the department of

OCEANOGRAPHY

CURRENT RESEARCH ACTIVITIES

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OF THE

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University of Washington
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INTRODUCTION

The comprehensive program of oceanographic research carried out at the University by a diverse group of faculty, staff, students, and support personnel has expanded considerably during the past year. The five to six million dollar annual research program provides substantial support for the graduate teaching program; thus, a larger variety of facilities and projects has become available for graduate student research leading to M.S. and Ph.D. degrees. During the year, nine Master of Science degrees were awarded and six students achieved the Ph.D. degree. Currently there are 309 undergraduates and 111 graduate students enrolled in the department.

The educational and research capabilities of the department have been enhanced in the past year with the addition of eleven new faculty members: Peter E. Borella, Research Associate; Robert N. Dexter, Research Associate; Steven R. Emerson, Research Assistant Professor; John I. Hedges, Research Assistant Professor; Mark L. Holmes, Research Associate; H. Paul Johnson, Research Associate; Thomas H. Kinder, Research Associate; Steven R. McLean, Research Associate; Robert J. Ozretich, Research Associate; Mary Jane Perry, Research Assistant Professor; Warren S. Wooster, Adjunct Professor.

Three major research journals are edited by departmental faculty. Dr. D. James Baker, Jr. has been appointed co-editor of *Dynamics of Atmospheres and Oceans*. Dr. Dean McManus is editor of *Marine Geology*. Dr. Francis A. Richards serves as editor of *Deep-Sea Research* and Dr. Dora P. Henry is a member of the journal's Editorial Advisory Board.

Twenty-five faculty and staff members of the department are presently collaborating on a book to be entitled *Puget Sound: Oceanography of the Inshore Waters of Washington*. The publication will provide a summary and synthesis of results of oceanographic studies to afford an understanding of the Sound as a system.

The Administrative Support Office for the Scientific Advisory Committee of Joint Oceanographic Institutions of Deep Earth Sampling (JOIDES) is being housed in the Department through June 1978. Dr. Maurice Rattray, Jr. is Chairman of the Executive Committee of JOIDES, Dr. Joe S. Creager serves as Chairman of the Planning Committee, Dr. Dean A. McManus is Assistant Chairman of the Planning Committee, and Dr. Peter E. Borella is Scientific Coordinator.

Plans are currently under way for the expansion and improvement of departmental facilities. A new marine sciences complex to include the Department of Oceanography, the College of Fisheries, the Division of Marine Resources, and the Institute for Marine Studies is projected.

Dr. Francis A. Richards, Associate Chairman for Research from 1968 to the present, has played a major role in the development of a large, highly diversified research program. However, he will be resigning from this position in September and take a two-year leave from the University to join the Office of Naval Research in Tokyo. While he was responsible

for the research program of the department, the research dollar level increased from 2.8 million to 5.7 million dollars per year, the number of permanent faculty grew from 38 to 51, and the number of grants and contracts from 42 to 135.

RESEARCH OPPORTUNITIES

Well-equipped teaching and research laboratories are augmented by a research fleet consisting of the 209 foot general oceanographic research vessel, the *Thomas G. Thompson*, two 65-foot research vessels, the *Hoh* and the *Onar*, the 50-foot *Kestrel*, and various small craft. The Department has recently completed a design study for a 134-foot coastal research vessel under a grant awarded by the National Science Foundation.

The faculty is augmented through joint appointments of personnel with the Applied Physics Laboratory, the Geophysics Program, the Atmospheric Sciences Department, and the Institute of Marine Studies of the University. Additional research opportunities for the department have been provided by association with the Pacific Marine Environmental Laboratory of NOAA and the U.S. Geological Survey. Several PMEL and USGS personnel are affiliate faculty members, and numerous joint research projects are being conducted, thus providing graduate students with additional opportunities for research. Cooperative arrangements with other governmental agencies, i.e., the National Marine Fisheries Services, the National Oceanographic Survey, the Coast Guard, the U.S. Navy, the Corps of Engineers, and the Department of Ecology also extend the research opportunities.

Independent research is sponsored by several federal, state, and other governmental agencies, including the National Science Foundation, the Office of Naval Research, the Energy Research and Development Agency, the U.S. Geological Survey, the National Oceanic and Atmospheric Administration (NOAA), the Metropolitan Municipality of Seattle (METRO), the U.S. Army Corps of Engineers, the Washington State Department of Ecology, and by private organizations. Departmental research projects range from one-man individual research to participation in multiuniversity, multidisciplinary projects, such as the International Program of Ocean Drilling (IPOD) supported by the Deep Sea Drilling Porject (DSDP), the International Southern Ocean Studies (ISOS), and the Mid-Ocean Dynamics Experiment (MODE), sponsored by the International Decade of Ocean Exploration (IDOE).

SHIP OPERATIONS

Departmental ship operations during 1976 constituted an expenditure of approximately 1.6 million dollars. The major portion of the support was contributed by the National Science Foundation; the Office of Naval Research, the Energy Research and Development Agency, the Washington State Department of Ecology, the Environmental Protection Agency, and the Municipality of Metropolitan Seattle also provided support. These funds were used for the continued operation of the *Thomas G. Thompson*, the *Hoh*, and the *Onar*, support of marine technicians, and the acquisition of sea-going equipment.

R/V *Thompson* participated in the International Southern Ocean Studies (ISOS) cruise in Drake Passage during February and March in a project that involved deployment and recovery of current, temperature, and sea level recorders. Salinity and temperature sections and density and nutrient measurements were also obtained, as were data to be used in assessing bottom water exchange between the Antarctic and the Pacific oceans.

In late March, the *Thompson* joined the JOINT-II expedition of the Coastal Upwelling Ecosystems Analysis (CUEA) Program to study upwelling off Peru. Hydrography, nutrient measurements, and underway mapping were carried out by the *Thompson*.

Immediately following the CUEA studies, the *Thompson* participated in a joint experiment involving Peruvians and North Americans. An array of three ocean bottom seismometers was deployed on the ocean side of the Peru Trench and one ocean bottom seismometer was placed on the continental slope. Shot lines, parallel and perpendicular to the trench, were fired and successfully recorded by all ocean bottom seismometers and many land stations.

Cruises in North American waters aboard the *Thompson* included collection of cores and sediments and planktonic organisms on the Washington shelf north of the Columbia River and projects to study the combined chemical, physical, and biological properties of water on the shelf off Westport, Washington.

R/V *Hoh*, R/V *Onar*, and R/V *Kestrel* were involved in shorter cruises throughout the year in Puget Sound, the Strait of Georgia, and Lake Washington for various biological, chemical, geological, and physical oceanography projects.

The Faculty

Aagaard, Knut, Ph.D., Washington. Physical oceanography, ocean circulation, Arctic oceanography.

Ahmed, Saiyed, Ph.D., Frankfurt. Enzymology, regulation, control mechanisms in phytoplankton, fungi and bacteria.

Anderson, Goerge C., Ph.D., Washington. Biological oceanography, plankton ecology.

Baker, D. James, Jr., Ph.D., Cornell. Physical oceanography, physics of large-scale ocean circulation, Antarctic oceanography, ocean instrumentation.

Banse, Karl, Ph.D., Kiel. Biological oceanography, plankton production, polychaete systematics.

Barnes, Clifford A., Ph.D., Washington (Professor Emeritus). Physical oceanography, water properties, circulation.

Borella, Peter E., Ph.D., U.S.C. Geological oceanography, sedimentation and sedimentary petrology.

Burns, Robert E., Ph.D., Washington. Environmental assessment, continental shelf, estuaries.

Cannon, Glenn A., Ph.D., Johns Hopkins. Physical oceanography, estuarine and coastal processes.

Carpenter, Roy, Ph.D., California, San Diego. Marine geochemistry of metals and hydrocarbons in coastal zone.

Cline, Joel D., Ph.D., U.C.L.A. Geochemistry research, nutrient cycles, and isotope geochemistry.

Coachman, Lawrence K., Ph.D., Washington. Physical oceanography, water properties circulation, Arctic oceanography.

Creager, Joe S., Ph.D., Texas A&M. Geological oceanography, sea-level changes, recent marine sediments, shallow-water sediment transportation.

Criminale, William O., Jr., Ph.D., Johns Hopkins. Geophysical fluid mechanics, air-sea interactions.

Damkaer, David M., Ph.D., George Washington. Biological oceanography, ecology and systematics of plankton copepods.

Desaubies, Yves J.F., Ph.D., California, San Diego. Physical oceanography, internal waves, ocean acoustics.

Devol, Allan, Ph.D., Washington. Biochemical oceanography, effects of metabolism on chemical distributions.

Dexter, Robert N., Ph.D., Washington. Chemical oceanography, marine chemical dynamics, trace organic distribution and transport.

Duxbury, Alyn C., Ph.D., Texas A&M. Descriptive physical oceanography, mechanics of estuarine and coastal circulation.

Emerson, Steven R., Ph.D., Columbia. Marine geochemistry/chemical oceanography, sediment diagenesis.

English, T. Saunders, Ph.D., Washington. Biological oceanography, nekton, sampling problems, Arctic plankton ecology.

