. m^{-3}) of 23 zooplankton taxa in five clustered zooplankton groups. Values given are peak abundances of the taxa, that is, concentrations of one-third or greater of the maximum concentration found for that taxon (after Barnett and John 1987).

		Fall-winter Nearshore		Spring-summer Transitional	Fall-winter Offshore	
		I	III	IV	V	II
Evadne spinifera	Cladocera	7.6				14.9
Penilia avirostris	Cladocera	197.7				
Evadne nordmonni	Cladocera	48.2				
Podon polyphemoides	Cladocera	3.5	3.5			
Acartia clausi	Copepod		25.9			
Oithona oculata	Capepod		38.9			
Cirriped nauplii	Barnacle	20.4	32.3	37.2		
Cirriped cypris larvae	Barnacle	3.8	3.6	93.5		
Unidentified fish eggs		2.3	5.5	5.5		
Acartia spp.[a]	Copepod		1918.9	1223.8		
Labidocera trispinosa[a]	Copepod		41.1	84.4		
Acartia tonsa	Copepod	352.1		664.1		
Corycaeus anglicus	Capepod	149.9		195.5	96.3	
Paracalanus parvus[a]	Capepod	151.8		256.9		
Paracalanus parvus Adult	Copepod	119.0		171.9	81.9	
Labidocera trispinosa Adult	Copepad	5.0		9.0	3.0	
Oithona plumifera	Copepad	59.1		85.8	148.4	81.6
Sagitta euneritica		96.0		248.0	222.0	
Cyphonautes larvae	Bryozoa	42.4	82.1	71.5	52.0	
Medusae				11.1		
Calanus pacificus	Capepod				155.0	
Rhincalanus nasutus	Copepad				11.3	
Eucalanus californicus	Capepod				3.3	1.7

[a] Immature

to its yearly cross-shelf mean were considered. A general agreement among taxa was observed over two blocks of time. There was a typical onshore shift from February to early April, a period generally following storm-generated mixing, and an offshore shift of most taxa from mid-April to July, a time of periodic upwelling.

Stability of the zooplankton over the shelf appeared to be quite high (Barnett and Jahn 1987). During the upwelling season of April, May, and July, zooplankton cross-shelf zonation was not diluted even though chemical-physical gradients were not apparent. Zonation was actually most intense from April to August. Even during intense wintertime mixing, there were no obvious changes in the weaker wintertime cross-shelf zonation. Peterson et al. (1979) also reported the maintenance of the nearshore population of copepods despite intense upwelling off of Oregon. It has been suggested that the 2-km strip of water immediately adjacent to the Oregon coast was not directly affected by upwelling (Wroblewski 1980). This may also be true for the SCB.

Star (1980, as cited by Mullin 1986) also described the onshore-offshore position (within the 75-m isobath) of the more common zooplankters near San Onofre in 1979 by cluster analysis. Three copepods, *Calanus*, *Corycaeus*, and *Paracalanus*, and the cladoceran *Evadne* were grouped in an offshore zooplankton assemblage, and the copepods *Acartia*, *Oithona*, and *Labidocera* were all associated in a nearshore cluster.

Hirota (1974) observed a general decrease in abundance of the ctenophore *Pleurobrachia bachei* from onshore to offshore within 10 km of the coast. This ctenophore is an important summer-fall component of the nearshore SCB plankton, with the highest concentration occurring in August. In contrast to the normal diel vertical migration of zooplankton, *Pleurobrachia* migrated downward at night from their daytime level of the upper 15 m (at or above the thermocline) to about 30-40 m. Hirota (1974) speculated that this reverse vertical migration pattern helps this species maintain high abundances close to shore. By living in surface waters during the day, they were moved shoreward by westerly-northwesterly sea breezes. At night the weaker land breeze moves the surface waters offshore. Gut analyses have shown no major change in feeding intensity between day and night. Over the entire size range of *Pleurobrachia*, the single most important food item was the copepod, *Acartia tonsa*, comprising about one-third of the ctenophore diet in terms of numbers and amount of carbon ingested. Other numerically important food items included the copepods *Euterpina acutifrons* (11.4%) and *Corycaeus anglicus* (7.6%), nauplii (5.9$), eggs (5.5%), the cladoceran *Evadne nordmanni* (5.2$), and the copepod *Paracalanus parvus* (4.3%). In terms of biomass, the copepod *Labidocera trispinosa* (27.4%) and the chaetognath *Sagitta euneritica* (10.8%) were the most important dietary components after *Acartia tonsa* (34.8$). This chaetognath was not consumed In proportion to its abundance, however, implying that through rapid escape responses the prey may limit the ctenophore's capture effectiveness.

Clutter (1967) found a strong horizontal zonation among a number of hypopelagic (approximately 3-30 cm above the sea floor) mysids in the nearshore environment between the La Jolla and Scripps Canyons. Despite the overlapping of mysid distributions, similar zonations were evident among the three transects studied. *Mysidopsis californica* was the most shoreward species, followed by the numerically dominant *Metamysidopsis elongata*, *Acanthomysis macropsis*, and, most seaward, *Neomysis kadiakensis*. Bathymetric distribution changed between transects among these species, but their shore to seaward order remained constant. The environmental factor most responsible for Metamysidopsis elongata distribution appeared to be the pattern of food availability that was imposed by the nearshore circulation.

Mysids also exhibit a vertical distribution pattern within the giant kelp (Macrocystis pyrifera) 'beds of the SCB. Clarke (1971) studied the distribution of mysids within these kelp beds and found a three-tier distribution categorized by habitat as canopy, subcanopy, and benthic species. The most common canopy species, Acanthomysis sculpts, swam among the surface fronds in enormous numbers, with Siriella pacifica occasionally present. Subcanopy species included those between the surface canopy and the bottom, and were commonly Acanthomysis macropsis and Neomysis rayi. Other species present were Acanthomysis columbiae, Acanthomysis sp., Mysidopsis sp., Neomysis kadiakensis, and possibly Proneomysis wailesi. Benthic species directly associated with the giant kelp include Heteromysis odontops, which occupies kelp holdfasts. Hypopelagic mysids living adjacent to kelp beds over sandy bottoms include Neomysis kadiakensis, Acanthomysis macropsis, Metamysidopsis elongata, and Mysidopsis californica. These hypopelagic species were at times so abundant that dense swarms extended over large areas. Canopy and subcanopy species of mysids were the most important mysids eaten by kelp fish.

The diel migration of demersal zooplankton into open water from within a kelp forest ecosystem off Santa Catalina Island was studied by Hammer (1980). The migration from the kelp holdfasts into open water was primarily a nocturnal phenomenon. Hammer further observed that 86% of the zooplankton consisted of the gammarid amphipods Batea transversal and Parapleustes oculatus, followed by--in order of numerical import.ante--ostracods (Vargula tsujii), isopods (Paracercepis cordata, Gnathia sp.), and the natantian shrimp, Lysmata californica. Migration into open water during the day was numerically dominated by copepods: harpacticoid *Tisbe* spp., and *Porcellidium* spp.; cyclopoids *Oithona* spp. and *Oncaea* spp.; and the calanoid *Clausocalanus* spp. copepodites.

Zooplankton migrations off the sand substrate within a kelp forest showed similar copepod diel migrations. Hammer (1981) found, however, that the nocturnal migrations were dominated by the caprellid amphipod *Caprella* spp. (67%), followed by the tanaid *Leptochelia* spp. (13%), and the gammarid amphipods (6$) *Photis* spp. and *Lysianassa* spp. Stretch (1985) made a similar study from a sand substrate outside the kelp forest, using a different collecting technique. He found that among the demersal gammarid amphipods, the nocturnal migration was dominated (86%) by *Rudilemboides stenopropodus* and approximately 11$ of the total benthic gammarid fauna migrated into the water column.

Feeding and Reproduction

The impact of macrozooplankton grazing pressure on phytoplankton standing crop in the nearshore environment has been shown to be significant. Mullin and Brooks (1970) found that *Calanus helgolandicus* (=*pacificus*) showed a daily ingestion rate of 14-26% of the phytoplankton production off La Jolla during a 5-month study. Eighty percent of this ingestion was by late copepodite stages and was greatest in the late spring when primary production was relatively low. Beers and Stewart (1970) have estimated that the microzooplankton ingested about 27% of the net production at the same stations over the same period.

Kleppel et al. (1988) demonstrated the occurrence of carnivorous feeding among crustacean zooplankton. As much as 97% of the carbon in the guts of crustacean zooplankton was contributed by animals at times of low phytoplankton biomass and production.

While the macrozooplankton clearly impact the phytoplankton, phytoplankton concentrations also have an effect on zooplankton production. For instance, egg production of Paracalanus parvus was positively correlated with concentrations of chlorophyll a (Checkley 1980), resulting in increased food limitation on egg production with distance offshore. Only in the generally eutrophic Santa Monica Bay did copepod egg production appear not to be food limited.

Reproduction is also affected by the abiotic habitats in which copepod eggs develop. Uye and Fleminger (1976) showed that the eggs from four species of nearshore and embayment Acartia have specific abiotic hatching requirements. These varying hatching requirements might be the underlying factors governing the abundance of different species of Acartia in different areas and times.

While microzooplankton serves as food for developing fish larvae, macrozooplankton may feed directly on ichthyoplankton. Brewer et al. (19S4) found various taxa of zooplankton attached to, or partially ingesting, ichthyoplankton in preserved samples from Santa Monica Bay. These taxa included three copepods (Corycaeus anglicus, Labidocera trispinosa, and Tortanus discaudatus), euphausid larvae (Nyctiphanes simplex), an amphipod (Monoculides sp.), a chaetognath (Sagitta euneritica), and an unidentified decapod larvae. C. anglicus was the species most commonly found clinging to fish larvae. A total of 4.6$ of the white croaker larvae had C. anglicus attached, while northern anchovy larvae and unidentified fish larvae had an incidence of 1.6 and 0.3% C. anglicus attachment respectively. At least 36 of the 54 (67%) bongo samples contained fish larvae with clinging C. anglicus. While some of this "attachment" may represent net feeding, Brewer et al. (1984) believed that the selective attack on fish larvae reflects natural predation.

Patchiness

The heterogeneous spatial distribution of zooplankton has long been recognized as an important aspect of the planktonic environment (Steele 1978). Investigations of heterogeneous distributions have been difficult because of the ephemeral nature of zooplankton aggregations (active or passive) and the need to sample rapidly in time and space to conduct such investigations.

Richter (1985) used a bottom-moored, upward-looking high-frequency acoustics device to survey zooplankton patches passing through the acoustic beams with the prevailing current. Sampling was conducted off San Diego Bay in 18 m of water. He found that small zooplankton occurred in patches on a scale from 10 to 100 m and that patch biomass was from 4 to 15 times the background level. Large zooplankton, consisting possibly of large copepods and small euphausiids and amphipods were usually found amid small zooplankton aggregations. Horizontal backscattering varied independently of both the temperature and the chlorophyll maximum.

