Moss Landing Marine Laboratories

Technical Publication 73-1

SOME ASPECTS OF THE TEMPERATURE, OXYGEN AND NUTRIENT DISTRIBUTIONS IN MONTEREY BAY, CALIFORNIA

Annual Report, Part 1, 1973

by

William M. Smethie, Jr.

A NATIONAL SEA GRANT PROJECT
supported by the
OFFICE OF SEA GRANT PROGRAMS
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
DEPARTMENT OF COMMERCE
Grant No. SGP2-94

Robert E. Arnal, Sea Grant Project Coordinator

Moss Landing Marine Laboratories
of the
California State University and Colleges
at
Fresno, Hayward, Sacramento, San Francisco, San Jose, and Stanislaus

Contributions from the Moss Landing Marine Laboratories No. 36
Technical Publication 73-1
CASUC-MLML-TP-73-01

SOME ASPECTS OF THE TEMPERATURE, OXYGEN AND NUTRIENT DISTRIBUTIONS IN MONTEREY BAY, CALIFORNIA

by

William M. Smethie, Jr.

1973

Moss Landing Marine Laboratories
of the
California State University and Colleges
at
Fresno, Hayward, Sacramento, San Francisco, San Jose, and Stanislaus

ABSTRACT

Seasonal variations in temperature, dissolved oxygen, and nutrients in the nearshore areas and in the canyon area of Monterey Bay, California during 1971-1972 were similar. During upwelling periods, however, water in the nearshore areas was higher in temperature and oxygen and lower in nutrients than water in the canyon area. This was caused by upwelled water moving north and south of the canyon into counterclockwise and clockwise flow in the northern and southern ends of the bay respectively. The water was heated by insolation and depleted of its nutrients by photosynthesis during this movement. The residence time of water in the nearshore northern and southern bay during upwelling is estimated to be 3 to 8 days, and this fits well into the above circulation pattern and average measured current velocities of 10 to 15 cm/sec. There is some evidence that this circulation pattern and the estimated residence time may be also valid for non-upwelling periods. Upwelling apparently occurred in Monterey Submarine Canyon at rates of 0.4 to 2.9 m/day and was stronger in 1971 than 1972.

The ratio of $\Delta AOU:\Delta NO_3:\Delta PO_4$ was observed to be 276:14:1 by atoms, and nitrate was observed to be the limiting nutrient. The near-surface preformed phosphate values varied seasonally with highest values during upwelling periods and lowest values during non-upwelling periods.

Ammonia concentrations were generally high near shore and were consistent with ammonia entering the bay via sewage into nearshore areas where the water residence time was 3-6 days.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

ACKNOWLEDGMENTS

The help of Sandra Benz, Scott McKain, David Seielstad and the many students who participated in the hydrographic sample collection and the laboratory analysis is greatly appreciated. The assistance of Frank Monnich, captain of R/V Amigo, in carrying out the sampling program is gratefully acknowledged.

I wish to thank the California State Climatology Office of San Francisco for providing the wind data from the Farallon Islands.

This research was supervised by Dr. W.W. Broenkow of Moss Landing Marine Laboratories, and this report constitutes a M.S. thesis in the Department of Natural Science at California State University, San Jose. The author appreciates the help of his research committee: Dr. W.W. Broenkow, Chairman, Dr. T.J. Conomos, (U.S. Geological Survey, Menlo Park), Dr. N. Felton, and Dr. R.L. Hassur.

This research was supported by Grant 2-35137 from the Office of Sea Grant Programs, National Oceanic and Atmospheric Administration, Department of Commerce and by the Association of Monterey Bay Area Governments.

CHAPTER 1

INTRODUCTION

Purpose of this study

Monterey Bay (Fig. 1) is an open embayment located on the central California coast. The surrounding coastline is moderately populated with 20 small cities and towns, having a total population of approximately 300,000. These municipalities discharge sewage via ten domestic sewer outfalls, of which eight discharge into the bay and two into the bay's tributaries (Harville 1971). Industrialization is sparse, but industrial wastes from a Pacific Gas and Electric power plant, Kaiser Refractories magnesia plant, and fish canneries enter the bay. A large area of land in the drainage basins tributary to Monterey Bay is cultivated perennially; thus, the bay is subject to agricultural runoff.

It is important to know the fate of domestic, industrial, and agricultural wastes in a marine environment, such as Monterey Bay. The flushing of Monterey Bay is of prime importance in determining the fate of these wastes. An understanding of nutrient-oxygen relations and the flow of nutrients through Monterey Bay will aid in the better understanding of biological processes occurring within the bay.

Previous hydrographic studies in Monterey Bay were of long duration and have well established seasonal changes in temperature and salinity occurring in the bay and their dependence upon seasonal changes occurring in the California Current system; however, these studies have not provided good areal coverage of the bay, particularly nearshore regions

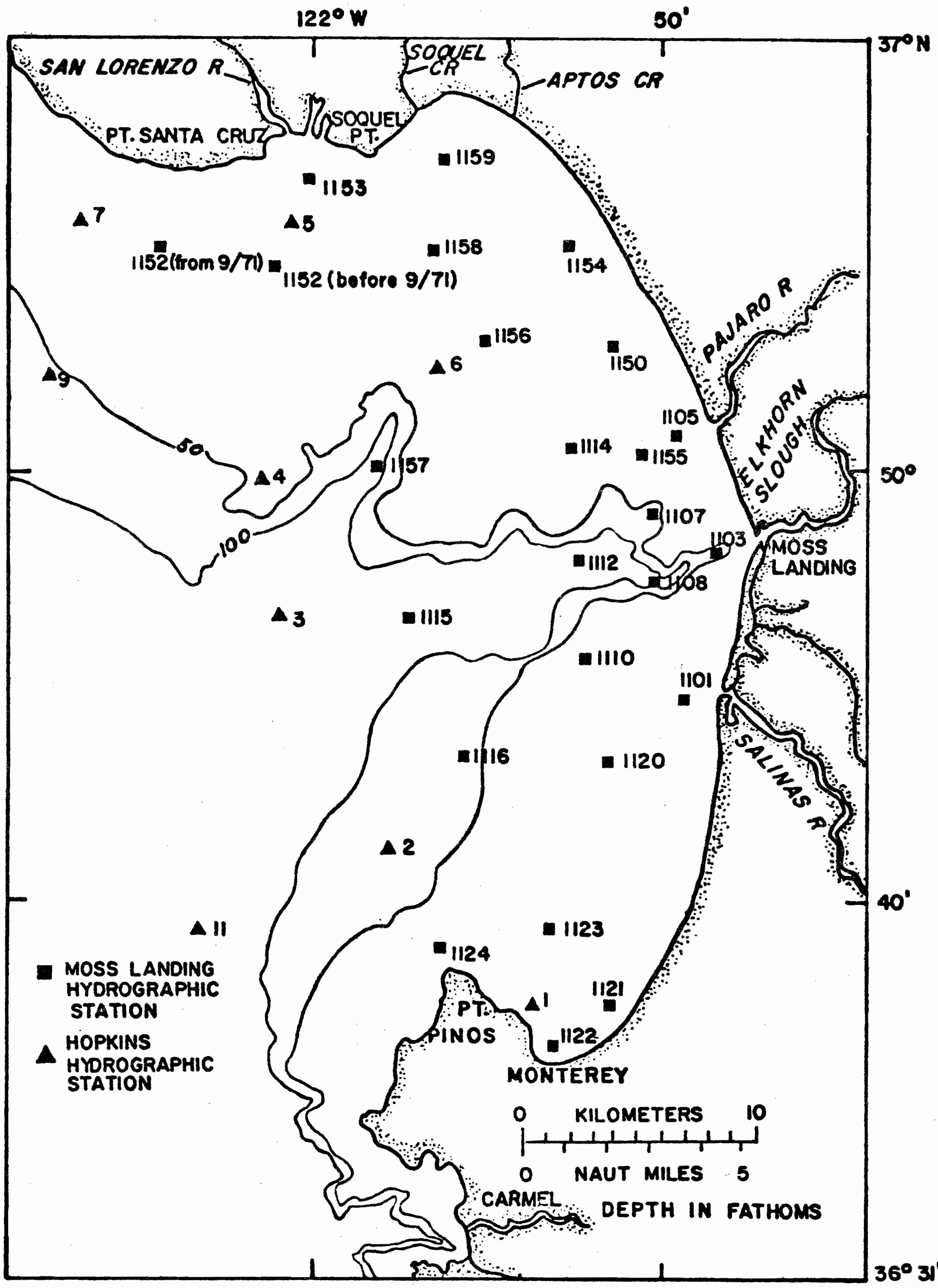

Figure 1. Hydrographic sampling stations in Monterey Bay, California.

where man's wastes are discharged, and previous studies have not provided complete nutrient data.

This thesis is based on data collected by personnel of Moss Landing Marine Laboratories and Hopkins Marine Station between February 1971 and May 1972 (Table 1). Although short in duration, this is the most extensive survey of temperature, salinity, oxygen, and nutrient concentrations in Monterey Bay. Sufficient data are available to better understand some aspects of the flushing of Monterey Bay and to describe the nutrient-oxygen relations. Since both flushing of the bay and the nutrient-oxygen relations may be influenced by seasonal changes or have seasonal cycles, a detailed description of the seasonal changes and seasonal cycles in nearshore areas and the mid-bay area is presented. This is followed by a discussion of upwelling and general water movement in Monterey Bay and a description of the nutrient-oxygen relations. Finally the residence time of water in the northern and southern ends of the bay is estimated from nutrient uptake rates, oxygen production rates, and heat absorption rates. It is shown that the relatively high ammonia concentrations generally found in nearshore areas can be accounted for by these residence times and ammonia entering the bay via sewer outfalls.

General description of Monterey Bay

Monterey Bay (Fig. 1) is located between 36°36' and 36°59' N latitude. It is shaped like a reverse C with bights in the extreme northern and southern ends. A line connecting Point Pinos to Point Santa

TABLE 1

SOURCE OF DATA

Date	Area Covered	Source
Feb. 71-Dec. 71	Monterey Bay	Moss Landing Marine Laboratories Technical Publication 72-1 (Broenkow 1972)
Feb. 71-Dec. 71	Monterey Bay	Hopkins Marine Station of Stanford University (1972)
Sept. 71-May 72	Monterey Bay and offshore	Unpublished data, Hopkins Marine Station of Stanford University
Jan. 72-May 72	Monterey Bay	Unpublished data, Moss Landing Marine Laboratories

Cruz defines the 37 km wide mouth of the bay and an artificial western boundary for the purpose of subsequent discussions. The bay is approximately 16 km wide from this western boundary and 42 km in length from the extreme northern end to the extreme southern end.

Three main tributaries, the Pajaro River, Elkhorn Slough, and the Salinas River, enter the central region of Monterey Bay. During dry months (May to October) the Salinas River is blocked by a sand bar, and its water flows northward to discharge through Elkhorn Slough. The San Lorenzo River and several other small streams enter the northern region of the bay.

Perhaps the most striking feature of Monterey Bay is Monterey Submarine Canyon, one of the world's largest submarine canyons (Martin 1964). The head of the canyon is located within 0.3 km of the shoreline at Elkhorn Slough, and the canyon bisects the bay almost symmetrically forming northern and southern shelf regions. The width of the canyon increases from approximately 0.2 km at its head to approximately 12 km at the mouth of Monterey Bay as the depth of the canyon increases from 18 m to 865 m. The northern shelf covers an area of approximately 238 km^2 and gradually deepens from the shoreline to 90 m at the canyon edge. Soquel Canyon, an 8 km long branch of Monterey Submarine Canyon, extends into the northern shelf to approximately 10 km from shore southeast of Soquel Point. The southern shelf covers an area of approximately 195 km^2 and is somewhat deeper than the northern shelf with a depth of about 180 m at the canyon edge. The southern rim of the canyon runs in a southwest direction and intersects the northern rim of Carmel Canyon south of Point Pinos. Monterey Bay has an area of approximately 534 km^2 of which 433 km^2 (81%) lies over the continental shelf, and 101 km^2 (19%) lies over Monterey Submarine Canyon.

Oceanography of the California Current system

The California Current system is an eastern boundary current characterized by a wide ($\sim$1000 km), shallow ($<$500 m), slow ($\sim$25 cm/sec) current flowing southward along the western coast of North America, a northern flowing countercurrent, and seasonal upwelling (Wooster and Reid 1963). The southern flowing current is known as the California Current and is part of the eastern gyral in the North Pacific Ocean. It transports low-temperature, low-salinity, nutrient-rich Subarctic water southward along the North American coast (Reid and others 1958).

The California Countercurrent is a subsurface current that flows northwest along the North American coast from Baja California to beyond Cape Mendocino with its core at a depth of about 200 m (Reid and others 1958). North of 30° N latitude it appears to extend to between 50 and 100 km offshore, and speeds have been measured up to 22 cm/sec (Reid 1962). Warm, high-salinity Equatorial Pacific water is transported northward by this current (Reid and others 1958; Sverdrup and others 1942).

During fall or early winter, the California Countercurrent surfaces between Point Conception and British Columbia and is then known as the Davidson Current. The Davidson Current lies landward of the California Current and extends to approximately 80 km offshore with speeds measured between 16 and 47 cm/sec (Reid and Schwartzlose 1962; Schwartzlose 1963).

The development of the Davidson Current appears to be related to changes in the seasonal wind field. During spring and summer, a high pressure cell is located over the Pacific Ocean and a low pressure cell over the North American continent, resulting in strong winds from the north and northwest. In fall and winter the high pressure cell weakens and moves southward, and the low pressure cell becomes intermittent (Reid and others 1958). This results in a period of relatively little wind in the fall and westerly and southwesterly winds north of Point Conception in the winter (Smith 1968). The Davidson Current develops in late fall and is strengthened during periods of southwesterly winds. Surface water is transported 90^{o} to the right of the wind direction under the influence of the Coriolis force resulting in convergence of this water along the North American coast and subsequent sinking (Bolin and Abbott 1963).

The strong north and northwest winds occurring in spring and summer cause surface water to be transported offshore under the influence of the Coriolis force. Subsurface water, probably from less than 200 m, rises to replace the water moved offshore, and this process is known as wind induced upwelling. A result of coastal upwelling is the formation of a semi-closed vertical circulation cell with water moving inshore at some depth, probably less than 200 m, rising to the surface adjacent to the shoreline, and being transported offshore by the wind (Sverdrup and Fleming 1941). This causes the sea surface offshore to be at a higher level than the sea surface nearshore. Coastal upwelling occurs to as far as 50 km offshore (Smith 1968) at estimated rates ranging from 0.7 m/day (McEwen 1929 in Smith 1968) to 2.7 m/day (Saito 1951; Hidaka 1954 in Smith 1968).

Northerly and northwesterly winds are usually strongest off Baja California during April and May, central California during May and June, northern California during June and July, and Oregon during August. Periods of strongest upwelling occur during these months, but upwelling occurs any time during the year when wind conditions are favorable (Smith 1968). During periods of upwelling, water adjacent to the California coast is low in temperature and oxygen content and high in salinity and nutrient content as the result of subsurface water being brought to the surface.

Drift-bottle studies indicate that surface water moves intermittently onshore between San Francisco and Monterey Bay during upwelling periods (Schwartzlose 1963). There are two possible reasons for this. First, upwelling is generally most intense at Point Conception (35^{o} N latitude) and Cape Mendocino (41^{o} N latitude), and eddies associated with these areas of intense upwelling transport surface water to and from shore (Sverdrup and others 1942). Secondly, the winds are sporadic, and an abrupt cessation of the northerly winds would relax the offshore force and allow onshore flow to restore isostatic balance.

Seasonal changes in Monterey Bay

Seasonal hydrographic changes occurring in Monterey Bay and in nearshore water along the California coast are similar and are caused by seasonal changes in the California Current system. The annual variation of temperature and salinity between 1950 and 1962, at a CalCOFI (California Cooperative Oceanic Fisheries Investigations) station 10 km offshore and 40 km south of Monterey Bay, are quite similar to those at a CalCOFI station (station 3, Fig. 1), located just outside the mouth of Monterey Bay (Fig. 2, Lynn 1967). These seasonal variations have been well established for Monterey Bay. The original work by Skogsberg (1936) was based mainly on temperature data collected at stations in central and southern Monterey Bay twice weekly from 1929 to 1933. Subsequent investigations on a weekly basis from 1934 to 1937 in central and southern Monterey Bay (Skogsberg and Phelps 1946), 1951 to 1955 over Monterey Submarine Canyon just outside the mouth of Monterey Bay (Bolin and Collaborators 1964), and 1954 to 1966 over the entire bay (Bolin and Abbott 1963; Abbott and Albee 1967), fully confirmed Skogsberg's original work. The following description of the seasonal hydrographic variations is drawn mainly from the work of Bolin and Abbott (1963).

Three oceanographic periods have been described to occur in Monterey Bay: The Davidson Current period typically from November to February, the upwelling period from February to September, and the oceanic period from September to November. The timing and intensity of these periods vary from year to year.

During the Davidson Current period the California Countercurrent surfaces north of 35^{o} N latitude, and water from the south converges against the coast and sinks. At the beginning of this period, the

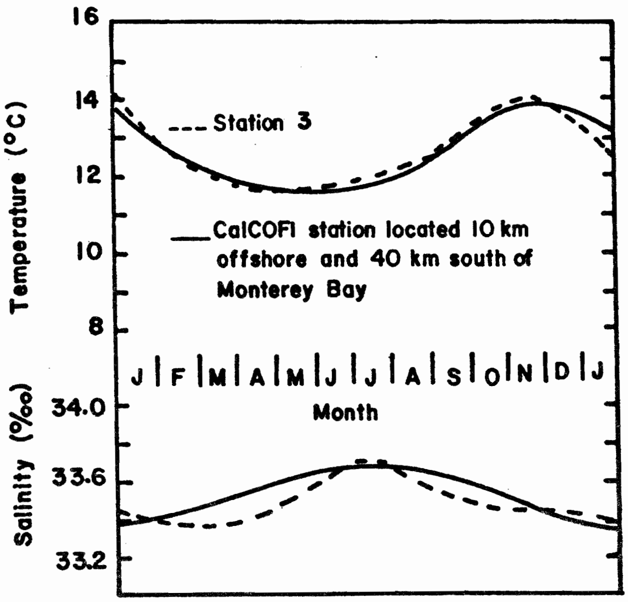

Figure 2. Mean variation of temperature and salinity from 1950-1962 at the mouth of Monterey Bay (station 3) and 40 km south of Monterey Bay.

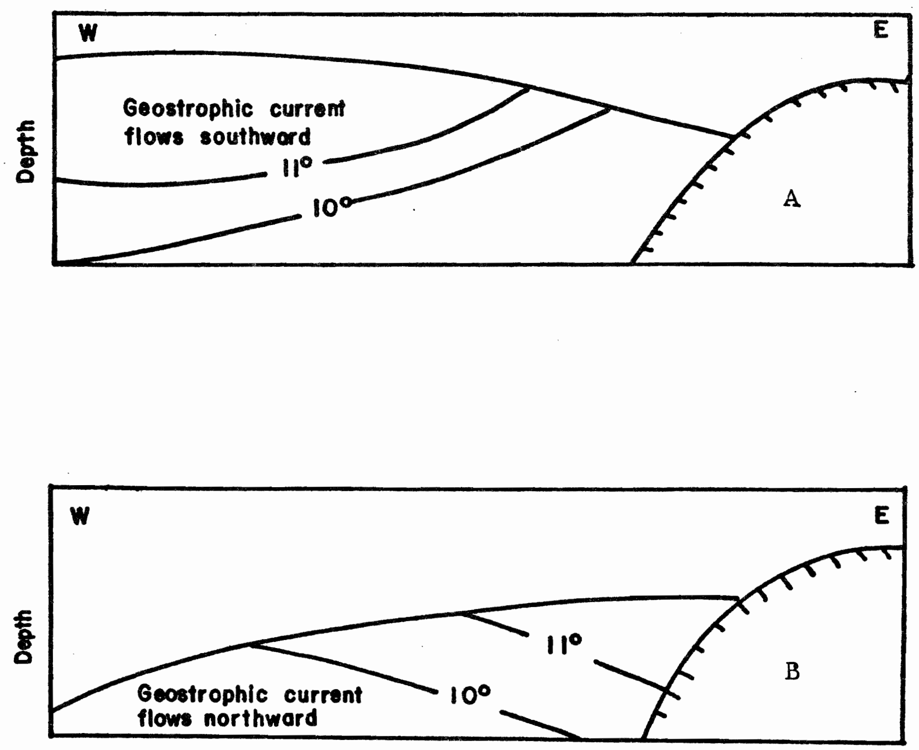

Figure 3. Idealized vertical temperature distribution and sea surface slope across A) the California Current, and B) the Davidson Current.

surface temperature decreases abruptly ($\sim 1.8^{\circ}$ C), but subsurface temperature increases throughout the period to its annual maximum causing a low thermal gradient ($< 1^{\circ}$ C) to develop in the upper 50 m. The drop in surface temperature can be explained by decreased insolation and deep vertical mixing of surface water caused by storms occurring during this time of year. The increase in subsurface temperature can be explained by descending isotherms. This is caused by water sinking as it converges on the coast and by the change in geostrophic currents between the oceanic and Davidson Current periods. During the oceanic period the sea surface slopes downward, isotherms slope upward towards the coast, and the geostrophic current flows southward (Fig. 3). During the Davidson Current period the sea surface slopes upward, isotherms slope downward toward the coast, and the geostrophic current flows northward (Fig. 3). The change from a southern flowing geostrophic current to a northward flowing geostrophic current results in a descent of isotherms adjacent to the coast. Surface temperatures generally vary less than 1° C over the entire bay, and weekly variations at any given station are generally less than 1° C. Salinity is low (33.4 $^{\circ}/oo$) and variable due to surface runoff and rain at this time of year.

The transition between the Davidson Current period and the upwelling period is sometimes ill-defined but can be quite abrupt if strong upwelling occurs early in the year. Rising subsurface water causes isotherms to rise and surface and subsurface water to reach their lowest annual temperatures. The 8° C isotherm may rise above 100 m and a thermal gradient of 3° C or more develops in the upper 50 m. The surface temperature varies by 3^{o} C or more over the entire bay with warmer water being found in the northern and southern ends. This appears to be caused by upwelled water remaining in the northern and southern ends and being heated by insolation (Bolin and Abbott 1963; Shephard 1970). Throughout the upwelling period, the surface temperature varies erratically (3^{o} C or more) at any given location in the bay. This is possibly caused by erratic onshore movement of surface water or sporadic upwelling. As summer approaches, the surface temperature gradually increases with the increase in insolation. Salinity increases during the upwelling period as the result of high salinity water rising to the surface.

The rate of upwelling in Monterey Bay has been estimated to average 1.5 m/day (Skogsberg 1936). Vertical movement can be detected as deep as 700 m; however, water reaching the surface may come from only 200 m or less (Skogsberg 1936; Bolin and Collaborators 1964). Upwelling is somewhat sporadic throughout the upwelling period and becomes more so at the end (Bolin and Abbott 1963).

When upwelling ceases, the dense, previously upwelled water sinks, and offshore surface water flows onshore marking the beginning of the oceanic period. This transition is often ill-defined, and at times, oceanic water only partially invades the bay with a temperature interface between cool, recently upwelled bay water and warm oceanic water (Skogsberg 1936). During this period, surface temperatures reach an annual maximum ($\sim 16^{o}$ C), and the temperature gradient remains above 3^{o} C in the upper 50 m. Surface temperatures vary by 2 to 3^{o} C over the bay, and weekly variations at any given location are less erratic than during the upwelling period. Salinity, which begins to decline near the end of the upwelling period, continues this trend, then levels off or rises slightly.

Nutrient concentrations in surface water increase during the upwelling period as water beneath the photic zone rises to the surface. The phytoplankton standing crop also increases as the upwelling period progresses due to ample nutrient supply and increasing sunlight. It reaches its maximum in about June and its minimum in December or January when sunlight and nutrient concentrations are low (Bolin and Abbott 1963).

CHAPTER 2

METHODS

Stations sampled

Hydrographic sampling was conducted monthly by personnel at Moss Landing Marine Laboratories in Monterey Bay beginning in February 1971. Thirteen northern and central bay stations (Fig. 1 and Table 2) were sampled from February 1971 through June 1971. This was expanded to 16 stations in July 1971 and to 21 stations, covering the entire bay, in September 1971. From February 1971 through May 1971, stations were sampled within a four day period and thereafter within a three day period. Northern bay stations, central bay stations, and southern bay stations were sampled on separate days.

Personnel at Hopkins Marine Station have taken hydrographic data at six stations in Monterey Bay on either a weekly or monthly basis since 1951. In September 1971 their program was expanded to 12 stations inside and outside Monterey Bay, and their sampling schedule was coordinated with Moss Landing's. Nutrient samples collected during these coordinated cruises were analyzed at Moss Landing Marine Laboratories. These data are used in this thesis, but data collected prior to September 1971 are used only if collected during the time periods of Moss Landing cruises.

Navigation was done by horizontal sextant angles, loran, and radar with an accuracy of about 0.25 nautical miles. Stations are assumed to have been occupied within a 0.25 nautical mile radius of their nominal positions.

TABLE 2

Hydrographic stations in Monterey Bay

Station Number *	Latitude N.	Longitude W.	Depth (m)
1124	36°38.8'	121°56.3'	40
1122	36°36.6'	121°52.9'	16
1121	36°37.6'	121°51.2'	18
1123	36°39.2'	121°53.1'	68
1120	36°43.1'	121°51.5'	57
1116	36°43.3'	121°55.6'	97
1110	36°45.6'	121°52.0'	70
1101	36°44.7'	121°49.3'	15
1103	36°48.1'	121°48.2'	110
1108	36°47.4'	121°50.0'	240
1112	36°48.0'	121°52.2'	240
1115	36°46.6'	121°57.2'	718
1157	36°50.2'	121°58.1'	366
1114	36°50.5'	121°52.7'	59
1105	36°50.8'	121°49.6'	15
1154	36°55.2'	121°52.7'	15
1158	36°55.1'	121°56.7'	26
1159	36°57.1'	121°56.2'	15
1153	36°56.8'	122°00.1'	15
1152	36°55.3'	122°04.4'	35
1150	36°52.9'	121°51.3'	18

TABLE 2 (cont.)