Ewart, Terry E., Ph.D., Washington. Physics, ocean microstructure, diffusion, acoustic transmission.

Feely, Richard H., Ph.D., Texas A&M. Chemical oceanography, marine geochemistry and sedimentation processes.

Fleming, Richard H., Ph.D., California, Berkeley. Physical and general oceanography.

Frost, Bruce W., Ph.D., California, San Diego. Biological oceanography, marine zoogeography, plankton ecology and systematics.

Galt, Jerry A., Ph.D., Washington. Physical oceanography, numerical modeling and general circulation.

Gregg, Michael C., Ph.D., California, San Diego. Physical oceanography, ocean microstructure.

Halpern, David, Ph.D., M.I.T. Physical oceanography, ocean atmosphere response studies.

Hamilton, Peter, Ph.D., Liverpool. Physical oceanography, estuarine and coastal circulation, upwelling ecosystems.

Hayes, Stanley P., Ph.D., Cornell. Physical oceanography, air-sea interaction, internal waves.

Hedges, John I., Ph.D., Texas. Organic geochemistry; characterizing terrestrial and marine-derive organic molecules in coastal zones.

Henry, Dora P., Ph.D., California, Berkeley. Systematics and ecology of barnacles.

Hickey, Barbara, Ph.D., California, San Diego. Physical oceanography, the dynamics of circulation in the equatorial region and on the continental shelf.

Holmes, Mark L., Ph.D., Washington. Geological oceanography, marine geophysics, continental margins.

Irish, James D., Ph.D., California, San Diego. Physical oceanography, tides, internal waves, instrumentation.

Johnson, H. Paul, Ph.D., Washington. Paleomagnetism and marine geophysics.

Jumars, Peter A., Ph.D., California, San Diego. Biological oceanography, benthos.

Kinder, Thomas H., Ph.D., Washington. Physical oceanography, water properties, circulation.

Lam, Ronald K., Ph.D., California, San Diego. Physical oceanography, estuarine dynamics.

Larsen, Lawrence W., Ph.D., Johns Hopkins. Physical oceanography, hydrodynamics, waves.

Lewin, Joyce C., Ph.D., Yale. Physiology and systematics of diatoms, biological deposition of silica.

Lewis, Brian T.R., Ph.D., Wisconsin. Marine geophysics, marine seismology.

Ling, Hsin Yi, Ph.D., Washington University (St. Louis). Geological oceanography, micropaleontology and biostratigraphy.

Lister, Clive R.B., Ph.D., Cambridge. Geothermal studies, marine geophysics, global tectonics.

Lorenzen, Carl, Ph.D., Cornell. Biological oceanography, marine food chain dynamics, carbon cycling in the ocean.

Martin, Seelye, Ph.D., Johns Hopkins. Geophysical fluid dynamics, properties of sea-ice.

McCulloh, Thane H., Ph.D., U.C.L.A. Geology of petroleum, geophysical prospecting, continental shelf and slope resources.

McLean, Stephen R., Ph.D., Washington. Coastal and estuarine physical oceanography, turbulent boundary layer mechanics, sediment transport processes.

McManus, Dean A., Ph.D., Kansas. Geological oceanography, continental shelf sediments.

Merrill, Ronald T., Ph.D., California, Berkeley. Geomagnetism and paleomagnetism.

Murphy, Stanley R., Ph.D., Washington. Physical oceanography, underwater acoustics, ocean turbulence.

Murray, James W., Ph.D., M.I.T./Woods Hole Oceanographic Institute. Marine geochemistry, trace metals.
Ozretich, Robert J., Ph.D., Washington. Chemical oceanography, bacterial processes.
Pavlou, Spyros P., Ph.D., Washington. Chemical oceanography, marine chemical dynamics, trace organic distribution and transport.
Perry, Mary Jane, Ph.D., California, San Diego. Biological oceanography, phytoplankton physiology, nutrient cycling.
Rattray, Maurice, Jr., Ph.D., Caltech. Physical oceanography, hydrodynamics, estuarine circulation, internal waves.
Richards, Francis A., Ph.D., Washington. Chemical oceanography, nutrient and gas cycles in the sea, oxygen-deficient marine environments.
Roden, Gunnar I., M.S., U.C.L.A., Physical oceanography, ocean fronts, meso-scale ocean circulation and structure, time-series analysis.
Schoener, Amy, Ph.D., Harvard. Biological oceanography, artificial substrate colonization, biogeography, benthos.
Smith, J. Dungan, Ph.D., Chicago. Coastal and estuarine physical oceanography, turbulent boundary layer mechanics, sediment transport processes.
Sternberg, Richard W., Ph.D., Washington. Geological oceanography, marine sedimentation processes.
Taft, Bruce A., Ph.D., California, San Diego. Physical oceanography, ocean circulation.
Wearn, Richard B., Jr., Ph.D., Harvard. Physical oceanography, midocean dynamics, ocean pressure fluctuations.
Welander, Pierre L.R., Ph.D., Stockholm. Theory of general ocean circulation, large-scale atmosphere-ocean interaction.
Winter, Donald F., Ph.D., Harvard. Applied mathematics, hydrodynamics, biological modeling.
Wooster, Warren S., Ph.D., California, San Diego. Physical oceanography, ocean circulation, fishery oceanography and ocean affairs.
Worsley, Thomas R., Ph.D., Illinois. Stratigraphy, micropaleontology, marine geology, sedimentary processes, paleoecology.

The Professional Staff

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Daly, Kendra
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Lahore, Henry
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CURRENT RESEARCH ACTIVITIES REPORT

This report is organized by program elements that define a single or a closely related set of oceanographic questions. These research elements contain, to varying degrees, the fundamental disciplines upon which oceanography is based and range from those that involve a single discipline to those that depend upon all of the fundamental disciplines. The faculty, staff, and students associate with each research topic are identified in the body of the report; square brackets indicate the faculty members under whose direction the students' research is undertaken. Inquiries may be addressed to them or to the Associate Chairman for Research.

SUMMARY OF CURRENT RESEARCH

I. Dynamics and Thermodynamics of the Upper Ocean

The processes taking place in the upper ocean govern the behavior of the ocean and, to a large extent, of the atmosphere. They play a major role in considerations of climatic fluctuations, a field receiving increased attention at the present time. Research is aimed at explaining the processes involved in the exchanges of properties between the ocean's upper layers and the overlying atmosphere or ice. These exchanges include energy, momentum, heat, water, salt, oxygen, carbon dioxide, and other gases.

A. Laboratory Studies of Sea Ice

1. Ice growth in a wave field

Experiments on the formation of grease and pancake ice in a laboratory wave tank located in a cold room are continuing. From these experiments, in which both grease and pancake ice are grown, we find that ice growth takes place through convective heat and salt transfer. At present, we are measuring the parameters of this growth process in the experiments and subsequently plan to relate them to a theoretical model.

Experiments on the fate of oil spilled under grease and pancake ice are also continuing; observations show that as much as 50% of the oil may be pumped onto the surface of the pancake and then be trapped there by the rims of the cakes. In the Bering Sea, because of the large number of seals, walruses, and birds that inhabit the ice surface, this petroleum trapping may have serious biological implications. (Martin, Kauffman)

2. The melting of ice walls in warm seawater

A laboratory and theoretical study of the melting of a vertical ice wall in warm salty water is being pursued. This study has application to the fate of icebergs off Greenland and Newfoundland in the North Atlantic, and to the dissipation of the large Antarctic bergs. The majority of the ablation takes place through a turbulent boundary layer; the theoretical problem is made difficult by the wall boundary condition, where the melting temperature depends on the wall salinity. At the present time, we are using an integral model of the flow and comparing it with the experimental data.

A joint field experiment with the International Ice Patrol is being planned for June 1977; the ship will be anchored next to an iceberg off Newfoundland, and a detailed study of the temperature and salinity field around the berg will be conducted. (Josberger [Martin])

3. Ice properties and oil entrainment in the Beaufort Sea

Studies on the interaction of oil and sea ice, supported by the Bureau of Land Management, are continuing. A field survey of the

ice properties near Prudhoe Bay, Alaska, is planned for March as part of our program to understand and predict the interaction of petroleum with different kinds of sea ice. (Kauffman, Martin)

B. Wind Wave Spectra

During the winter of 1972-73, a submerged pressure gauge was mounted on the summit of Cobb Seamount, Northeast Pacific. The depth of the sensor was 35 m. The purpose of the experiment was to record winter wave conditions for the Maritime Administration. Seven months of three records per day were obtained. Each record lasted one-half hour with a sample density of .8789 seconds. The tidal constituents have been calculated for Cobb Seamount. Several publications have resulted from this study. The analysis is now focused on signals in the period range of 5 minutes to 20 seconds. This is a band of low energy relative to either the wind waves or tides, yet we find appreciable variations in energy within this band dependent upon storm conditions. This band is important for the input of internal wave energy into the ocean. Continued requests for information derived from these data have been received from people concerned with ship construction. The data are also being used in studies at the Webb Institute of Naval Architecture.