Mullin (1979) reported on simultaneous sampling from two ships in March 1976 off Del Mar, California. He collected zooplankton in 5-m increments from 35 m to the surface and compared these profiles on horizontal distances from 100 m to 10 km. Bottom depth did not exceed 50 m throughout the study, and samples were taken during both day and night. The predominant horizontal scales of variability fell into three groups: (1) larvaceans were homogeneous in distribution at all spatial scales; (2) Calanus pacificus, Sagitta, and Evadne increased in variability with distance; and (3) Corycaeus anglicus was quite variable even in closely spaced samples. This implied that while larvacean patches were on a scale larger than 10 km, Corycaeus formed patches smaller than 100 m. When day and night samples were treated separately, different patterns emerged. Samples taken during the day were less similar as the distance apart increased, while samples taken at night showed no decrease in percent similarity with increasing separation. This indicated that patch characteristics can change diurnally.

A year later, Star and Mullin (1981) sampled from a depth of 36 m along a longshore transect in the same general location. Using data from Star and Mullin (1981), Mullin (1986) discussed the horizontal distribution of various taxa along the transect (Figure 6.6). Similarities in horizontal distributions can be seen in (1) *Calanus* developmental stages, (2) *Eucalanus* developmental stages, and (3) *Metridia* and *Pleuromamma* genera. He suggested that these patterns might arise from common locations of birth or similar responses to the environment.

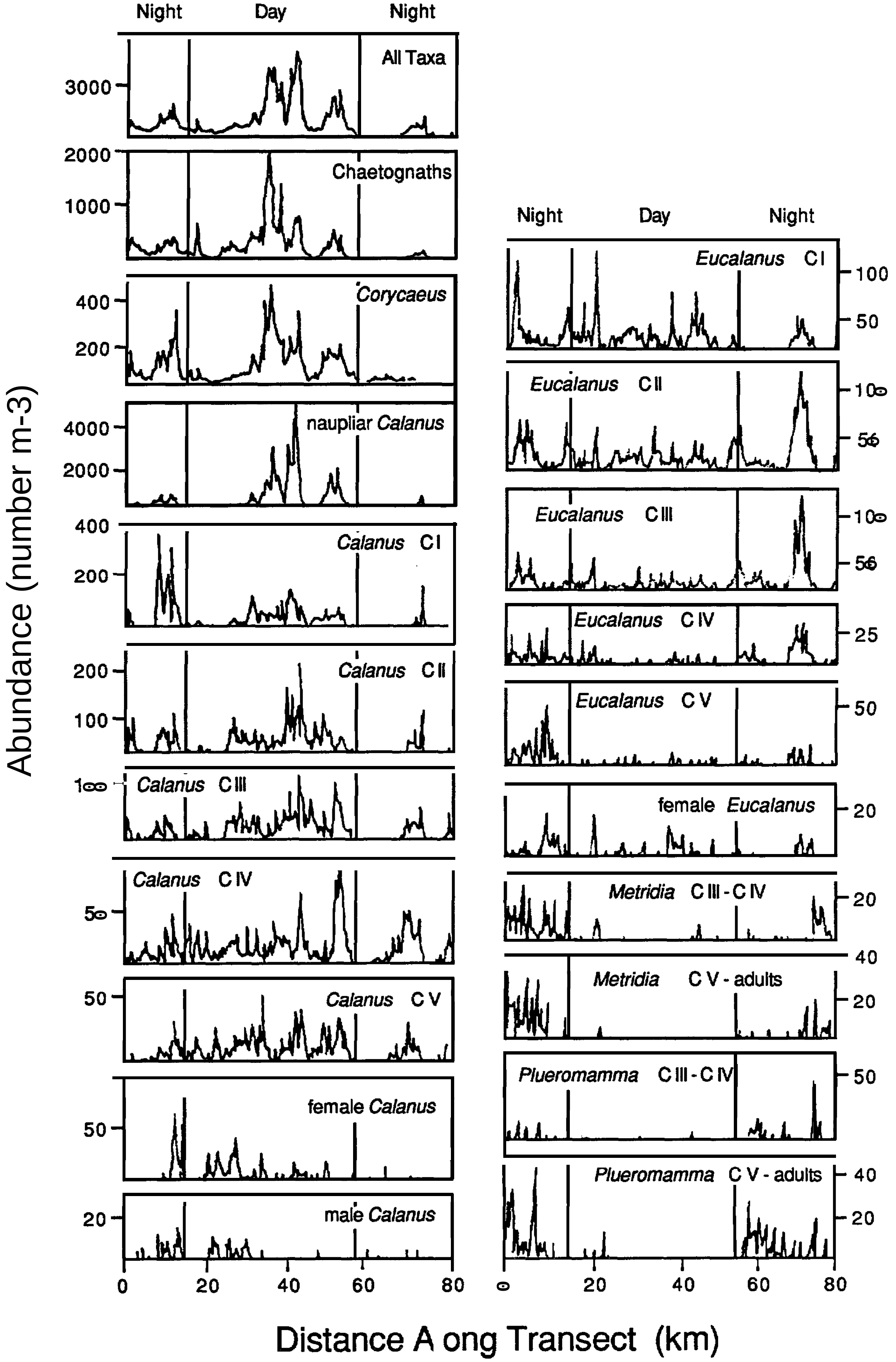
OFFSHORE ZOOPLANKTON

TRANSITION ZONE

While the three separate zones are natural divisions progressing seaward from the coast, only a few studies have assessed the transition zone between nearshore and offshore (that is, the zone over the continental slope. Some of these studies were discussed in the previous section (Beers and Stewart 1967, 1969b; Hirota 1974; Barnett and Jahn 1987).

Pieper et al. (in press) also studied the transition zone off Santa Monica Bay by use of a 21-frequency array of transducers for acquiring acoustically derived biovolume of zooplankton. Additionally, temperature, conductivity, chlorophyll *a*, and depth data were collected. Two transects were sampled during the daylight hours in October 1982. The first one extended from Point Dume over the continental shelf (40-m bottom depth) to a station 23.5 km offshore in the Santa Monica Basin (900-m bottom depth). This transect consisted of seven vertical casts over 5.5 hours. The second,

Figure 6.6. Horizontal distribution of zooplankton taxa at a depth of 34 m in a longshore transect in the SCB (from Mullin 1986).


Night
Day
Night
All Taxa
3000
Chaetognaths
2000
1000
Corycaeus
400
200
naupliar Calanus
4000
2000
Calanus C I
400
200
Calanus C II
200
100
Calanus C III
100
Calanus C IV
50
Calanus C V
50
female Calanus
50
male Calanus
20
0
20
40
60
80
Night
Day
Night
Eucalanus C I
100
50
Eucalanus C II
100
50
Eucalanus C III
100
50
Eucalanus C IV
25
Eucalanus C V
50
female Eucalanus
20
Metridia C III - C IV
20
40
Metridia C V - adults
20
Plueromamma C III - C IV
50
Plueromamma C V - adults
40
20
0
20
40
60
80
Abundance (number m-3)
Distance Along Transect (km)

6.24b

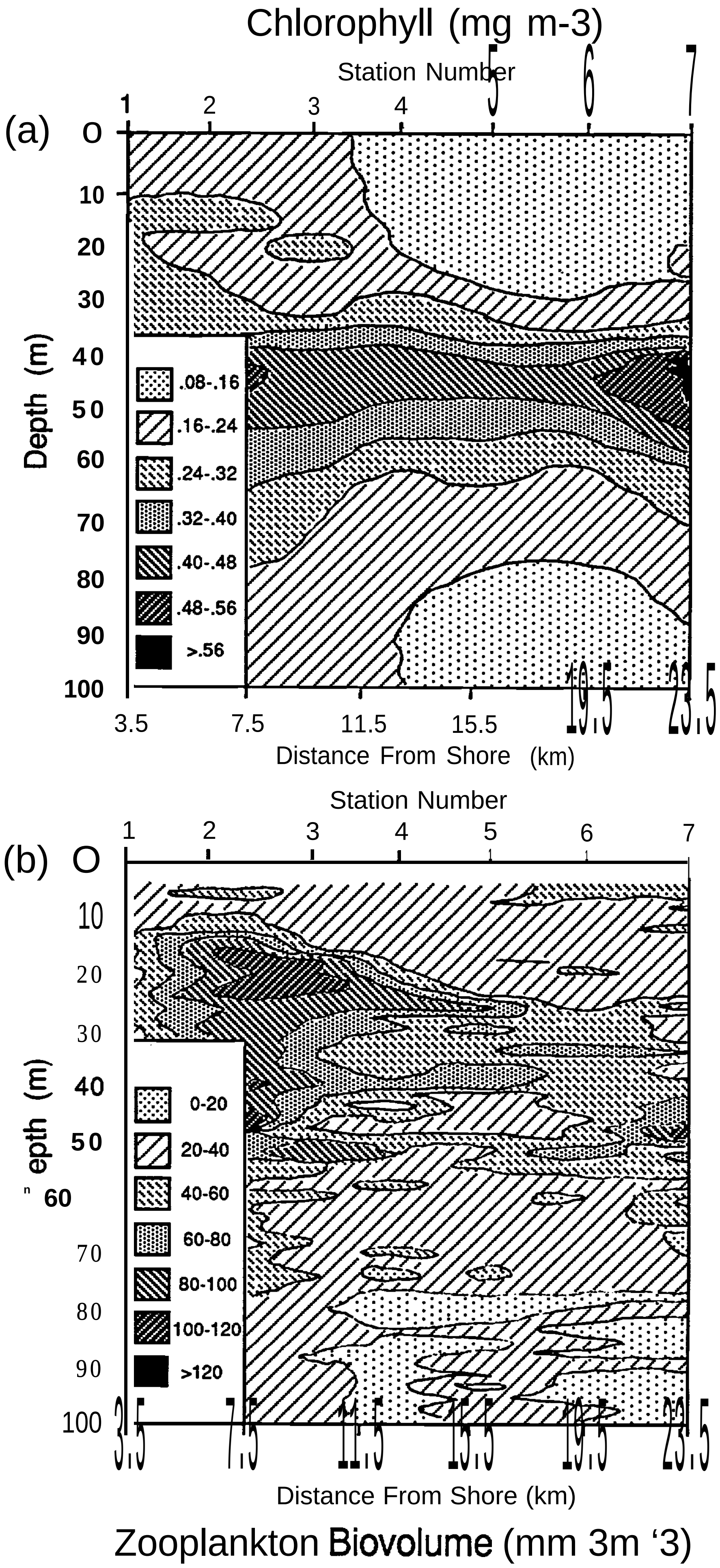
more southern, transect ran 35 km from the above outermost station to a station off Santa Monica in about 40 m of water, and it consisted of 6 vertical profiles taken over 4.5 hours. Both transects show a thermocline around 20 m over the shelf and an undulating isotherm with a high over the shelf break and a wavelength of 15-20 km. The cause of this wave-like isotherm is unknown but may include surface and sub-surface currents deflecting isolines to internal waves or local eddies.