Station Number *	Latitude N.	Longitude W.	Depth (m)
4401	36°37.6'	121°53.6'	44
4402	36°41.2'	121°57.9'	100
4403	36°46.7'	122°01.0'	950
4404	36°50.9'	122°01.5'	85
4405	36°52.3'	121°56.5'	60
4406	36°55.8'	122°00.7'	22
5507	36°56.0'	122°06.7'	50
5508	36°59.3'	122°12.2'	40
5509	36°52.2'	122°07.6'	95
5510	36°42.0'	122°12.0'	1100
5511	36°39.3'	122°03.2'	1100
5512	36°32.0'	121°58.0'	350

* 11xx designates Moss Landing Marine Laboratories stations;
44xx designates Hopkins Marine Station CALCOFI stations;
55xx designates Hopkins Marine Station AMBAG stations.

Samples were collected with 5-liter Niskin plastic sampling bottles at standard depths of 0, 10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 400 m, and at 5 m at nearshore stations. Accepted depths were determined from wire angle for depths 30 m or less and by a combination of wire angle and the thermometric depth of the bottom bottle for greater depths.

Temperature, salinity, and dissolved oxygen

The *in situ* temperature was determined from paired reversing thermometers. Where agreement was 0.05° C or better, duplicate temperatures were averaged.

Salinity samples were analyzed in the laboratory within three weeks of collection using a Beckman Model RS-7B precision induction salinometer. Substandard seawater, standardized each month with Copenhagen water, was used to calibrate the salinometer before and after each set of 24 or fewer samples. Salinity was computed from the conductivity ratio using the equations of Cox and others (1967). Precision of the analyses was about ± 0.006 ‰ (2 SD).

Carpenter's (1965) modification of the Winkler method was used to determine dissolved oxygen. Samples were drawn from the Niskin bottles as soon as they were retrieved and treated immediately to fix oxygen in the basic form. These samples were acidified and titrated in the laboratory within 12 hours of collection. Precision of the analysis is about ± 0.06 ml/liter (2 SD). Apparent oxygen utilization (AOU), the difference between the computed oxygen solubility and the observed oxygen concentration (Redfield 1942), and per cent saturation were calculated using the equations of Truesdale and others (1955).

Nutrient ions

Samples (500 ml) were filtered through 3 μm pore diameter glass fiber filters into polyethylene bottles and quick frozen in a dry ice-alcohol solution aboard ship. These samples were stored at -10° C until time of analysis in the laboratory. Groups of 36 samples were quick-thawed just prior to the analyses for phosphate, nitrate, nitrite, ammonia, and silica. Standards and reagent blanks were prepared fresh daily and were determined with each set of samples. All samples were analyzed within three weeks of collection.

Reactive phosphate was determined by Murphy and Riley's (1962) method described by Strickland and Parsons (1968), using ascorbic acid to reduce the phospho-molybdate complex. The sample absorbance was determined at 885 nm in 10 cm cells on a Beckman DU II Spectrophotometer. Precision of the analyses is about ± 0.03 μg-atom/liter (2 SD).

Nitrate was determined by the cadmium-reduction method of Wood and others (1967) followed by the nitrite color development. The sample absorbance was determined as 543 nm in 1 cm cells using a Spectronic 20 colorimeter. Precision of the analyses is about ± 0.5 μg-atom/liter (2 SD).

Ammonia was determined by Solorzano's (1969) indophenol method. The sample absorbance was determined at 640 nm in 10 cm cells using the Beckman DU. Precision of the method is about ± 0.1 μg-atom/liter (2 SD).

CHAPTER 3

TEMPORAL AND SPATIAL VARIATIONS IN MONTEREY BAY

Tidal changes

This investigation was concerned predominantly with seasonal changes in physical and chemical parameters and with the spatial distribution of these parameters in Monterey Bay. In nearshore areas temporal and spatial variations of these parameters can be due, in part, to sampling on different times of the tidal cycle. Thus, it is important to know how these parameters vary during a tidal cycle.

During this investigation, two 25-hour studies were conducted to determine local changes caused by the tide. The first study was made during 7-8 August 1971, at stations 1103 and 1108 at the head of Monterey Submarine Canyon (Fig. 1). Each station was sampled 10 times during the 25-hour period at the standard sample depths. Subsurface isotherms rose during ebbing tides indicating ascending water and sank during flooding tides indicating descending water (Fig. 4). This is in agreement with previous current meter observations in the canyon (Gatje and Pizinger 1965; Njus 1968). Vertical water movement appeared to be approximately 80 m in 120 m of water at station 1103 and 115 m in 220 m of water at station 1108. Physical and chemical parameters varied from 20 to 75 per cent of their vertical range from 1 to 150 m, with largest changes observed in the pynocline (Broenkow and McKain 1972). For some parameters the daily range observed in the upper 10 m was as great as the total range from February 1971 to May 1972 (Table 3).

TABLE 3

Range of 0 to 10 m average values between February 1971 and May 1972, during the 25-hour study on 7-8 August 1971 in Monterey Submarine Canyon Stations.

Parameter	All canyon stations Feb. 1971 to May 1972	Station 1103* 25-hour study	Station 1108 25-hour study
Temperature, ^{o}C	9.8 to 16.3	10.5 to 13.4	11.1 to 12.8
Salinity, $^{o}/oo$	33.20 to 33.97	33.75 to 33.83	33.75 to 33.81
AOU, µg-atoms/liter	-160 to +135	-150 to +235	-195 to +85
PO_4-P, µg-atoms/liter	0.3 to 1.7	0.3 to 1.7	0.4 to 1.5
NO_3-N, µg-atoms/liter	0 to 20	3 to 18	2 to 13
NH_3-N, µg-atoms/liter	0 to 1.5	0 to 1.5	0 to 1.2

* from Broenkow and McKain 1972.

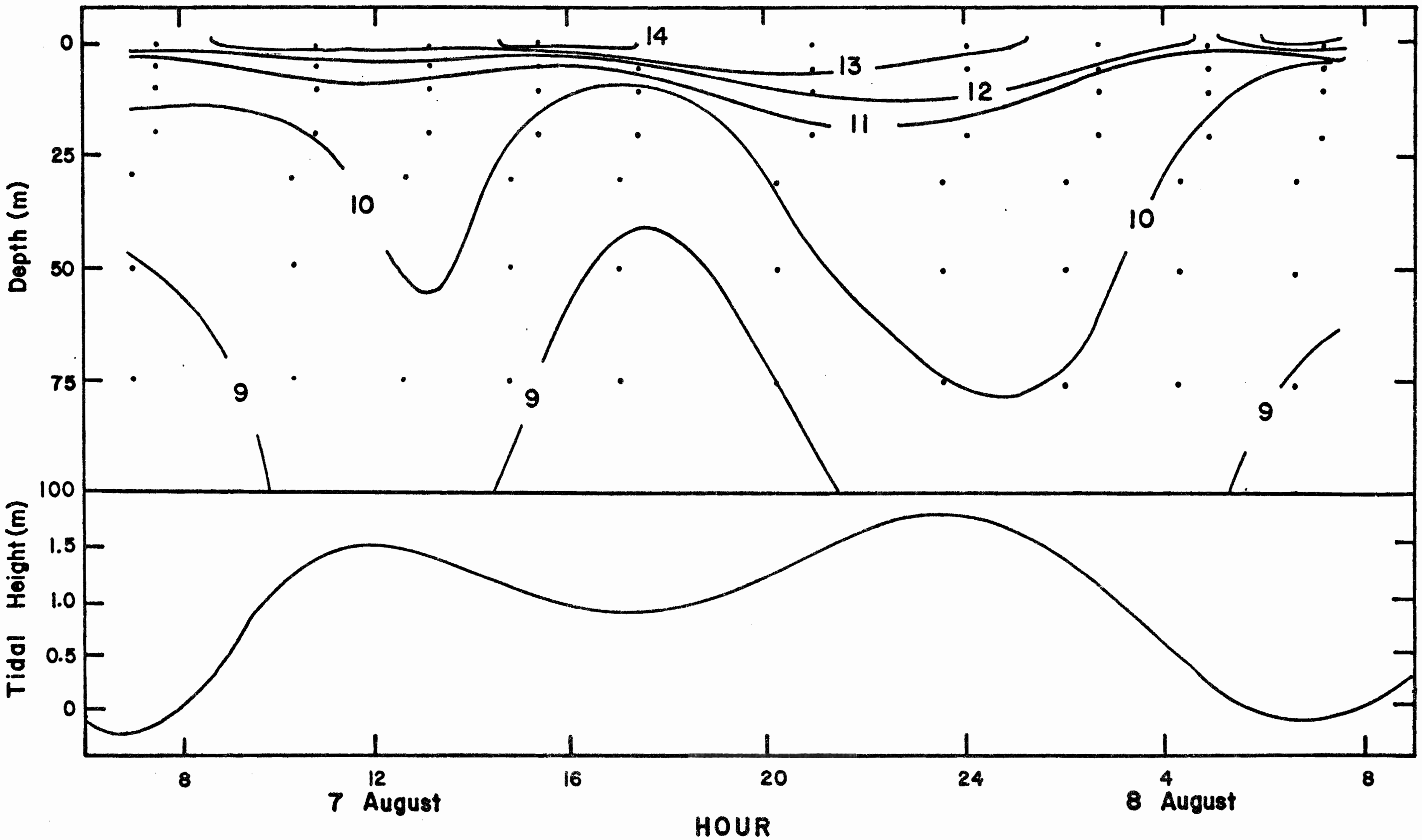

Figure 4. Tidal height and vertical distribution of temperature, 7-9 August, 1971 at station 1103 (Fig. 1).

The second study was conducted during June 1972. Three drogues were released in the northern end of the bay and tracked for 25 hours, and hydrographic stations were sampled at the drogues approximately every hour. Vertical water movement appeared to be 5 to 10 m in 20 to 30 m of water (R. Waidelich, personal communication), and this was probably caused by a combination of tidal movement and variations in depth as the water moved on and off shore. Changes in the physical and chemical parameters were considerably less than the changes observed in the canyon study.

In general, there appears to be little tidally-induced variation in physical and chemical parameters in the upper 10 m over shelf areas of Monterey Bay but large variations over the head of Monterey Submarine Canyon. Tidally induced variations over the seaward areas of the canyon are probably somewhat less than those over the head of the canyon.

Oceanographic periods and seasonal changes

Because changes in physical and chemical parameters are dependent on well established oceanographic periods, the oceanographic periods that occurred during this investigation are described below. A comparison of the resultant seasonal changes in the canyon area and in the nearshore areas is also made.

Changes in the thermal conditions have been used to determine the timing of the oceanographic periods (p.9), and monthly averages of temperature were calculated at each sampling depth for all canyon stations (1103, 1108, 1112, 1115, and 1157) (Fig. 1). Month to month variations at any canyon station are at least partially obscured by tidal variations, but it is assumed that by averaging, the tidal influence will be reduced.

Upwelling had begun by mid-February 1971 and lasted until the latter part of July 1971. This is evident from the rise of the 9 and 10° C isotherms between February and March and the shallow depth at which they remained during this period (Fig. 5). Surface and subsurface water was coolest during March and April (Fig. 6), and increased insolation accompanied by the vertical movement of upwelling water resulted in a strong thermal gradient (3° C in the upper 50 m) in June and July (Fig. 7).

The end of upwelling and the beginning of the oceanic period occurred during the latter part of July. This is evident from the abrupt 2.5° rise in surface temperature (Fig. 6) and from the sinking of previously upwelled water as indicated by sinking isotherms (Fig. 5). The temperature gradient remained greater than 3° C in the upper 50 m throughout this period (Fig. 7), which is in agreement with previous studies (Skogsberg 1936; Bolin and Abbott 1963).

The transition between the oceanic period and the Davidson Current period occurred at the end of September. This was indicated by the decrease in the surface temperature while, in accordance with the geostrophic current reversal, the subsurface temperature increased (Fig. 6). The low temperature gradient ($< 1^{\circ}$ C in the upper 50 m) was a result of this (Fig. 7). Descending isotherms (Fig. 5) indicate either the

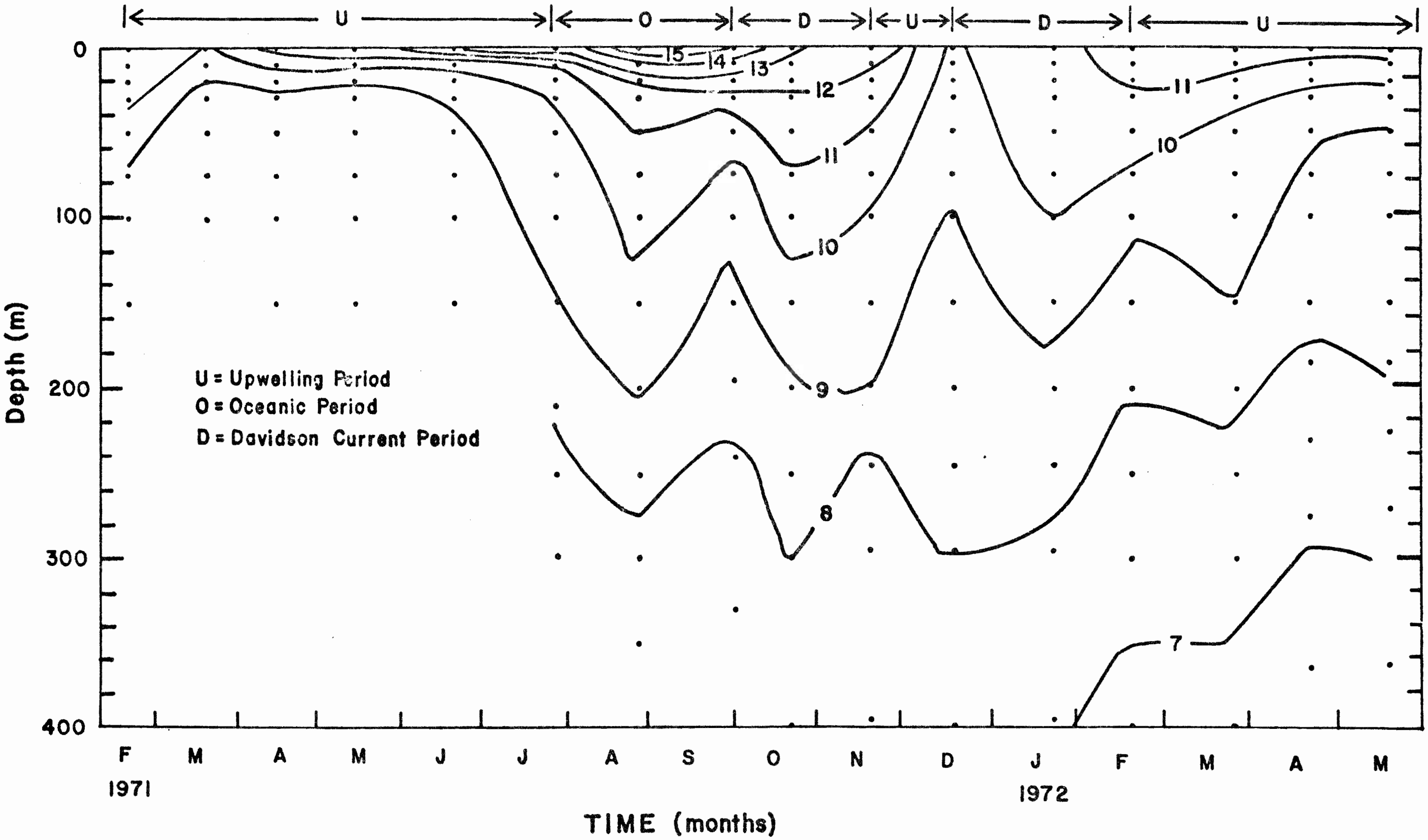

Figure 5. Average vertical distribution of temperature (°C) in Monterey Submarine Canyon (stations 1103, 1108, 1112, 1115, 1157), (Fig. 1).

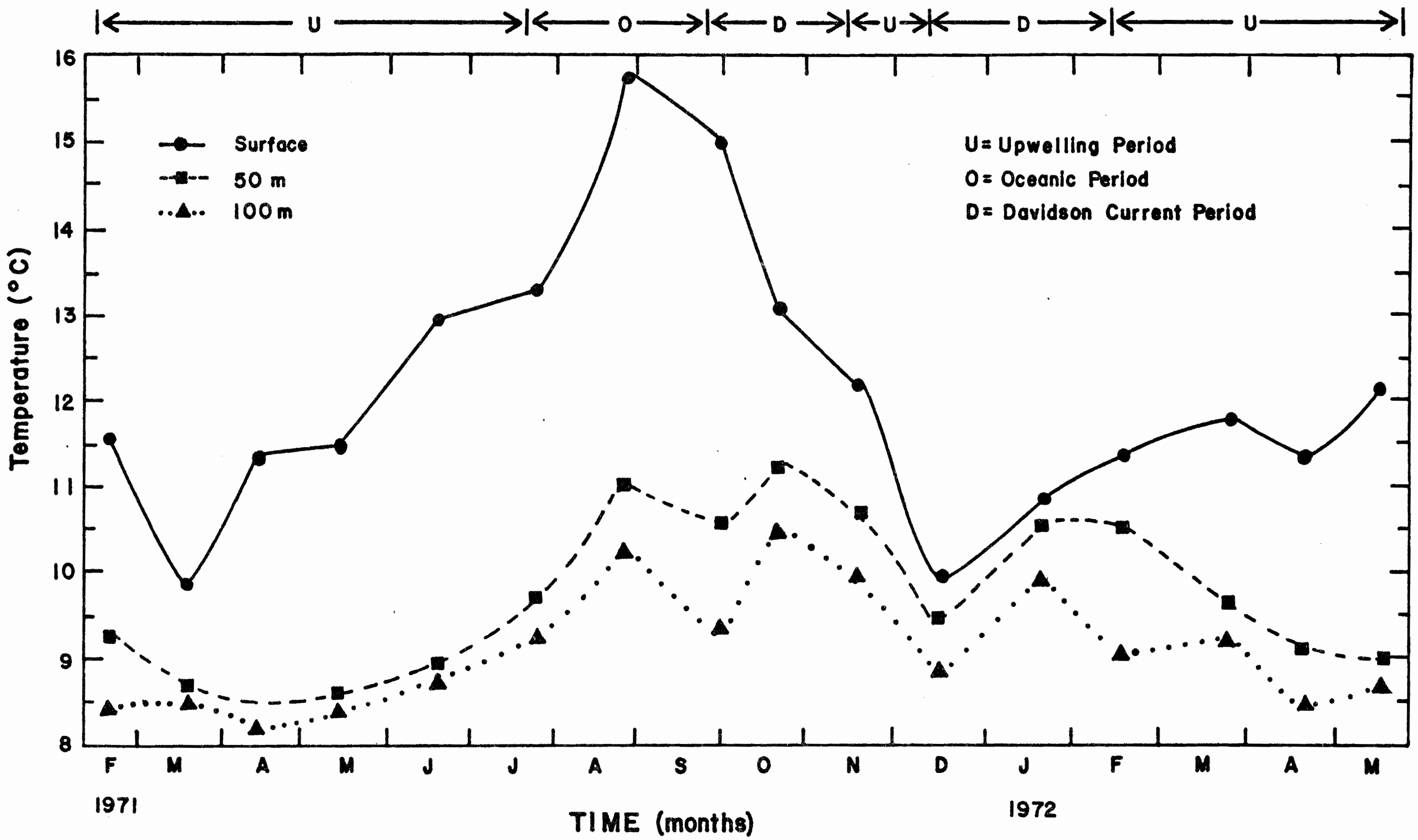

Figure 6. Variation of average surface and subsurface temperature in Monterey Submarine Canyon.

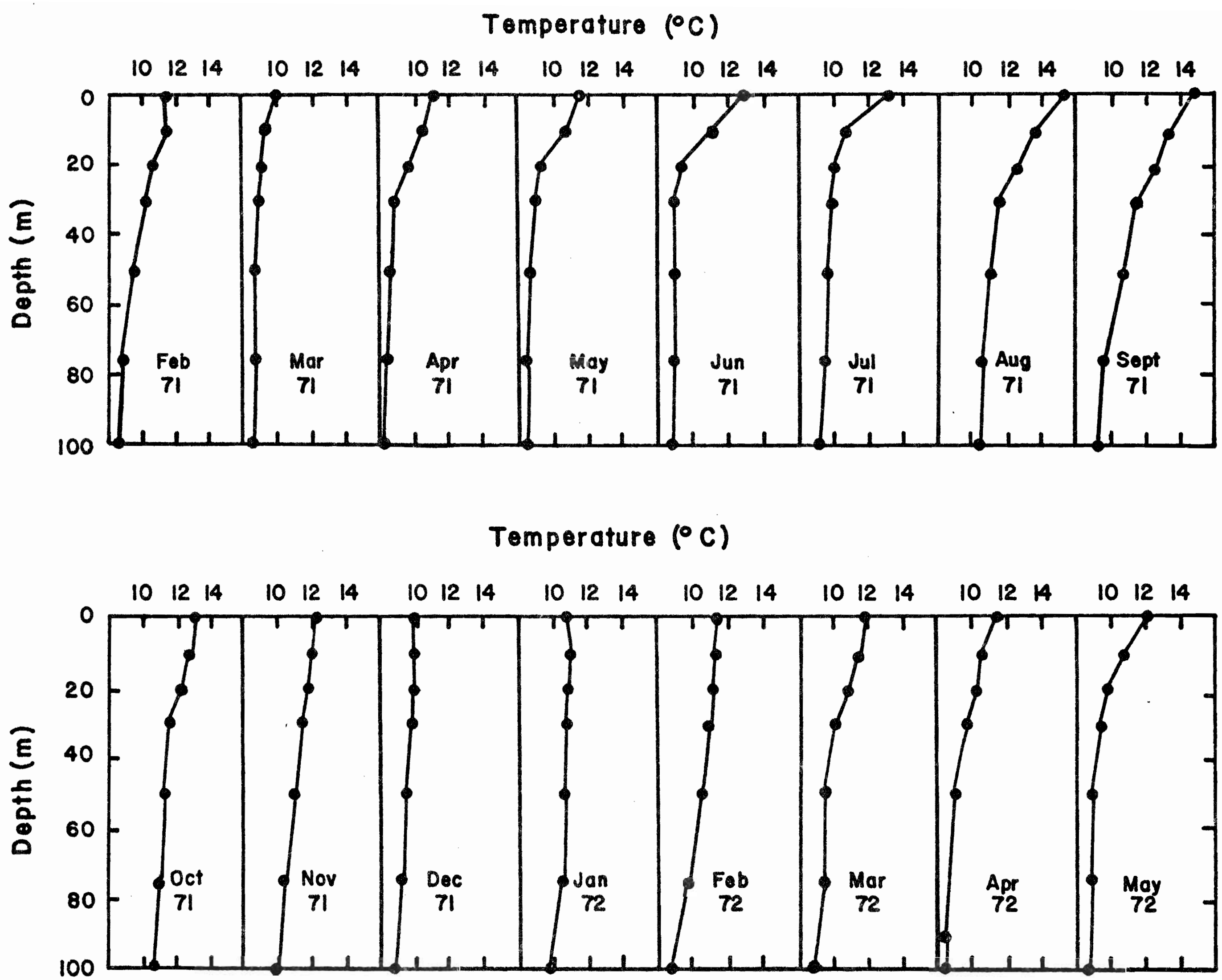

Figure 7. Average depth profiles of temperature for Monterey Submarine Canyon.

transition from a southerly flowing geostrophic current to a northerly flowing geostrophic current, or water sinking as it converged on the coast, or a combination of both factors.

Normally, highest annual temperatures at 10 m are observed in November and December (Fig. 2), but during 1971 the Davidson Current period was interrupted between mid-November and mid-December by a brief period of upwelling. This is apparent from the abrupt rise in isotherms above 200 m (Fig. 5) and the accompanying decrease in temperature (Fig. 6). Upwelling does not normally occur during this time of year, but it is not entirely unexpected because favorable wind conditions can occur throughout the year.

Following this brief period of upwelling, the Davidson Current period resumed, as indicated by a low temperature gradient in the upper 50 m (Fig. 7), subsurface temperature near the annual maximum (Fig. 6), and sinking isotherms (Fig. 5).

The Davidson Current period ended in mid-February 1972 and upwelling began. This transition was accompanied by rising isotherms (Fig. 5) and decreasing subsurface temperatures (Fig. 6). Rising isotherms indicated that water at 100 m and below began to rise in mid-January, but water above 100 m did not begin to rise until mid-February. In late winter 1972, the rise of isotherms was not as rapid as in late winter 1971, and the 1972 period appears to have been less intense. As in 1971, a strong temperature gradient in the upper 50 m developed as insolation increased with the approach of summer (Fig. 7).

TABLE 4

Oceanographic periods in Monterey Bay between February 1971 and May 1972.

Upwelling	Feb. 1971 to Aug. 1971
Oceanic	Aug. 1971 to Oct. 1971
Davidson Current	Oct. 1971 to Nov. 1971
Upwelling	Nov. 1971 to Dec. 1971
Davidson Current	Dec. 1971 to Feb. 1972
Upwelling	Feb. 1972 to May 1972

The rise and fall of the isopleths of salinity, AOU (apparent oxygen utilization), phosphate, and nitrate were very similar to the rise and fall of isotherms (Fig. 5) and lend further support to the vertical water movement just described for the oceanographic periods summarized in Table 4.