Open ocean wave data collected under the wave-sediment interaction program (see VII *A*) will be used in further studies of wind wave spectra. (Larsen)

C. Mixed Layer Dynamics

An investigation of the response of the upper ocean to the passage of a mild storm in 1976 found that the interleaving of discrete lenses of water played a dominant role in the changes of heat content and in the levels of turbulence at the base of the mixed layer. Similar intrusive features have been found at the boundaries of major current systems and are of major importance in generating microstructure. Therefore, a program has begun to study intrusive dynamics in a variety of situations. (Gregg)

A multi-institution mixed layer experiment (MILE) will occur during August and September 1977 at Ocean Station P (50°N, 145°W). One of the objectives is the acquisition of a data set to evaluate the predictive capabilities of one-dimension mixed-layer models. Three current meters will be deployed in a joint program to provide data for a study of the vertical finestructure and horizontal meso-scales of the currents during the wind-generated deepening of the mixed layer. (Halpern; P. Niiler, Oregon State University; R. Davis, Scripps Institution of Oceanography)

Also during MILE, a towed CTD, developed by Ewart and Bendiner at the Applied Physics Laboratory for studies in Puget Sound, will be used for finestructure mapping. Horizontal scales of 200 m to 20 km and vertical scales of 2 m to 100 m will be studied. Secondary efforts will be made in Dabob Bay and Puget Sound. The most important goal is to define the three-dimensional spectrum of the dominant intrusions in the upper ocean which is the first step in an understanding of the temporal evolution of the intrusions. (Gregg)

D. Arctic Mixed Layer Investigations

During the past six years a number of measurements of velocity, stress, and density fields have been made in the upper 100 meters of the Beaufort Sea under late winter and early spring conditions. These have been part of a long-range project designed to provide a comprehensive examination of the upper layers of the Arctic Ocean and to give insight into the mechanics of specific surface mixed layer processes. The Arctic Ocean is one of the most favorable locations in which to carry out such investigations because a reasonably stable platform to which precision instruments can be attached is afforded by the sea ice cover.

In many of our past experiments the underside of the ice has been carefully examined and its topography mapped by divers in conjunction with the flow-measuring part of the project. In addition, mean and fluctuating velocity fields have been determined with up to 25 triplets of orthogonally mounted component-sensing current meters attached to fixed masts, and the density field has been elucidated using a Guildline CTD. More recently, the latter has been deployed in conjunction with a velocity and density profiling fish. All data are recorded on magnetic tape using a NOVA 1200 computer for control and are processed subsequently on that machine.

During the storms, well developed surface Ekman layers dominate the velocity field, whereas during meteorologically quiet periods lead-driven horizontal jets are found just beneath the ice and at the base of the mixed layer. In the former situation the Ekman layer is neutrally stable in its upper part and stably stratified in the vicinity of its base. In contrast the lead-convection process maintains a stably stratified mixed layer throughout. Preliminary examination of topographic effects indicates that the flow disturbances arising in natural Ekman layers are substantially greater than those resulting in situations where the earth's rotation can be neglected. This difference appears to be due to a blocking effect in the outer part of the Ekman layer where the force balance approaches a geostrophic one. (Smith)

The most recent Arctic mixed layer investigation was carried out over a 1.0 m thick refrozen lead in March-April 1976. The purpose of this experiment was to measure density velocity and stress profiles under a large area of smooth ice during one or more storms; thus, to provide a definitive set of turbulent Ekman layer data against which to test theoretical models. (Morrison [Smith])

E. Near-Surface Circulation Studies

1. Northeast Atlantic off Northwest Africa

During JOINT-I, Coastal Upwelling Ecosystems Analysis (CUEA), 10 March - 6 April 1974, simultaneous current records were obtained from 12 current meters placed between 0.8 m and 67 m in water approximately 75 m deep. The midshelf site was located about 32 km from the coast of Spanish Sahara. Throughout the experiment the vertical stratification and horizontal density gradient were weak. High frequency (cutoff frequency, f_c = 0.02 cph) fluctuations, which contained nearly 40% to 50% of the

variance, were removed from the records. Vertical profiles of low-pass (f_c = 0.02 cph) filtered currents were defined by a fifth-order least squares analysis. The thickness of the time-averaged near-surface offshore flow was about 32 m and the mean onshore momentum transport was greater by 70% than the mean offshore transport. When the equatorward component of the near-surface wind stress was large, the onshore and offshore transports were nearly equal to one another, suggesting that the structure of the flow was two-dimensional after the onset of a wind event. At another time when the winds were weak, the momentum flux was onshore throughout with no significant vertical shear. None of the profiles of the low-frequency currents contained offshore flow at intermediate depths, i.e., a 'double-cell' flow pattern. (Halpern; R.L. Smith, Oregon State University; E. Mittelstaedt, Deutsche Hydrographische Institute, Hamburg)

2. Eastern tropical North Atlantic

Moored wind recorder, current meter, and temperature measurements were made at two sites in the upper layers of the North Equatorial Countercurrent in the eastern Atlantic Ocean during August and September 1974. This program was a portion of the GATE C-Scale Oceanographic Experiment. Vector mean speeds at 8 m below the surface were about 40 cm/sec toward ENE and about 3° *cum sole* to the direction of the wind. The mean current vectors, which decreased in magnitude to 20 cm/sec at 36 m, rotated counterclockwise with depth. Nearly 80% of the shear was measured between 28 m and 36 m, and was produced either by the use of two different kinds of current meters or by the variation in the stratification which occurred at this depth level. Semidiurnal-period oscillations were prominent throughout the uppermost 36 m; the amplitude of the horizontal kinetic energy of these fluctuations decreased with depth. Rotary component spectra indicated that these tidal currents rotated in the clockwise direction. Cartesian component spectra indicated that the amplitude of the meridional component of the semi-diurnal tidal current was larger than the zonal records. Inertial-period (76 hours) fluctuations were observed though they were not as well defined as the semi-diurnal period motions because of the relatively short record (assuming the amplitude of these motions was stationary) or because of the limited periods of generation. (Paul [Halpern])

3. Strait of Juan de Fuca

Current measurements during winter-spring (19 February - 3 May 1976) were made at 5 m in the Strait of Juan de Fuca. The predominant direction of the near-surface currents in this partially mixed estuary was seaward. Rectilinear diurnal and semidiurnal period tidal currents and shallow-water (25.7 hr and 8.2 hr) tidal currents rotating clockwise around an elliptical hodograph accounted for a large percentage of the temporal variability. The amplitudes of the diurnal and semidiurnal tidal currents were approximately 37 cm sec^{-1} and 48 cm sec^{-1}, respectively. Although a number of storms occurred, inertial oscillations were not measured at either depth level. Analyses of these data are continuing. Additional measurements are being made (November 1976 - February 1977) at three sites in Juan de Fuca Strait, and similar measurements will be made during summer (May - August 1977). This project is being conducted under the Marine Ecosystems Analysis Program (MESA). (Halpern; Holbrook, Pacific Marine Environmental Laboratory)

4. Eastern and central tropical North Pacific

Measurements of winds and of upper ocean temperatures and currents made at 15°N, 126°W during September and October 1975, at 12°N, 138°W during March and April 1976, and at 8°N, 150°W during August to November 1976 as part of the Deep Ocean Mining Environmental Study (DOMES) are being processed. Preliminary results indicate: (1) a subsurface eastward flowing undercurrent at 15°N; (2) an eastward flowing surface current (possibly the North Equatorial Countercurrent) at 12°N; and (3) a relatively poor agreement between the direct measurements within the upper 300 m and baroclinic geostrophic currents. Analyses of these data are continuing. (Halpern)

5. Eastern tropical South Pacific

During JOINT-II, Coastal Upwelling Ecosystems Analysis (CUEA), scheduled for March - May 1977, the principal objective of the physical oceanographers involved in the program will be to determine the flow regime and the distribution of physical properties with sufficient spatial and temporal detail to reveal the physical aspects that make the Peruvian regime so much more productive than other major upwelling systems. My contribution will be to define the temporal and vertical variations of the near-surface temperature and current fields and the response of these fields to the variable wind-stress and wind-stress curl fields. (Halpern)

II. Planetary-Scale Oceanic Processes

The research in this element is directed toward explaining the planetary distribution of properties in the ocean and sediment and their variability in space and time and toward understanding the processes responsible for their maintenance.

The ocean with its large capacity and slow deep circulation is an effective integrator of annual and seasonal fluctuations in its inputs. By the same reasoning, however, it probably plays a major role in climatic fluctuations and other long-period phenomena. Relationships between atmospheric conditions and ocean currents, temperature, salinity, and life enable interpretation of sedimentary composition and distribution in terms of past climatic fluctuations. The geochemical cycle depends on these planetary-scale processes and they must be understood in order to predict the large-scale effects that will arise when rates of material inputs are changed.

A. Effect of Bathymetry on the Wind-Thermohaline-Driven Circulation Model

The effect of variable bathymetry is being added to our analytic quasilinear model of the combined wind-driven and thermohaline circulation. This model, although not strongly stratified, is an ideal one with which to demonstrate the effects of baroclinicity and bathymetry in changing ocean circulation patterns. It can show the dependence of the bathymetric effects on the relative magnitudes of wind and thermohaline driving and on the vertical and horizontal mixing. The baroclinicity has been identified as an important influencing factor on bathymetrically induced circulation changes; thus the importance of using a model in which its effect can be shown explicitly.