The chlorophyll a and zooplankton biovolumes for the northern transect are shown in Figure 6.7. The zooplankton biovolume section shows a maxima from 15 to 30 m over the outer edge of the shelf. The maximum gradually deepens offshore. The center of the high zooplankton biomass near the edge of the shelf corresponds to a small increase in chlorophyll a. However, chlorophyll a is generally reduced in the region of this zooplankton maximum. It is possible that the zooplankton have reduced the chlorophyll a concentration in this area by grazing. Offshore of the edge of the shelf, zooplankton biovolumes are variable with depth, yet are generally higher in the region of the chlorophyll a maximum (25-55 m). A zooplankton biovolume and chlorophyll a maximum also occur at the offshore end of the transect between 40 and 50 m. The southern transect showed a similar coherence between chlorophyll a and zooplankton biomass, particularly over the shelf and slope. These data indicate that the continental slope transition may be an area of increased productivity, and may deserve greater attention of investigators in future work.

LONG-TERM FLUCTUATIONS

A number of investigators (Smith 1968; Ryther 1969; Cushing 1975; Walsh 1977; Eppley et al. 1979) have maintained that for eastern boundary currents, including the California Current, wind-driven coastal upwelling is

Figure 6.7. Horizontal sections of (a) chlorophyll **a** and (b) zooplankton biomass from off Point Dume to 23.5 km offshore in the Santa Monica Basin, 7 October 1982.


Chlorophyll (mg m-3)
Station Number
1
2
3
4
5
6
7
(a)
0
10
20
30
40
50
60
70
80
90
100
Depth (m)
.08-.16
.16-.24
.24-.32
.32-.40
.40-.48
.48-.56
>.56
3.5
7.5
11.5
15.5
19.5
23.5
Distance From Shore (km)
Station Number
1
2
3
4
5
6
7
(b)
0
10
20
30
40
50
60
70
80
90
100
Depth (m)
0-20
20-40
40-60
60-80
80-100
100-120
>120
3.5
7.5
11.5
15.5
19.5
23.5
Distance From Shore (km)
Zooplankton Biovolume (mm 3m '3)

the main source of new nutrients entering the euphotic zone. Others (Reid 1962; Bernal and McGowan 1981; Roesler and Chelton 1987) have found a correlation between zooplankton biomass, cold water temperature, and increased flow of the California Current. Chelton et al. (1982) analyzed 30 years of CalCOFI data in order to determine which of these factors plays the dominant role in California Current zooplankton biomass fluctuations. They compared the longshore component of wind stress with the mean monthly zooplankton volumes and concluded that, while wind-induced upwelling may play some role in zooplankton fluctuations, other factors were more important. They suggest that large fluctuations in zooplankton abundance appear to be unrelated to wind-driven upwelling, but related to changes in the transport of the California Current--that is, greater transport is accompanied by greater productivity in the California Current and the SCB.

The causes of variable California Current flow have not been fully identified. The strength of the California Current may be correlated with El Nino (El Nino Southern Oscillation, ENSO) occurrences in the eastern Tropical Pacific. Positive El Nino events often correlate with low California Current transport, while negative El Nino events are associated with strong California Current flow. While not all California Current fluctuations can be associated with El Nino events, it appears that these events are important to California Current transport and, thus, zooplankton fluctuations.

MICROZOOPLANKTON

As already noted in the nearshore zooplankton section, Beers and Stewart (1969b) found a gradient of decreasing microzooplankton from onshore to offshore in the SCB. They also found an increasing concentration of microzooplankton relative to the concentration of chlorophyll a with distance offshore, and they suggested that the microzooplankton may play a more significant role in the offshore realm than in the nearshore.

Beers and Stewart (1969a) compared microzooplankton vertical structure in the nearshore and offshore zones. The ratio of microzooplankton in the euphotic zone to those found below the euphotic zone was 6.4:1 in the area over the continental shelf, whereas this ratio was much smaller (2:1) at the offshore station.

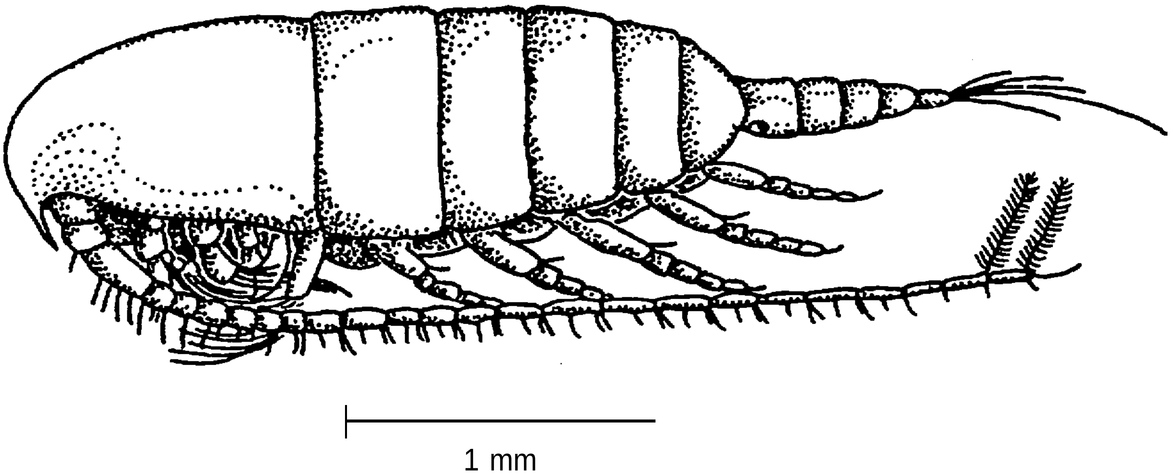
Temporal changes in the taxonomic composition of the radiolarian population in the upper 200 m of the SCB exhibited a distinct seasonality dependent upon the circulation pattern in the SCB (Casey 1966 as cited by Beers 1986). Radiolarians transported from equatorial waters dominated in the summer, and sub-Arctic species were most abundant during the winter.

MACROZOOPLANKTON

Macrozooplankton of the offshore region are often composed of many of the same species as are found nearshore. In addition to these, more oceanic and deeper-water species are collected. Of the calanoid copepods, Calanus, Pleuromamma, and Metridia are common offshore genera in the SCB. C. pacificus (Figure 6.8) is the species most studied, and, because it can be laboratory reared (Mullin and Brooks 1967; Paffenhofer 1970), much has been learned of its trophic biology. The trophic knowledge thus gained, as well as that for other selected zooplankters, is reviewed by Beers (1986). Micronekton (taxa capable of evading typical plankton nets) are also commonly found offshore. Euphausids are typical members of the micronekton, and Euphausia pacifica and Nematoscelis difficilis (Figure 6.9) are ordinarily found in the offshore region of the SCB (Brinton 1976).

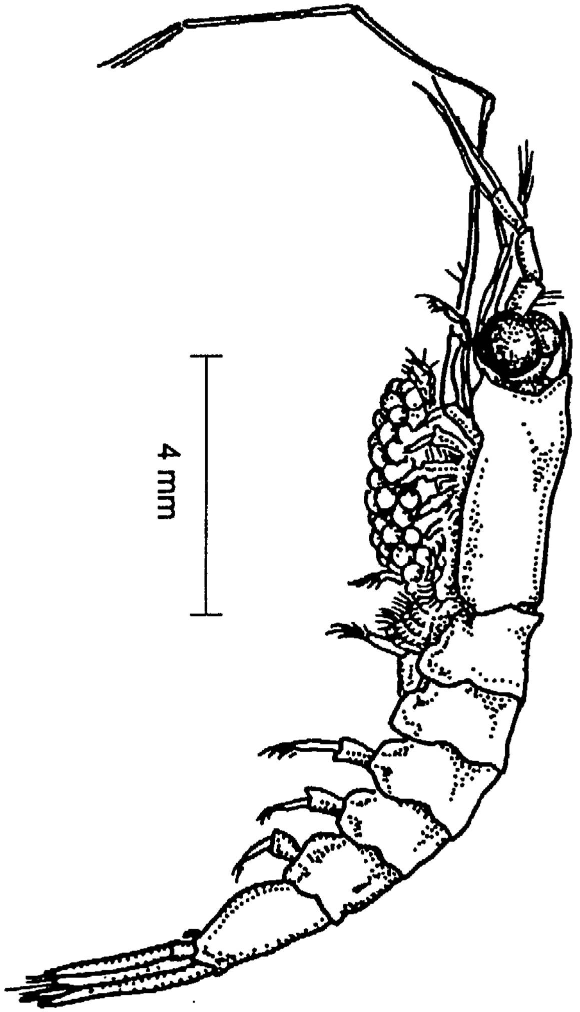
An occasional contributor to the micronekton of the SCB is the pelagic phase of the red crab, Pleuroncodes planipes. Normally found off the

Figure 6.8- Calanus pacificus, female (from Holliday and Pieper 1980)



6.27b

Figure 6.9. *Nematoscelis difficilis* (from Brinton 1967).


4 mm

Pacific coast of Baja California (Longhurst 1967), it occurs sporadically in the SCB in accompaniment with warm water intrusions from the south and, in particular, during El Nino events such as the winter-spring period of 1982-1984 (Beers 19S6). Mass beach strandings have been reported as far north as Monterey (Glynn 1961). The red crab feeds on larger phytoplankton and microzooplankton (Longhurst et al. 1967) and represents a nutritional resource for various fish, marine mammals, and sea birds (Boyd 1963).

Horizontal Distribution

The causes and importance of interannual zooplankton variability in the SCB were summarized in the introduction to this chapter. Given that the SCB is in a transition region, an understanding of processes north, south, an west of the SCB is important in gaining insight about the zooplankton found within the area.