The NW component of the surface wind at the Farallon Islands (about 40 km offshore and 120 km north of Monterey Bay) varied erratically (Fig. 8), but there was a general correspondence to the oceanographic periods described above. During upwelling periods, three day averages of the NW wind component erratically peaked above 20 knots. During the oceanic period the NW wind component was usually less than 15 knots, and during the Davidson Current period after December an erratic SE wind component was observed. The brief period of upwelling between November and December was preceded by a period of strong NW winds, and another interval of strong NW winds occurred during the upwelling period. During winter and early spring of 1972, the NW wind component was generally not as large as in 1971, and there were intermittent periods of southerly winds. This difference in the wind field

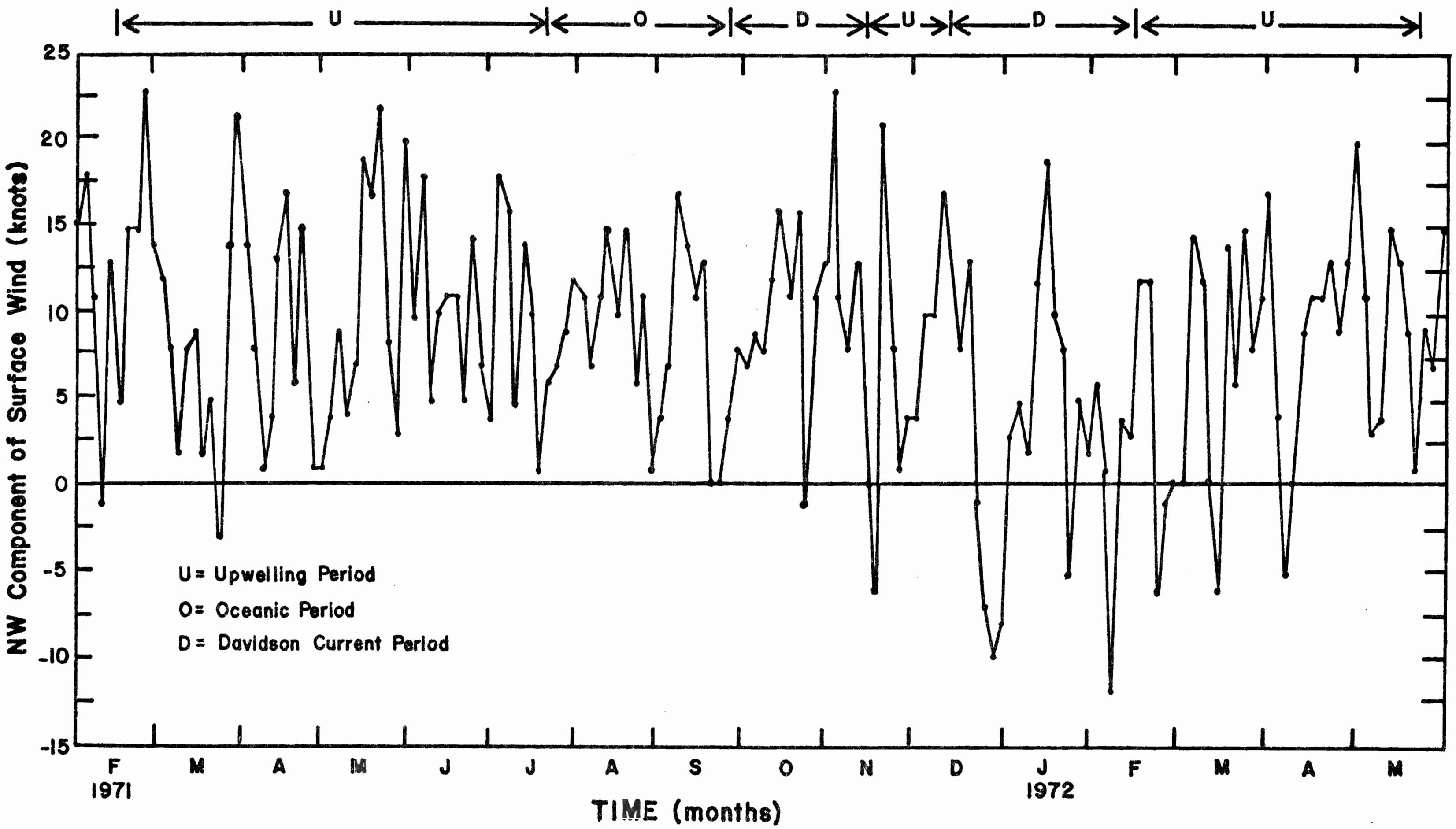

Figure 8. Variation of the 3-day average NW surface wind at the Farallon Islands (40 km offshore and 120 km north of Monterey Bay). The 3-day average is based on wind observations taken at 1600 hours.

presumably resulted in the less intense upwelling observed in 1972 than in 1971.

The available wind data were not entirely adequate to explain the oceanographic periods observed in Monterey Bay. The three day NW wind component averages were based on daily wind observations taken at 1600 hours. The sea level barometric pressure varies diurnally, and wind speeds are generally maximal in the afternoon. This can account at least partially for the relatively high NW wind component observed during the oceanic and Davidson Current periods. The daily average may have given better correlation. The erratic variation of the wind is apparently real and was observed by Sverdrup and Fleming (1941) in their study of upwelling along the California coast. Erratic variation of the wind could account for the sporadic upwelling and the attendant large temperature variations previously observed in Monterey Bay (Skogsberg 1936; Skogsberg and Phelps 1946; Bolin and Abbott 1963).

To compare seasonal changes occurring in near surface water of the canyon region and the nearshore regions during these oceanographic periods, 1 to 10 m averages were calculated for the canyon region, the nearshore northern region (stations 1150, 1153, 1154, and 1159), and the nearshore southern region (stations 1, 1121, and 1122) (Fig. 1). From February 1971 through May 1971, the canyon region averages were based only on stations 1103, 1108, and 1112, and the northern nearshore region on stations 1153 and 1154.

During the 1971 upwelling period, low temperature (9.5 to 12^{o} C), high salinity (33.75 to 33.90 $^{o}/oo$), high AOU (-30 to +20 μg-atoms/

liter O_2-O), nutrient rich (0.9 to 1.6 µg-atoms/liter PO_4-P, 7 to 8 µg-atoms/liter NO_3-N) water was generally found over Monterey Submarine Canyon (Figs. 9 to 13). As summer approached, temperature gradually increased as insolation increased, and salinity and AOU varied erratically. Phosphate and nitrate concentrations also varied erratically but decreased in June and remained at this lower level during July. This nutrient decrease was presumably caused by increased primary productivity in the summer and the reduced upwelling rate near the end of the upwelling period.

Over the canyon a sharp rise in temperature and a sharp decrease in salinity and nutrient concentrations occurred between the 1971 upwelling period and the oceanic period. The low salinity (33.24 $^{o}/oo$) observed in August was a clear indication that California Current water had entered Monterey Bay from some distance offshore. Water of 33.2 $^{o}/oo$ salinity normally is found about 170 km offshore of Monterey Bay in August (Lynn 1967). The surface water of the California Current had remained at the surface longer than the upwelled water found in the bay during July; it apparently had been heated by insolation, and its nutrient content decreased by phytoplankton uptake. This explains the observed rise in temperature and decrease in nutrient concentration. The nitrate concentration decreased to near zero at the end of September, and during this period it appeared to be a limiting nutrient.

Phosphate and nitrate concentrations remained at low levels (0.5 to 0.6 µg-atoms/liter PO_4-P, 1 to 6 µg-atoms/liter NO_3-N) over the canyon during the oceanic and Davidson Current periods, temperature gradually

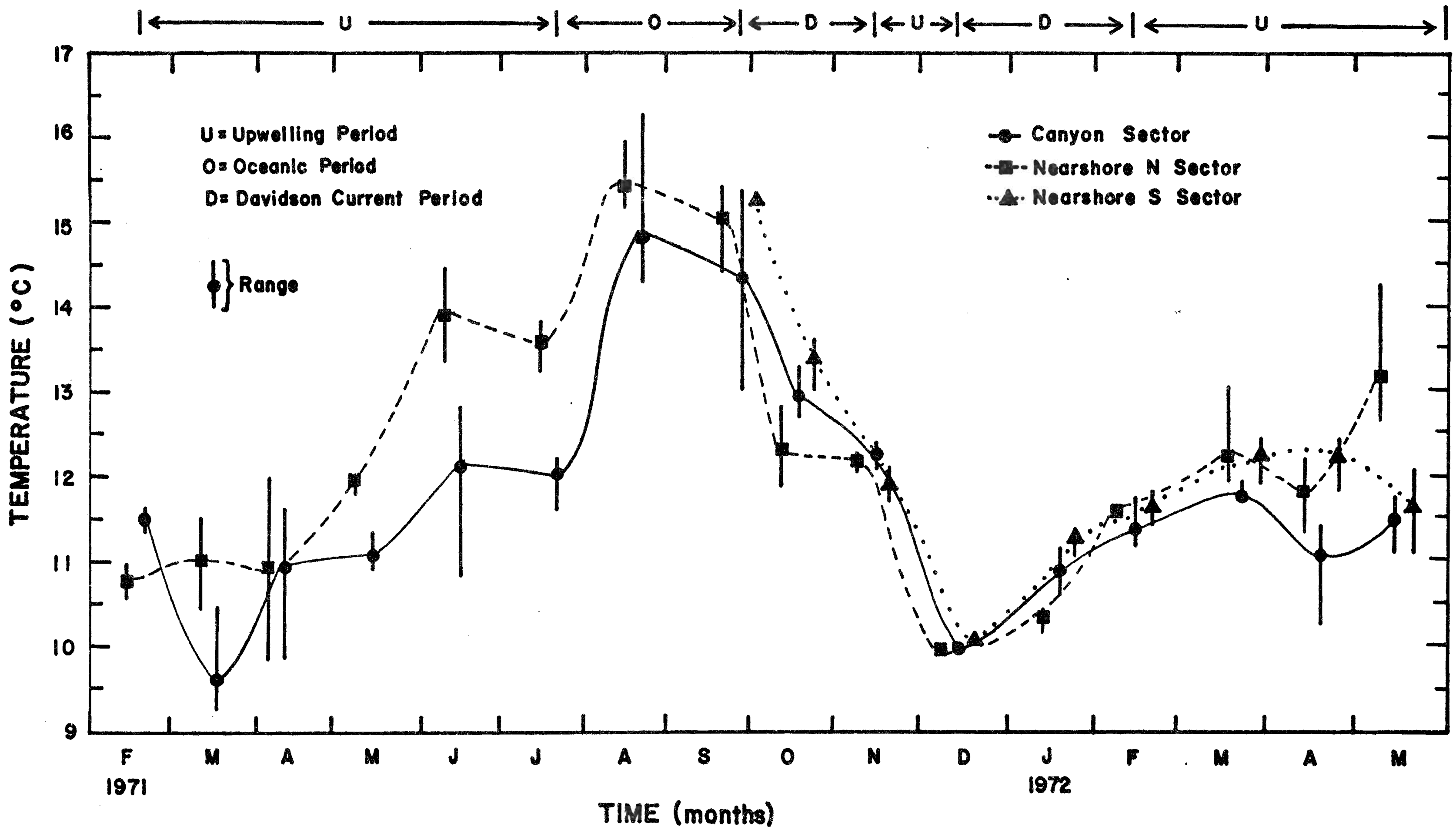

Figure 9. Monthly variation of average temperature in upper 10 m water in Monterey Submarine Canyon (stations 1103, 1108, 1112, 1115, 1157), the northern nearshore sector (stations 1150, 1153, 1154, 1159), and the southern nearshore sector (stations 1, 1121, 1122) in Monterey Bay. (Fig. 1).

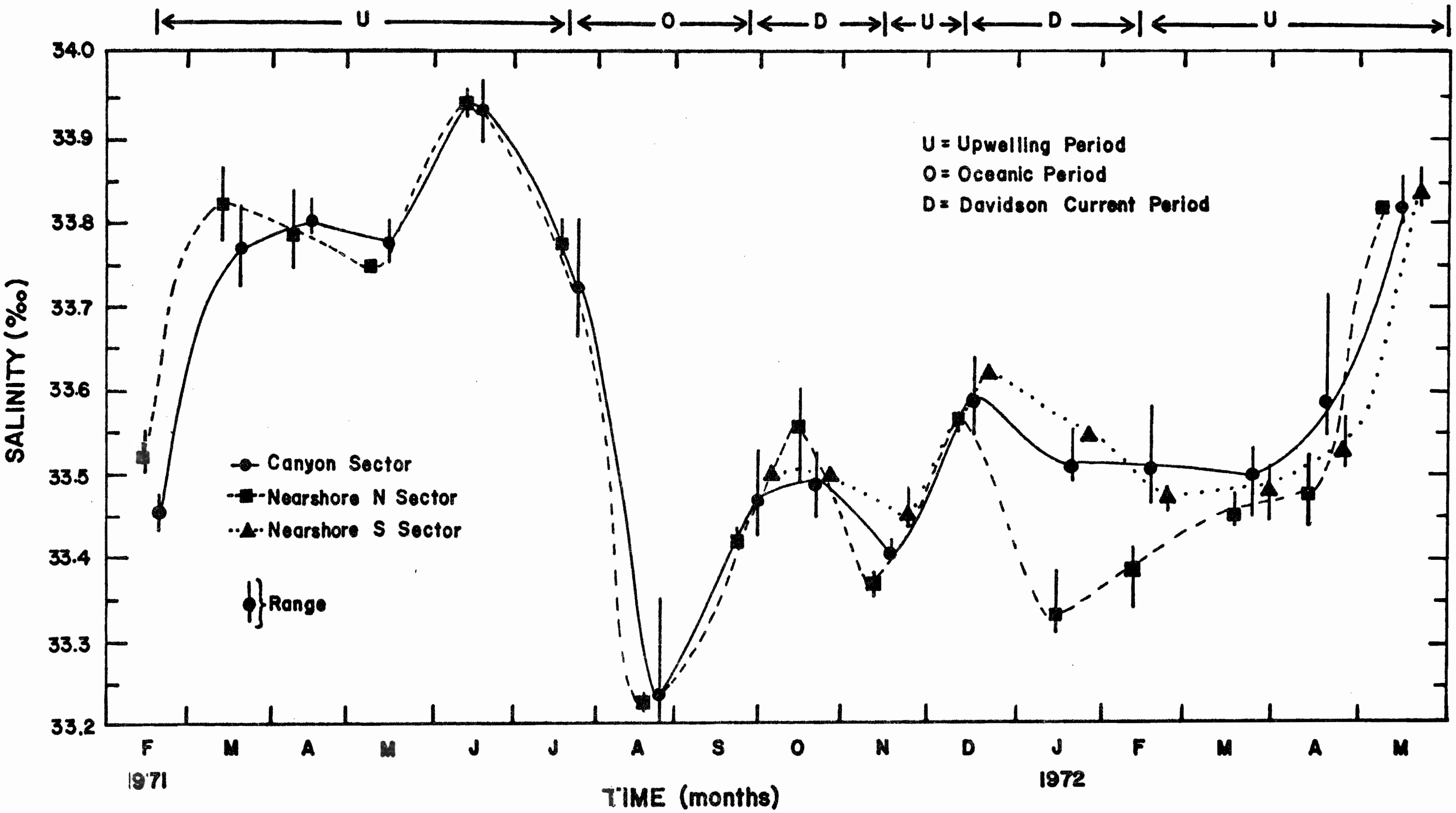

Figure 10. Monthly variation of average salinity in upper 10 m water of selected sectors of Monterey Bay (Figs. 1, 9).

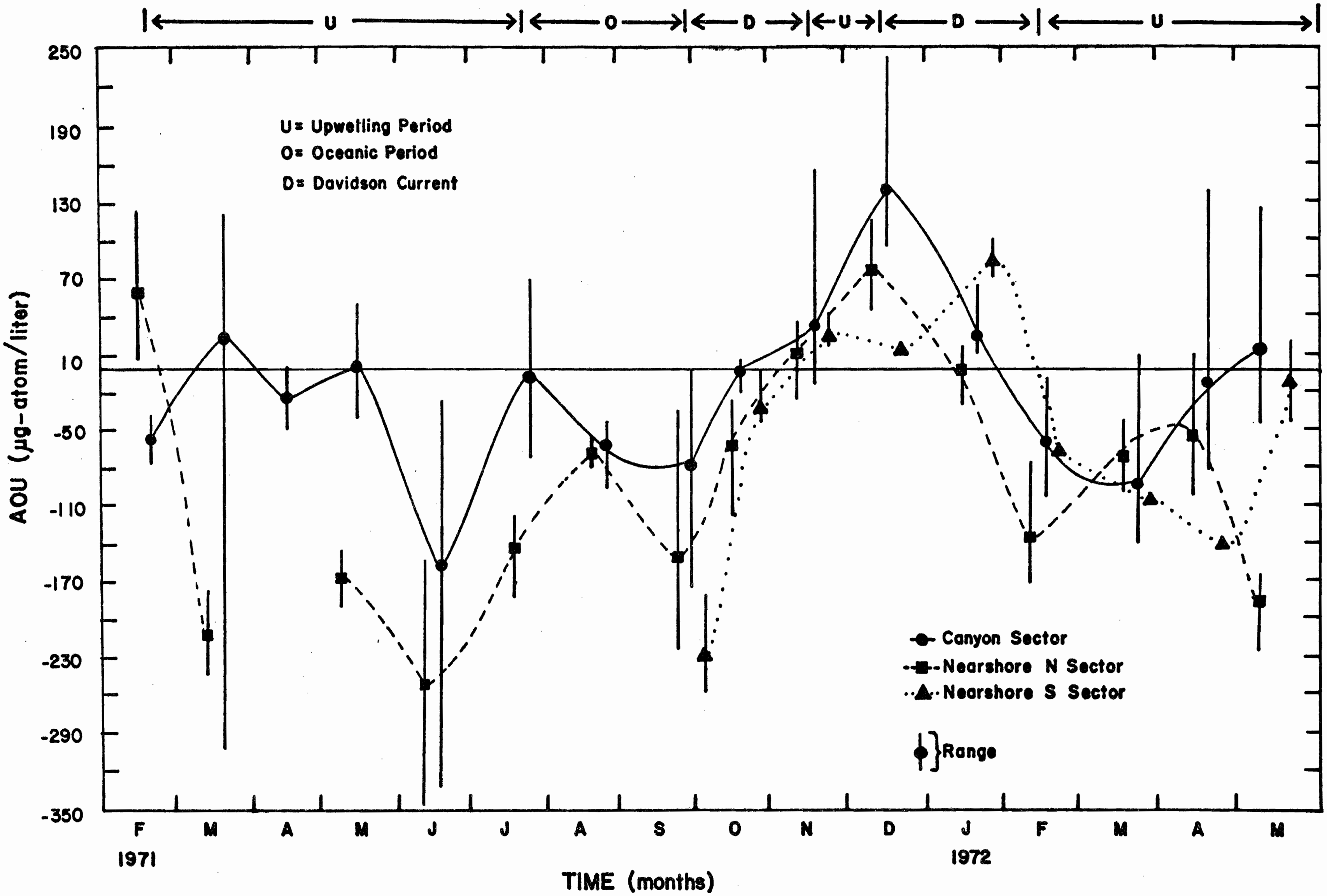

Figure 11. Monthly variation of average apparent oxygen utilization (AOU) in upper 10 m water of selected sectors of Monterey Bay (Figs. 1, 9).

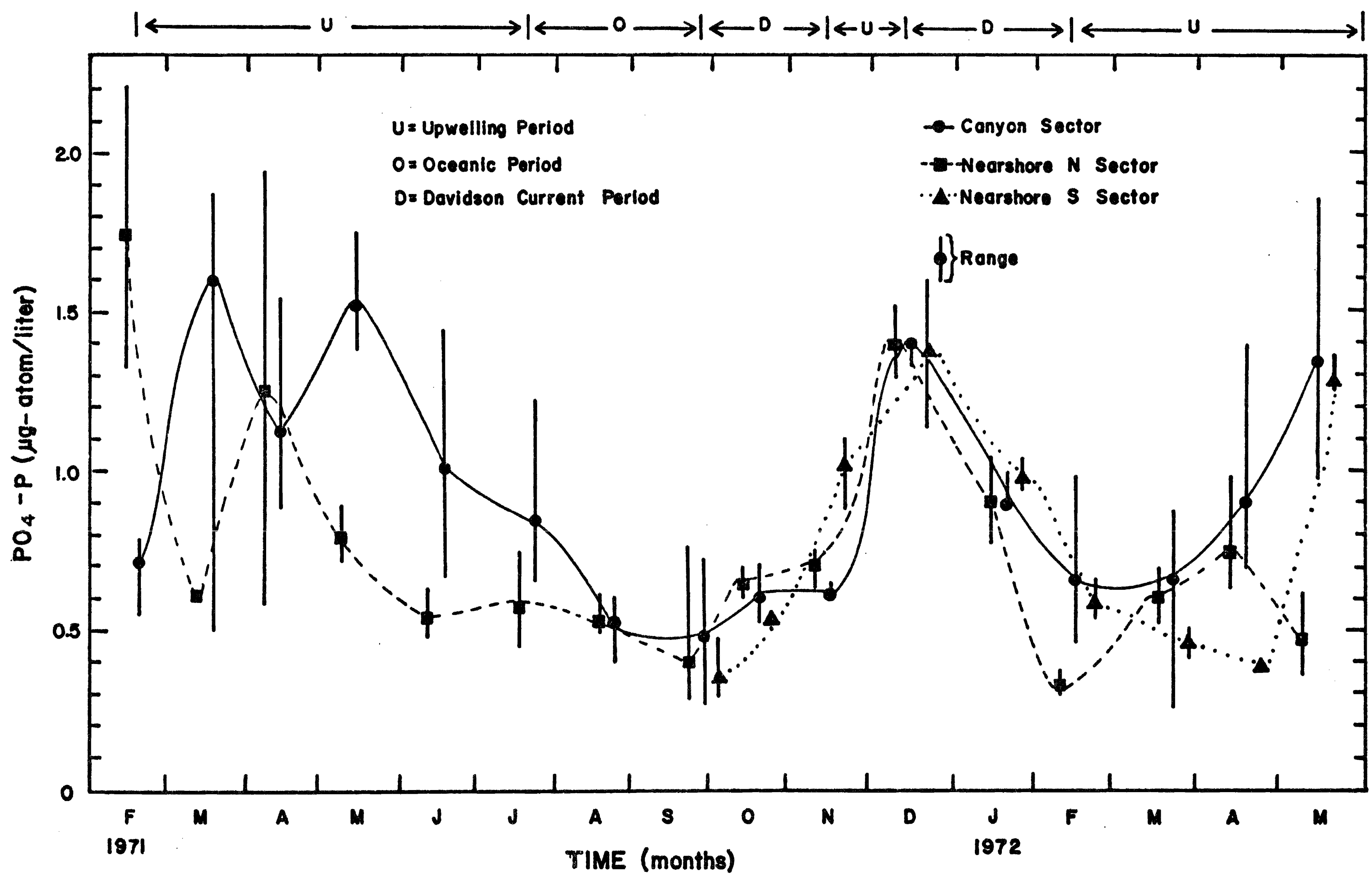

Figure 12. Monthly variation of average phosphate concentration in upper 10 m water of selected sectors of Monterey Bay (Figs. 1, 9).

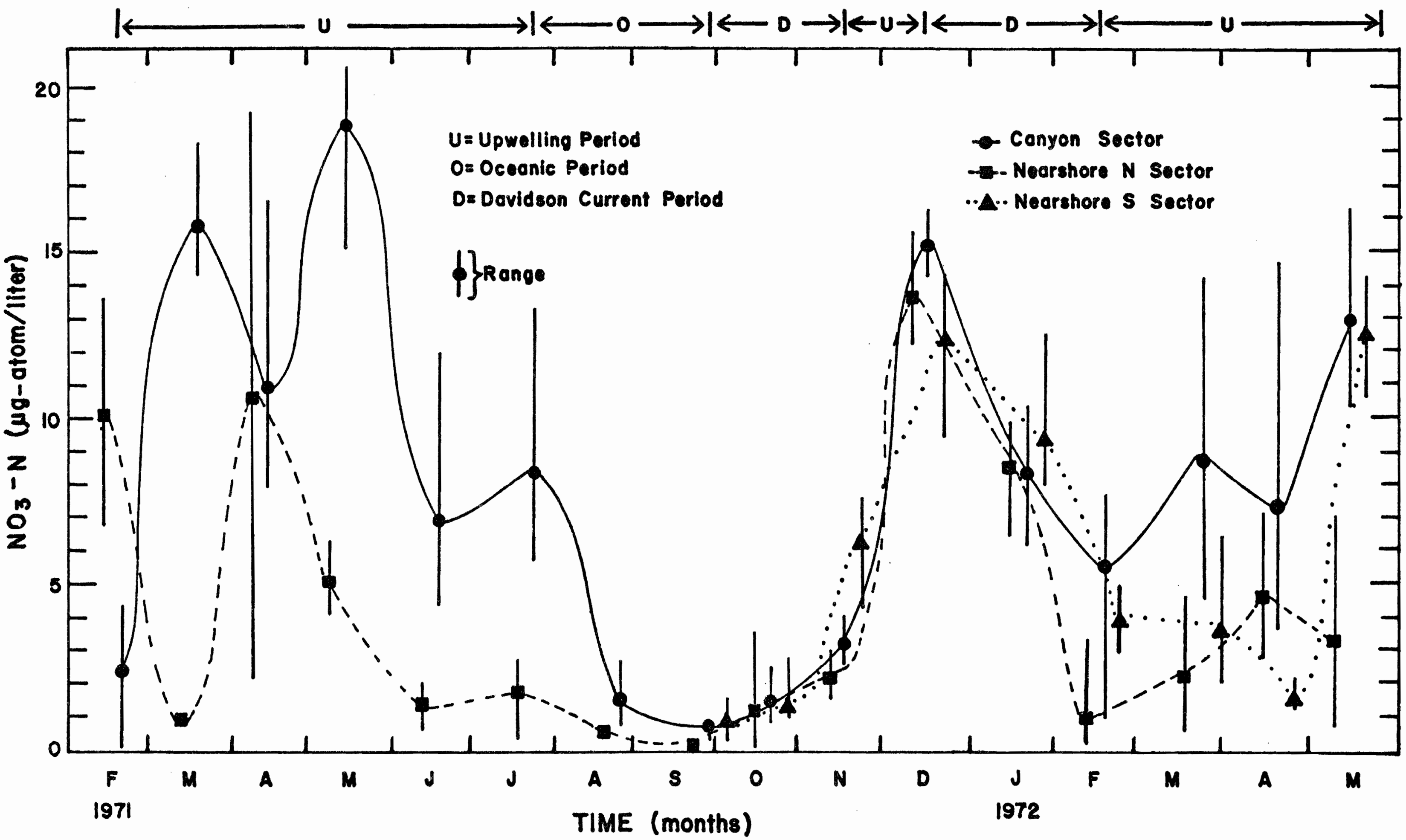

Figure 13. Monthly variation of average nitrate concentration in upper 10 m water of selected sectors of Monterey Bay (Figs. 1, 9).

decreased (15 to 12^{o} C), salinity was erratic (33.2 to 33.5 ^{o}/oo), and AOU gradually increased (-80 to +40 µg-atoms/liter O_2-O). The brief episode of upwelling in November and December resulted in very cold water (10^{o} C), high in AOU (130 µg-atoms/liter O_2-O) and nutrient concentration (1.4 µg-atoms/liter PO_4-P, 15 µg-atoms/liter NO_3-N) at the surface. Surface salinity also increased to 33.6 ^{o}/oo during this episode. During the second Davidson Current period, AOU, nutrient concentrations, and salinity decreased and temperature increased. Changes in these constituents during the 1972 upwelling period were similar to those in 1971.