For our purpose it is most convenient to follow Fofonoff (1962) in decomposing the total transport into three parts: the Ekman transport, the baroclinic geostrophic transport, and the barotropic geostrophic transport. The essential feature of this form of decomposition is that the velocity at the bottom is due to the barotropic geostrophic flow only, and therefore this is the only part of the flow that is directly affected by bathymetry. The baroclinic geostrophic flow, which is described totally by the mass field, responds to the change in the barotropic flow, which in turn modifies the mass field. This depends, of course, on the bathymetry not reaching into the depths of significant density gradients.

The iteration procedure of the Rattray-Welander model is followed: 1) the zero-order mass field is found from a diffusive balance, 2) the zero-order baroclinic velocity field is found from the zero-order density distribution, 3) the Ekman transport is found from the wind stress, 4) the zero-order barotropic flow for a particular bottom configuration is found from the Ekman and the zero-order baroclinic transports, and 5) the next iteration cycle is begun by obtaining the first-order mass field including the effects of the zero-order advection. The iteration is continued in this manner to any desired approximation. (Rattray)

B. Global Climate Modeling, with Particular Reference to the Role of the Oceans

The global energy-balanced models of Budyko, Sellers, and North have been extended to specifically include the meridional heat transport by the oceans. One diffusive and one advective ocean model is constructed, the latter including horizontal gyres as well as a vertical deep-water loop.

In addition, attempts have been made to introduce a more realistic parameterization of the atmospheric heat flux and to include submodels of the ice which take into account ice thickness and the difference between sea ice and land ice.

The calculations are made numerically by intergration in time, while some submodels are discussed analytically. The first calculations indicate that the sensitivity of the position of the ice-boundary on the solar constant in previous models hangs critically on the assumption of a constant horizontal eddy diffusivity in the atmosphere, and that the real system may be much more stable. A manuscript has been submitted for publication. (Liu [Welander])

C. Time-Dependent Air-Water-Ice Systems

The work on simple, differentially heated air-water-ice systems, with eventual application to natural systems, has continued. The self-sustained oscillations predicted for a freshwater system heated internally and cooled to freezing from above has been experimentally demonstrated. The extension to a corresponding saltwater system has been made. A search for natural oscillatory systems of the same type has been initiated. Specifically, we are looking into the possibility that similar oscillations occur in lakes on warm, volcanic ground. Three manuscripts have been submitted for publication. (Bauer [Welander])

D. Dynamics of the Southern Ocean

International Southern Ocean Studies (ISOS) is a program of dynamics and monitoring experiments in the Southern Ocean aimed toward the understanding of the long-term, large-scale variability of dynamical processes there and the interaction of the Southern Ocean with the global oceanic and atmospheric circulation. The project is supported by the IDOE of NSF and is jointly managed by the University of Washington and Texas A&M University. More than 15 national and international institutes are participating in the study. Liaison between ISOS and the polar experiment of the Global Atmospheric Research Program being planned by meteorologists for 1979-1980 is also carried out here. (D.J. Baker)

The First Dynamical Response and Kinematics Experiment (FDRAKE, 1975) component of ISOS took place in Drake Passage. The vessels engaged in the experiment were R/V *Melville* of Scripps Institution of Oceanography, R/V *Conrad* of Lamont-Doherty Geological Observatory, and the Argentine-operated ARA *Islas Orcadas* (formerly USNS *Eltanin*). The latter ship investigated the physical and chemical properties of Drake Passage and the Scotia Sea from January 10 to March 3, 1975 (associate chief scientist, R.B. Wearn, University of Washington). The 1975 cruise began with a close-

spaced section of STD casts and hydrographic sections across Drake Passage. The second leg was devoted to a joint study with the *Conrad* across the polar front region in the western Scotia Sea. Distinct termperature-salinity regions and interleaving features were observed and are under study together with the data from the other ships. (Wearn)

As a continuation of FDRAKE, further field work was carried out in the Drake Passage in February and March 1976 aboard the University of Washington vessel R/V *Thomas G. Thompson*. The data on the meso- and large-scale variability of the Antarctic Circumpolar Current will be used to determine the feasibility of monitoring its transport, with the objective of relating transport variations to the forcing functions caused by oceanic-ice-atmosphere interactions. Specific to FDRAKE, 1976, objectives were (1) to recover an array of current, temperature, and sea level (shallow pressure) recorders deployed from R/V *Melville* during FDRAKE, 1975, in February and March 1975, (2) to deploy across the Drake Passage an array of current, temperature, and deep- and shallow-pressure recorders to remain for one year, (3) to obtain sections of temperature and salinity across the passage to use with the kinematic measurements to estimate transport and to assess the smallest horizontal scales and spatial statistics of significant baroclinic structure, (4) to obtain density measurement at pairs of stations bracketing the moorings having more than one current meter for use in comparing geostrophic and measured vertical gradients of kinematic quantities, (5) to obtain high precision nutrient measurements for use with those obtained during FDRAKE, 1975, for study of water mass distributions and chemical balances in the Circumpolar Current, (6) to obtain data in the east-west trending trench at the southern end of the Drake Passage to assess bottom water exchange between Antarctic and Pacific, and (7) to launch drogued surface drifters for long-term tracking by satellite. The cruise track is shown in Figure 1.

During the first 1976 crossing of the passage, five current meters were deployed by a team from Oregon State University and deep-sea pressure recorders (five sensors on three moorings) by a University of Washington team. The position of the two types of moorings is shown in Figure 2. This is the first time that deep-pressure recorders have been used in an experiment to measure the long-term variation of the change of the barotropic component of mass transport through the passage.

Near Livingston Island, the R/V *Thompson* made a rendezvous with the Soviet research vessel *Professor Viese*, which was making current and hydrographic-STD observations to the west as part of a cooperative program. Visits were made between the vessels; salinity, nutrient, and oxygen standard materials were exchanged; and hydrographic and STD stations were made simultaneously for intercalibration. (Baker, Wearn; E.J. Krause, Applied Physics Laboratory)

A statistical study of existing hydrographic data from the Southern Ocean has yielded valuable information on the significant space-scales of the Antarctic Circumpolar Current. Eddy intensity was found to be stronger over regions of steep bottom topography. Further work is in progress to correlate these data with data on the driving forces of wind

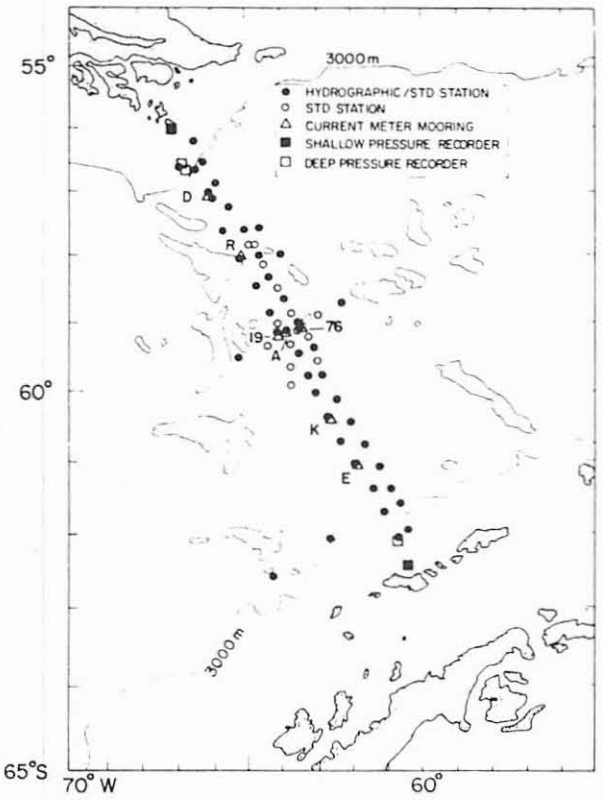


Figure 1. FDRAKE 1976, mooring and station plan.