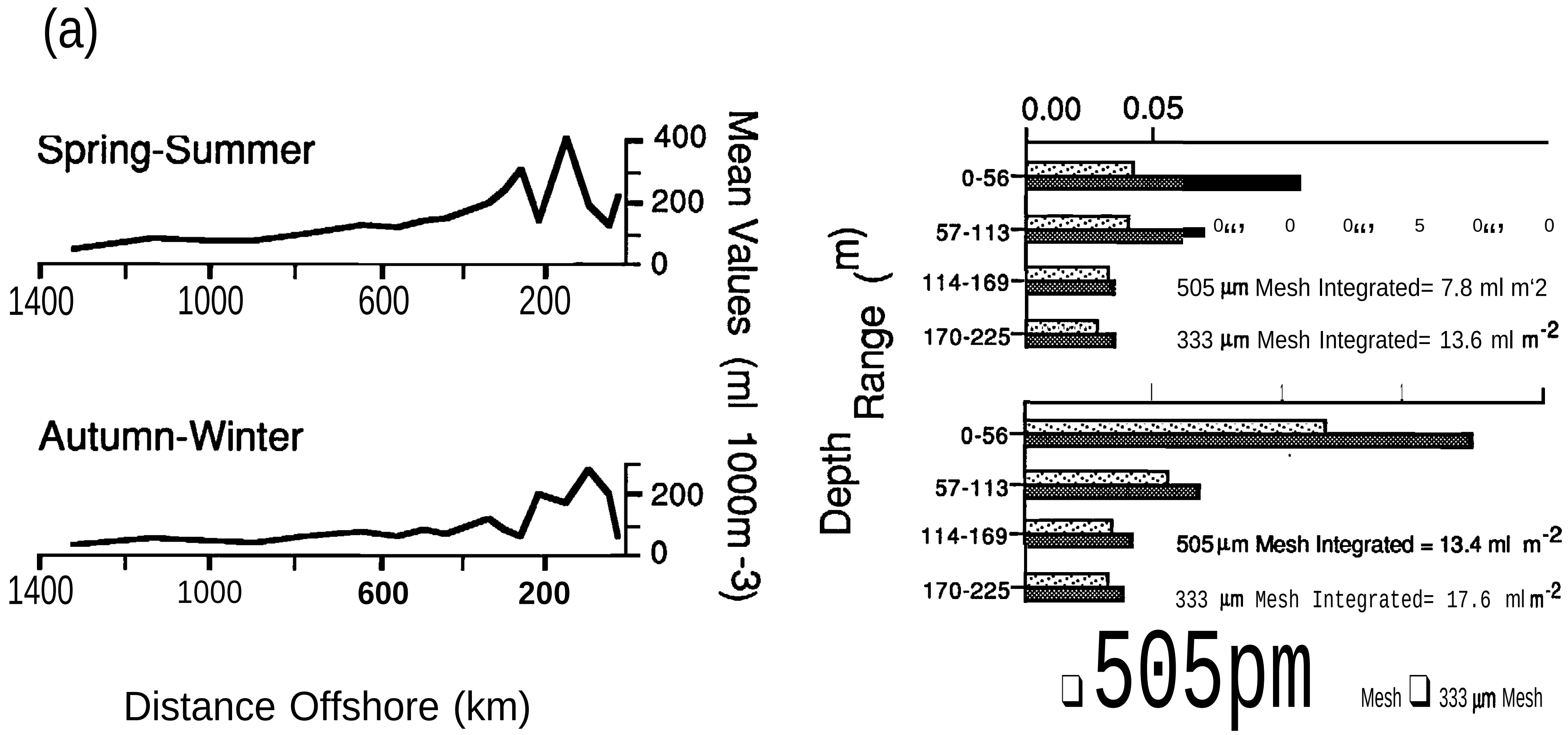
In the northern part of the CalCOFI grid, and sometimes encompassing the northern part of the SCB, variability in zooplankton volumes appears to be associated with variations in California Current transport (Roesler and Chelton 1987). In this area, the zooplankton response to advection was rapid (months). Adult forms of zooplankton dominated collections when equatorward advection was strong (high-nutrient, non-food limited), and larval forms dominated collections when advection was weak. In the southern part of the CalCOFI grid, which sometimes includes the southern part of the SCB, variability showed longer time-scale responses (3-5 months) and the biomass was dominated by juvenile and larval stages of zooplankton. Roesler and Chelton (1987) concluded that zooplankton abundance in the southern area was controlled by local biomass response to changes in the advective environment. They suggested that biogeographical boundaries of subtropical species would move north and south in response to advective changes (see also McGowan and Miller 1980).

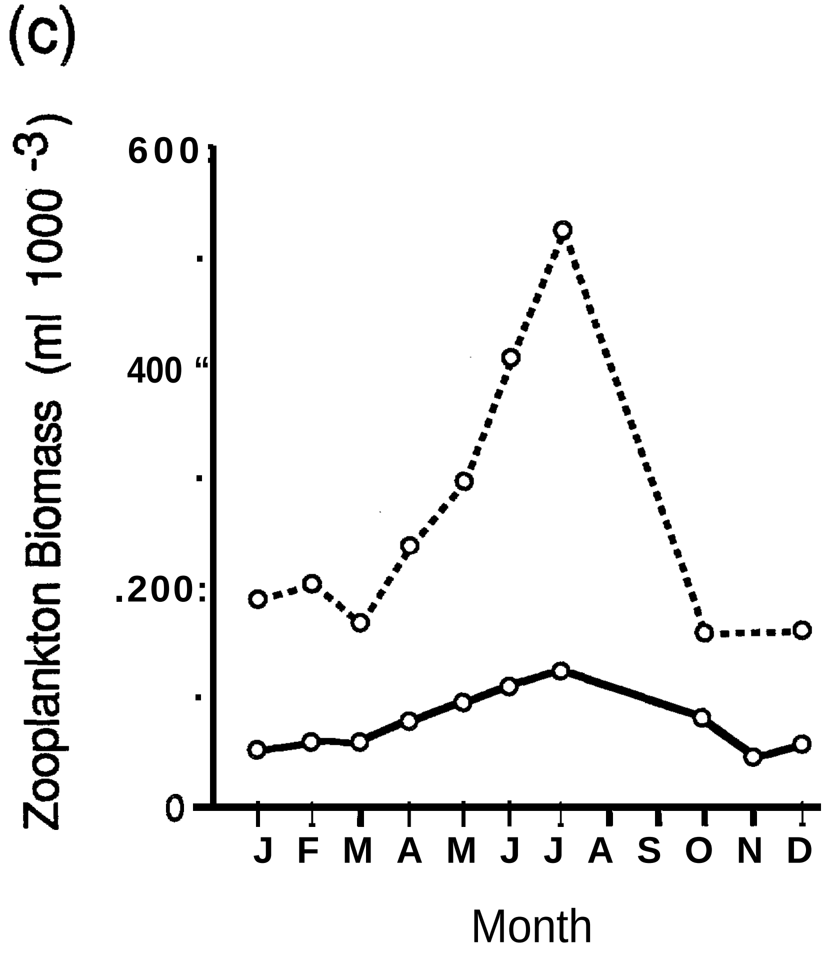
The majority of zooplankton samples collected during the years of CalCOFI sampling were not sorted by taxonomic group, but analyzed by zooplankton displacement volume, a biomass analog. Bernal (1981) shows the mean zooplankton biomass of spring-summer and fall-winter over CalCOFI line 90 (onshore to offshore, starting off Los Angeles Harbor and passing southeast of Santa Catalina Island) for the years 1960-1969 (Figure 6.10.a). The bimodal peak in spring-summer biomass (Figure 6.10.a) corresponded to variations in longshore transport. The peak at 180 km offshore occurred at the location of a net change in direction of flow from north to south in the upper 200 m. The further offshore peak (270 km) occurred at the location of the maximum southward flow of the California Current.

Colebrook (1977) conducted one of the few studies of the distribution of zooplankton taxa from the CalCOFI data set. Five years of CalCOFI zooplankton samples (1955-1959) were selected for principal component analysis of the geographical distributions of 17 taxa. The first of the principal components was shown to be a north to south concentration gradient, and the second was an onshore to offshore gradient. These two components accounted for 61% of the variability found. Figure 6.11 shows a plot of the first vector (north-south) plotted against the second vector (onshore-offshore). From this figure, the relative contribution of each vector as well as the strength of that vector can be inferred by the relative position of the taxonomic category. For example, the radiolarians, amphipods, and ctenophores have a very strong north-south gradient, with the high concentration in the north, while the mysids' north-south concentration gradient is highest in the south. The second vector influence is strongly seen in the cladocera, chaetognaths, and crustacean larvae concentrated

Figure 6.10. **Zooplankton** biomass (ml $1000m^{-3}$) in **SCB.** A. Horizontal onshore to offshore mean values for 1960-1969 on **CalCOFI** line 90 for **spring**-summer and fall-winter periods (from **Bernal** 1980). B. Vertical mean distribution for 12 daytime and 12 nighttime stations in April 1965 (from Brooks and **Mullin** 1983). C. Monthly mean distribution from 1955-1956 (dashed line) during high zooplankton biomass period and 1958-1959 (solid line) during period of low zooplankton biomass (data from Smith 1971).