Seasonal trends in near surface water in the nearshore regions generally followed the seasonal trends in near surface water in the canyon region (Figs. 9 to 13). However, near surface water was not always homogeneous throughout the bay. During upwelling periods, the water in nearshore areas was consistently warmer (11 to 14^{o} C), lower in AOU (-140 to -250 µg-atoms/liter), phosphate (0.5 to 1.2 µg-atoms/liter), and nitrate (1 to 10 µg-atoms/liter) than water over the canyon. In contrast to the upwelling periods, during the oceanic and Davidson Current periods, the physical and chemical parameters of near surface water were more nearly homogeneous over the entire bay; an exception was AOU, which remained slightly lower in the nearshore regions than in the canyon region. In addition, low salinity was observed in the northern nearshore region in January and February 1972, which can be accounted for by rainfall and accompanying surface runoff during these months.

The average ammonia concentration in near surface water in the northern nearshore region was usually equal to or greater than that in the canyon region (Fig. 14). In the southern nearshore region, it was always greater than in the northern nearshore region or in the canyon region. This will be further discussed later.

In summary, the near surface water of Monterey Bay was fairly homogeneous during the oceanic and Davidson Current periods when nutrient concentrations and AOU were generally low, and temperature was generally high. During the upwelling period, cool, nutrient rich, high AOU water was found over Monterey Submarine Canyon, and warmer, nutrient poor, low AOU water was found near shore.

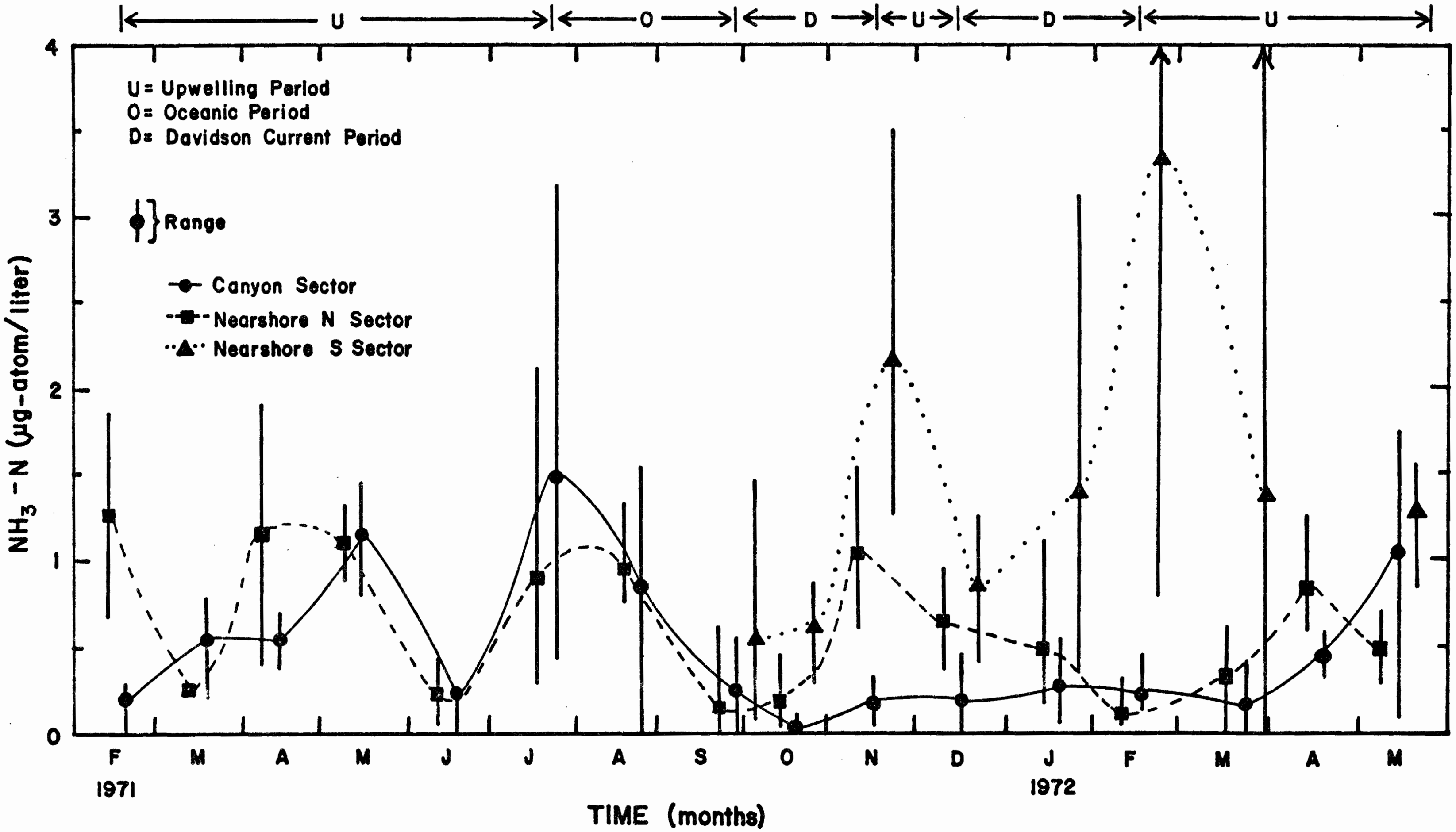

Figure 14. Monthly variation of average ammonia concentration in upper 10 m water of selected sectors of Monterey Bay (Figs. 1, 9).

CHAPTER 4

PHYSICAL AND BIOCHEMICAL PROCESSES RELATED TO SPATIAL DISTRIBUTIONS

Upwelling and its effect on lateral distributions

The details of the upwelling process within Monterey Bay are not well understood, and there are not enough data from this study to describe the process fully. Possible processes are presented here to account for the observed distributions of physical and chemical parameters within the bay, and movements of surface water during upwelling are discussed. Rates of upwelling in Monterey Bay are determined, and distributions of physical and chemical parameters during non-upwelling periods are contrasted to distributions during upwelling periods.

Two types of near surface distributions were observed during upwelling periods. The most frequently observed distribution was low temperature, high AOU, nutrient rich, near surface water over Monterey Submarine Canyon and parts of the shelf areas and higher temperature, lower AOU, lower nutrient, near surface water in the northern and southern ends of the bay (Figs. 15 and 16, Appendix 1). The occurrence of upwelled water over the shelf areas varied from month to month and recently upwelled water was sometimes found adjacent to shore. In March and April 1972, low temperature, high AOU, high nutrient water was found offshore of Monterey Bay with temperature increasing and AOU and nutrients decreasing towards shore (Figs. 17 and 18). Highest temperatures and lowest AOU and nutrient concentrations were again observed in the northern and southern ends of the bay.

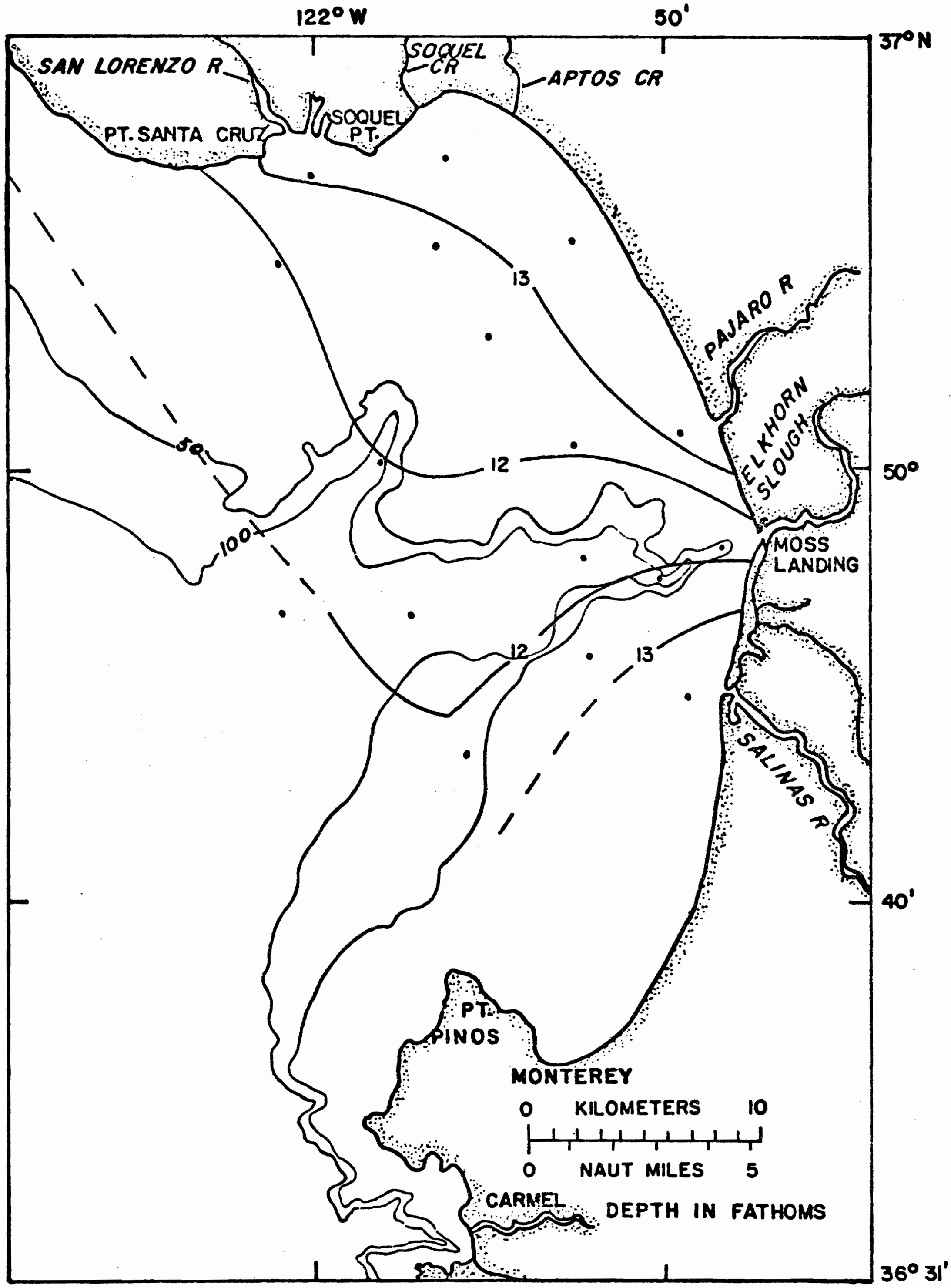

Figure 15. Distribution of average temperature (°C) in the upper 10 m of Monterey Bay, 23-24 July, 1971, upwelling period.

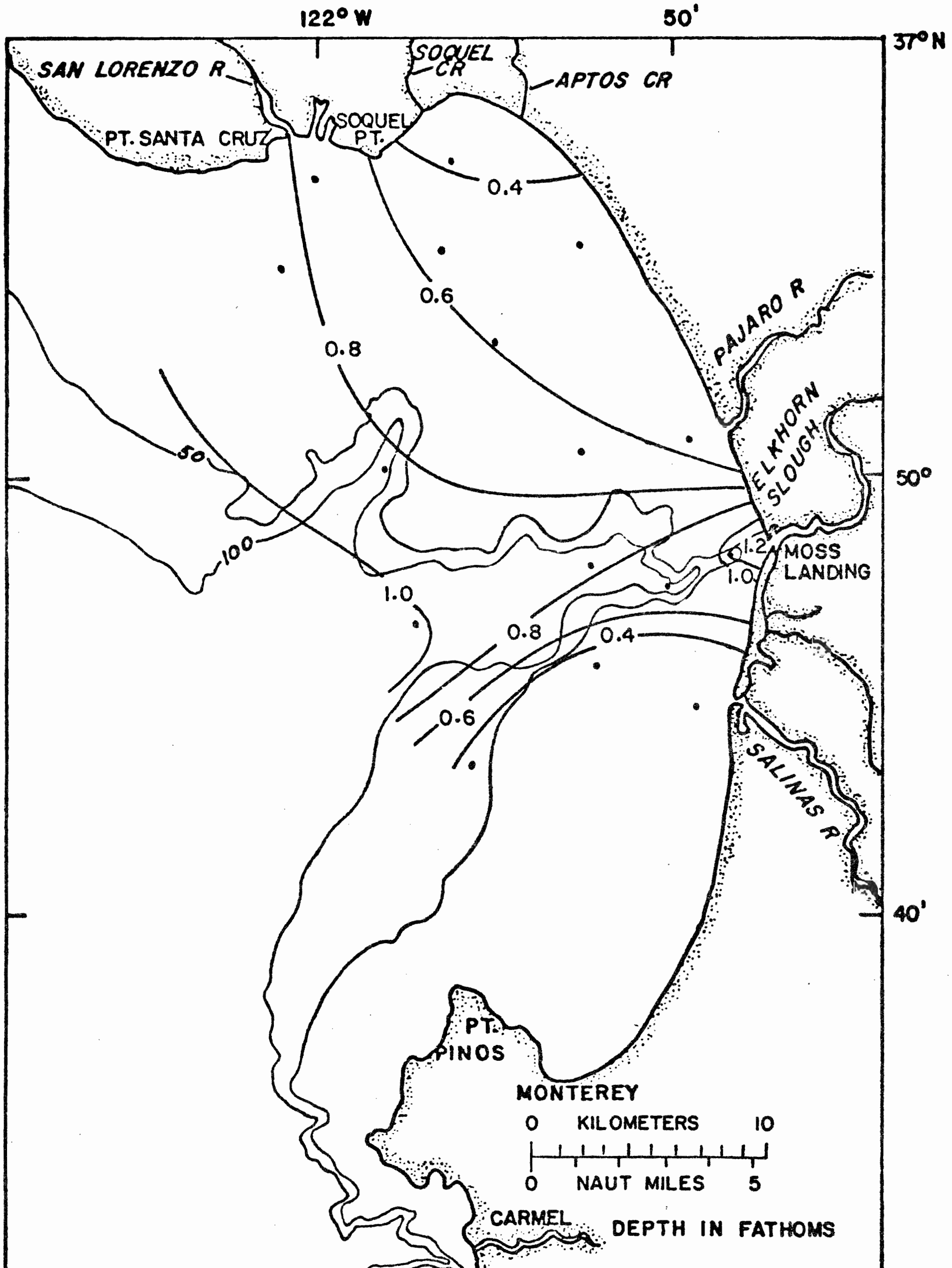

Figure 16. Distribution of average phosphate concentration (µg-at/liter) in the upper 10 m of Monterey Bay, 23-24 July, 1971, upwelling period.

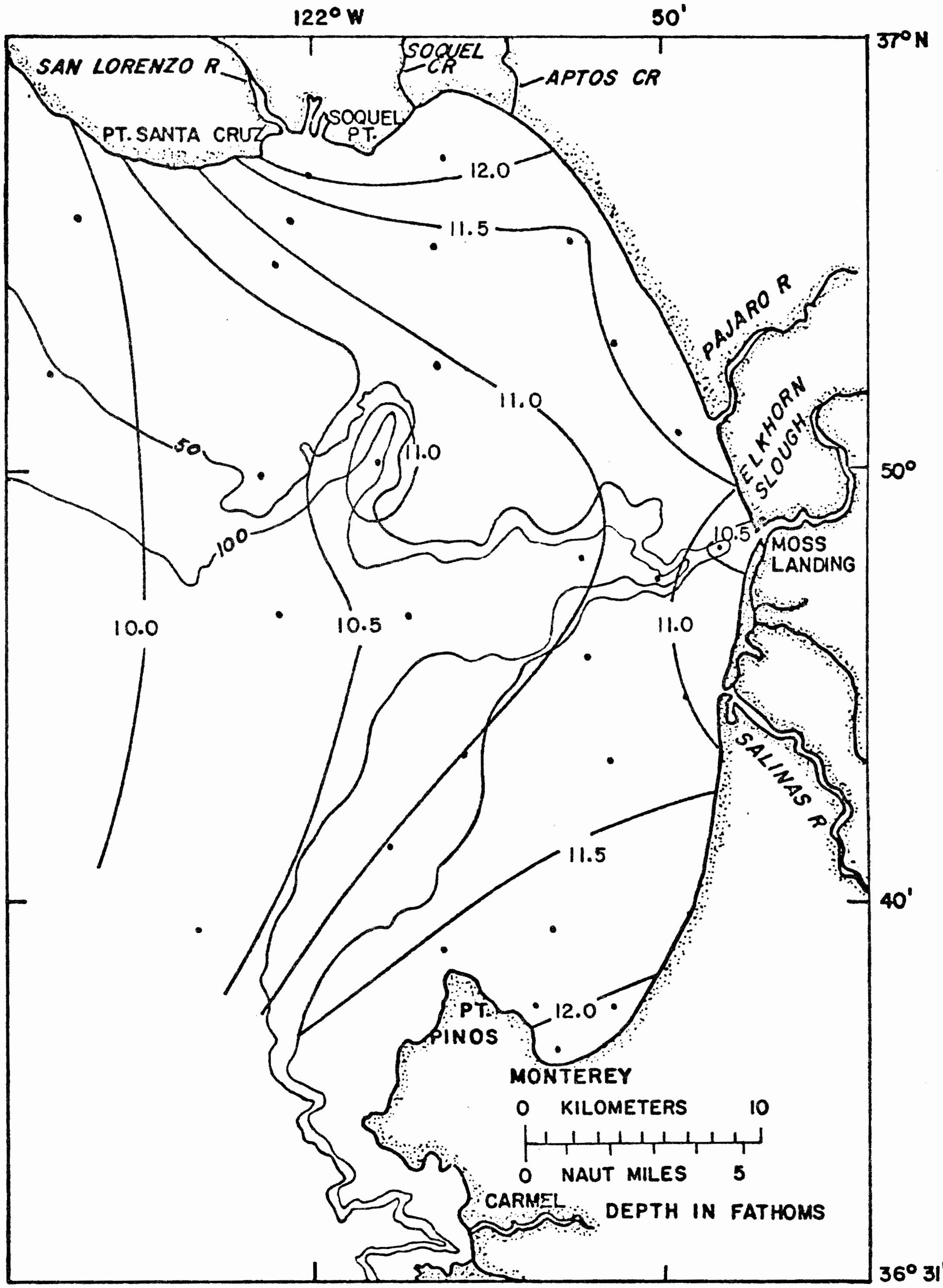

Figure 17. Distribution of average temperature (°C) in the upper 10 m of Monterey Bay, 17-18 April 1972, upwelling period.

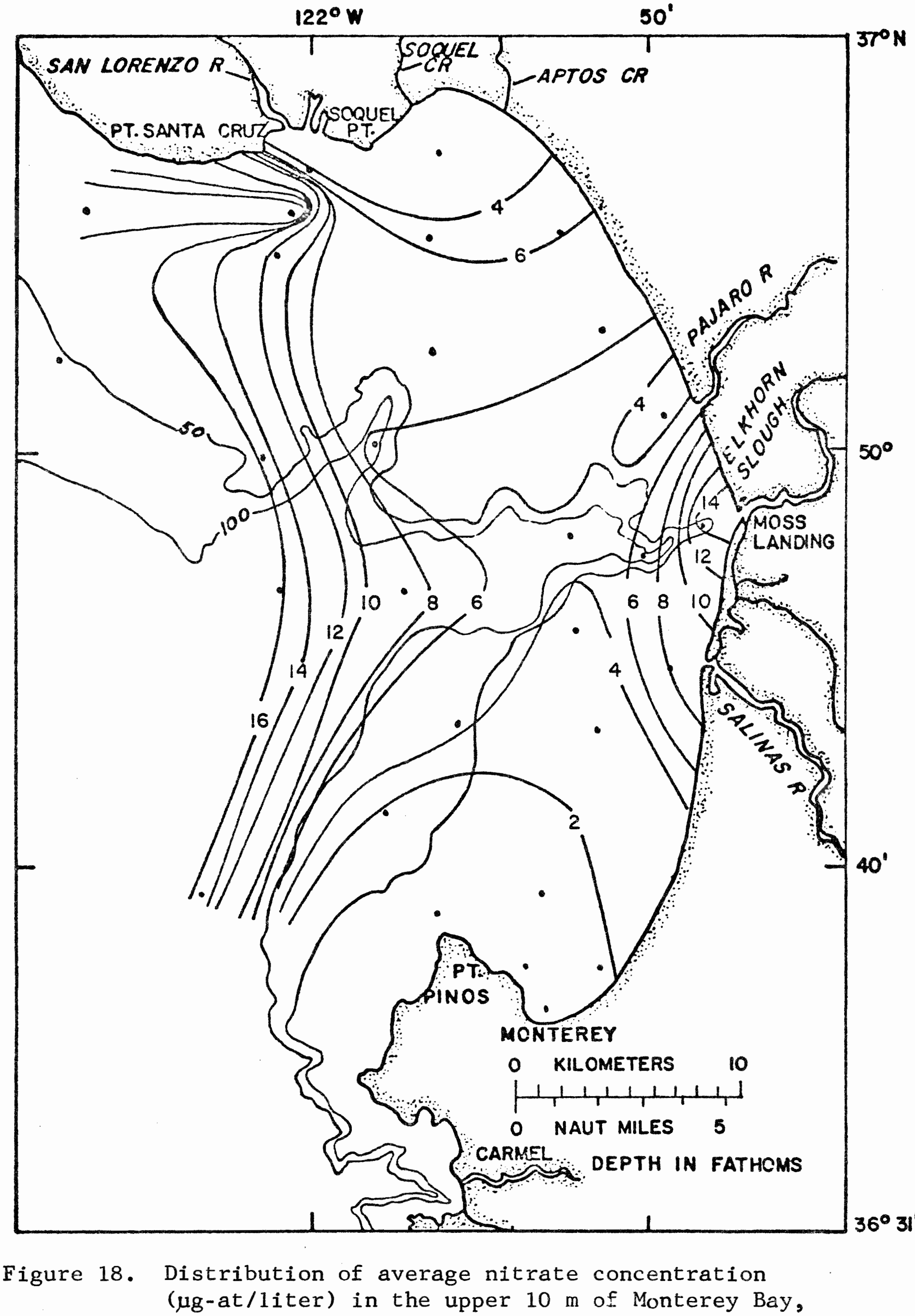

Figure 18. Distribution of average nitrate concentration (μg-at/liter) in the upper 10 m of Monterey Bay, 17-19 April 1972, oceanic period.

The observation of high temperature, low AOU, low nutrient water in the northern and southern ends of Monterey Bay is consistent with the hypothesis that upwelled water had moved northward and southward from the canyon area and was subsequently heated by insolation and depleted of nutrients by phytoplankton uptake. During photosynthesis by phytoplankton, a net oxygen production resulted in low AOU. Under these assumptions, the warmer, lower AOU, nutrient impoverished, near surface water had resided in the bay for the longest time, the oldest water being found in the northern and southern ends of the bay. This is consistent with previous investigations (Bigelow and Leslie 1930; Bolin and Abbott 1963; Shephard 1970) and with the observed differences between nearshore sectors and the canyon sector (Figs. 9, 11, 12, and 13). Sometimes there was little difference between a nearshore sector and the canyon sector: this was caused by recently upwelled water lying close to shore.

Since the horizontal distributions do not unambiguously reveal the path water parcels take as they move northward and southward of the canyon, these conclusions must be viewed with caution. However, drogue studies (Skogsberg 1936; unpublished data, Oceanographic Services Inc.; W.W. Broenkow, personal communication) are consistent with the hypothesis that water flows shoreward in the central region of the bay and that counterclockwise and clockwise flows are present in the northern and southern ends of the bay respectively. Average current speeds measured by these drogue studies varied between 10 and 15 cm/sec. Garcia (1971) has shown that this type of circulation could be driven by oceanic currents outside the bay. Assuming this type of circulation does occur, water would move from the canyon area along shore toward the northern and southern bights. Whether the offshore flow is northerly or southerly cannot be determined solely from these data. Geostrophic currents off the mouth of Monterey Bay appear to be predominently from the south during most of the year (Wyllie, 1966).