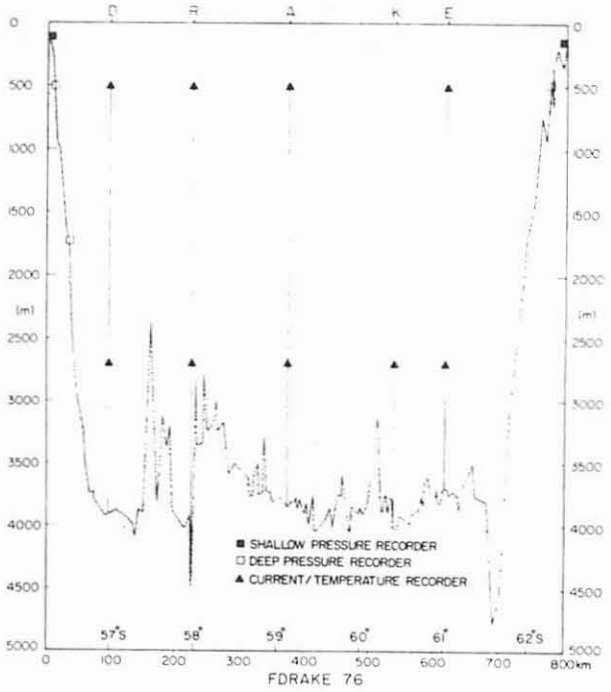


Figure 2. Long-term array deployed in 1976.

and heat flux to determine large-scale air-sea interaction and variability. A catalog of sea-level data has been prepared and is being used to identify possible climatic indices for the Southern Ocean. (Lutjeharms [D.J. Baker])

E. Dynamics of Equatorial Waters

A dynamics of equatorial waters program (EQUA), designed to describe the time- and space-scales and the balance of forces of the equatorial undercurrent in the central Pacific, was initiated in 1976. In addition to moored wind, current, and temperature measurements obtained at 0°, 150°W during August and September 1976, satellite-tracked drifters drogued at 35 m were deployed, and temperature, salinity, and current profiles were made at 0.5° intervals between 1.5°S and 1.5°N along 150°W. Preliminary results indicate: (1) a good agreement between the progressive vector diagrams of the 50 m level moored current measurements and the trajectory of the drogues during a portion of the time, (2) temperature and current fluctuations with approximately a 25-day period, (3) a south to north movement of the equatorial undercurrent, (4) a lack of evidence of intense equatorial upwelling as indicated by the meridional temperature section, and (5) depth-averaged Richardson number of order 1 at the top of the undercurrent. Analyses of these data are continuing. Additional measurements are planned for 0°, 125°W during April to June 1977. (Halpern; R. Davis and W. Patzert, Scripps Institution of Oceanography; D. Hansen, NOAA Atlantic Oceanographic and Meteorological Laboratories)

F. Abyssal Processes in the North Pacific

A study of near-bottom currents in the North Pacific (30°N, 158°W) was begun in February 1974 with the deployment of an array of current meters. The meters were placed at two levels: 100 m and 1200 m above the bottom. The array was maintained for 19 months and the results are now being analyzed. The primary focus of the analysis is on the low frequency (less than one cycle per month) fluctuations indicated in the records. (Taft; L. Magaard, University of Hawaii)

III. Meso-Scale Oceanic Processes

Studies on meso-scale processes seek to explain those oceanic features that are embedded in the planetary-scale phenomena but have an identifiable existence of their own. These include frontal patterns, eddy structures, domes, and oceanic upwelling areas; distributions of unusual properties; and topographically induced flow patterns. Meso-scale processes typically can respond with periods from days to years and can be associated with weather patterns and biologically productive and unproductive regions. They may have a large influence on the planetary-scale motions and in turn be modified or caused by these motions.

A. Fronts of the Central Pacific

The relationship between ocean fronts and atmospheric forcing is being investigated. Significant progress has been made in understanding the dynamics of oceanic fronts. It has been determined that fronts will intensify and develop where there is an imbalance between gradients of temperature and salinity advection on the one hand and gradients of heat and salt flux divergence on the other. Fronts near the sea surface are strongly influenced by the horizontal shear of the wind, which produces convergence in Ekman transport as well as in the turbulent heat and salt fluxes. Surface fronts are strongly influenced also by horizontal gradients of the radiative heat flux and by precipitation. Fronts below pycnocline depth are often associated with differential vertical advection of temperature and salinity. Not all oceanic fronts are baroclinic: where the horizontal temperature and salinity gradients balance each other, the baroclinic flow vanishes. The physical processes affecting surface and subsurface fronts differ; therefore, the upper and lower fronts occur at different locations. Because the configurations of the surface heat and salt flux fields are independent of each other, temperature and salinity fronts in the upper oceanic layer may exist independently.

A study of the time variation of the surface temperature fronts using NOAA infrared measurements from satellites is in progress. Preliminary results show that the fronts are remarkably stationary over periods of a week or two. (Roden)

B. Long-Wave Perturbations of Dynamic Height in the North Pacific

A study of the sea surface profile, using closely spaced (27 km) dynamics heights on long (2700 km) north-south sections, showed that perturbations with wavelengths between 400 and 600 km are common in the latitude band between 20° and 50°N. The wave amplitudes decrease from 30 cm in the western Pacific to 10 cm in the eastern, with the largest decrease occurring near the Emperor seamount chain near 170°E. The amplitudes of the perturbations decrease exponentially with depth in the central Pacific.

The perturbations are related to the curl of the wind stress. In the central part of the ocean the distribution of the curl is zonal, which acts as a line source for planetary waves with meridional wavenumbers. The amplitude of the perturbations varies seasonally with the

intensity and the duration of atmospheric forcing. There is some indication that the wave amplitudes decrease with distance from the forcing region. Several theories of free and forced baroclinic Rossby waves can explain the observed features, but no single one stands out as the most plausible one.

The connection of multiple oceanic fronts and baroclinc Rossby waves of the type seen in the dynamic height sections will be investigated. (Roden)

C. Offshore Tides

The program for the study of tides on the continental shelves currently is dependent on data from the wave-sediment interaction program. The instrumentation developed for this program provides data at 15 minute intervals for the duration of the mooring which may be as long as two months. These data are examined for tides and shelf waves, thus stockpiling information until a problem area is identified that justifies a program of its own. (Larsen)

D. Kuroshio Studies

In 1971 and 1973 cruises were made to the south of Japan to study the characteristics of the flow of the Kuroshio. The first cruise concentrated on the area west of the Izu-Ogasawara Ridge and involved detailed tracking of the Kuroshio path and deep velocity measurements. The second cruise concentrated on the flow of the Kuroshio over the Izu-Ogasawara Ridge. Analysis of the data from the first cruise has been completed and a paper submitted for publication. The ridge cruise is now in its final stage of analysis. A manuscript is being prepared jointly with H.P. Freitag describing the response of the structure of the Kuroshio to the ridge in the surface layers and at imtermediate levels (approximately 1,000 m).

As a part of the North Pacific Experiment (NORPAX) sea level data in the western Pacific has been analyzed to determine the fluctuations in the surface geostrophic flow of the Kuroshio on long time-scales (seasonal and year to year). Amplitude of the year to year fluctuations is about 5 cm which amounts to a percentage variation of 10% of the mean flow. These fluctuations will be compared with indices of the large-scale flow in the North Pacific in an attempt to establish the phase relationship between the driving forces and the response of the surface flow of the Kuroshio. (Taft)

E. Meso-scale Eddies

Planning for an intensive study of the dynamics of meso-scale eddies as a part of the POLYMODE program is now under way. The main field program will be carried out in the western Atlantic in the summer of 1978. The experimental plan is to combine density profiles and SOFAR float tracks to produce velocity profiles for the entire water column on the horizontal scale of one eddy. Dynamical analysis will be carried out by examining the balance of terms in the quasi-geostrophic potential vorticity equation. As an input to the design of the 1978 field program a preliminary cruise to the selected region in the spring of 1977 is planned to determine the

horizontal and vertical space-scales and the time-scales of variations in water properties and the flow field. The historical data base of hydrocast and STD (CTD) profiles is also being examined for signatures in the property distributions that can be related to the geographic distribution of eddy energy in the North Atlantic. (Taft; C. Ebbesmeyer, Evans-Hamilton, Inc., Seattle; J. McWilliams, National Center for Atmospheric Research)

F. Bering Sea

1. Continental slope region

Results from two intensive hydrographic surveys over the central continental slope region indicate that the flux of water from the central basin to the shallow shelf, which is required to compensate the outflow at Bering Strait to the north and might be expected there, has to occur elsewhere. Rather, the central slope dynamics are dominated by a diffuse salinity front so that shelf-basin exchange is not important in the total water budget; the bulk of shelf-basin exchange probably occurs near Unimak Pass to the south and Cape Navarin to the north.

A cellular feature near Pribilof Canyon has properties similar to the current rings that are found near the Gulf Stream. The Bering Sea ring may be a permanent feature formed by bathymetric steering of the Bering Slope Current. (Kinder, Coachman)

2. Bristol Bay

Under the Outer Continental Shelf Environmental Assessment Program (OCSEAP) we have deployed and recovered instrument moorings and carried out CTD surveys within Bristol Bay and the adjacent continental shelf. During the past year instrument moorings consisting of a combination of current meters and pressure gauges were maintained at fourteen different sites to elucidate the flow regime of the region; the record-length of valid data from some sites now exceeds one year. Seven moorings deployed in September 1976 to monitor the winter circulation will be retrieved after the ice breaks up in May 1977. The CTD surveys were carried out in March, June, August, and September 1976. Broad coverage of the study area was achieved only in June. The March cruise was curtailed by the ice cover to a small area near Unimak Pass, while the August and September surveys were limited in areal coverage by combinations of limited ship-time, equipment malfunction, and personnel accidents.

Results from the March CTD mapping near the ice edge revealed static instabilities with a vertical scale of meters extending over $\sim$ 100 km. These features, which are unique because of their large vertical extent, cannot be attributed easily to an artifact of the equipment or sampling technique. Apparently this transient condition of static instability is associated with the interleaving of the Bering Sea and shelf water-mass types by meso-scale wind forcing.