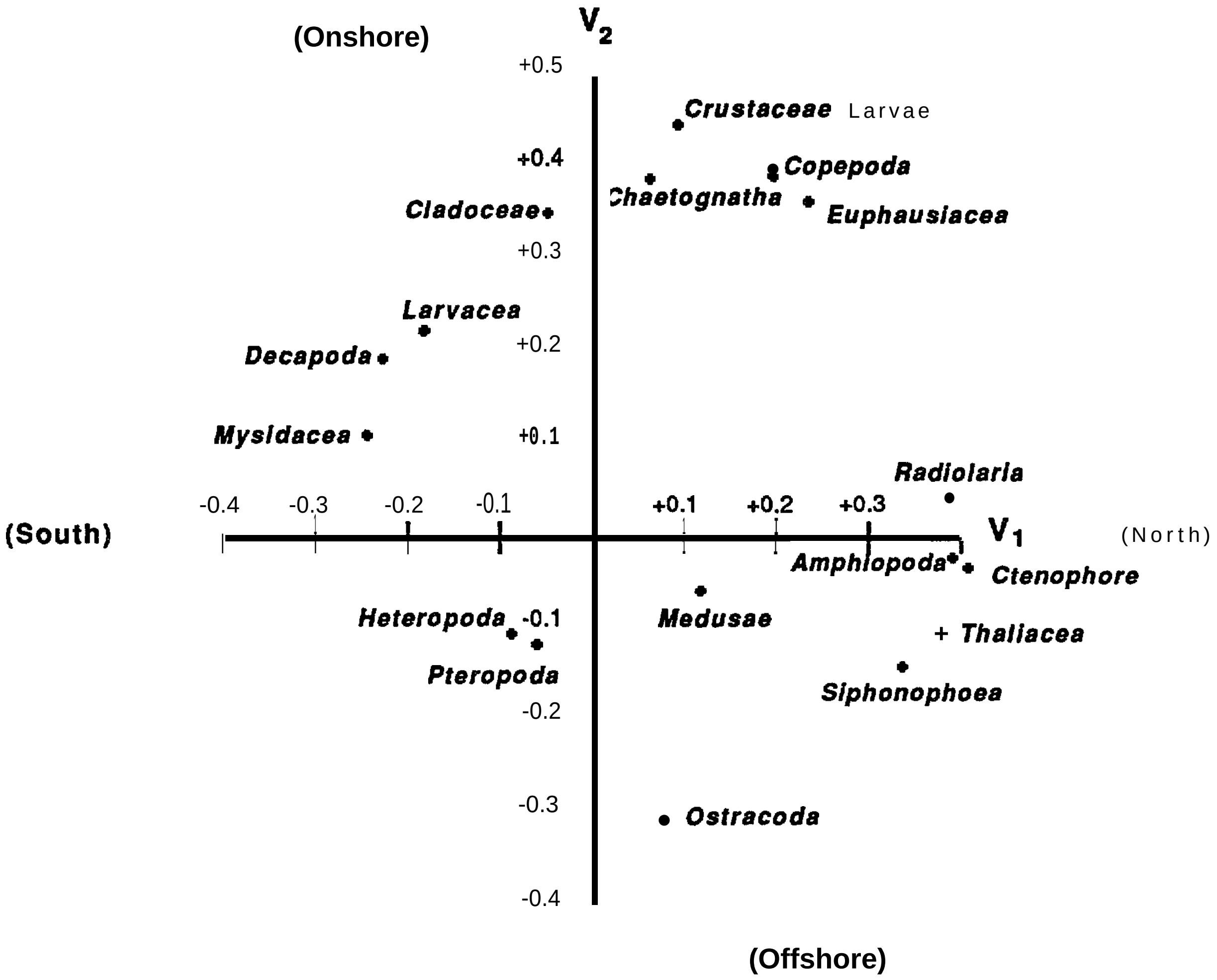
6.29b


(a)
Spring-Summer
Autumn-Winter
400
200
0
200
0
1400
1000
600
200
1400
1000
600
200
Mean Values (ml 1000m -3)
Distance Offshore (km)
0.00
0.05
Depth Range (m)
0-56
57-113
114-169
170-225
0,,, 0 0,,, 5 0,,, 0
505 µm Mesh Integrated= 7.8 ml m‘2
333 µm Mesh Integrated= 13.6 ml m-2
0-56
57-113
114-169
170-225
505 µm Mesh Integrated = 13.4 ml m-2
333 µm Mesh Integrated= 17.6 ml m-2
❑ 505pm Mesh ❑ 333 µm Mesh


(c)
Zooplankton Biomass (ml 1000 -3)
600
400
200
0
J
F
M
A
M
J
J
A
S
O
N
D
Month

6. 29c

Figure 6.11. A plot of the first and second vectors from a principal components analysis of the geographical distributions of 17 zooplankton taxa (after **Colebrook** 1977).


(Onshore)
V2
+0.5
Crustaceae Larvae
+0.4
Copepoda
Chaetognatha
Euphausiacea
Cladoceae
+0.3
Larvacea
+0.2
Decapoda
Mysidacea
+0.1
Radiolaria
(South)
-0.4
-0.3
-0.2
-0.1
+0.1
+0.2
+0.3
V1
(North)
Amphlopoda
Ctenophore
Heteropoda
-0.1
Medusae
Thaliacea
Pteropoda
Siphonophoea
-0.2
-0.3
Ostracoda
-0.4
(Offshore)

onshore, and in the ostracods, whose gradient is from offshore to onshore (high to low). The heteropods and pteropods are distributed slightly more to the south and offshore. The only group to show little clustering relative to either of these two vectors was the medusae.

Taxonomic groups, which may be composed of many independently distributed species, show an overall gradient longshore or onshore-offshore. Detailed distributions of these 17 taxa during this 5-year period can be found in Isaacs et al. (1969, 1971) for the spring, fall, and winter respectively, and in Fleminger et al. (1974) for the summer seasons. A further breakdown of Colebrook's (1977) taxonomic categories might reveal a distinct set of species representing north to south and onshore to offshore communities. Different species of euphausids show such a pattern. Brinton (1962) reported that euphausid distributions in the SCB show higher percentages of sub-Arctic species to the north higher percentages of Equatorial species in the south. Transition species generally showed patterns similar to sub-Arctic species.

O'Connell (1971) studied zooplankton horizontal distributions in the SCB in a more limited manner, sampling in the autumn of 1961 and 1962 from a depth of 5 m with a towed pump system. Of the four taxonomic groups he considered, only chaetognaths showed a systematic decrease in abundance with an increase in distance from shore. Euphausids and large and small copepods did not show this trend, but did sometimes show an increase in areas of low water temperature.

Fleminger (1967) grouped CalCOFI collected copepods into species groups which fell into major biogeographical-habitat groups. The copepod fauna of the SCB represented combinations of Transitional, sub-Arctic, Equatorial, and Central species, with the absence of sharply zoned assemblages (Fleminger 1967). Fenaux and Dallot (1980) have shown that for the Southern

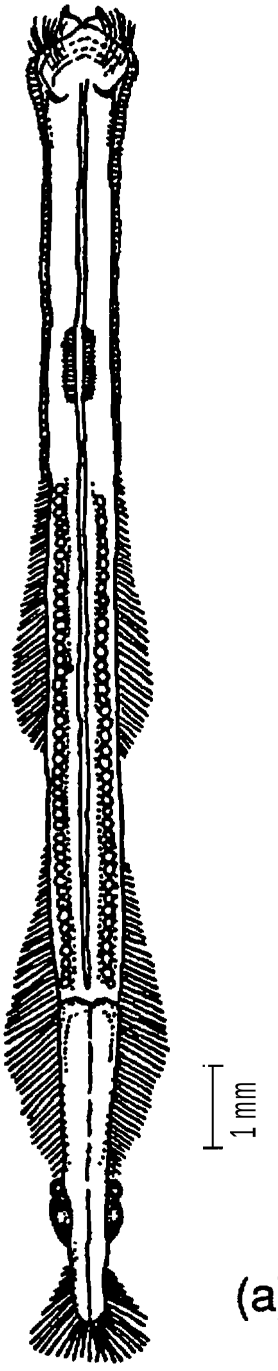
California and Baja California coasts, the appendicularians can also be grouped by species corresponding approximately to the major water masses of the Central and Equatorial Pacific. Other taxa have also been reduced to species distributions for various years of the CalCOFI sampling; these include chaetognaths (Figure 6.12.a) (Alvarino 1965), pelagic molluscs (McGowan 1967), thaliaceans (Figure 6.12.b) (Berner 1967), and euphausids (Brinton 1967, 1973; Brinton and Wyllie 1976).

Vertical Distribution

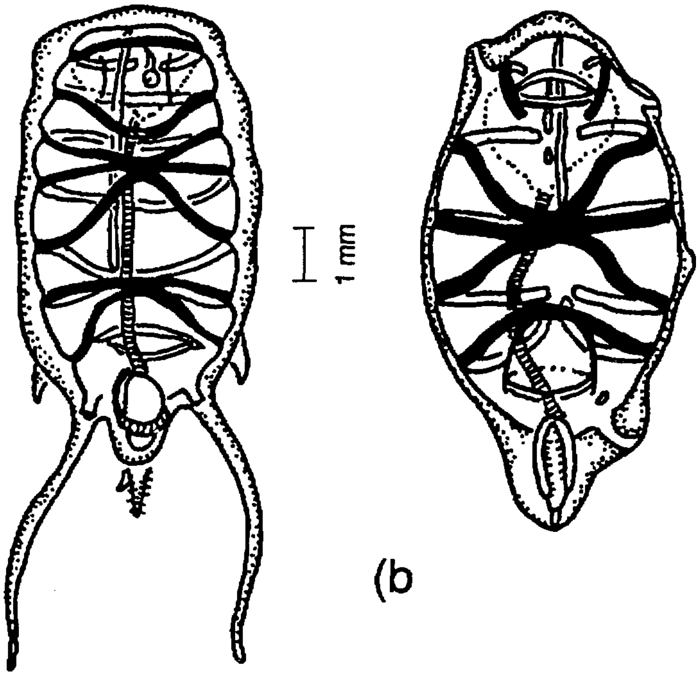
The dynamics of vertical structure, or vertical migration, of zooplankton have interested biological oceanographers for decades. The pattern of zooplankton ascent at dusk and descent at dawn is well-known. A persistent concern, however, is the amount of net avoidance among the more mobile macrozooplankton during the daylight hours near the surface. If this occurs, it could be perceived as a relative change in zooplankton concentrations between the surface and depth from day to night. Despite this possible source of ambiguity, a relative increase in surface concentration at night is generally considered as indicative of vertical migration.

The vertical distribution of zooplankton biomass is shown by Brooks and Mullin (1983) for 12 daytime and 12 nighttime samples in April 1965 in the SCB (Figure 6.10.b). For collections from nets of two mesh sizes, the upper 56 m contained the most zooplankton. With the effects of vertical migration, the upper layers of the water column supported an even larger percentage of the zooplankton. Figure 6.13 shows the vertical distribution of selected species during the day and night. All species migrated into the upper 56 m from deeper depths, but a significant portion of Eucalanus bungii females remained below 169 m at night. For all species except Euphausia

Figure 6.12. A. __**Sagitta euneritica**__ (from **Alvarino** 1965). B. Two forms of __Thalia democratic__ (from Berner 1967).