The near surface distributions of low temperature, high AOU, high nutrient water over Monterey Submarine Canyon indicate upwelling may occur within Monterey Bay in the canyon (Figs. 15 and 16). This would be the expected result of the strong NW winds offshore of Monterey Bay during the upwelling period (Fig. 8). Surface water offshore of Monterey Bay would be moved westward by Ekman transport, and with no other forces acting, water in Monterey Bay would flow seaward to replace it. During the upwelling season, however, winds in Monterey Bay generally blow from the west during the day and from the east during the night, with strongest winds during the day. Thus, the net local winds may tend to oppose the movement of Monterey Bay water offshore and decrease the rate of upwelling within the bay. This topographic effect may account for the minimum upwelling effect of the latitude of Monterey Bay observed by Sverdrup and others (1942).

The observed distributions of physical and chemical parameters in March and April 1972 (Figs. 17 and 18) could have been caused by advection into Monterey Bay of previously upwelled offshore waters. These distributions also could have been caused by a stronger rate of upwelling offshore than in Monterey Bay. From the data available, it cannot be determined precisely what caused the observed distributions, but as previously mentioned, there is evidence for onshore movement of water during upwelling periods (p. 8). The distributions may be related to the intermittent southerly winds during these two months (Fig. 8), which would cause less intense upwelling and could cause shoreward Ekman transport.

The effects of apparently intense upwelling were observed at the head of Monterey Submarine Canyon eight out of the nine upwelling months in this study. During these eight months, near surface water at the head of the canyon was lower in temperature and higher in AOU and nutrient concentrations than surrounding water (Figs. 15 to 18). This would be expected from the funnelling of subsurface water by the canyon as it moved into the bay to replace water being upwelled and moved offshore. Vertical tidal movement would also be effective in lowering temperature and raising AOU and nutrient concentrations at the head of the canyon. Ascending water during ebbing tides causes cool, high AOU, nutrient rich, subsurface water to mix with surface water during each tidal cycle; this mixture is lower in temperature and higher in AOU and nutrients than surrounding surface water. During non-upwelling periods, surface water over the canyon was frequently lower in temperature, higher in AOU, and higher in nutrient concentrations than surrounding surface water, indicating this type of mixing had occurred. Intensification of upwelling at the head of Monterey Submarine Canyon was probably the result of both funnelling of subsurface water by the canyon and vertical tidal movement.

Some authors have indicated that upwelling in Monterey Bay is more intense along the canyon flanks than the canyon axis due to water moving up the walls of Monterey Submarine Canyon. This was concluded from observations of cooler water over the canyon flanks than over the canyon axis (Lammers 1971) and isopleths of temperature, salinity, and nutrients dipping into the canyon (Bigelow and Leslie 1930). Cooler water over the canyon flanks than over the canyon axis was not observed in this study. Isopleths dipping into the canyon and peaking in the canyon were observed sporadically during upwelling and non-upwelling periods and may have been only a sampling artifact caused by tidal oscillations.

The coolest water reaching the surface of Monterey Bay during upwelling periods was 10° C. The maximum depth at which 10° C water was found was 125 m indicating that upwelled water reaching the surface came from this depth, and ascending movements were observed to occur as deep as 400 m (Fig. 5).

The rate of upwelling was estimated from the rise of σ_t surfaces between 150 and 30 m (Table 5). During the 1971 upwelling period, isotherms, isohalines, and thus σ_t surfaces remained at fairly constant levels after the rise between mid-February and mid-March (Fig. 5). It was assumed that the observed rate of upwelling between mid-February and mid-March continued throughout the 1971 upwelling period, although it was probably less during July as evidenced by the sinking 9° C isotherm. These rates do not indicate maximum or minimum values but average rates over monthly periods. They agree well with Skogsberg's (1936) average value of 1.5 m/day and indicate that upwelling was less intense during 1972 than 1971.

TABLE 5

Rates of upwelling in Monterey Submarine Canyon based on rise of σ_t surfaces between 30 and 150 m.

Date	Range (m/day)	Average (m/day)
16 Feb. 71 - 16 Mar. 71		1.4
18 Nov. 71 - 16 Dec. 71	2.6 - 3.2	2.9
17 Feb. 72 - 23 Mar. 72	0.6 - 1.0	0.8
23 Mar. 72 - 18 Apr. 72	0.4 - 3.1	1.7
18 Apr. 72 - 16 May 72		0.4

During the oceanic period (represented by September 1971, Figs. 19 and 20) and the Davidson Current period (represented by January 1972, Figs. 21 and 22), water in Monterey Bay was more homogeneous than during upwelling periods, as previously shown (Figs. 9 to 13) (see Appendix 1). There was some erratic variation of measured physical and chemical parameters, and the source water entering the bay was not clearly distinguished from water already present in the bay. The accumulation of older water in the ends of the bay was therefore not apparent as during upwelling periods. However, occasionally a closed contour was observed in the northern end of the bay (Figs. 19 and 20) indicating the presence of an eddy. Thus, as during the upwelling periods, it is likely that water also resides longer in the ends of the bay than in the center of the bay during the oceanic and Davidson Current periods.

In general, during upwelling periods relatively old near surface water was found in the northern and southern ends of Monterey Bay, and recently upwelled water was found in Monterey Submarine Canyon. This distribution of near surface water likely resulted from onshore movement of water in central Monterey Bay and counterclockwise and

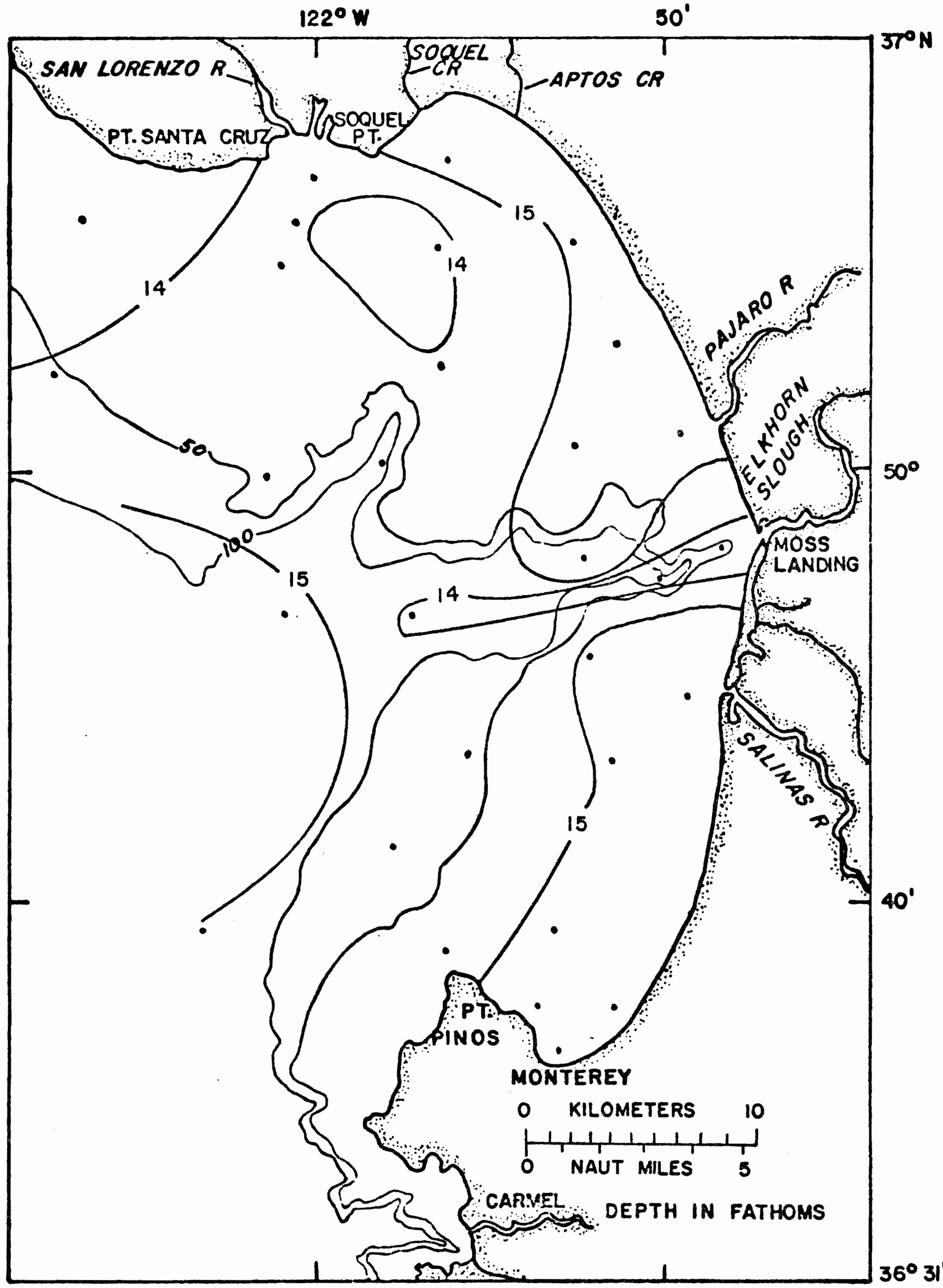

Figure 19. Distribution of average temperature (°C) in the upper 10 m of Monterey Bay, 29 September-1 October 1971, oceanic period.

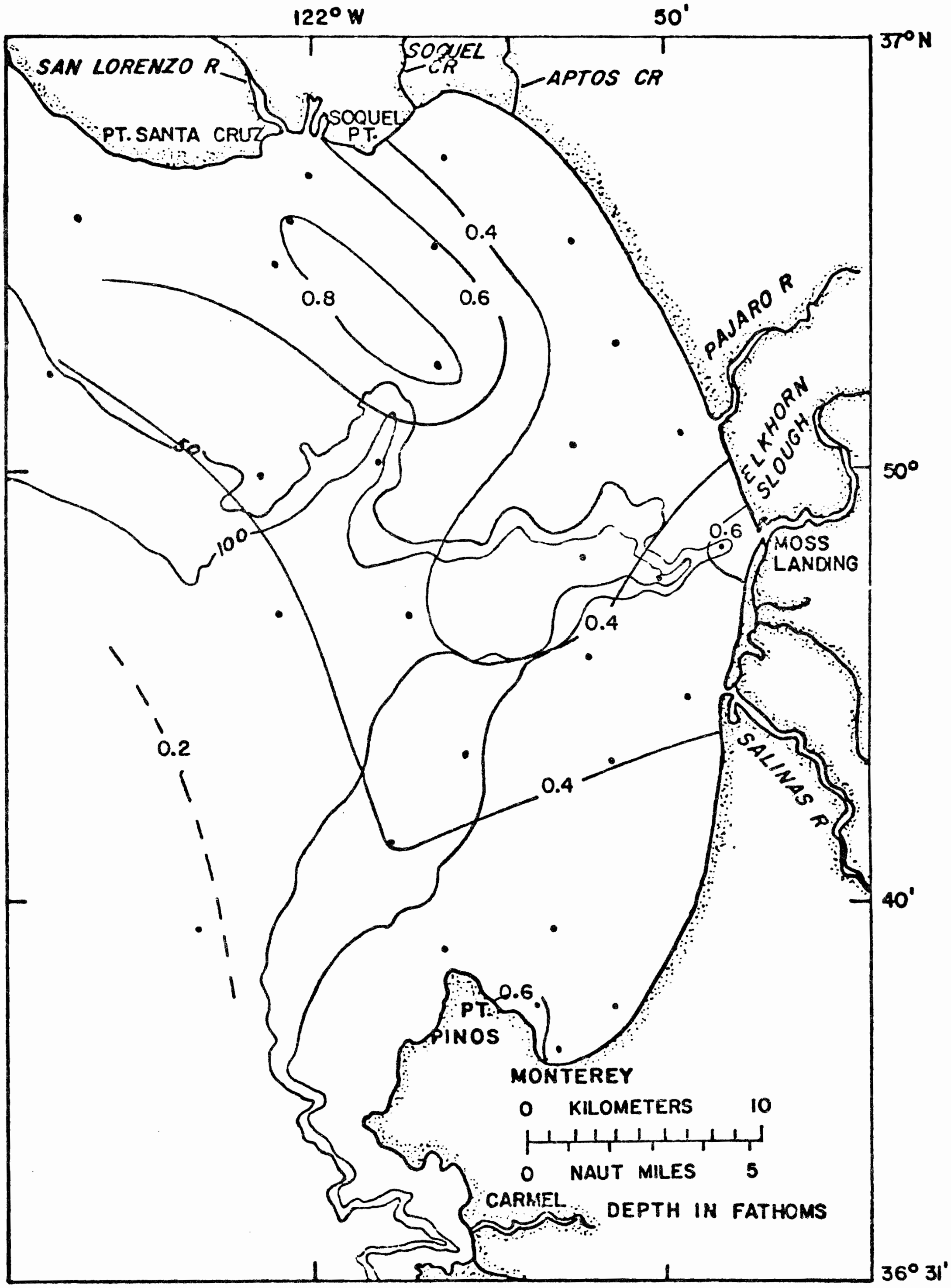

Figure 20. Distribution of average phosphate concentration (μg-at/liter) in the upper 10 m of Monterey Bay, 29 September-1 October 1971, oceanic period.

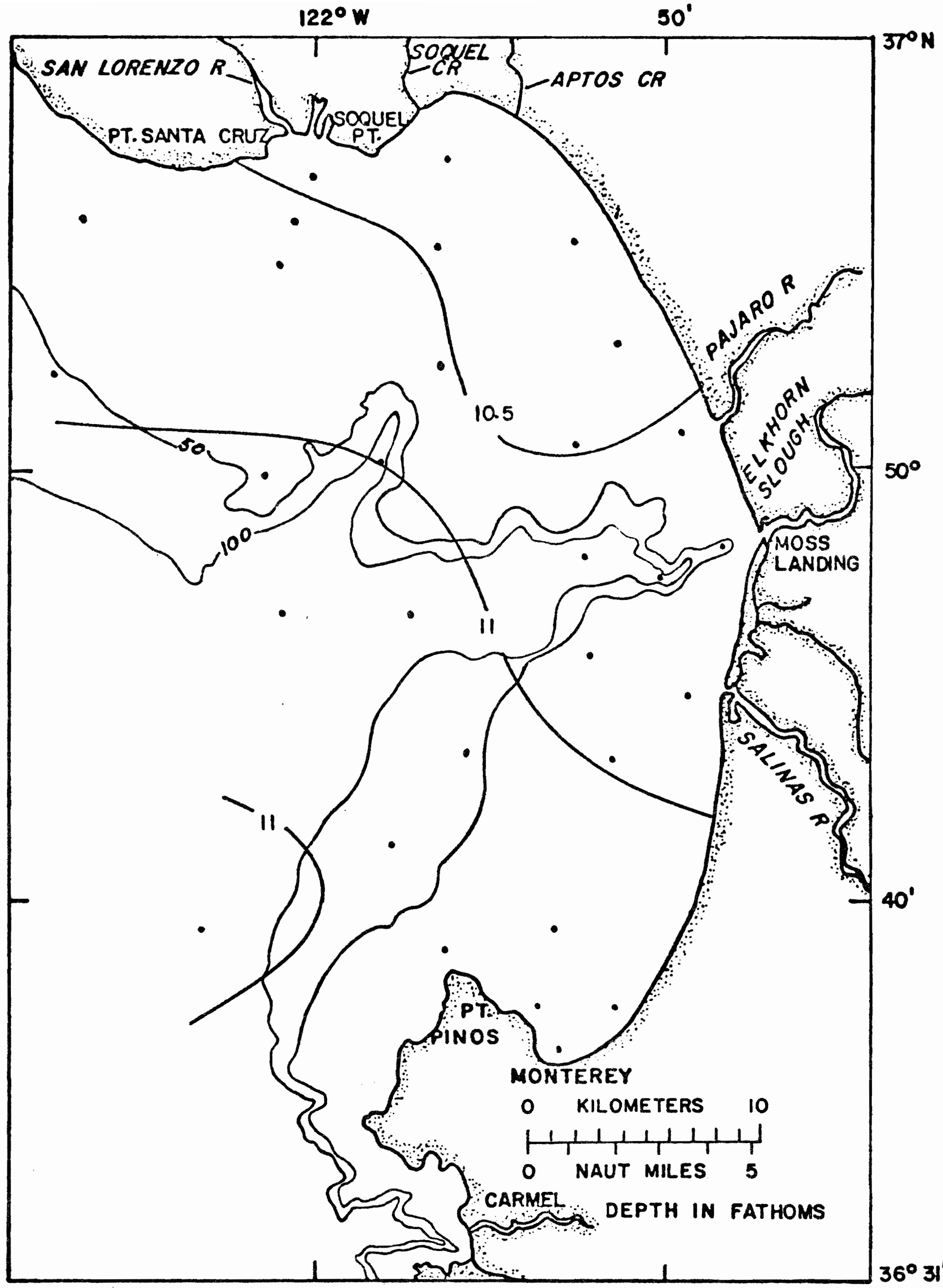

Figure 21. Distribution of average temperature (°C) in the upper 10 m of Monterey Bay, 19-21 January 1972, Davidson Current period.

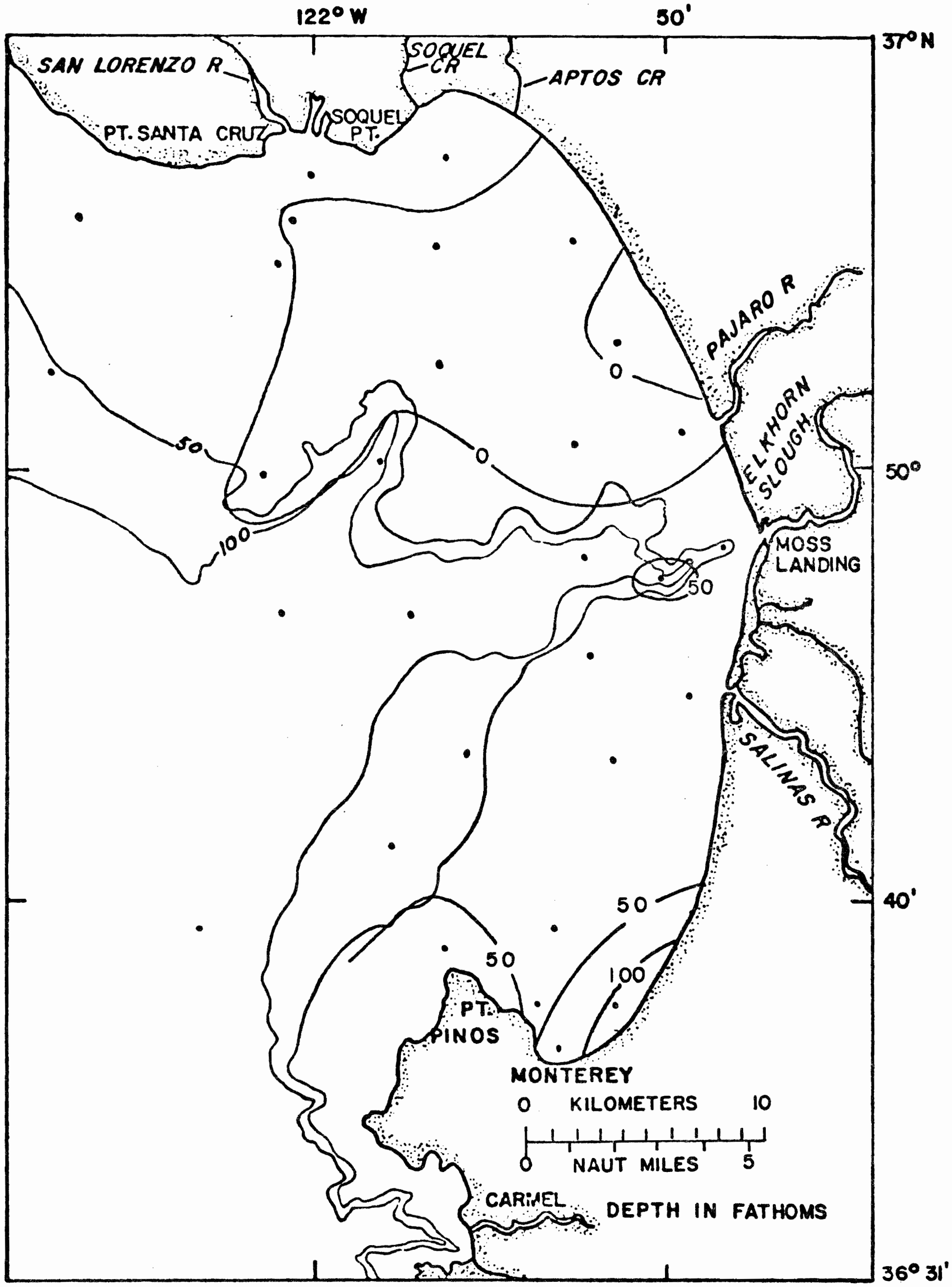

Figure 22. Distribution of average apparent oxygen utilization (µg-at/liter) in the upper 10 m of Monterey Bay, 19-21 January 1972, Davidson Current period.

clockwise flow in the northern and southern ends respectively. During non-upwelling periods, current patterns could not be inferred from the distribution of physical and chemical parameters, but it is quite possible that current patterns similar to those during the upwelling period prevailed. Upwelling appears to have occurred in the canyon with average rates of 0.4 to 2.9 m/day and apparent intensification of upwelling was observed at the head of the canyon.

Nutrient-Oxygen Relations

Nutrient-oxygen relations can be used to describe the biochemical history of water parcels. This is useful for estimating productivity and for tracing movement of water masses. In this section, the observed nutrient-oxygen relations in Monterey Bay and their seasonal changes will be described. It will also be shown that the biochemical history of the water is consistent with general water movement previously discussed.

Distributions of nutrients and oxygen in the oceans and the relations between nutrient concentrations and oxygen concentration are largely dependent on the biochemical cycle: nutrient uptake by phytoplankton and nutrient regeneration by bacterial and animal respiration (Redfield 1942; Redfield and others 1963). Phytoplankton remove nutrients from the water during photosynthesis in proportions necessary for growth. Fleming (1940) has shown the average atomic ratios of carbon:nitrogen:phosphorous in plankton to be 106:16:1. In a statistical sense, phytoplankton remove nutrients from water in this ratio and release 276 atoms of oxygen during photosynthesis (Redfield and others 1963). During decomposition, nutrients are released from organic matter in this same ratio, and 276 atoms of oxygen are consumed. Both processes occur in the photic zone, but during periods of net photosynthetic carbon fixation, nutrients are depleted while the oxygen concentration is increased, and AOU is decreased. Below the photic zone only decomposition occurs, and nutrients are regenerated while oxygen is depleted, and AOU is increased.

Nutrient concentrations below the photic zone are not entirely of immediate oxidative origin because of the presence of preformed nitrate and preformed phosphate. These quantities, which are conservative properties, are generally proportional to each other for a given source area, and originate when surface water sinks beneath the photic zone, the surface concentrations at the time of sinking becoming the preformed nitrate and preformed phosphate. They are defined as

$$N_p = N_{obs} - \frac{16}{276} AOU$$

and

$$P_p = P_{obs} - \frac{1}{276} AOU$$

where N_p and P_p are preformed nitrate and preformed phosphate respectively, N_{obs} and P_{obs} are observed nitrate and observed phosphate respectively. AOU, the apparent oxygen utilization, is defined as

$$AOU = O_2' - O_2$$

where O_2' is the oxygen solubility and O_2 the observed oxygen concentration (Redfield 1942).

Negative AOU indicates net oxygen production, positive values indicate consumption. To determine if changes in dissolved oxygen and phosphate concentrations in Monterey Bay occurred in the expected atomic ratios of 276:16:1, scatter diagrams of AOU vs phosphate concentration and nitrate concentration vs phosphate concentration were plotted for each monthly cruise.

The ratios of $\Delta AOU:\Delta NO_3:\Delta PO_4$ (Table 6) were determined from the scatter diagrams for depth ranges of 0 to 30 m and 50 to 100 or 400 m. These values were determined by inspection, and no statistical tests can be applied. The average $\Delta AOU:\Delta NO_3:\Delta PO_4$ ratio for the upper 30 m was 292:13.4:1 and for below 50 m was 266:14.5:1 with an overall average ratio of 279:14:1. This is in good agreement with the classical O:N:P ratio of 276:16:1. Nitrogen is released from decomposing organic matter as ammonia, which in general is then oxidized to nitrite, then to nitrate (Vaccaro 1965). The nitrogen cycle is complicated and this oxidative sequence is not always strictly observed. In the photic zone, ammonia and nitrite (along with nitrate) are assimilated by phytoplankton during photosynthesis. This may account in part for the observed $\Delta NO_3:\Delta PO_4$ ratio of 14:1 instead of the expected 16:1.