Mappings from closely spaced (< 10 km) STD stations across the 50 m isobath during the June cruise revealed the structure of the front in the study area. Shoreward of the front the water column is almost homogeneous, while seaward of the front a two-layer system of stratification is found.

Presumably the change in vertical structure that demarcates the front is the result of complete tidal mixing at depths $\leq$ 50 m.

Early results from the current-meter records show that the flow regime is dominated by energetic tides (20 to 30 cm s^{-1}). Mean velocities are slow ($\sim$ 1 cm s^{-1}) and parallel the isobaths. Low frequency (at periods longer than one day) activity is significant, however, and appears to be episodic at some sites and nearly periodic (2 to 10 day period) at others. The amplitude of the most energetic of these pulses or oscillations is about 20 cm s^{-1}, and changes in temperature and salinity accompany these high-speed events.

The field program has been successful in amassing much data. While field work will continue in 1977, the major effort will be toward analysis of the data on hand and pursuit of the interesting questions that are suggested by the preliminary results discussed here. (Kinder, Coachman, Tripp; J. Schumacher and R. Charnell, Pacific Marine Environmental Laboratory)

3. Water masses of the deep basin

All available hydrographic information from the Bering Sea has been examined and that of high quality has been selected for the analysis of seasonal variability. Using 656 summer, 139 fall, and 43 winter stations, we have calculated horizontal and vertical sections of temperature and salinity, volumetric temperature-salinity correlations, dynamics heights, salt and heat contents of sections, and core characteristics. A promising cartographic technique using computer-drawn prospective views of the volumetric distributions has been developed. Much of this material is being incorporated in an oceanographic atlas to be published by the University of Washington Press. (Sayles [Aagaard, Coachman])

4. Current measurements and CTD surveys

During the summer and early autumn of 1976 we deployed 19 instrument moorings and conducted three CTD surveys. Analysis of the CTD data has just begun so results are not available.

Plans for 1977 have not been completed, however; the instrument array will be recovered during the summer. In February, surveys of Norton Sound, Bering Strait, Kotzebue Sound, and Chukchi Sea are planned. A helicopter-borne system will be used for the surveys.

The specific objectives of this OCSEAP project are: (1) to determine low-frequency flow fluctuations through Bering Strait, (2) to verify and examine the variability of the bifurcated northward flow that occurs west of Point Hope, (3) to define the time and space scales of eddies, and (4) to establish the circulation patterns in Norton and Kotzebue Sounds. (Coachman, Aagaard, Tripp, Darnall, Kinder; R.D. Muench, Pacific Marine Environmental Laboratory)

G. Beaufort Sea

1. STD mappings of the shelf

As part of OCSEAP we are in the second year of a program to obtain seasonally distributed temperature and salinity mappings of the shelf

and slope. The fourfold goals are to elucidate the shelf and slope circulation, to understand the seasonal progression of water mass transformations, to provide input for modeling efforts, and to investigate possible pollutant dispersal mechanisms. A helicopter is used to transport a portable CTD system capable of sounding to 600 m. At each station a hole is cut in the ice for the cast. Four cruises have been accomplished to date, and an additional one is scheduled for February-March 1977.

Among the interesting features illustrated by the data are a series of subsurface temperature inversions on the outer shelf and slope. In each case the area of temperature inversions sinks from the outer shelf into the slope waters. The T-S characteristics of the inversion region suggest that beginning in the fall, the north Alaskan shelf is in fact feeding water into the pycnocline region of the Arctic Ocean. The process is driven by strong thermohaline convection on the shelf which destroys the density layering characteristic of summer. (Aagaard, Darnall, Tripp)

2. Current measurements

Under OCSEAP we have also been engaged in an effort to make long-term Eulerian time-series of currents at selected locations on the shelf and slope of the Beaufort Sea, where the ice cover is not seasonally removed. The object is to contribute to the understanding of the time-dependent circulation and dynamics of the outer shelf and slope. Six current meters on three moorings were deployed through the ice in April 1976, and four of the meters were recovered in October. At that time two more were deployed. Another set of four will be deployed in March 1978 and the two from October retrieved. The four meters set in March will be acoustically linked to a subsurface data buoy which houses power supply, digital tape recorder, timing and control, and telecommuncation subsystems. On an opportunity basis, landings will be made on the ice and the data buoy interrogated acoustically using a very high information transfer rate technique. The data buoy system was developed in conjunction with the Applied Physics Laboratory. (Aagaard, Darnall, Tripp)

H. Barents and Kara Seas

A new program to study the regional oceanography of the Barents and Kara seas has been initiated. These are the westernmost of the arctic shelf seas north of the U.S.S.R., and are probably the most important scientifically. Although contiguous, they are substantially different. The Barents is a relatively deep shelf sea with irregular bathymetry. It is the immediate recipient of warm saline water from the Norwegian Current, which through mixing and heat exchange with the atmosphere undergoes a transformation within the Barents. This sea is also a major storm track center, and various climatic studies of the northern hemisphere indicate its considerable importance in the heat budget. It is in essence a transitional sea between the arctic and the subarctic, and its ice distribution and hydrography reflect this standing.

The Kara is a more characteristic Siberian shelf sea, with its inner part relatively shallow and smooth-bottomed. In ice cover and hydrography it is unmistakably arctic. Its probably unique importance among the arctic shelf seas is due to two features. One is the presence of two enormous

submarine canyons, the St. Anna and Voronin, extending far onto the shelf. It is likely that these canyons are instrumental in the interaction of the shelf waters with those of the Eurasian Basin of the Arctic Ocean. Specifically, the canyons appear to channel warm Atlantic water up and onto the shelf, where various turbulent processes effect heat transfers and water mass transformations that probably play a role in climate, ice cover, and the hydrography of at least the upper waters of the Eurasian Basin. The second important feature of the Kara Sea is its receipt of about two-fifths of the total fresh water discharge to the Arctic Ocean. This has particularly important and far-reaching consequences for ice cover and climate.

Our intent is to produce a comparative study of the regional oceanography of these two seas. Our emphasis will be on descriptive hydrography (water masses, spatial and temporal distribution, mixing, etc.), volumetric analysis, seasonal cycles, circulation, exchange with the atmosphere, and the effect of ice and fresh water on oceanic processes. The work will be based on critical examination and synthesis of existing data (ICES and WODC listings, unpublished data, remote sensing imagery, etc.). Our goal is to understand these two seas and their more important processes in the larger setting of the whole interactive Arctic. (Hanzlick [Aagaard])

I. Greenland Sea

To study the oceanic heat flux into the Arctic and its variability, an experiment in heat transport through the Greenland-Spitsbergen passage has been undertaken jointly with the University of Bergen. In July 1976 we deployed four moorings, each with two current meters equipped with thermistors, across the core of the West Spitsbergen Current at 79°N. These will be retrieved in the summer of 1977. The mooring separation varies from 5-20 km. An STD section across the current was made during deployment and another will be made during the retrieval period to compare hydrographic and current structure. (Aagaard, Darnall, Tripp)

J. Iceland Sea

1. Seasonal processes

The goal of this project is to understand the seasonal sequence of events in this important example of a subarctic sea, i.e., its goal is to understand the oceanic climatology in a short time-scale sense. Through a joint venture with the Marine Research Institute in Reykjavik, we have obtained very dense temperature and salinity coverage for the Iceland Sea in a series of four cruises beginning in summer 1974 and working through the fall and winter sequence of seasonal changes. The program was designed to examine questions such as the following. Where do the deep waters flow into the Iceland Sea? How are they modified during their transit and residence? Are deep water masses formed within the Iceland Sea? What are the relative roles of intermediate and deep waters. [Recent GEOSECS data indicate that the Denmark Strait overflow consists of an intermediate water mass, not a deep one.] What are the major indicated mechanisms in the seasonal budgets of salt and heat? What is the climatic role of the East Greenland Current, e.g., with respect to recent catastrophically heavy ice years around Iceland? The analysis of the data is nearing completion. (Swift [Aagaard], Tripp)

2. Overflow in Denmark Strait

The most important northern hemisphere source of deep water for the world ocean lies north of the Greenland-Iceland-Faeroes-Shetland ridge system, whence it pours out into the North Atlantic at very high speeds (3-4 knots have been measured). The International Council for the Exploration of the Sea, which has invested considerable effort in understanding and describing these overflows and their variability and dynamics, has recently initiated a program of long-term current monitoring. As part of the Monitoring Overflow to the North Atlantic Project (MONA) of the ICES Overflow Working Group, we deployed four current meters with thermistors on two moorings in the core of the deep water outflow just south of the Denmark Strait sill during August 1975. These were recovered a year later. Among the questions of interest are the following. What are the important time scales of the overflow through Denmark Strait? [The longest previous current records have been about one month.] Is there a seasonal aspect to the overflow? Is there still an overflow of the classic bottom water, or is the present overflow in fact a warmer, less saline intermediate water mass, as suggested by tritium data?