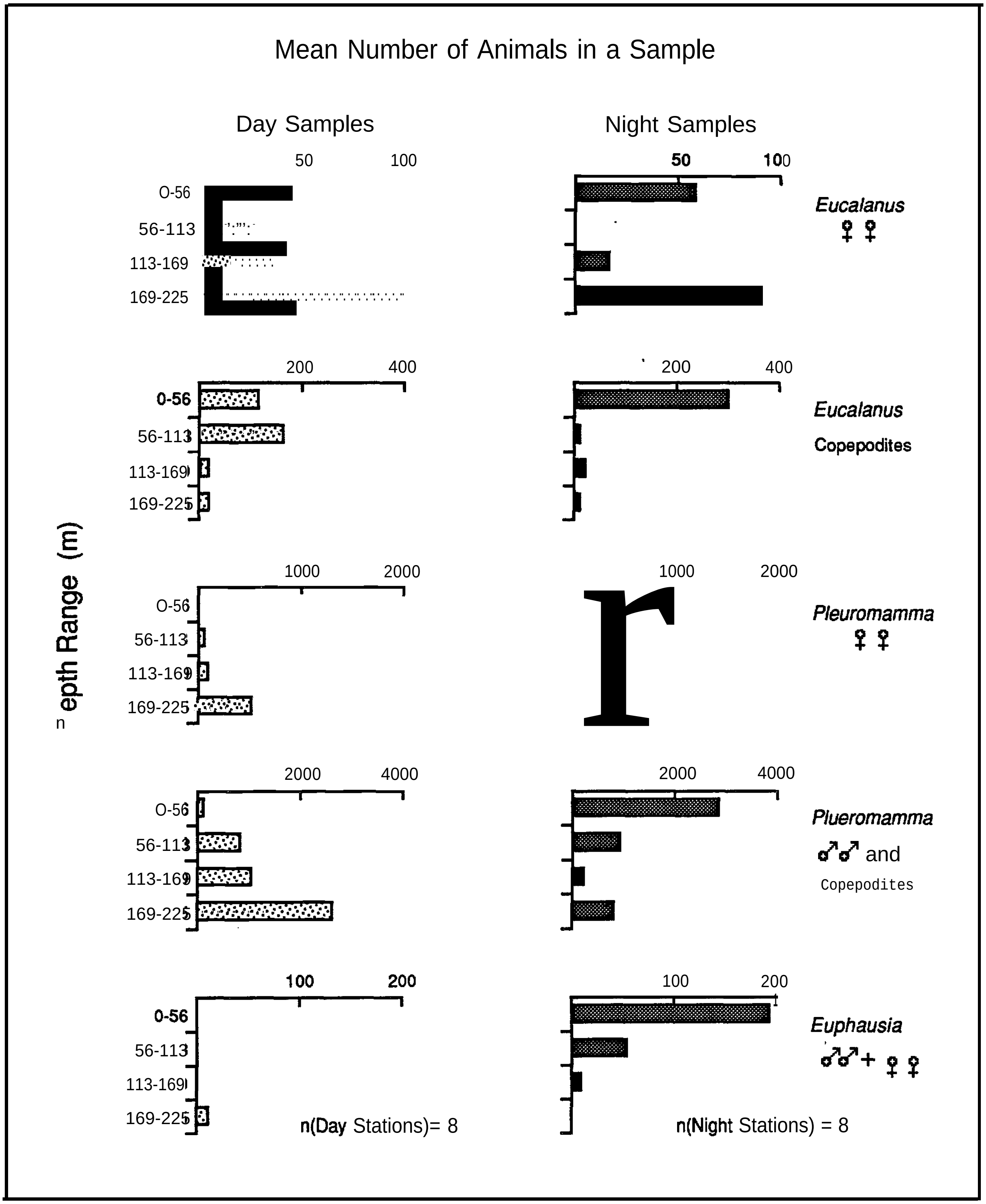
(a)



(b

6.31b

Figure 6.13. Day and night vertical distribution of selected species in April 1965 (from Brooks and Mullin 1983).


Mean Number of Animals in a Sample
Day Samples
Night Samples
Depth Range (m)
50
100
0-56
56-113
113-169
169-225
Eucalanus ♀♀
200
400
Eucalanus Copepodites
1000
2000
Pleuromamma ♀♀
2000
4000
Pleuromamma ♂♂ and Copepodites
100
200
Euphausia ♂♂+ ♀♀
n(Day Stations)= 8
n(Night Stations) = 8

pacifica, no difference was seen between day and night in the number of animals in the water column. It is thought that *E. pacifica* probably migrated up from below 225 m, since Pieper (1979) has shown acoustically that *E. pacifica* has an upper-depth distribution of 130-280 m during the day in the SCB.

Longhurst et al. (1966) reported on the daytime vertical distribution of a number of zooplankton taxa 10 miles west of La Jolla. *Acartia tonsa* was most abundant in the upper 50 m, *Calanus helgolandicus* (=*pacificus*) ranged between 50-120 m, and both *Eucalanus bungii* and *Pleuromamma borealis* were most abundant between 200-300 m. *Rhincalanus nasutus* was widely scattered through the water column but most abundant above 150 m.

The carnivorous copepods *Labidocera trispinosa* and *L. jollae* have vertical distributions very near the surface (Barnett 1974, as cited by Beers 1986). *L. jollae* copepodite stages through adult stage were almost exclusively neustonic. The more common *L. trispinosa* showed some depth variation with developmental stages. The eggs were centered between 15-20 m and, after hatching, the non-feeding nauplius I-II descended to depths that were seldom below 30 m. Nauplius II to copepodite III were primarily neustonic, copepodite IV and V were centered between 5-15 m, and the adults had a center of abundance from 15-20 m. No strong diel vertical migration was found for this species.

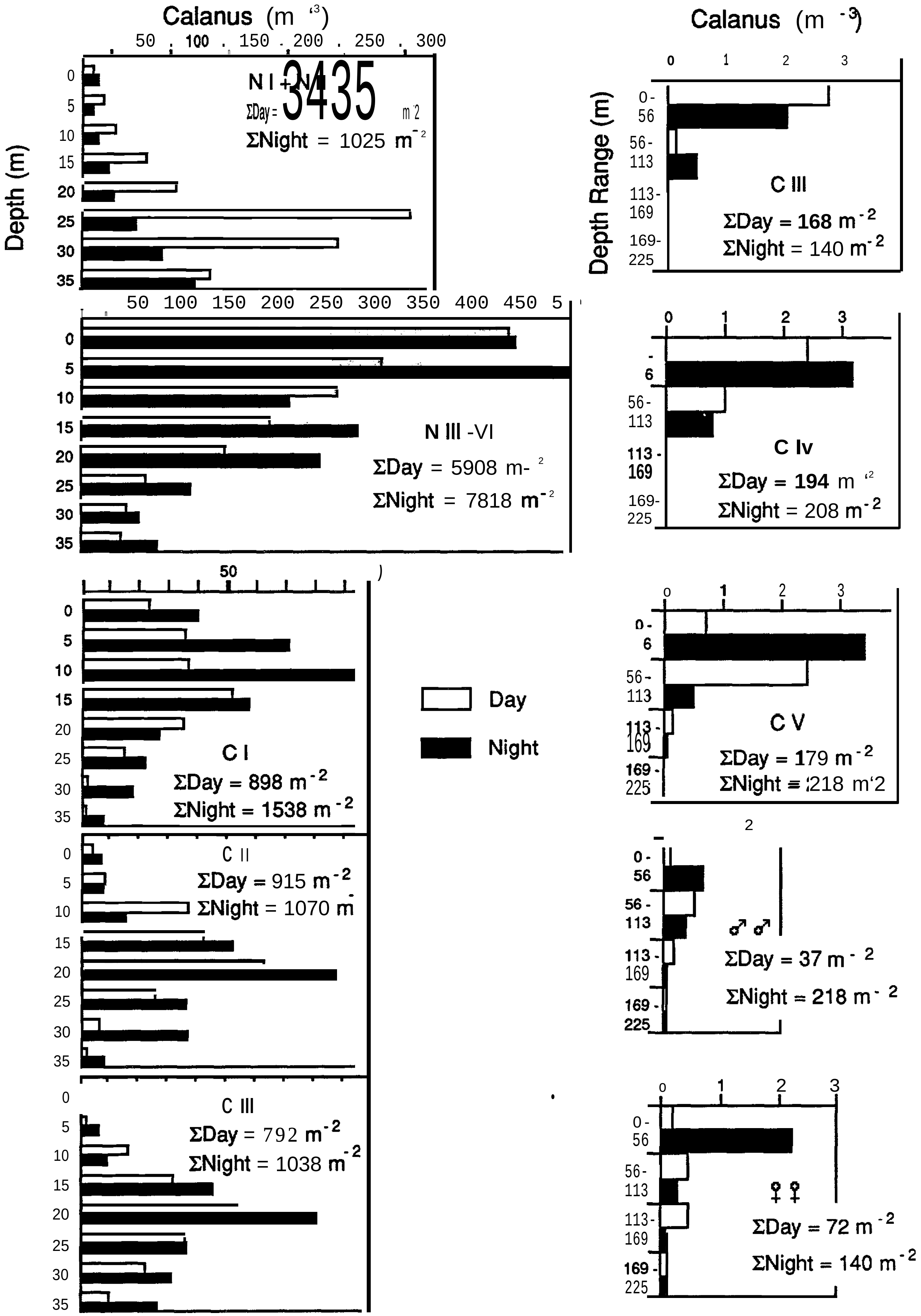
The daytime distribution of the copepod *Metridia pacifica* was almost entirely below 150 m; the species migrated up to the surface in two stages (Enright 1977). With approaching dusk they migrated into the depth range just below the thermocline (18-25 m). This depth was suggested to be a "staging area" for entry into the surface water as darkness falls. Vertical migration occurred at the remarkable rate of 30-90 $m\ h^{-1}$ for durations of more than an hour.

A description of the vertical distributions and diel vertical migrations of the developmental stages of *Calanus pacificus* was assembled by Mullin (1986), using Mullin (1979) for nauplier and early copepodite stages and Brooks and Mullin (1983) for later copepodite and adult stages (Figure 6.14). Vertical migration behavior among the developmental stages changed ontogenetically. Similar day-night distributions were seen from the nauplii through copepodite IV, but copepodite V adult males and females showed clear vertical migration. Huntley and Brooks (1982) also demonstrated seemlier ontogenetic vertical migration patterns for *C. pacificus* reared in the S10 deep tank.

The authors of this chapter (Pieper and Dawson unpubl. data) investigated the vertical distribution of *C. pacificus* developmental stages over a 24-hour period in the San Pedro basin (March 1987) while following a 20-m window-shade drogue. They also observed that the vertical migration pattern changed ontogenetically, but with some major differences from the above studies. Figure 6.15 shows the developmental stages of *C. pacificus* and their respective day-night vertical distribution characteristics. As the copepods developed from nauplius through mature copepodite stages, the diel vertical migration pattern reversed itself. The nauplier and early copepodite stages showed higher surface concentrations during the day and the maximum at depth at night. This change between copepodite III and IV to a traditional diel pattern of a deeper concentration during the day, moving up to the surface at night for copepodite V and the adult males and females.