The PO_4 - AOU and PO_4 - NO_3 intercepts are the PO_4 concentration at zero AOU or NO_3 concentration. Changes in these intercepts reflect changes in the $\Delta AOU:\Delta PO_4$ and $\Delta NO_3:\Delta PO_4$ ratios and hence changes in the preformed phosphorous and nitrogen values near the surface. Except in September 1971, the PO_4 intercept at zero NO_3 concentration varied little with time (Fig. 23). This indicates that preformed phosphate and

TABLE 6

Ratios of $\Delta AOU:\Delta NO_3:\Delta PO_4$ by atoms determined from all stations in Monterey Bay

Month	0 to 30 m AOU : NO_3 : PO_4	Deeper than 50 m AOU : NO_3 : PO_4
February 1971	165 : 9.0 : 1	280 : 17.5 : 1
March 1971	260 : 14.9 : 1	260 : 14.9 : 1
April 1971	165 : 14.1 : 1	300 : 14.1 : 1
May 1971	280 : 14.7 : 1	380 : 14.7 : 1
June 1971	270 : 12.1 : 1	270 : 12.1 : 1
July 1971	245 : 13.2 : 1	245 : 13.2 : 1
August 1971	230 : 13.0 : 1	230 : 13.0 : 1
September 1971	450 : ---- : 1	250 : 22.6 : 1
October 1971	210 : 15.2 : 1	210 : 15.2 : 1
November 1971	265 : 15.8 : 1	265 : 15.8 : 1
December 1971	500 : 13.7 : 1	250 : 13.7 : 1
January 1972	525 : 13.5 : 1	270 : 13.5 : 1
February 1972	290 : 11.2 : 1	245 : 11.2 : 1
March 1972	235 : 13.2 : 1	235 : 13.2 : 1
April 1972	277 : 13.6 : 1	277 : 13.6 : 1
May 1972	295 : 12.5 : 1	295 : 12.5 : 1
Average	292 : 13.4 : 1	266 : 14.5 : 1
Overall Average	279 : 14 : 1	

preformed nitrate are conversative properties as has been generally observed (Redfield and others 1963) and that nitrate would be the limiting nutrient rather than phosphate. The increase in the PO_4 - NO_3 intercept in September can be explained by the observation that NO_3 was depleted to zero in the upper 30 m. This resulted in the intercept being essentially the PO_4 concentration of the 30 m water instead of surface water which had a lower PO_4 concentration.

The PO_4 intercept at zero AOU shows apparent seasonal trend (Fig. 23). During upwelling periods, the intercept is generally higher than during non-upwelling periods. Since waters of Monterey Bay are mainly a mixture of California Current water from the north and California Countercurrent water from the south (originally derived from Equatorial Pacific water), it is possible that the observed changes in the PO_4 - AOU intercept resulted from changing preformed phosphate as the ratio of California Current water to California Countercurrent water varied. If this were the case, the greatest change would be expected between the oceanic period and the Davidson Current period; however, a change was not observed at this time and the observed variation appears to be related to the upwelling process. The following discussion is offered as a possible explanation for the observed seasonal trend.

Scatter diagrams of AOU vs PO_4 are shown for an upwelling month (March 1971) and a non-upwelling month (August 1971) (Fig. 24). For the August PO_4 - AOU intercept to be shifted to the position of the March PO_4 - AOU intercept, AOU would have to decrease without a corresponding decrease in PO_4 concentration or phosphate would have to increase without

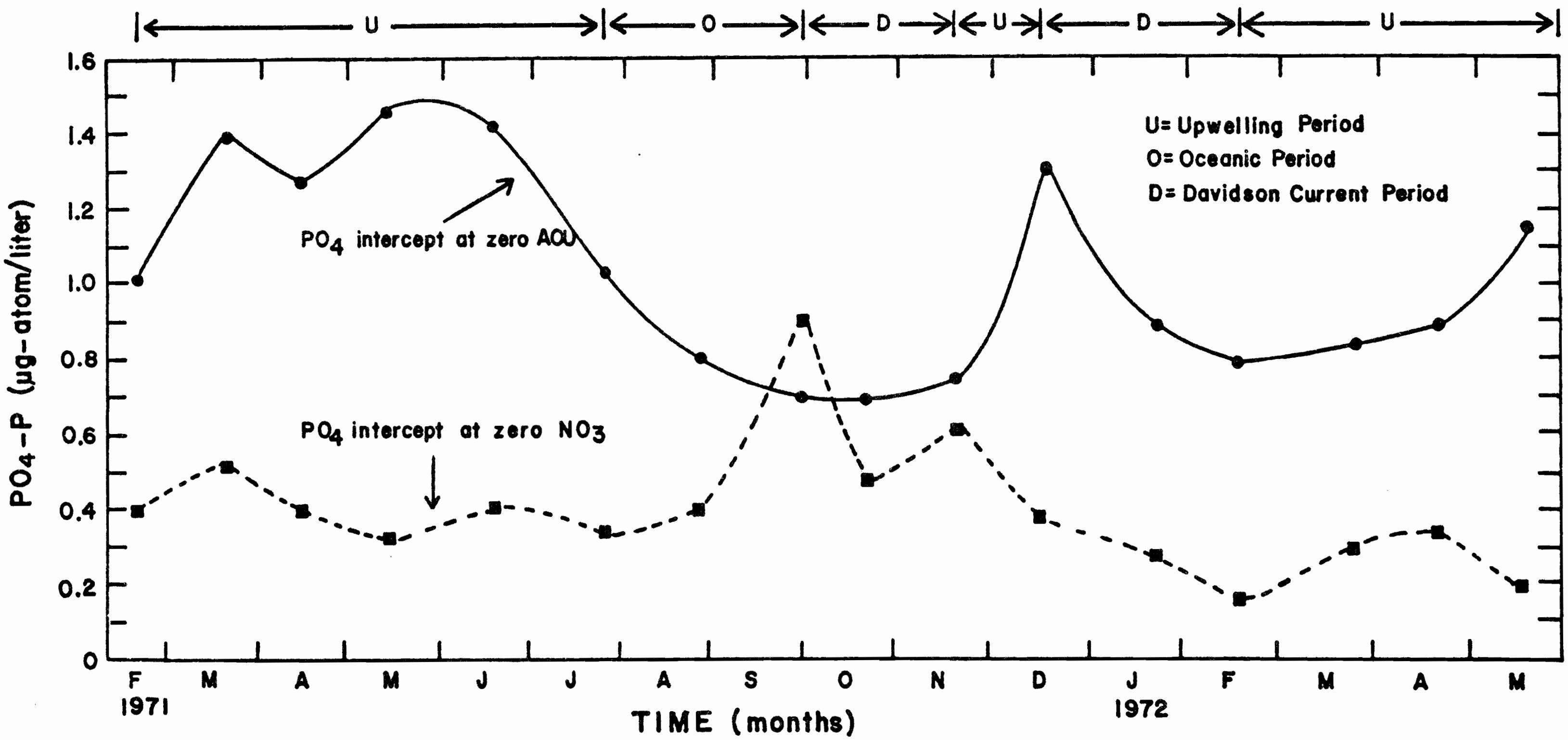

Figure 23. Variation of the PO_4-AOU intercept and the PO_4-NO_3 intercept in Monterey Bay. (See Fig. 24).

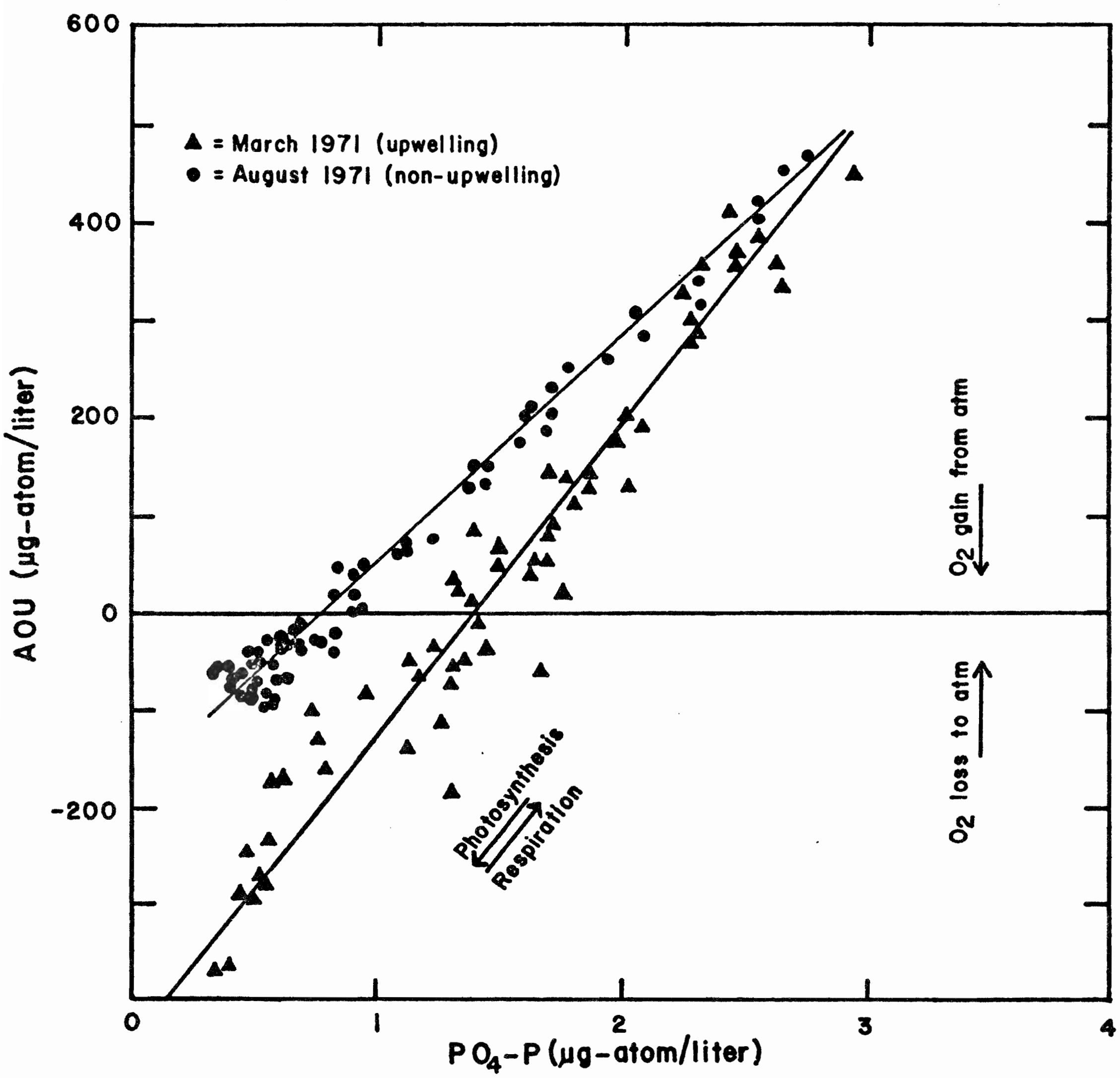

Figure 24. AOU vs PO_4 scatter diagram for all stations sampled in Monterey Bay, 16-20 March 1971, and 27-28 August 1971.

an increase in AOU, or both. During upwelling, subsurface water rises and warms, resulting in a temperature increase, thus decreased oxygen solubility. The decrease in oxygen solubility causes AOU to decrease without a corresponding decrease in the PO_4 concentration. A 1^{o} C increase in temperature of 34 ^{o}/oo salinity water at 10 to 15^{o} C causes a decrease in oxygen solubility of 25 μg-atoms/liter (Truesdale and others 1955). During upwelling, temperature differences between surface water and 100 m water in the canyon vary between 1.5^{o} C and 4^{o} C (Fig. 7). This would account for a decrease in AOU of 40 to 100 μg-atoms/liter. The difference between the March and August curves at the midpoint between the intercepts is 160 μg-atoms/liter, and the temperature gradient is 1.5^{o} C between 100 m and the surface during March; thus, *in situ* heating may only partially account for the seasonal difference between the PO_4 - AOU intercepts.

Oxygen exchange across the sea surface can also account for a decrease in AOU without a corresponding decrease in PO_4. As water enters the photic zone during upwelling, nutrients are assimilated by phytoplankton and oxygen is produced, causing a decrease in AOU. This causes no shift in the PO_4 - AOU intercept because the decrease in AOU is accompanied by a decrease in PO_4. However, as the water becomes supersaturated with oxygen (negative AOU values), oxygen tends to escape to the atmosphere resulting in a decrease in the PO_4 - AOU intercept. During the upwelling season, surface water in Monterey Bay was relatively young and apparently moved through the bay faster than its oxygen content could equilibrate with the atmosphere. No decrease in the PO_4 - AOU intercept was observed. Once upwelling ceased, however, the water that entered the bay had been at the surface long enough for excess oxygen to diffuse into the atmosphere, and the PO_4 - AOU intercept decreased. This process has been observed off the Washington and Oregon coasts (Stefansson and Richards 1964) where a similar decrease in the intercept was noticed.

During the 1972 upwelling period, the PO_4 - AOU intercept did not reach as high a level as during the 1971 season. It has been indicated that upwelling was not as intense during 1972 as 1971. Consequently, upwelled water remained longer at the surface in Monterey Bay during 1972 than 1971, and the photosynthetically produced excess oxygen had more time to equilibrate with the atmosphere resulting in the smaller PO_4 - AOU intercept.

The increase in the PO_4 - AOU intercept in December may have been caused by another mechanism. The period of upwelling just prior to this sampling caused cool (10° C), high AOU water (130 to 250 μg-atoms/liter) to be brought to the surface. This water rapidly absorbed oxygen from the atmosphere as it moved from the canyon to other areas of the bay (Fig. 25), but no significant photosynthetic PO_4 uptake occurred, presumably due to the lack of sunlight and low phytoplankton standing stock. The transfer of oxygen from the atmosphere across the sea surface would also occur during other upwelling episodes when the upwelled water reaching the surface was undersaturated.

The processes just described apply only to water sufficiently shallow to mix with photic zone water. In Monterey Submarine Canyon,

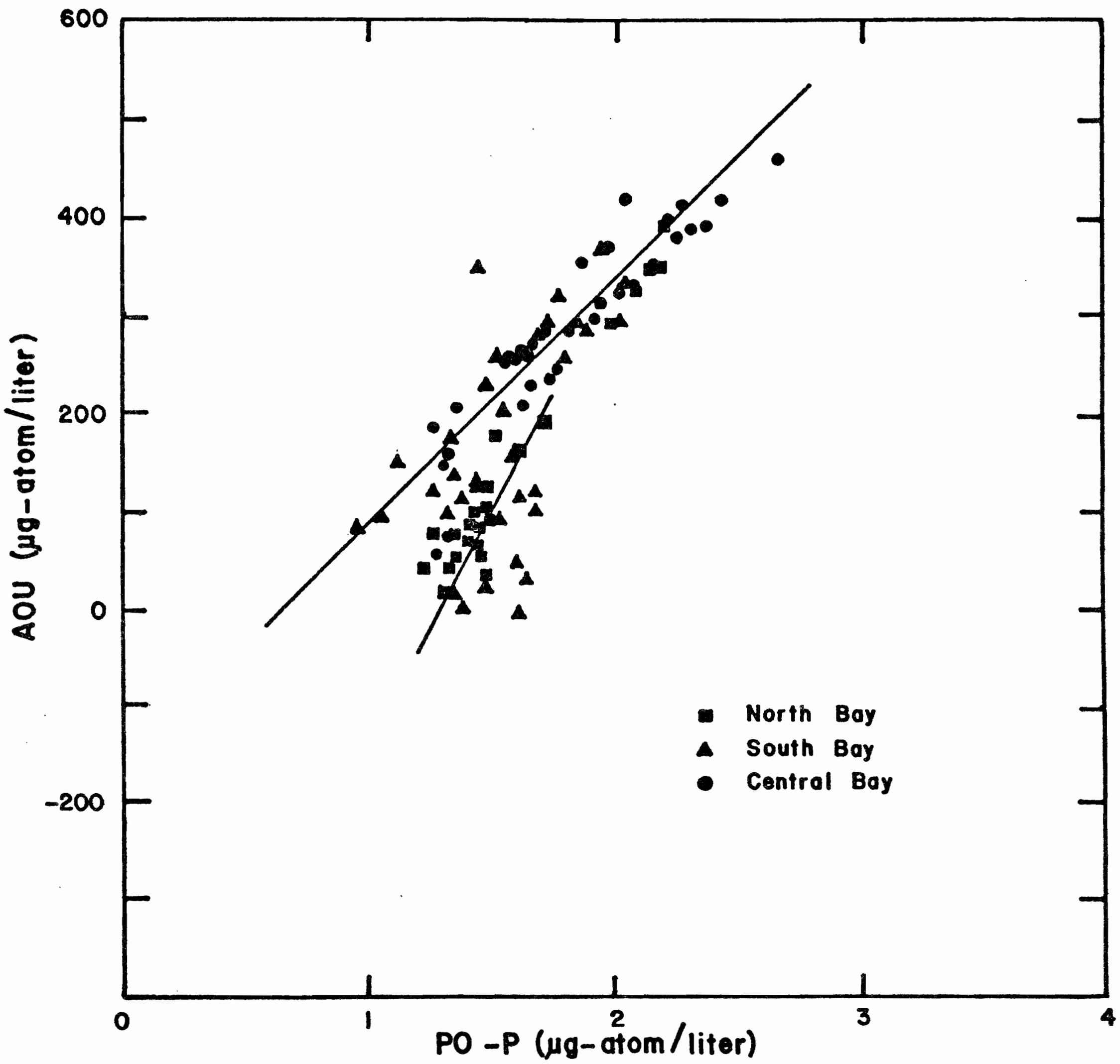

Figure 25. AOU vs PO_4 scatter diagram for all stations sampled in Monterey Bay, 15-17 December 1971.

water from as deep as 100 m and possibly deeper may mix with photic zone water as the result of vertical tidal movement. The previous argument neglects possible deep water seasonal changes in the PO_4 - AOU intercept, and if no deep water seasonal changes occur, the same relation between PO_4 and AOU should be observed the year round. Thus, at depths greater than 100 m, all AOU - PO_4 values should converge. This is generally the case but there are a few situations during both upwelling and non-upwelling periods in which the deep values do not converge to a common value. Seasonal changes at depth are smaller than those at the surface.

In September 1971 the nitrate concentration was depleted to zero between the surface and 30 m, and during March, June, August, and October 1971 and February 1972, it was reduced to zero concentration in the surface water in certain areas of the bay; thus, nitrate rather than phosphate was observed to be a limiting nutrient in Monterey Bay. Phosphate concentration always remained above 0.2 µg-atoms/liter as has been observed in the California Current (Reid and others 1958). Stefansson and Richards (1963, 1964) have also concluded that nitrate is limiting in North Pacific waters.

AOU - PO_4 scatter diagrams reveal the biochemical history of water parcels: high AOU - PO_4 values indicating the release of nutrients from organic matter and oxygen consumption (hence a relatively long isolation from the photic zone); low PO_4 - AOU values indicating PO_4 assimilation and oxygen production (hence a period of residence in the photic zone). During upwelling in Monterey Bay, lower AOU - PO_4 values were generally observed in the ends of the bay (Fig. 26), indicating the

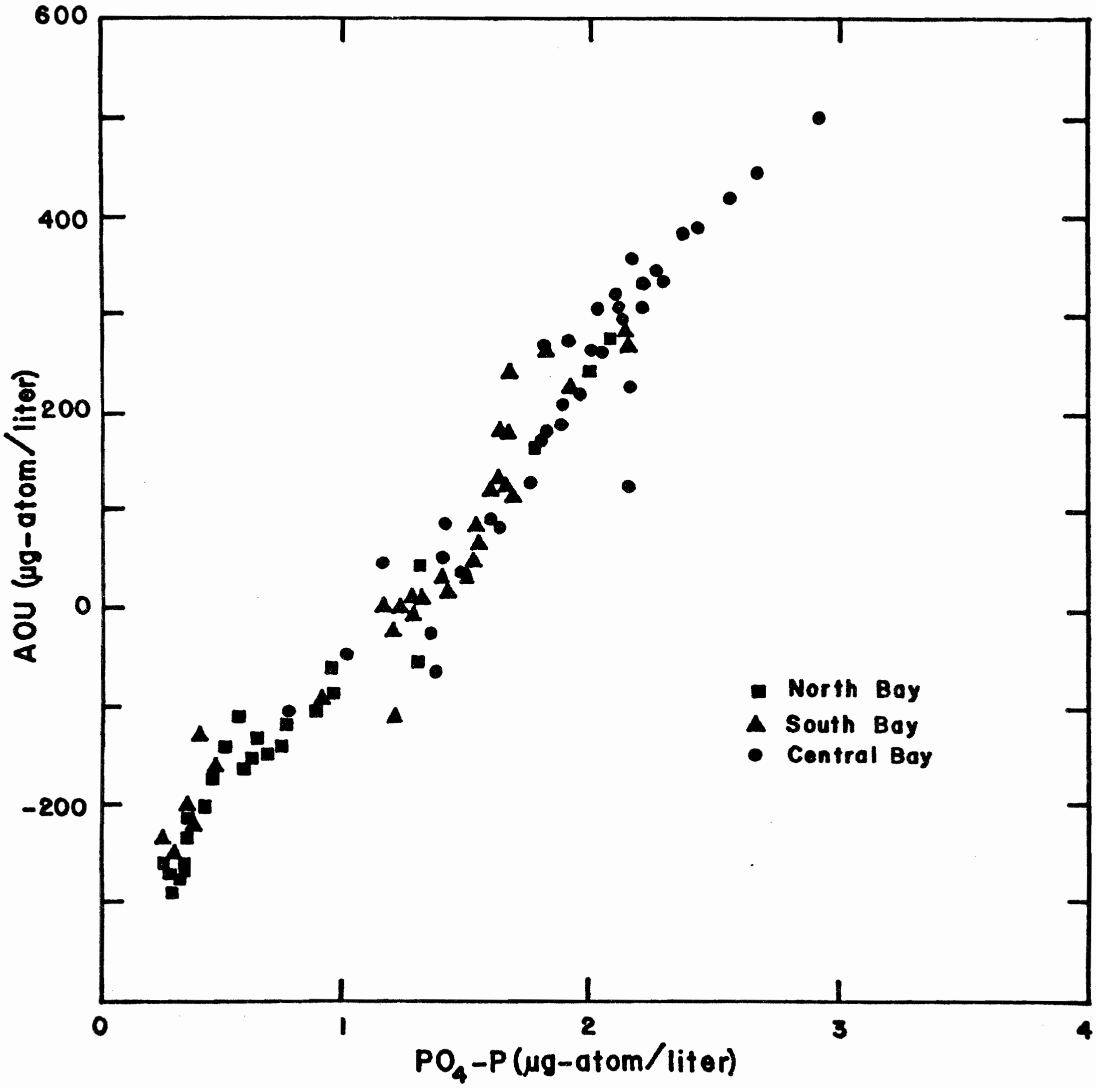

Figure 26. AOU vs PO_4 scatter diagram for all stations sampled in Monterey Bay, 15-17 May 1972.

northern and southern water masses had longer residence times than surface water in the central area of the bay. This is consistent with a movement of water from the canyon area of the bay towards the ends of the bay as previously discussed (p. 45).

In summary, the overall ratio of $\Delta AOU:\Delta NO_3:\Delta PO_4$ was observed to be 279:14:1 by atoms which compares favorably with the classical O:N:P ratio of 276:16:1. The seasonal variation on the PO_4 - AOU intercept reflects the rate of upwelling and can be explained by *in situ* heating and oxygen exchange across the sea surface. Nitrate appears to be the limiting nutrient, and biochemically old surface water is found in the northern and southern ends of Monterey Bay during upwelling.

CHAPTER 5

RESIDENCE TIME

Determination of residence time

In the previous chapter it was shown that during upwelling periods, oldest surface water was found in the ends of Monterey Bay and that this water apparently originated in the canyon area or offshore. The residence time of water in the ends of the bay can be determined from estimated nutrient assimilation, oxygen production, and heat absorption rates as the water moves from its presumed source area to the ends of the bay.