Preliminary runs of the four time-series show extremely energetic records in both temperature and velocity, with the least variability at the deeper meters (25 m off the bottom) and offshore, but at these meters the mean flow is greatest. The major tidal components are small but distinct in the spectra; no inertial peak can be seen. The low-frequency maximum is in the band corresponding to 1.5-2.5 days, in agreement with the instability model of Smith. The appropriateness of comparison with Smith's model is also indicated by the following: (1) While the mean flow at each meter is apprxoimately along the isobaths, the variances in components parallel and normal to isobaths are comparable; (2) at each meter the normal components are highly coherent at the low-frequency peak and are in quadrature, the current vector rotating clockwise; and (3) the velocity and temperature records for each meter are highly coherent and consistent in phase. Both vertically and laterally, the current- and temperature-series from different meters also show very high coherence, particularly near the low-frequency energy peak.

In analyzing the current and temperature time-series, there are several natural focal points. One is that much of the variance may represent internally generated phenomena (such as proposed by Smith), as contrasted with events forced externally. A second point is that Ross, working with the same one-month data set as Smith, has been able to filter in such a way that certain important low-frequency overflow transport events seem clearly correlated with variations in the downstream atmospheric pressure gradient. A third point is a possible secular change in the T-S properties of the overflow water toward warmer, less saline water than was the case a few years ago. There appears to be enough material, e.g., the present temperature time-series, a number of hydrographic sections taken during the MONA experiment year, and a historical sequence of data, to explore this issue. (Aagaard, Darnall, Tripp)

K. Arctic Ocean

During 1973-1974 we maintained at ice island T-3 current meters that recorded current speed and direction, and also temperature

continuously at depths of 90, 150, 300,and 500 m. The island drift was determined by satellite navigation. Baroclinic tidal motions, both diurnal and semidiurnal, and a range of lower-frequency phenomena are evident in the records. We are continuing analysis of these records with particular emphasis on the tidal bands, the vertical current structure, and the relationship between currents, ice motion, and atmospheric events. (Hanzlick [Aagaard], Tripp)

IV. Small-Scale Physical Processes

The purpose of research in small-scale physical processes is to improve understanding of turbulence, short internal waves, microstructure, layering, and sound transmission and their interactions in a stratified, geophysical shear flow. These processes provide the mechanism for non-advective fluxes important to maintaining oceanic distributions. In addition, their presence causes a severe sampling problem in determining the large-scale, more slowly varying, state.

A. Mixing and Turbulence in Stratified Estuaries

In order to understand the vertical exchange of momentum and mass in natural stratified flows, field investigations of these processes as they occur in partially mixed and salt wedge estuaries as well as in fjords are being carried out in various arms of the Puget Sound system. Four centimeter diameter velocity component sensing, mechanical current meters, mounted in triplets and deployed in conjunction with one Guildline CTD and two SBE CTDs, provide the basic sensors. These usually are attached in one or more of the following ways:

1) from a wire lowered frame adjusted in depth every half hour so that the Guildline CTD is situated in the steepest part of the pycnocline and the SBE CTDs are in the two adjacent layers. [Several triplets of current meters are located in each layer.];

2) from a 4 m high bottom-mounted frame capable of supporting a dense array of current meters and several CTDs;

3) from a highly instrumented wire-lowered fish capable of continuously profiling velocity and density fields from a moving vessel;

4) from a ship-mounted mast capable of measuring velocity and Reynolds stress components in the upper 10 m of the water column while under way.

The first configuration is used for making turbulent salt flux, turbulent kinetic energy, and Reynolds stress measurements in sharp pycnoclines and in the surface layer. The bottom-mounted frame is used for making detailed measurements of flow in the bottom boundary layer and the profiling fish is used for investigating the spatial dependence of the mean flow around each experimental site. The ship-mounted mast system provides information on the spatial structure of the turbulent fluctuations, short internal waves, and the mean velocity field. Bedload and suspended load samplers also are employed when needed to resolve the sediment transport situation and to permit corrections to be made for suspended sediment induced stratification, an effect that can be particularly important in the immediate vicinity of the seabed.

At present, field work is being carried out in the Duwamish River, in Skagit Bay, and in Knight Inlet. The first is a salt-wedge estuary and special emphasis is being placed on activity in the neighborhood of

the freshwater-seawater interface; whereas, the second is a partially mixed estuary and in this location emphasis is on the tidally-driven bottom boundary layer and on the mixing processes that occur in the interior of the flow. The third site is a fjord and the main emphasis is on turbulent mixing due to large amplitude internal waves. (Smith)

Results procured to date from the Duwamish River indicate that 50% of the mixing takes place during "intense mixing events" which occur near the time of maximum ebb. These events have been studied in some detail during the past several years and their salient characteristics have been identified. At such times, both the turbulent kinetic energy and the vertical turbulent salt flux jump by an order of magnitude. Also the surface salinity and surface mixed layer thickness increase dramatically as the salt wedge is eroded from above. During ebbs with exceptionally high tidal currents, the salt wedge disappears entirely due to the intense mixing. The internal Froude number for the tidal flow reaches its critical value just prior to the intense mixing events indicating that they are due to internal hydraulic jumps that form when internal wave energy can no longer radiate in the upstream direction. In other parts of the tidal cycle turbulent transfer by other mechanisms also can be observed. These include entrainment of denser water into the upper layer, entrainment of lighter water into the pycnocline, and shear instabilities. In addition to continued study of the intense mixing events, the importance of boundary layer mixing along the edges of the channel is under investigation.

The Knight Inlet project is part of an international study that involves elucidation of both the mean flow and turbulent mixing in a relatively deep, straight reach just upstream of a 50 m sill. During the past November, measurements of general salinity structure in the upper part of this estuary were procured in conjunction with a three-day-long anchor station made near the center of the straight reach. At the anchor station high precision velocity and density profiles were collected in the upper 140 meters of the flow every five minutes, thus providing an extremely accurate set of data from which the tidal, gravitational, and wind-driven velocity fields can be computed. In addition, these data augmented by data collected with a closely-spaced set of Aanderaa current meters deployed from the research vessel by personnel from the Canadian Institute of Oceanographic Sciences provide a thorough characterization of the large amplitude internal waves that propagate through this reach on each flood tide. These several minute-period, nonlinear internal waves that cause a substantial change (over 10 m) in pycnocline depth as they pass appear to be important in the mixing process especially under high runoff conditions. (Partch, Gardner [Smith])

B. Turbulent Flow over Wavy Topography

The boundaries of rivers and estuaries as well as many sections of the continental shelf are covered with topographic features ranging in scale from ripples to bars and sand ridges; yet no accurate procedures exist for computing the effect of these disturbances on the flow above them. The adjustments that occur in this turbulent boundary layer can be examined best when they are caused by regular bed forms; a suitable site for this type of study is afforded by the dune fields of the lower Columbia

River when they are subjected to the high flows of late spring. In the past, detailed measurements of mean velocity and Reynolds stress have been made over these sand waves using small mechanical current meters.

Mean flow data were reduced by assuming that the downstream dependence of the velocity field could be approximated by a spatially-averaged profile plus two perturbation profiles multiplied respectively by the wave height and its slope. The vertical profiles were taken to be low-order polynomials of the logarithm of the distance from the boundary. The low variances produced by this decomposition serves as a good indicator of its general utility in nonuniform flow problems and provides a sound physical basis for understanding the salient features of flow over two-dimensional topography. Measured Reynolds stress fields were decomposed in a similar manner.

Spatially-averaged velocity and stress fields were examined in some detail. The former was found to be nonlogarithmic and to yield an increasing shear velocity with distance from the boundary. Examination of the zero-order stress profile yielded the same result. Recently we have shown that a simple momentum defect theory can be used in conjunction with steady, uniform stratified flow principles to reproduce the measured velocity and stress fields with surprising accuracy. With this as a basis, theoretical studies of the spatially varying velocity field now are under way.

The goal of these calculations is to provide an accurate model of near bottom flow and boundary shear stress so that finite amplitude ripple and dune growth theories can be constructed. Our previous work on this subject also has involved the effect of suspended sediment on boundary layer flow mechanics and this will be included in the new dune growth models. Further experimental and theoretical efforts concerning nonuniform boundary layers will address the three-dimensional situation that exists in the vicinity of sand ridges and river bars. (McLean, Smith)

C. Small-Scale Mixing and Microstructure

The existence of centimeter-scale fluctuations in temperature profiles has been known for over a decade. The spatial spectrum of this microstructure has been reasonably well defined for temperature, but not for velocity or salinity. Our knowledge of the processes has been obtained by relating the microstructure to larger scale, 1 m to 30 m, features in the profile. However, our understanding of the processes responsible for creating this microstructure is limited by the present inability to follow the time evolution of specific patches of turbulent activity.

A continuing microstructure program has been developed to refine existing measurement systems and develop new ones, conduct field programs, and develop new methods of analysis of the data.

The instrumental efforts are aimed at completing the development of temperature and salinity systems before beginning a program in velocity microstructure. Low noise temperature circuits are being tested in

Jervis Inlet, British Columbia, in preparation for an abyssal microstructure recorder. The four-electrode conductivity probe is being redesigned to produce density data suitable for some of the statistical treatments applied to the temperature records.