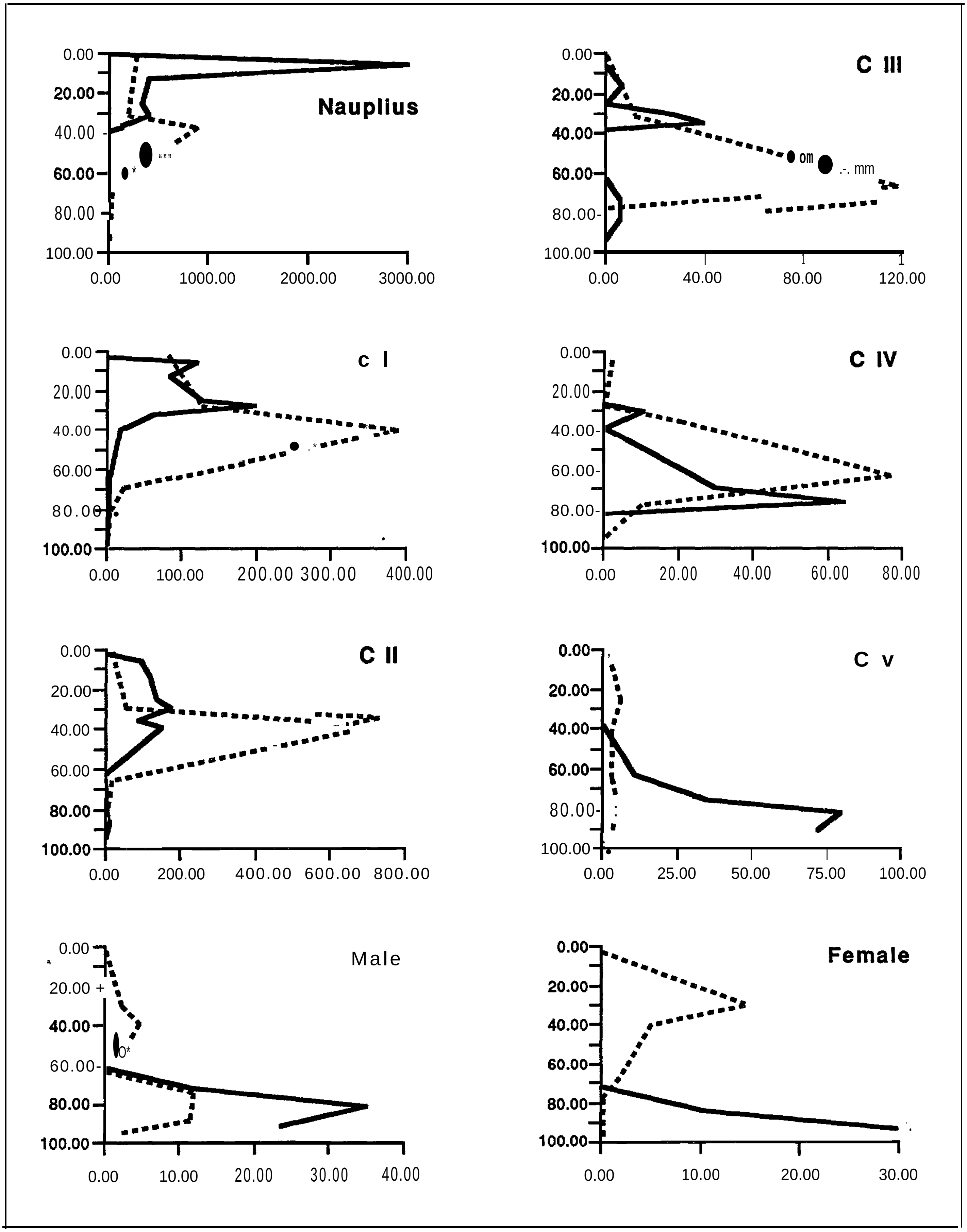
The authors' 1987 study may differ from those of Mullin (1979) and Brooks and Mullin (1983) for methodological reasons. If there is a reversal in vertical migration behavior between early and late developmental stages, as found by Pieper and Dawson, the latter two studies might have missed it.

Figure 6.14. Day and night vertical distribution of developmental stages of Cal anus **pacificus** (from **Mullin** 1986).


Calanus (m⁻³)
50 100 150 200 250 300
Depth (m)
0 5 10 15 20 25 30 35
N I + N II
ΣDay = 3435 m⁻²
ΣNight = 1025 m⁻²
50 100 150 200 250 300 350 400 450 5
N III -VI
ΣDay = 5908 m⁻²
ΣNight = 7818 m⁻²
50
C I
ΣDay = 898 m⁻²
ΣNight = 1538 m⁻²
C II
ΣDay = 915 m⁻²
ΣNight = 1070 m⁻²
C III
ΣDay = 792 m⁻²
ΣNight = 1038 m⁻²
Day
Night
Calanus (m⁻³)
0 1 2 3
Depth Range (m)
0-56
56-113
113-169
169-225
C III
ΣDay = 168 m⁻²
ΣNight = 140 m⁻²
C IV
ΣDay = 194 m⁻²
ΣNight = 208 m⁻²
C V
ΣDay = 179 m⁻²
ΣNight = 218 m⁻²
2
♂♂
ΣDay = 37 m⁻²
ΣNight = 218 m⁻²
♀♀
ΣDay = 72 m⁻²
ΣNight = 140 m⁻²

6. 33b

Figure 6.15. Vertical migration pattern of **Calanus pacificus** developmental stages. San Pedro Basin, March 19S7. Concentration (no. m^{-3}) vs. Depth Day: Solid line, Night: Dashed line.


Nauplius
0.00
20.00
40.00
60.00
80.00
100.00
0.00
1000.00
2000.00
3000.00
C III
0.00
40.00
80.00
120.00
c I
0.00
100.00
200.00
300.00
400.00
C IV
0.00
20.00
40.00
60.00
80.00
C II
0.00
200.00
400.00
600.00
800.00
C v
0.00
25.00
50.00
75.00
100.00
Male
0.00
10.00
20.00
30.00
40.00
Female
0.00
10.00
20.00
30.00

Brooks and Mullin's (1983) sampling was too coarse to see the vertical migration patterns in the upper 56 m, and Mullin (1979) did not sample deep enough to detect the early-stage migrations to below 35 m. Conversely, there is no apparent sampling problem in the data from deep-tank reported by Huntley and Brooks (1982). Also, sampling from the authors' study was from depth above and below the drogue, where advection could have transported in (or out) various "pulses" of organisms. Thus, the conflicting results between the Pieper and Dawson work and that of Huntley and Brooks remain unresolved.

Further complicating the pattern, Pieper and Holliday (1984) reported that female *Calanus pacificus* from the San Pedro Basin had a tri-modal vertical distribution in the upper 100 m during the daytime in collections from May 1978. This distribution appeared to be related to the reproductive phase of the female. At a near-surface peak (9 m), 73% of the females were gravid and their presence coincided with the peak distribution of male *C. pacificus*. At the mid-depth peak (36-40 m), 94$ of the females were gravid and all of the non-gravid females at this depth and above had attached spermatophores. In deeper water (80-100 m), 60% of the females were gravid and no spermatophores were attached to non-gravid individuals. In addition, 90% of these females were relatively transparent, possibly implying energetically spent” individuals.

In addition to diel vertical migration, *C. pacificus* also displays a seasonal vertical distribution pattern that may be a survival strategy related to food availability. In the fall of 1982, Alldredge et al. (1984) observed copepodite V *C. pacificus* in a state of diapause in the Santa Barbara Basin. A 20-m thick layer of these copepods was observed from a one-person submersible at a depth of 450 m. This non-migrating layer occurred at an estimated concentration of up to 26 x 10^6 individuals m^{-3} just above the sill depth, below which conditions became anoxic. Numerous predators were observed feeding on the aggregation, including the deep sea smelt *Leuroglossus stilbius* and the physonectid siphonophore *Apolemia* sp. Alldredge et al. (1984) suggest that *C. pacificus* enters a diapause stage in response to the seasonal upwelling cycle along the California coast. *C. pacificus* might reside in the surface water during the seasonal upwelling period in winter and early spring. With the decline of food in the fall they would enter this deep-water torpid phase, awaiting the following year's upwelling. In 1984, two years after Alldredge, B. H. Robison (pers. comm.) made similar dives reconfirming the existence of this deep layer in the Santa Barbara Basin.

Investigations of deeper-water zooplankton have largely centered around studies of sound-scattering layers in the SCB. Clarke (1966) studied the vertically migrating mesopelagic organisms in the Santa Barbara Channel in 1965. A 12 kHz fathometer was used for sound-scattering records, and a 6-foot Isaacs-Kidd midwater trawl, outfitted with a photometer, thermistor, pressure sensor, and a flowmeter, was used to collect the organisms. Clarke reported on three migrating taxa which had their maximum concentration at a particular light intensity (isolume). The euphausids were shallowest and showed day-night depth ranges of 150-200 m and 0-50 m respectively, while sergestids had peak day-night densities at 225-325 m and 75-225 m respectively. The bulk of the lantern fish, primarily *Lampanyctus leucopsarus*, were found below the sergestids, and they migrated with a deeper isolume.

Clarke (1966) found that the pasiphaeid shrimp showed no marked correlation with a particular light level; however, *Pasiphaea pacifica* appeared to migrate in a diurnal pattern. This species was most abundant in the day at depths greater than 400 m and at night from 225 to 275 m. **P. emarginata** lives in such deep water that its vertical range was not sampled adequately.

Ebeling et al. (1970) investigated the **pelagic** communities of the shallow (0-150 m), upper **mesopelagic** (150-400 m), lower **mesopelagic** (400-600 m), and **bathypelagic** (>600 m) depth zones over the Santa Barbara and Santa Cruz Basins. They collected from 1964 to 1969, using--as did Clarke--an instrumented 6-foot **Isaacs-Kidd** midwater trawl. Four resident community groups were identified from these areas: (I) mid-depth predators over the shallow (600 m) Santa Barbara Basin; (II) shallow invertebrate zooplankton equally abundant over both basins; (III) **mesopelagic;** and (IV) **bathypelagic** predators over the deeper (2000 m) Santa Cruz Basin. These resident communities also had dispersed within them transient groups, usually seasonally abundant, which were **advected** from the north, south, and west of the SCB.

Group I was largely composed of fish in a community of mid-depth predators over the Santa Barbara Basin. This community was dominated by deep-sea smelt, **Leuroglossus stilbius;** the lantern fish **Stenobrachius leucopsarus;** and the **pasiphaeid** shrimp **Pasiphaea pacifica** and **P. emarginata.** Also common were the **amphipods** **Hyperia** spp. and **Paracallisoma coesus** and the **medusae** **Tiaropsidium kelseyi** and **Aegina citrea. Ebeling et** al. (1970) believe that the larger predators in this group prey on the shallower communities especially at night, when they merge near the surface following vertical migration (**Ebeling** et al. 1970).

Group II was made up of various **zooplankters** which apparently flourished during periods of thermal stratification in the summer and fall. This group was composed of the **euphausids** **Nematoscelis difficilis** and

Euphausia pacifica; the amphipods *Paraphronema crassipes*, *Primno macropa*, and *Phronema sedentaria*; the shrimp *Sergestes similis*; and various species of chaetognaths.