During upwelling, subsurface water which is low in oxygen and high in nutrients enters the photic zone where it mixes with water that has been somewhat depleted of nutrients and raised in oxygen by photosynthesis. The result is that water in the photic zone has a higher oxygen and lower nutrient concentration than the water below the photic zone (Fig. 27). If the vertical velocity of the water, w, is known, the net advective flux of oxygen and nutrients into the photic zone, F, can be calculated from

$$F = w(C_z - C_o), \qquad (1)$$

where C_z is the concentration of oxygen or nutrients at the base of the photic zone and C_o is the average concentration of oxygen or nutrients in the photic zone. Assuming that no horizontal mixing occurs in the photic zone from areas outside the region of upwelling (i.e. newly upwelled water moves out of the area of upwelling and is replaced by more upwelled water) and that oxygen exchange across the sea surface is

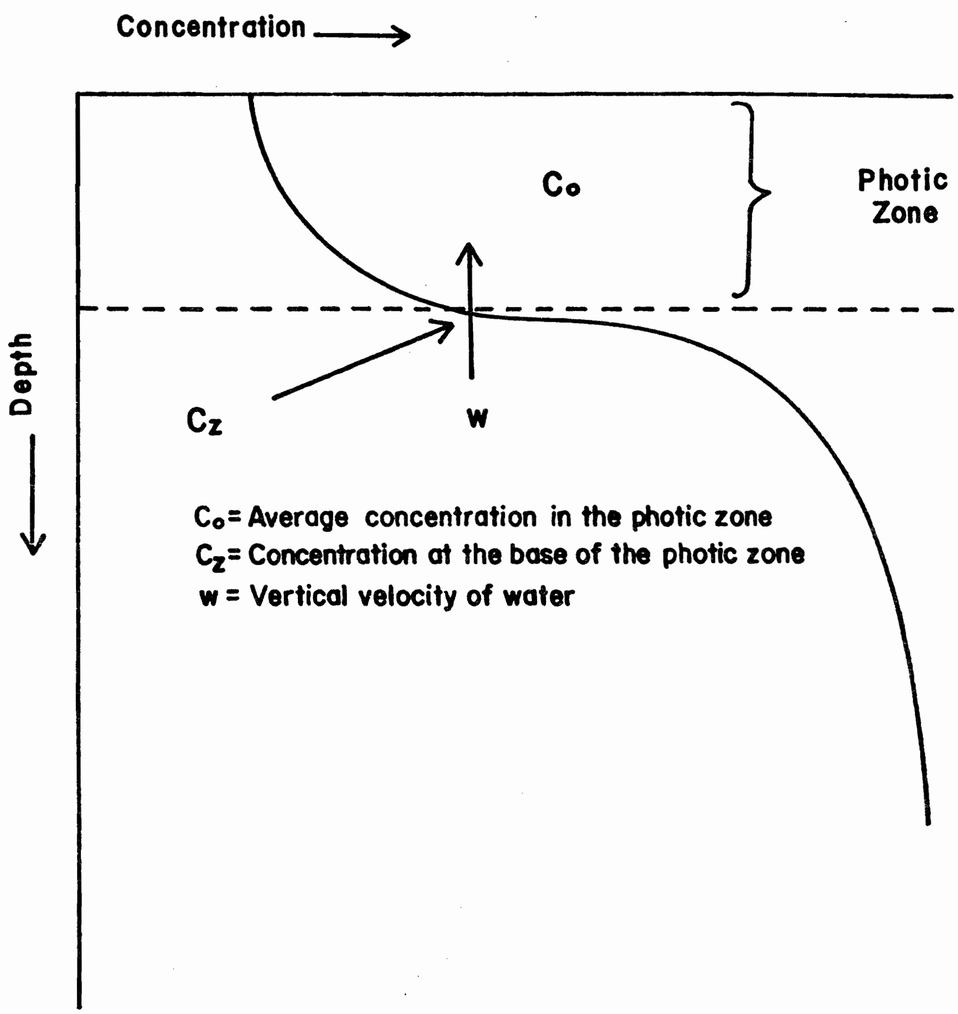

Figure 27. Idealized vertical distribution of a nutrient in an area of upwelling.

negligible, then C_z - C_o is entirely due to oxygen production or nutrient uptake. Under these conditions the flux of oxygen and nutrients into the photic zone equals the net water column oxygen production rate or nutrient uptake rate, R; that is

$$R = F. \qquad (2)$$

Assuming upwelling occurred in Monterey Submarine Canyon and that there was no horizontal mixing from areas outside the canyon, the oxygen production rate, the phosphate uptake rate, and the nitrate uptake rate were calculated for every upwelling month using equations (1) and (2). The photic zone was taken to be three times the average Secchi disk depth in the canyon, and the average and extreme upwelling rates for each month were used. The oxygen production and nutrient uptake rates were converted to net carbon assimilation rates (Table 7) using the accepted O:C:P atomic ratios of 276:106: 1 and the observed $\Delta NO_3:\Delta PO_4$ ratio of 14:1 (Table 6). The computed productivity values ranged from 0.15 to 1.4 $gC/m^2/day$ for all months when upwelling was observed as compared with 0.24 to 0.9 $gC/m^2/day$ observed in the California Current (Wooster and Reid 1963), and 0.04 to 1.5 $gC/m^2/day$ measured by the carbon-14 method at six stations in Monterey Bay from January to May 1972 (Table 7) (D. Garrison, personal communication).

Residence times of near surface water (upper 10 m) (Table 8) were calculated from the observed nutrient depletion and oxygen increase and from the calculated nutrient uptake and oxygen production rates from

$$T_r = \frac{Cs - Ce}{R},$$

where T_r is the residence time, C_s is the average concentration in near

TABLE 7

Summary of productivity data (gC/m^2 day) as estimated from PO_4 uptake, NO_3 uptake, O_2 production, and the carbon-14 method.

Method	Mar 71	Apr 71	May 71	Jun 71	Jul 71	Dec 71	Mar 72	Apr 72	May 72
PO_4 uptake	0.34	0.57	0.55	1.39	0.92	0.26	0.28	0.56	0.15
NO_3 uptake	0.32	0.52	0.50	0.79	0.78	0.32	0.18	0.60	0.16
O_2 production	0.46	0.60	0.82	1.10	0.67	0.36	0.68	0.60	0.22
carbon-14 method *									
minimum							0.34	0.33	0.20
maximum							0.91	1.50	0.90
average							0.58	0.82	0.54

* Determined at stations 1121, 1122, 1103, 1158, and 1159 (Fig. 1)

TABLE 8

Average residence times of water in Monterey Bay

Method of Calculation	Average Residence Time (days) at Stations 1153 and 1159	Average Residence Time (days) at Stations 1150 and 1154	Average Residence Time (days) at Stations 1, 1121, and 1122
Phosphate uptake			
Average*	3	3	3
Range*	0 to 9	1 to 7	1 to 4
Nitrate uptake			
Average*	3	3	3
Range*	1 to 7	1 to 5	1 to 4
Oxygen production			
Average*	2	2	1
Range*	1 to 5	1 to 4	1 to 2
Heat absorption			
Average	6	6	8
Range	3 to 10	3 to 9	2 to 13

* Only nutrient uptake rates and oxygen production rates calculated from average upwelling rates were used in determining these averages and ranges. Residence times were also calculated from nutrient uptake rates, and oxygen production rates calculated from extreme upwelling rates and extreme C^{14} primary productivity rates. These residence times ranged from 0 to 14 days.

surface source water, C_e is the average concentration in apparently older near surface water in the ends of the bay, and R is the nutrient uptake or oxygen production rate per unit surface area. Three assumptions were made in making this calculation: 1) no mixing occurred with water originating outside the source area, and the oxygen exchange across the air-sea interface was negligible; thus, the observed decrease in nutrient concentration and increase in oxygen concentration was due entirely to nutrient uptake and oxygen production; 2) oxygen production and nutrient uptake rates were constant in near surface water throughout the entire bay; 3) rates which were calculated for the entire photic zone occurred in only the upper 10 m. The Secchi disk depth was less than 10 m for every month except May 1972, indicating that more than 80% of the incident light was absorbed in the upper 10 m and consequently that the bulk of productivity occurred in the upper 10 m. This assumption agrees with the carbon-14 productivity measurements of D. Garrison (personal communication).

The net heat absorption per unit area, Q, is given by

$$Q = c \rho \Delta T z, \qquad (3)$$

where c is the heat capacity and ρ the density of seawater, ΔT is the change in the mean water column temperature from the surface to depth z, and z is the depth to which the heat is absorbed. If the net heat flux across the sea surface, Q, (Table 9) is known and $(T_e - T_s)$ is substituted for ΔT in equation (3), the residence time, T_r, can be calculated from

$$T_r = \frac{c \rho (T_e - T_s) z}{Q},$$

where T_e and T_s are the mean water column temperatures from the surface to depth z for water in the ends of Monterey Bay, and water in the source area, respectively. The depth to which heat was absorbed was determined by superimposing temperature depth profiles of the source water (in the canyon or offshore) over profiles of the warmed water in the nearshore areas. The depth at which the profiles intersected was the depth to which the excess heat was assumed to have been absorbed. All nearshore stations except 1 (Fig. 1) were sampled to only 10 m, but warming may have occurred to greater depths. Excess heat was assumed to have been absorbed to only 10 m, unless depth profiles intersected at a shallower depth. The error due to this assumption would result in an underestimation of the residence time, but this error is probably not greater than the error between the actual heat absorption and that interpolated from Wyrtki's (1966) data (Table 9).

TABLE 9

Average net heat flux for coastal waters near Monterey Bay (from Wyrtki 1966)

Month	Net heat flux (cal/cm^2/day)
Jan.	- 20
Feb.	0
Mar.	+200
Apr.	+200
May	+300
Jun.	+400
Jul.	+300
Aug.	+300
Sept.	+200
Oct.	+100
Nov.	+ 20
Dec.	- 20

Residence times based upon heat flux were calculated for all upwelling months except December, when parameters were too uniform for the calculation. During March and April 1972, the source water was assumed to be offshore water represented by stations 3, 4, 7, 9, and 11 (Fig. 1); however, rates of oxygen production and nutrient uptake for the canyon were still used in the calculation.

Numerous assumptions were made for these calculations, and the residence times calculated must be considered only as estimates. The average residence time during the upwelling periods was generally 3 to 8 days with a range of 0 to 13 days (Table 8). The oxygen production method consistently gave lower residence times. This can be accounted for by a net oxygen loss across the air-sea interface during the upwelling period where waters in the northern and southern area of the bay were generally supersaturated with dissolved oxygen.

Zero residence time values reflect the condition that recently upwelled water sometimes is found adjacent to shore in the north and south shelf areas. This appears to be the result of episodic flushing of the nearshore areas. A residence time of one day is unlikely, because water would have to move at an average speed of 20 cm/sec from the canyon to the ends of the bay. As previously mentioned, the average current speed in the bay appears to be 10 to 15 cm/sec, and this speed is not unidirectional. General circulation within the bay appears to be that of onshore movement in the central region of the bay and counterclockwise and clockwise flow in the northern and southern areas respectively (p. 45). Residence times between 3 and 13 days fit into this model reasonably well. A residence time of 2 days is somewhat short, requiring a unidirectional flow of 10 cm/sec from the canyon to the north and south ends of the bay.

In summary, the residence time of water between central Monterey Bay and the northern and southern ends appears to be 3 to 8 days during upwelling periods. This may or may not be valid for periods other than upwelling, but there is some evidence that counterclockwise and clockwise flow in the northern and southern ends of the bay respectively persists throughout the year.

Distribution of ammonia in Monterey Bay

The residence time of water in Monterey Bay is important in predicting the impact of sewage on the bay. Ten sewers (Fig. 28) discharge between 8.50×10^4 and 1.37×10^5 m^3/day of effluent into Monterey Bay and its tributaries. Ammonia and phosphate concentrations are high in sewage, and these two constituents can be used as tracers of sewage, ammonia being the best tracer because of its much higher concentration and general absence in recently upwelled waters. The expected ammonia concentration due to sewage in Monterey Bay can be calculated from water residence times, sewage discharge rates, ammonia concentration in sewage, and geometric data for Monterey Bay (Appendix 2). It will be shown that the observed ammonia distribution in the ends of the bay can be accounted for by sewage discharge.

As previously mentioned, nitrogen is released upon degradation of organic matter in the form of ammonia. The ammonia is then oxidized to

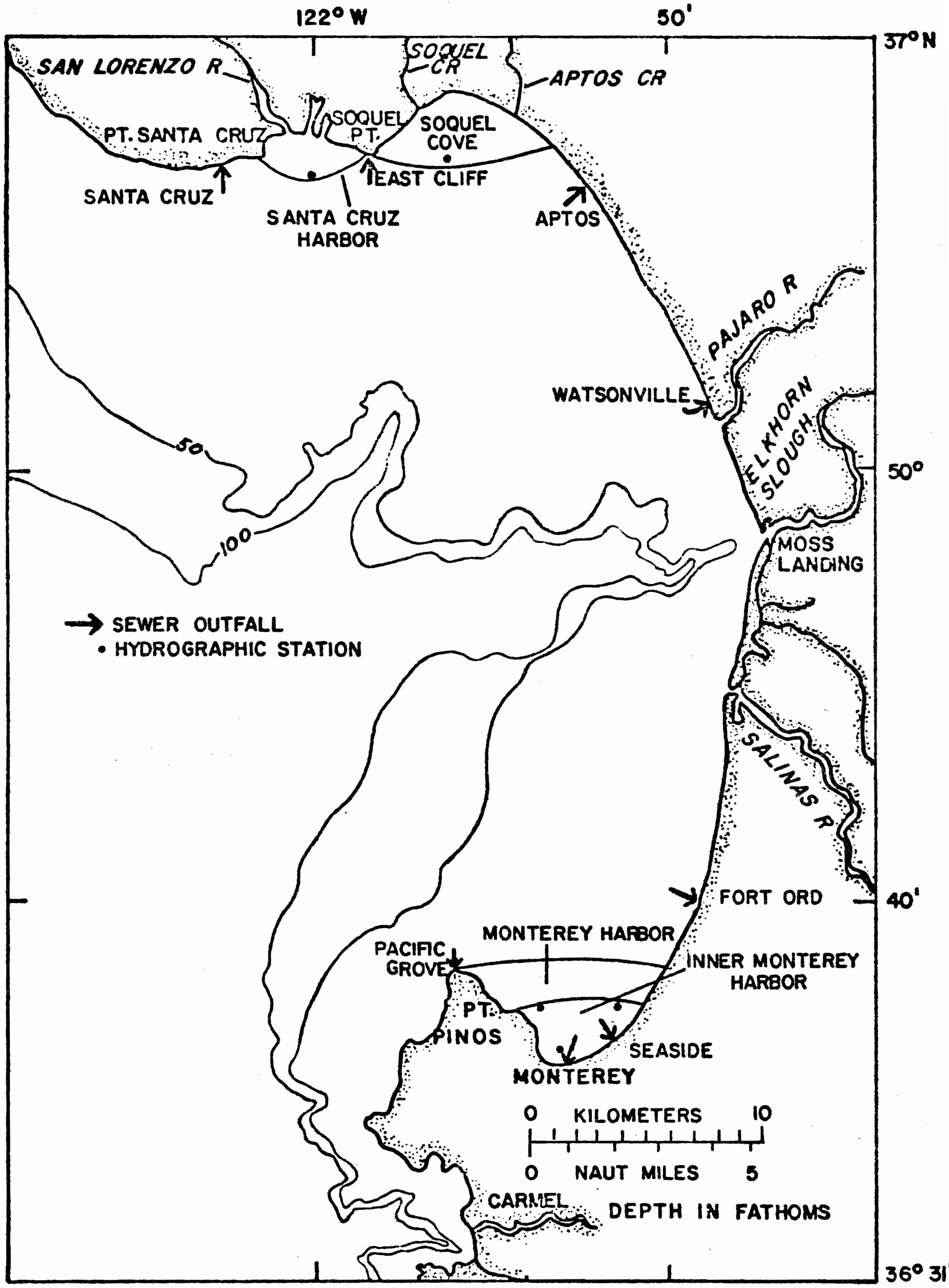

Figure 28. Location of sewer outfalls and definition of areas for which water volumes and sewage effluent dilutions are calculated.

nitrite which is in turn oxidized to nitrate (Vaccaro 1965). This sequence of oxidation reactions, which is bacterially mediated, results in low ammonia concentrations in water that has remained below the photic zone for some length of time. In deep ocean water, ammonia concentrations are low and fairly constant. In surface water, large changes are observed and ammonia is constantly produced by zooplankton excretion and decomposition of organic matter. Bacterial oxidation of ammonia to nitrate may require three to four months (von Brand and Rakestraw 1949), however ammonia is also quickly assimilated by phytoplankton. Thus a complete understanding of the ammonia kinetics is as yet impossible.

The spatial distribution of ammonia in Monterey Bay was highly variable. Deep water in the canyon normally contained less ammonia than water in the photic zone and often low-ammonia water (0 to 0.2 µg-atoms/liter) was found at the surface over the canyon. Occasionally, however, concentrations between 1 and 1.5 µg-atoms/liter were found in canyon deep water. Ammonia concentration in the photic zone normally varied between 0 and 3 µg-atoms/liter, with higher concentrations adjacent to shore, as previously indicated by its seasonal variability (Fig. 14).

High ammonia concentrations in nearshore areas more than likely indicate a landward source (Fig. 29). Although some ammonia enters Monterey Bay with surface runoff, the main landward source is domestic sewage. Samples of pure effluent taken at Santa Cruz, Watsonville, and Seaside outfalls between May 1970 and June 1972 had ammonia concentrations ranging from 90 to 1600 µg-atoms/liter. These concentrations are

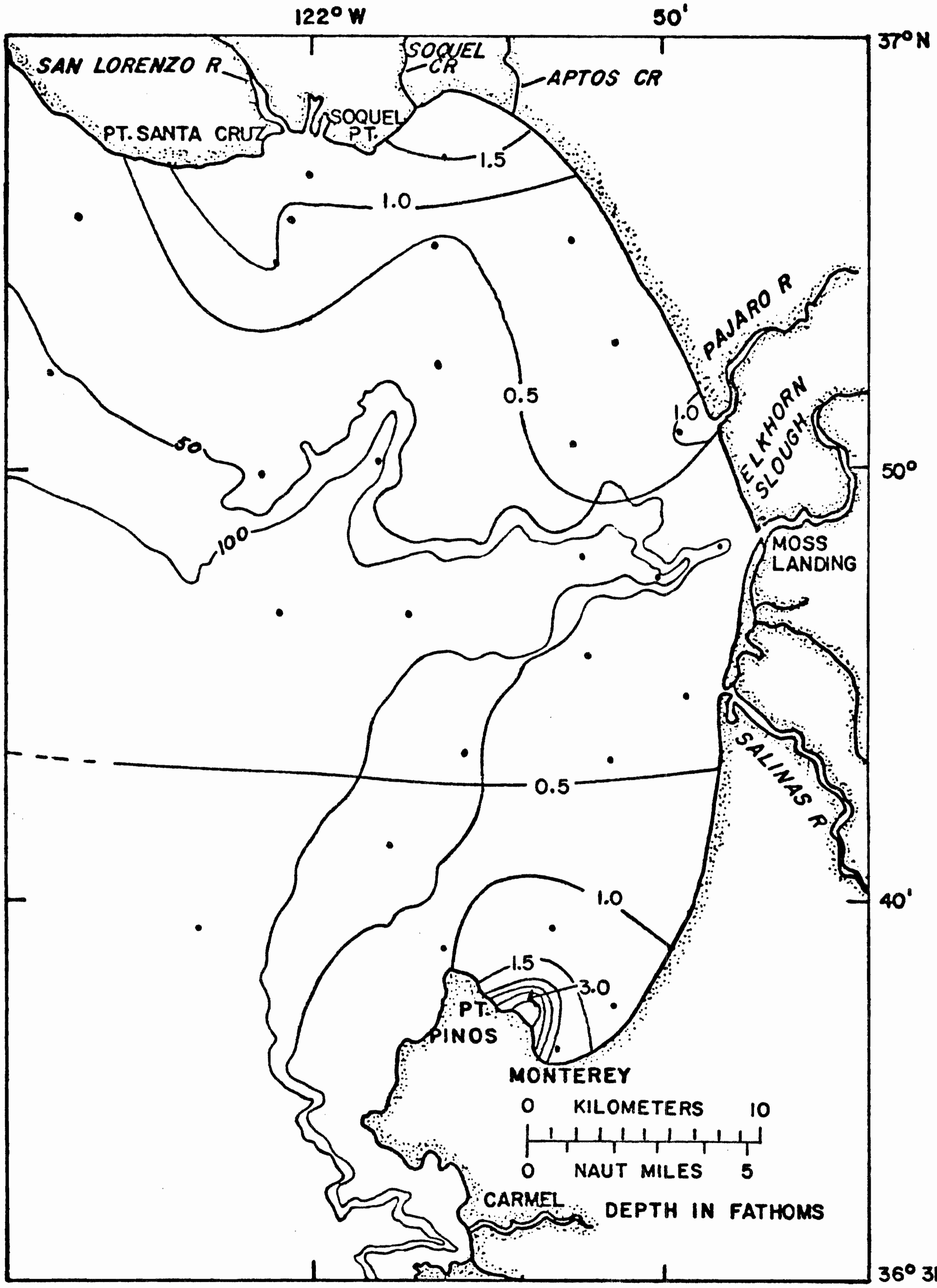

Figure 29. Horizontal distribution of average ammonia concentration (µg-at/liter) in the upper 10 m of Monterey Bay, 17-19 November 1971.

half of the ammonia concentrations (900 to 3200 μg-atoms/liter) found in Southern California domestic sewage (California State Water Control Board, 1964).

Although highest (0 to 10 m) average concentrations were always found adjacent to shore, the stations at which these relatively high concentrations were observed varied (Table 10).

TABLE 10

Frequency of occurrence of relatively high ammonia concentrations at nearshore stations. (See Figs. 1 and 28)

Station	Location	No. of times high NH_3 observed	No. of times sampled
1153	Santa Cruz Harbor	8	16
1159	Soquel Cove	3	11
1105	Pajaro River Mouth	6	16
1103	Moss Landing Harbor	6	16
1101	Salinas River Mouth	2	16
1121	North of Monterey Harbor	4	9
1122	Monterey Harbor	1	9
1	Pacific Grove	9	9

Station 1 consistently showed a very high ammonia concentration, and the surface concentration was 50 μg-atoms/liter in April 1972. These high ammonia concentrations had a very local distribution because much lower values were usually found at stations 1122 and 1121 nearby (Fig. 1). The source of ammonia to this localized area is not known.

During some months, nearshore ammonia concentrations were found to be greater at 10 m than at the surface. This is evidence that sewage sometimes accumulates beneath a shallow thermocline. It is not likely that this ammonia originated from the sediments because the sea floor in these areas is sandy and has a low organic content (<1% organic carbon).

Expected ammonia concentrations in excess of naturally occurring concentrations (Table 11) were calculated from

$$C_w = \frac{T_r \; R_d \; C_s}{V},$$

where C_w is the expected ammonia concentration in excess of background, C_s is the ammonia concentration in sewage, T_r is the residence time of water, R_d is the volume discharge rate of sewage, and V is the volume of the area of concern.

The maximum daily volume of sewage discharged into Monterey Bay and its tributaries (approximately 13.7×10^4 m^3) is small in comparison to the volume of the bay. It would require 110 years to fill the upper 10 m of the entire bay at this average discharge rate. To fill the upper 30 m, 210 years would be required and 840 years would be required to fill the entire bay. Thus, if sewage effluent were evenly mixed throughout the bay, it would be extremely diluted.

It is not likely that sewage mixes evenly throughout the bay. Assuming a residence time of 3 to 6 days and mixing in only the upper 10 m, the concentration of ammonia in excess of background would be 0.09 to 0.24 μg-atoms/liter for an average ammonia concentration of 1600 μg-atoms/liter in sewage (Table 11). If mixing occurred to 30 m under these conditions, the expected ammonia concentration in excess of background would be 0.04 to 0.12 μg-atoms/liter. It is thus realistic to expect sewer outfalls to account for about 0.04 to 0.24 μg-atoms/liter NH_3-N observed in Monterey Bay.

TABLE 11

Expected ammonia concentration in excess of background in various sectors of Monterey Bay.

Residence Time (days)	(NH_3) in sewage (µg-atoms/liter)	Expected NH_3 increase (µg-atoms/liter)					
		Monterey Bay* 0-30 m	Monterey Bay* 0-10 m	Inner Monterey* Harbor	Santa Cruz Harbor	Soquel Cove	Monterey Harbor*
1	1600	0.01-0.02	0.03-0.04	0.17-0.23	1.5-2.3	0.17-0.30	0.07-0.09
3	"	0.04-0.06	0.09-0.12	0.51-0.70	4.6-6.9	0.51-0.90	0.20-0.27
6	"	0.07-0.12	0.18-0.24	1.0 -1.4	9.3-14	1.0 -1.8	0.41-0.54
14	"	0.17-0.28	0.42-0.56	2.4 -3.3	22 -32	2.4 -4.2	0.95-1.3
1	800	0.01	0.02	0.09-0.12	0.79-1.2	0.09-0.16	0.04-0.05
3	"	0.02-0.03	0.05-0.06	0.27-0.37	2.4-3.7	0.27-0.48	0.11-0.14
6	"	0.04-0.06	0.10-0.13	0.55-0.74	5.0-7.3	0.54-0.96	0.22-0.29
14	"	0.09-0.15	0.22-0.30	1.3 -1.7	12 -17	1.3 -2.2	0.50-0.66
1	90	0.01	0.01	0.01	0.09-0.14	0.01-0.02	0.01
3	"	0.01	0.01	0.03-0.04	0.27-0.41	0.03-0.05	0.01-0.02
6	"	0.01	0.01	0.06-0.08	0.55-0.81	0.06-0.11	0.02-0.03
14	"	0.01-0.02	0.02-0.03	0.14-0.19	1.3-1.9	0.14-0.25	0.06-0.07

* See Table 12

Average monthly ammonia concentration in the upper 10 m water of Monterey Bay varied from 0.22 to 0.90 μg-atoms/liter during this study with an overall average concentration of 0.56 μg-atoms/liter. A sizable amount of this observed ammonia concentration (10 to 40%) could be accounted for by domestic sewage entering the bay. This conclusion should be viewed with caution, however, because the effect of ammonia excretions by zooplankton and ammonia uptake by phytoplankton is unknown. If ammonia excretion exceeds ammonia uptake, the concentration of ammonia within the bay is an overestimation of sewage impact on the bay. If ammonia uptake is greater than ammonia excreted, concentration of ammonia in the bay is an underestimation of sewage impact. This should be kept in mind in the following discussions of expected ammonia concentrations in localized areas within the bay.

In Santa Cruz Harbor an ammonia concentration of 32 μg-atoms/liter could build up from the Santa Cruz outfall alone if water had a residence time of 14 days and if the sewage was high in ammonia concentration (1600 μg-atoms/liter) (Table 11). This does not happen since the major outfall (Santa Cruz) is located approximately 1 km west of Santa Cruz Harbor (Fig. 28), and apparently little effluent circulates through the harbor. The highest observed ammonia concentration in excess of background (taken to be the monthly average of ammonia concentration in the upper 10 m of Monterey Bay) in Santa Cruz Harbor was 1.5 μg-atoms/liter. This could be accounted for by a high ammonia concentration in sewage and a residence time of one day or by a moderate ammonia concentration (800 μg-atoms/liter) and a two day residence time. These residence times may be unrealistically short, but since the sewage is not discharged directly into the harbor, this concentration could have resulted from a larger residence time.

The highest observed ammonia concentration in Soquel Cove in excess of background was 0.7 µg-atoms/liter in November 1971. Assuming the sources of sewage to Soquel Cove are the East Cliff and Aptos outfalls (Fig. 28), this concentration could result from a discharge of high ammonia sewage with a residence time of three days, a discharge of moderate ammonia sewage with a residence time of six days, or any condition between these two (Table 11).

The highest concentration of ammonia observed in inner Monterey Harbor (excluding station 1 because of its very localized anomalous ammonia concentration) was 0.7 µg-atoms/liter in excess of background in November 1971 and May 1972. This concentration can be accounted for by a high ammonia sewage discharge from Monterey and Seaside outfalls (Fig. 28) and a three day residence time or a moderate ammonia sewage discharge and a six day residence time (Table 12). The 3 to 6 day residence times in Soquel Cove and inner Monterey Harbor are in good agreement with the estimated 3 to 8 day residence time of water in the ends of Monterey Bay.

In summary, up to 40% of the average ammonia concentration in Monterey Bay can be accounted for by sewage discharged into the bay and its tributaries. Highest ammonia concentrations are generally found in nearshore areas in the vicinity of sewer outfalls. Higher concentrations in the northern and southern ends of the bay can be accounted for by sewage discharged into these areas and the previously estimated 3 to 6 day residence time of water in these areas.

TABLE 12

Average sewage discharge rate into various sectors of Monterey Bay

	10^4 m^3/day	10^6 gal/day
Monterey Bay, 0-10 m and 0-30 m (from all outfalls)	8.50 to 13.7	22.5 to 36.3
Inner Monterey Harbor (Monterey and Seaside outfalls)	1.36 to 1.85	3.6 to 4.9
Santa Cruz Harbor* (Santa Cruz outfall*)	1.85 to 2.72	4.9 to 7.2
Soquel Cove (East Cliff and Aptos outfalls)	0.98 to 1.7	2.6 to 4.5
Monterey Harbor (Pacific Grove, Monterey and Seaside outfalls)	2.04 to 2.68	5.4 to 7.1

*Santa Cruz outfall does not dishcarge directly into Santa Cruz Harbor

CHAPTER 6

SUMMARY

Oceanographic periods observed during this study are in general agreement with those originally described by Skogsberg (1936). Seasonal variations in temperature, salinity, oxygen, phosphate, and nitrate were similar for the canyon area and nearshore areas of the bay. During upwelling periods, however, near surface water was higher in temperature and oxygen concentration and lower in phosphate and nitrate concentrations in nearshore areas than in the canyon area. During the oceanic and Davidson Current periods, near surface water was fairly homogeneous throughout the bay.

Over the head of Monterey Submarine Canyon, daily variations of physical and chemical parameters can be as large as seasonal variations due to large vertical movement of water caused by the tide. Daily variations over shelf areas, due to tidal movement, are small, and daily variations over other parts of the canyon are probably somewhat less than over the head of the canyon.

Upwelling apparently occurred in Monterey Submarine Canyon during all months of upwelling except perhaps March and April 1972. During March and April 1972, previously upwelled water was possibly advected into the bay from offshore, but observed distributions of physical and chemical parameters could also have resulted from weak upwelling in Monterey Bay and stronger upwelling offshore of Monterey Bay. Upwelling was more intense during the 1971 upwelling period averaging 1.4 m/day than during the 1972 upwelling period averaging 1.0 m/day. This correlates with offshore wind data. The NW wind component was stronger during the 1971 upwelling period than during the 1972 upwelling period when intermittent periods of southerly winds were observed. Apparent intensification of upwelling at the head of Monterey Submarine Canyon was observed eight out of nine upwelling months during this study, but these effects may also be tidal in origin.

During upwelling periods water appeared to move north and south from the canyon area into the inferred counterclockwise and clockwise flow in the northern and southern ends of the bay respectively. This is consistent with drogue studies and the spatial distributions of temperature, oxygen and nutrients. This apparent flow pattern was not as evident during the oceanic and Davidson Current periods because of the homogenity of the near surface water. However, an occasional closed contour of a physical or chemical parameter and the results of drogue studies during these periods provide some evidence that the circulation pattern was similar during both the upwelling and non-upwelling seasons.

The average ratio of $\Delta AOU:\Delta NO_3:\Delta PO_4$ was 279:14:1 by atoms of O, N, and P and is in good agreement with the expected O:N:P ratio of 276:16:1. A seasonal variation was observed in the PO_4-AOU intercept, with high values occurring during upwelling periods and low values during non-upwelling periods. This can be explained by _in situ_ heating during upwelling and oxygen exchange across the air-sea interface during non-upwelling. During the 1972 upwelling period, the PO_4-AOU intercept did not reach as high a value as during the 1971 upwelling period. This is in agreement with other evidence that upwelling was not as intense in 1972 as in 1971. Nitrate was observed to be the limiting nutrient as is generally the case in the Pacific Ocean. Biochemically old surface water was observed in both the northern and southern ends of the bay during upwelling periods.

Rates of carbon fixation estimated from phosphate uptake, nitrate uptake, and oxygen production rates ranged from 0.15 to 1.4 gC/m^2 day during upwelling months. This is in good agreement with 0.24 to 0.9 gC/m^2 day measured for the California Current and 0.04 to 1.5 gC/m^2 day measured for Monterey Bay. Since nutrient uptake rates and oxygen production rates were calculated from rates of upwelling in Monterey Submarine Canyon, this agreement supports the hypothesis that upwelling occurs locally in Monterey Submarine Canyon.

Residence time of water during upwelling was estimated to average 3 to 8 days in the northern and southern ends of the Monterey Bay, with an extreme range of 0 to 13 days. The 3 to 8 day average fits well into the circulation pattern described above, with mean velocities of 10 to 15 cm/sec. These residence times may also be valid during non-upwelling periods.

Ammonia concentrations were highly variable with time and showed no seasonal trend. The spatial variation was also highly variable, but higher concentrations were generally found near shore. The ammonia concentration in sewage is high and the observed high concentrations near shore can be accounted for by ammonia entering the bay via sewage and a water residence time of 3 to 6 days. This is in good agreement with the estimated average residence time of 3 to 8 days.

REFERENCES

Abbott, D.P. and R. Albee. 1967. Summary of thermal conditions and phytoplankton volumes measured in Monterey Bay, California 1961-1966. Calif. Coop. Oceanic Fish. Invest. Rep. 11:155-156.

Bigelow, H.B. and M. Leslie. 1930. Reconnaissance of the waters and plankton of Monterey Bay, July, 1928. Bull. Mus. Comp. Zool. Harvard Univ. 70:427-581.

Bolin, R.L. and D.P. Abbott. 1963. Studies on the marine climate and phytoplankton of the coast of California 1954-1960. Calif. Coop. Oceanic Fish. Invest. Rep. 9:23-45.

Bolin, R.L. and Collaborators. 1964. Hydrographic data from the area of the Monterey Submarine Canyon 1951-1955. Hopkins Marine Station, Stanford Univ., Pacific Grove, Calif. (Final report prepared under Office of Naval Research Contract N6onr-25127 and National Science Foundation Contracts NSFG 911 and 1780). 101 p.

Brand, T. von and N.W. Rakestraw. 1941. Decomposition and regeneration of nitrogeneous organic matter in sea water. IV. Biol. Bull. 81:63-69.

Broenkow, W.W. 1972. Oceanographic observations in Monterey Bay, California February 1971 to December 1971. Moss Landing Marine Laboratories, Moss Landing, Calif. Tech. Pub. 72-1. 205 p.

Broenkow, W.W. and S. McKain. 1972. Tidal oscillations at the head of Monterey Submarine Canyon and their relation to oceanographic sampling and the circulation of water in Monterey Bay. Moss Landing Marine Laboratories, Moss Landing, Calif. Tech. Pub. 72-5. 42 p.

Carpenter, J.H. 1965. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnol. Oceanog. 10:141-143.

Cox, R.A., F. Culkin, and J.P. Riley. 1967. The electrical conductivity/chlorinity relationship in natural sea water. Deep-Sea Res. 14:203-220.

Engineering-Science Inc. 1964. Report on collation, evaluation, and presentation of scientific and technical data relative to the marine disposal of liquid wastes. California State Water Quality Control Board, Sacramento, Calif.

Fleming, R.H. 1940. The composition of plankton and units for reporting population and production. Sixth Pacific Sci. Congr. Calif., 1939. 3:535-540.

Garcia, R.A. 1971. Numerical Simulation of currents in Monterey Bay. M.S. Thesis, U.S. Naval Postgraduate School, Monterey, California, 153 p.

Gatje, P.H. and D.D. Pizinger. 1965. Bottom current measurements in the head of Monterey Submarine Canyon. M.S. Thesis, U.S. Naval Postgraduate School, Monterey, California. 61 p.

Harville, J.P. (ed.). 1971. Environmental studies of Monterey Bay and the central California coastal zone. Moss Landing Marine Laboratories, Moss Landing, Calif. Ann. Rep. 148 p.

Hopkins Marine Station of Stanford University. 1972. Mimeographed. CALCOFI hydrographic data collected on approximately bi-weekly cruises on Monterey Bay, California, January - December 1971. Pacific Grove, Calif. 72 p.

Lammers, L.L. 1971. A study of mean monthly thermal conditions and inferred currents in Monterey Bay. M.S. Thesis, U.S. Naval Postgraduate School, Monterey, California. 160 p.

Lynn, R.L. 1967. Seasonal variation of temperature and salinity at 10 meters in the California Current. Calif. Coop. Oceanic Fish. Invest. Rep. 11:157-186.

Martin, B. 1964. Monterey Submarine Canyon, California: genesis and relationship to continental geology. Ph.D. Thesis, University of Southern California, Los Angeles. 249 p.

Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27L:31-36.

Njus, I.J. 1968. An investigation of the environmental factors affecting the near-bottom currents in Monterey Submarine Canyon. M.S. Thesis, U.S. Naval Postgraduate School, Monterey, California. 68 p.

Redfield, A.C. 1942. The processes determining the concentration of oxygen, phosphate and other organic deriviatives within the depths of the Atlantic Ocean. Papers Phys. Oceanog. Meteorol. 9(2):1-22.

Redfield, A.C., B.H. Ketchum, and F.A. Richards. 1963. The influence of organisms on the composition of sea-water, p. 26-77, v. 2. In M.N. Hill (ed.), The sea. Interscience Publishers, New York and London.

Reid, J.L., Jr, G.I. Roden, and J.G. Wyllie. 1958. Studies of the California current system, Calif. Coop. Oceanic Fish. Invest., Prog. Rep., 1 July 1956 - 1 January 1958:27-56.

Reid, J.L., Jr. 1962. Measurements of the California Countercurrent at a depth of 250 meters. J. Mar. Res. 20:134-137.

Reid, J.L., Jr. and R.A. Schwartzlose. 1962. Direct measurements of the Davidson Current off central California. J. Geophys. Res. 67:2491-2497.

Schwartzlose, R.A. 1963. Nearshore currents of the western United States and Baja California as measured by drift bottles. Calif. Coop. Oceanic Fish. Invest. Rep. 9:15-22.

Shephard, A.B. 1970. A comparison of oceanic parameters during upwelling off the central coast of California. M.S. Thesis, U.S. Naval Postgraduate School, Monterey, California. 209 p.

Skogsberg. T. 1936. Hydrography of Monterey Bay, Calif. Thermal conditions, 1929-1933. Trans. Amer. Philos. Soc. N.S. 29:1-152.

Skogsberg, T. and A. Phelps. 1946. Hydrography of Monterey Bay, Calif. thermal conditions, part II (1934-1937). Proc. Amer. Philos. Soc. 90(5):350-386.

Smith, R.L. 1968. Upwelling, p. 11-46, v. 6. In H. Barnes (ed.) Oceanography and marine biology; annual review. George Allen and Unwin Ltd. London.

Solorzano, L. 1969. Determination of ammonia in natural waters by the phenolhypochlorite method. Limnol. Oceanog. 14:799-801.

Stefansson, U. and F.A. Richards. 1963. Processes contributing to the nutrient distributions off the Columbia River and Strait of Juan De Fuca. Lomnol. Oceanog. 8:394-410.

Stefansson, U. and F.A. Richards. 1964. Distributions of dissolved oxygen, density, and nutrients off the Washington and Oregon coasts. Deep-Sea Res. 2:355-380.

Strickland, J.D.H. and T.R. Parsons. 1968. A practical handbook of sea water analysis. Fish. Res. Board Can. Bull. 167. 311 p.

Sverdrup, H.U. and R.H. Fleming. 1941. The waters off the coast of southern California, March to July, 1937. Bull. Scripps. Inst. Oceanog. Univ. Calif. Tech. Ser. 4:261-378.

Sverdrup, H.U., M.W. Johnson, and R.H. Fleming. 1942. The oceans. Prentice Hall, New York. 1087 p.

Truesdale, G.A., A.L. Downing, and G.F. Lowden. 1955. Solubility of oxygen in pure water and sea water. J. Appl. Chem., 5:53-62.

Vaccaro, R.F. 1965. Inorganic nitrogen in sea water, p. 365-408. In J.A. Riley and G. Skirrow (eds.), Chemical oceanography, v. 1. Academic Press, London and New York.

Wood, E.D., F.A. Armstrong, and F.A. Richards. 1967. Determination of nitrate in sea water by cadmium-copper reduction to nitrite. J. Mar. Biol. Ass. U.K. 47:23-31.

Wooster, W.S. and J.L. Reid, Jr. 1963. Eastern boundary currents. p. 253-280. In M.N. Hill (ed.), The sea, v. 2. Interscience Publishers, New York and London.

Wyrtki, K. 1966. Seasonal variation of heat exchange and surface temperature in the north Pacific Ocean. Univ. Hawaii, Honolulu, Institute of Geophysics Rep. No. 66-3.

APPENDIX 1

Ranges of 0 to 10 m average values in Monterey Bay

Date		Temp. (oC)		Sal. (o/oo)		AOU (µg-at/l)		PO_4 (µg-at/l)		NO_3 (µg-at/l)		NH_3 (µg-at/l)	
		L	H	L	H	L	H	L	H	L	H	L	H
	TOTAL BAY*	10.6	11.8	33.42	33.46	- 90	120	0.6	2.2	0.1	14	0.0	1.9
Feb 16, 20	Offshore*	11.2	11.6	33.44	33.64	- 80	20	0.6	0.8	0.1	9	0.0	0.5
1971	Nearshore*	10.9	11.6	33.42	33.55	- 60	3	0.6	1.3	2.0	7	0.4	0.7
	Northern end*	10.6	11.8	33.47	33.63	- 60	120	2.2		3.0	14	1.0	1.9
	TOTAL BAY	9.3	11.5	33.40	33.88	-300	120	0.5	2.1	0.0	18	0.0	1.4
Mar 16, 20	Offshore	9.6	9.9	33.69	33.82	-300	80	0.5	1.5	0.0	15	0.0	0.8
1971	Nearshore	9.9	11.5	33.63	33.87	-240	- 60	0.6	2.1	1.0	13	0.0	1.4
	Northern end	10.4		33.71	33.78	-180	- 80	0.6		1.0		0.3	
	TOTAL BAY	9.8	12.0	33.69	33.86	- 60	180	0.6	1.9	2.0	19	0.0	1.9
Apr 13, 17	Offshore	9.8	9.9	33.74	33.83	- 30	120	1.0	1.5	9.0	18	0.0	0.7
1971	Nearshore	11.6	12.0	33.65	33.77	- 60	5	0.6	1.2	2.0	12	0.0	0.6
	Northern end	9.8		33.83	33.84	20	180	1.9		19		1.9	
	TOTAL BAY	10.9	12.0	33.67	33.86	-190	110	0.6	2.1	4.0	21	0.0	1.4
May 11, 15	Offshore	10.9	11.3	33.78	33.86	- 50	- 10	1.3	1.4	11	20	0.8	1.4
1971	Nearshore	11.3	11.8	33.67	33.75	-190	- 30	0.7	1.5	4.0	17	0.8	1.2
	Northern end	11.8	12.0	33.75	33.82	-100	-150	0.6	1.0	6.0	10	1.1	1.3
	TOTAL BAY	10.8	14.4	33.90	33.97	-350	- 20	0.5	1.6	0.6	12	0.0	1.0
June 18.19	Offshore	10.8	12.8	33.94	33.97	-330	- 30	0.7	1.4	4.0	12	0.0	0.2
1971	Nearshore	12.3	14.4	33.91	33.96	-350	- 20	0.5	1.2	1.0	7	0.1	1.0
	Northern end	13.3		33.93	33.97	-340	-150	0.6		2.0		0.4	

Date		Temp. (°C)		Sal. (°/oo)		AOU (μg-at/l)		PO_4 (μg-at/l)		NO_3 (μg-at/l)		NH_3 (μg-at/l)	
		L	H	L	H	L	H	L	H	L	H	L	H
	TOTAL BAY	11.7	13.8	33.66	33.81	-190	70	0.2	1.2	0.1	13	0.2	3.2
July 23, 24	Offshore	11.9	12.6	33.66	33.74	-120	50	0.6	1.0	2.0	9	0.5	1.2
1971	Nearshore	13.2	13.7	33.74	33.76	-190	-120	0.2	0.6	0.1	3	0.3	0.4
	Northern end	13.7	13.8	33.77	33.80	-180	-130	0.4	0.7	0.4	2	0.3	2.1
	TOTAL BAY	13.7	16.3	33.18	33.36	-100	- 40	0.4	0.6	0.3	3	0.0	1.5
Aug 27, 28	Offshore	13.8	16.3	33.20	33.35	-100	- 50	0.4	0.6	0.7	3	0.0	1.0
1971	Nearshore	14.7	15.9	33.21	33.30	-80		0.5		0.3	1	0.4	1.1
	Northern end	15.2	15.3	33.23	33.24	- 70	- 60	0.5	0.6	1.0		0.8	1.3
	TOTAL BAY	13.0	15.5	33.41	33.54	-260	- 4	0.2	0.9	0.0	3	0.0	2.0
Sept 29, 30	Offshore	13.0	15.4	33.43	33.54	-150	- 40	0.2	0.6	0.2	2	0.0	0.6
Oct 1, 1971	Nearshore	15.0	15.5	33.41	33.43	-220	-170	0.3	0.4	0.0	0.2	0.0	
	Northern end	14.4	15.4	33.43		-180	- 40	0.3	0.8	0.0	0.2	0.0	0.6
	Southern end*	15.1	15.3	33.50	33.51	-260	-180	0.3	0.7	0.1	2	0.1	1.4
	TOTAL BAY	11.8	14.3	33.27	33.61	-140	20	0.4	1.0	0.0	6	0.0	0.9
Oct 20, 21,	Offshore	12.7	14.1	33.29	33.50	- 50	5	0.4	0.8	1.0	4	0.0	0.1
22 1971	Nearshore	11.8	13.1	33.51	33.61	-120	- 40	0.5	0.7	0.0	4	0.0	0.3
	Northern end	12.1	12.4	33.56	33.58	- 60	- 40	0.6		0.0	1	0.1	0.4
	Southern end	12.8	13.6	33.50		- 40	20	0.5	0.6	1.0	3	0.3	0.9
	TOTAL BAY	11.3	12.5	33.36	33.54	- 30	150	0.5	1.4	1.0	15	0.0	3.5
Nov 17, 18,	Offshore	11.7	12.5	33.41	33.49	- 30	150	0.5	0.9	3.0	8	0.0	0.8
19 1971	Nearshore	12.1	12.2	33.38	33.41	- 40	30	0.6	0.8	1.0	2	0.3	1.1
	Northern end	11.7	12.1	33.36	33.38	20	40	0.7	0.8	2.0	3	1.4	1.5
	Southern end			33.43	33.48	20	40	0.9	1.2	4.0	8	1.2	3.5

Date		Temp. (°C) L	Temp. (°C) H	Sal. (°/oo) L	Sal. (°/oo) H	AOU (µg-at/l) L	AOU (µg-at/l) H	PO_4 (µg-at/l) L	PO_4 (µg-at/l) H	NO_3 (µg-at/l) L	NO_3 (µg-at/l) H	NH_3 (µg-at/l) L	NH_3 (µg-at/l) H
	TOTAL BAY	9.8	10.1	33.46	33.75	20	250	1.1	1.7	9.0	19	0.0	1.2
Dec 15, 16,	Offshore	9.9	10.1	33.46	33.61	20	150	1.2	1.4	13.0	19	0.0	0.5
17 1971	Nearshore	9.8	9.9	33.56	33.70	40	240	1.3	1.7	12.0	18	0.4	0.6
	Northern end	9.9		33.56		100	120	1.5		14.0	16	0.7	0.9
	Southern end	9.8	10.0	33.62	33.66	20	140	1.1	1.6	9.0	16	0.4	1.2
	TOTAL BAY	10.1	11.4	33.31	33.56	- 40	100	0.8	1.2	6.0	16	0.1	3.1
Jan 19, 20,	Offshore	10.6	11.2	33.49	33.56	10	60	0.8	1.0	6.0	16	0.1	1.0
21 1972	Nearshore	10.4	10.9	33.32	33.54	- 40	20	0.8	1.2	8.0	10	0.2	0.3
	Northern end	10.3	10.4	33.31	33.38	10		0.9	1.0	6.0	9	0.6	1.1
	Southern end	11.0	11.4	33.55	33.56	20	100	0.9	1.0	8.0	12	0.2	3.1
	TOTAL BAY	10.8	11.8	33.35	33.58	-170	- 10	0.3	1.0	0.0	15	0.0	8.9
Feb 16, 17,	Offshore	10.8	11.4	33.39	33.58	-100	- 10	0.5	1.0	4.0	15	0.0	0.7
18 1972	Nearshore	11.5	11.7	33.38	33.48	-150	-100	0.3	0.6	0.0	6	0.0	0.4
	Northern end	11.5	11.6	33.34	33.40	-170	- 80	0.3	0.4	0.0	1	0.1	0.3
	Southern end	11.4	11.8	33.46	33.49	- 80	- 60	0.5	0.7	3.0	5	0.2	8.9
	TOTAL BAY	10.7	12.6	33.44	33.62	-130	50	0.3	1.4	0.0	15	0.0	4.2
Mar 22, 23,	Offshore	10.7	11.9	33.45	33.58	-130	- 40	0.3	1.4	4.0	15	0.0	0.8
24 1972	Nearshore	11.8	12.6	33.44	33.50	-100	- 50	0.4	0.6	1.0	7	0.0	0.6
	Northern end	11.9	12.3	33.45	33.48	-100	- 40	0.5	0.7	0.0	3	0.1	0.6
	Southern end	11.8	12.5	33.46	33.51	-110	- 90	0.4	0.6	3.0	6	0.0	4.2
	TOTAL BAY	9.8	12.5	33.51	33.76	-140	140	0.4	2.3	1.0	21	0.1	20
Apr 17, 18,	Offshore	9.9	11.4	33.55	33.76	- 80	10	0.7	1.7	4.0	17	0.1	1.0
19 1972	Nearshore	11.0	11.8	33.52	33.61	- 60	20	0.8	1.0	4.0	8	0.7	1.4
	Northern end	12.1	12.2	33.44	33.45	-100		0.6		3.0		0.6	
	Southern end	11.6	12.5	33.51	33.57	-140	-120	0.4		1.0	2	0.2	20

Date		Temp. (^{o}C)		Sal. ($^{o}/oo$)		SOU (µg-at/l)		PO_4 (µg-at/l)		NO_3 (µg-at/l)		NH_3 (µg-at/l)	
	TOTAL BAY	11.0	14.2	33.80	33.86	-220	120	0.4	1.9	1.0	16	0.1	1.8
May 15, 16,	Offshore	11.1	11.7	33.83	33.86	- 10	4	1.0	1.4	10.0	14	1.1	1.5
17 1972	Nearshore	11.8	12.6	33.83	33.84	-160	- 80	0.6	0.9	5.0	13	0.5	1.0
	Northern end	13.1	14.2	33.82		-220	-200	0.4		1.0		0.3	0.7
	Southern end	11.0	12.0	33.82	33.86	- 40	20	1.2	1.4	11.0	13	0.8	1.6

* TOTAL BAY: ALL stations
Offshore: Stations 3, 4, 9. 11, 1108, 1112, 1115, 1157
Nearshore: Stations 1101, 1105, 1150, 1154
Northern end: Stations 1153, 1159
Southern end: Stations 1, 1121, 1122, 1123
(See Fig. 1)

APPENDIX 2

Volumes of various sectors of Monterey Bay as defined in Figure 28

Sector	Volume
Monterey Bay	421.2 x 10^8 m^3 (11.13 x 10^{12} gal)
Monterey Bay above 30 m	105.18 x 10^8 m^3 (2.78 x 10^{12} gal)
Monterey Bay above 10 m	46.87 x 10^8 m^3 (1.235 x 10^{12} gal)
Santa Cruz Harbor	1.88 x 10^7 m^3 (4.97 x 10^9 gal)
Soquel Cove	8.86 x 10^7 m^3 (23.40 x 10^9 gal)
Monterey Harbor	48.28 x 10^7 m^3 (127.54 x 10^9 gal)
Inner Monterey Harbor	12.6 x 10^7 m^3 (33.3 x 10^9 gal)

APPENDIX 3

Rates of sewage discharge into Monterey Bay and its tributaries

Sewer Outfall	Minimum Discharge Rates		Maximum Discharge Rates	
	(10^3 m^3/day)	(10^6 gal/day)	(10^4 m^3/day)	(10^6 gal/day)
Santa Cruz	18.5	4.9	22.2	7.2
East Cliff	7.2	1.9	14.0	3.7
Aptos	2.6	0.7	3.0	0.8
Watsonville	12.1	3.2	23.8	6.3
Castroville *	0.8	0.2	1.1	0.3
Salinas-Main Plant *	11.3	3.0	30.0	8.0
Fort Ord *	8.3	2.2	11.0	2.9
Seaside	4.5	1.2	6.8	1.8
Monterey	9.0	2.4	11.7	3.1
Pacific Grove	5.3	1.4	6.8	1.8

* Discharge rates obtained from Sanitary Engineering Field Study of Monterey Bay February 2-13, 1970 by the California State Department of Public Health, Bureau of Sanitary Engineering.