Group III, or the offshore mid-depth community, was more diverse than its nearshore counterpart (Group 1). Two decapods dominated this community: *Pasiphaea chacei* and *Gennadas propinquus*. Other important members included the medusae *Atolls wyvelli* and *Colobonema sericeum*, the amphipod *Scina* spp., the mysid *Gnathophausia ingens*, and the two fish *Idiacanthus antrostomus* and *Cyclothone signata*.

Group IV, or the offshore deep community of the Santa Cruz Basin, was characterized by species which largely avoided the Santa Barbara Basin. This community appeared relatively stable throughout the year, and dominant species were 1 or 2 orders of magnitude less abundant than the overlying offshore mid-depth community (Group II). This group was dominated by the deep-sea fish *Cyclothone acclinidens*, *Melanostigma pammelas*, *Scopelogadus mizolepis bispinosus*, and *Holtbyrnia melanocephala*; the shrimp *Hymenodora frontalis*; and the mysids *Eucopia* spp. and *Boreomysis* spp.

Ebeling et al. (1970) observed that sound scattering (12 kHz) showed strong upper and lower layers in both the Santa Barbara and Santa Cruz Basins. The shallow invertebrate community (Group II), along with some transitory groups of animals, appeared to be associated with the sound-scattering layers. The mid-depth communities, however, tended to mix with the shallow invertebrates through vertical migration.

The benthopelagic (very near the bottom) zooplankton of the Santa Catalina Basin was sampled by Gowing and Wishner (1986) at 1 and 50 m off the bottom (1300 m), using a multiple-sampling, opening-closing net system operated from a submersible. Their samples averaged 85$ copepods, and a gut analysis of calanoid copepods showed them to be predominantly detritivores

(63%) and carnivores (23$). Bacteria, some of which were metal-precipitating bacteria, were also found in the gut. Considering the relative high ingestion rates (5.4 ug C mg^{-1} dry wt h-l) of these zooplankters (Wishner and Gowing 1987), these benthopelagic copepods may play a significant role in the distribution of metals in the near bottom water by ingesting the bacteria and capsules and delivering the metal capsules to the bottom via fecal pellets (Gowing and Wishner 1986).

Temporal Structure

The seasonal distribution (monthly means) of zooplankton biomass from samples taken along CalCOFI lines 80 (offshore from Point Conception) and 90 in the SCB are shown in Figure 6.10.C. In order to show the effects of differential transport of the California Current, data averaged from 1955 and 1956 are plotted as indicators of cold-water years (high California Current transport), and data from 1958 and 1959 are used as indicators of warm-water years. The warm- and cold-water years were chosen from the data presented by Chelton (1981), and the zooplankton volume data were gathered from oblique tows at the depth of 0-140 m (Smith 1971). Although the data indicate a similar seasonal trend, with biomass peaking in July, a dramatic difference in biomass between these two periods is also shown.

There seems little doubt that change in sea-surface temperature is related to relative reduction in biomass of the zooplankton. However, a marked similarity is also shown in the pattern of year-to-year fluctuations in upwelling, as indicated by principal component analysis for the first seven months of each year, as well as fluctuations in biomass of zooplankton. This implies some causal relationship (Colebrook 1977). Upwelling not only brings nutrients to the surface, but also affects temperature stratification of the water column. Thus, the considerable interannual variability in zooplankton biomass can be associated with variations in strength of the California Current (Roesler and Chelton 1987) as well as the intensity of coastal upwelling (Colebrook 1977).

Feeding

Calanoid copepods have been the focus of most feeding studies because they are both important in the pelagic ecosystem and are amenable to laboratory culture. *Calanus pacificus* is the local species of copepod which has received the most attention in regard to feeding dynamics. The laboratory culture of this species is reviewed by Beers (1986) and is considered to be primarily herbivorous. Landry (1980), however, has shown that *C. pacificus* has the ability to switch between herbivory and carnivory. Kleppel et al. (1988) suggest that *C. pacificus* tended toward herbivory when algal biomass and production were high, and towards carnivory when algal biomass and production were low. Other “herbivorous” copepod species, such as *Rhincalanus nasutus*, were shown by Mullin and Brooks (1967) to feed actively in the laboratory on newly hatched *Artemia nauplii*. While the carnivorous predation rates of *C. pacificus* are not as high as that of the carnivorous *Labidocera trispinosa*, Landry (1978) believes that, given the generally higher standing stock of *C. pacificus* in the SCB, its impact on nauplier standing stock may be significant. Paffenhofer and Strickland (1970) found no evidence that *C. pacificus* would feed on natural detritus from the SCB, but would feed on freshly prepared detritus from phytoplankton as well as *Calanus* fecal material.

Barnett (1974) studied the dietary aspects of the copepod *Labidocera trispinosa* (reviewed by Beers 1986). He found that there was a dietary change from primary herbivory in late nauplier to early copepodite stages, omnivory by late copepodite stage, and mainly carnivory in the adults.

Early food preferences included the diatom *Rhizosolenia* spp., naked dinoflagellates of 10-40 um (for example, *Gyrodinium* sp.), armored dinoflagellate *Prorocentrum micans*, and various ciliates. Late copepodites showed a preference for the naked dinoflagellate *Gymnodinium* spp., armored dinoflagellate *P. micans*, *Ceratium* spp., and *Gonyaulax polyedra*, as well as the zooplankton copepod nauplii and copepodites of small species, copepod eggs, and small cladocerans. Adult *L. trispinosa* showed a preference for all stages of various species of copepods and other small zooplankton, with the only phytoplankter in the diet being *P. micans*. Over the complete generation of *L. trispinosa*, phytoplankton were calculated to comprise less than 10% of the total carbon intake. Landry (1978) has reported that the ability of *L. trispinosa* to capture copepod prey decreased abruptly after the copepod develops beyond the nauplier stages, but the capture rates were greatest in the largest nauplii. He concluded that the greatest impact of *L. trispinosa* on the natural zooplankton assemblage would be on the later nauplier stages of larger prey species. Since the larger nauplii in plankton samples from the SCB are usually those of *Calanus pacificus* (Dawson and Pieper pers. comm.), feeding by *L. trispinosa* may have a large impact on this population.

Among the gelatinous zooplankton, Silver (1975) studied the feeding habitats of three common California Current salps, *Salpa fusiformis*, *Thalia democratic*, and *Cyclosalpa bakeri*--all of which are species that are known to swarm. She found that the species composition of phytoplankton ingested by swarm-forming *S. fusiformis* differed from those ingested by *C. bakeri*, implying that these species are in biologically different waters when they swarm. Since swarms can persist up to several months in duration, she concluded that the phytoplankton consumed by these swarming salps could pose a considerable resource depletion for the other zooplankton.

While swarming salps may have a depleting effect on the phytoplankton, Dunbar and Berger (1981) have shown that they may be of considerable advantage to the benthic community. They showed that in the spring of 1978 in the Santa Barbara basin what appeared to be salp fecal pellets accounted for more than 70% of the total organic carbon input to the benthic environment. Although this observation is an isolated one, zooplankton fecal pellet flux is an energetic input to the benthic community and is an area of active research at this time.

SUMMARY AND PROSPECTUS FOR FUTURE RESEARCH

Over the past 100 years of zooplankton research in the SCB, much of the sampling has been carried out over short time periods (the length of a cruise) and in limited geographic areas. These data have been invaluable in increasing our knowledge of distributions, behavior, physiology, and other aspects of zooplankton ecology. Only the 32-year CalCOFI data set, however, is extensive enough to show the interrelationship between macrozooplankton biomass and eastern Pacific and global circulation patterns. These results have emphasized the large interannual fluctuations in biomass and the aperiodic nature of of these variations. In fact, yearly fluctuations (Figure 6.1) are much larger than the yearly mean (Figure 6.12c).

Although it contains some unique species, the SCB is largely a transition zone between sub-Arctic, Central, and Equatorial species. Thus , biomass fluctuations may also be accompanied by changes in species composition. The boundary (or clinal region) between cold, nutrient-rich, California Current water (and its associated sub-Arctic species) can vary in position relative to warmer, nutrient-poor water from the south (Equatorial water) and west (Central water).

Smaller-scale processes are superimposed on these large-scale fluctuations. A specific process (such as coastal upwelling off the Pales Verdes Peninsula) will occur every year. However, its impact relative to zooplankton production and species composition would likely change in different years. Similarly, the impact of biological interactions (for example, fish predation on zooplankton) would be expected to vary with variations in species composition (for example, species of predators and their food preferences).

A number of marine zooplankton researchers met at Lake Arrowhead, California, in 1988 to discuss future directions in zooplankton research (Marine Zooplankton Colloquium 1, 19S9). The following conclusions from this colloquium are particularly important to the understanding of zooplankton ecology in the SCB. Similarly, they should be emphasized in planning future research programs. The following statements and their order were selected by the present authors.

1. We need to study individual zooplankters relative to their ambit, rather than by our sampling convenience, in order to understand how they respond in their environment.
2. We need to better understand how environmental variance, rather than mean conditions, affects zooplankton ecology, physiology, and behavior.
3. When possible, we need to conduct these studies in situ, and utilize non-invasive and non-disturbing approaches.
4. Most of our scientific approaches so far have been geared toward intermittent observations on individuals, populations, and communities.
5. We need to strive for either continuous observations or observations on time *or* space scales which are sufficiently

frequent for the processes to be studied.

6. Without an understanding of physical, chemical, and numerous biological processes, an understanding of individual performances, population dynamics, and community function of zooplankton cannot be achieved.

Conversely, modelers would like to know average conditions and basic patterns for predictive systems models. Also, organizations interested in environmental impacts would like to determine baselines of many parameters to enable them to assess human impact on the system.

The 32-year CalCOFI data set appears to fulfill the requirements of zooplankton ecologists, modelers, and environmental managers for zooplankton biomass on interannual scales. Much of the data discussed in the present review, while extremely valuable in furthering our knowledge of zooplankton ecology, does not satisfy present recommendations or needs of the above groups. Zooplankton biologists suggest a need for studies more directly applicable to the ambit of a particular organism (smaller-scale studies). Conversely, the oceanographic variability (including both currents and physical morphology) of the SCB makes it difficult to obtain a baseline to determine human impact when the variance of such a baseline is so high.

Our challenge for the future Is to find ways to provide data for all potential interests. Zooplankton biologists have a primary interest in understanding population and community structure and function. The species is the basis of such understanding. Similarly, we suggest that baselines of a particular species or group of species might, eventually, provide the necessary background to determine potential environmental impacts.

The shelf-slope break and slope regions appear to be both important biologically and under-studied. Since this area is both a boundary region

and a mixing zone, it will be most important to obtain concurrent data on as many parameters as possible (both physical and biological). Studies in this area might provide important data on food aggregations for fishes (Chapter 9), marine birds (Chapter 10), and marine mammals (Chapter 11).

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