Extensive measurements were made in the North Atlantic, especially near Bermuda, during October-November 1975. These were made, in conjunction with other investigators, with a variety of free-fall devices. The next major program will be in the Mixed Layer Experiment (MILE) at Ocean Station P in August-September 1977. Incidental measurements are being made in Dabob Bay, the Hood Canal, and Jervis Inlet in preparation for this program.

The analysis of a large amount of microstructure data from the middle of the Subtropical Gyre in the North Pacific has shown that the levels of the spectra of temperature fluctuations in the internal wave range of the vertical wavenumber spectrum do not change significantly at different seasons of the year, implying that the level of the internal wave spectrum is nearly constant; and that the microstructure levels change by more than a factor of 100, implying that the levels of small-scale mixing are changing markedly. The internal structure of these records are being examined for differences in the characteristics of the microstructure patches.

Data from the Atlantic is being analyzed in conjunction with velocity data taken by other investigators. It is planned to examine the relation of near inertial period internal waves to the microstructure patches. (Gregg)

D. Fluctuations in the Ekman Boundary Layer

Linear perturbation theory is being used to explore the nature of the fluctuating motion within the geophysical boundary layer. The mean motion which can be fully turbulent is characterized by a velocity profile that is a combination of logarithmic lower portion joined by a spiral and by parameterization of the turbulence by a variable eddy viscosity. Oscillations are then considered as either natural or forced, depending upon the kind of physical problem that is being analyzed. The output is cast in terms of the velocity components, pressure, and the density together with the correlations of the various combinations of these quantities. (Spooner [Criminale])

E. Wave-Characteristic Solutions to Instability Problems

Instead of formulating the analysis of instability by normal mode decomposition, an alternative means is used where only Fourier decomposition is employed. The resulting equations are still partial differential equations (in terms of wavenumbers and time) but can be solved for many situations. In particular, plane Couette flow or a mean flow that is decelerating-accelerating results in simple first order equations that are solved by characteristics. A flow such as plane Poiseuille flow can be solved by incorporating the boundary conditions into the system at the outset. The overall advantage of this approach rests with having the complete solution to any problem and a quick means of assessing any initial-value problem. (Criminale)

F. Oceanic Structure

A program to study the temperature, salinity, and velocity structure from internal waves scales (10^3m) down to turbulence scales (10^{-3}m) is being conducted by the Ocean Physics Deaprtment, Applied Physics Laboratory. Measurements are being made from the Self Propelled Underwater Research Vehicle (SPURV) which is an acoustically controlled, instrumented platform capable of operating at depths to 1700 m at speeds of 2 to 3m/sec for up to five hours. Currently SPURV carries a suite of three temperature-conductivity sensor pairs and pressure as well as heading, orientation, and other engineering information. The vehicle also can carry a fluorometer or sound velocimeter as required. We are adding a Neil Brown conductivity sensor, metal film thermometer, and hot-film anemometer for high frequency measurements. SPURV is a stable platform which will introduce noise in the data at a level well below the level of turbulent patches in the upper km of the ocean. Field testing of this high-frequency instrumentation will occur in the fall of 1977. (Ewart, Irish)

G. Structure of the Bottom Boundary Layer in the Equatorial North Pacific

Moored arrays of current meters maintained at two locations in the equatorial North Pacific (8°27'N, 150°49'W; 11°42'N, 138°24'W) for approximately six months provide data for a study of the structure of the abyssal boundary layer. Each mooring had current meters at 6, 30, 50 m above the bottom. In addition to the current meters, high resolution CTD profiles using a Neil Brown CTD system were obtained in the vicinity of each mooring. The current meter data indicate mean flows to the northwest at both locations with greater mean speed at the eastern location. Low frequency (less than inertial) variations with amplitudes greater than 5 cm/sec were observed. The CTD stations revealed a variety of near-bottom profiles. Usually the temperature gradient was nearly adiabatic; however, profiles with both sub- and superadiabatic gradients were observed. (Hayes)

V. Coastal Dynamics, Upwelling, and Downwelling

The coastal regions have interesting and important properties distinct from the open ocean, both because they act as lateral boundaries and because they are much shallower. The purpose of this program is: to understand the currents and mixing processes and their dependence on the local driving forces and on the conditions in the adjacent ocean; to determine the rates of upwelling or downwelling and their effect on nutrient replenishment and the resulting biological production; the transport processes of sediment over and across the continental shelf; and the chemical reactions that occur as river water enters the sea.

A. Field Studies of Coastal Dynamics

Since 1971 we have been involved in the measurement of currents and winds on the continental shelf off Washington and Oregon. Although current measurements have been made in all seasons, our primary emphasis has been on the autumn and winter seasons, during which severe storms drive strong north-northwesterly currents along the shelf. Of particular interest is the fact that significant sediment transport occurs only under the influence of the most severe of these storms; during these periods a substantial amount of sediment is transported from the mouth of the Columbia River to the continental slope north-northwest of the river mouth. Another salient feature of the currents over the Washington continental shelf is a reversal of direction with a period ranging from three to five days, which appears to be associated with movement of storms across the northeast Pacific Ocean. Such reversals are not entirely unexpected during the winter; however, they are found in currents below 50 m throughout the summer as well.

From 1971 to 1974, direct current measurements on the continental shelf off Washington were made at two stations, one on the central shelf and one at the shelf break. Six current meters were usually deployed at each station. Density sections were taken upon deployment and retrieval of meters. Wind speed and direction were measured at Westport. These data are currently undergoing intensive analyses. Parameters such as velocity shear, response of both components of velocity to wind, volume transport, and the response of the density field to the wind and to the Columbia River influx are being investigated as a function of season and of longshore position. Simultaneous records from the shelf off Washington and Oregon have been used to show that current fluctuations are coherent over alongshore separations of at least 200 km during the summer. A set of simultaneous current records over the continental shelf and slope have been used to establish the existence of jet-like poleward undercurrent over the slope.

An experiment to investigate the coherence of currents from Vancouver Island to mid-Oregon during the winter and spring seasons was implemented successfully in 1975. Results indicate that current fluctuations were coherent over distances of 500 km and that the spring transition occurred within one day at all locations from Vancouver Island to Oregon. An intensive hydrographic experiment was carried out simultaneous with the longshore experiment to investigate the response of the density field to

the wind. Analysis of data obtained from both of these programs is continuing. The data are being compared with an existing time-dependent physical oceanographic model.

A current meter system capable of measuring three orthogonal components of the velocity field at frequencies up to 5 hz has been designed and tested. This device will be used to examine the turbulent structure of the bottom boundary layer, to investigate the interaction between wind waves and wind-driven bottom currents and to make measurements on the inner part of the continental shelf. Experiments designed to study the cross-shore structure of shelf currents and the seasonal variations of the poleward undercurrent over the slope are planned for 1977-1978, respectively. The latter project is in conjunction with Oregon State University. (Hickey, Smith)

The continuing study of critical resuspension of sediments (see VII *A*) will contribute to the understanding of the continental shelf by contributing additional data on bottom currents and tides. (Larsen)

Analysis of current measurements and related data, obtained during October-November 1971 in the Juan de Fuca submarine canyon, on the surrounding continental shelf, and in the entrance of the strait is continuing. Flow in the canyon substantiated, in general, earlier speculations. Inertial oscillations were observed only in the surface layer over the shelf; outflow was observed in the deeper waters in the mouth of the strait for periods of several days corresponding with out-canyon flow and major storms. (Cannon)

B. Barotropic Response to Storms

An experiment to study the response of the shelf circulation to storms and in particular to investigate the interdependencies among wind, current, and bottom pressure is being conducted. An array of six moorings measuring bottom pressure and midwater currents has been maintained on the continental shelf in the northeastern Gulf of Alaska since November 1975. Preliminary results indicate that during winter when the water on the continental shelf is well mixed, the bottom pressure gradient fluctuations are well correlated with the velocity fluctuations. The response is largely barotropic. However, during summer, the influence of offshelf perturbations and/or baroclinic effects appear more important. (Hayes)

C. Theory of Coastal Currents and Upwelling

A numerical model has been developed to study the time response of a rotating stratified shelf sea to local wind forcing. Assumptions of longshore uniformity are made, and so the model describes the vertical currents and density structure in a section normal to the coast. Both mixing and advection are included and, for a constant equatorward wind for the west coast shelf region, the system can be spun up from an initial state of rest with level isopycnal surfaces toward a steady state where the offshore advection along with vertical and horizontal turbulent diffusion produce the inclined isopycnal surfaces and density fronts associated with upwelling. The effect of the density structure on the alongshore current in producing characteristic shears compares with analyses of current meter records from the Oregon Coast.

The effect of shelf-like topography has also been studied with reference to the northwest African upwelling system, which has different physical characteristics than the Oregon-Washington shelf, including stronger more persistent winds, weak rather than strong stratification, and a relatively shallow shelf with a steep continental slope. Results compare favorably with hydrographic sections and current meter data from the region (Figure 3a-c).

Future developments include the extension of the model to three dimensions to study the effect of longshore variability and the development of a better representation of turbulent processes using recently developed higher order closure models. The model has also been used as a time-dependent physical input into an ecosystem model to study the growth of phytoplankton in an upwelling region. (Hamilton)

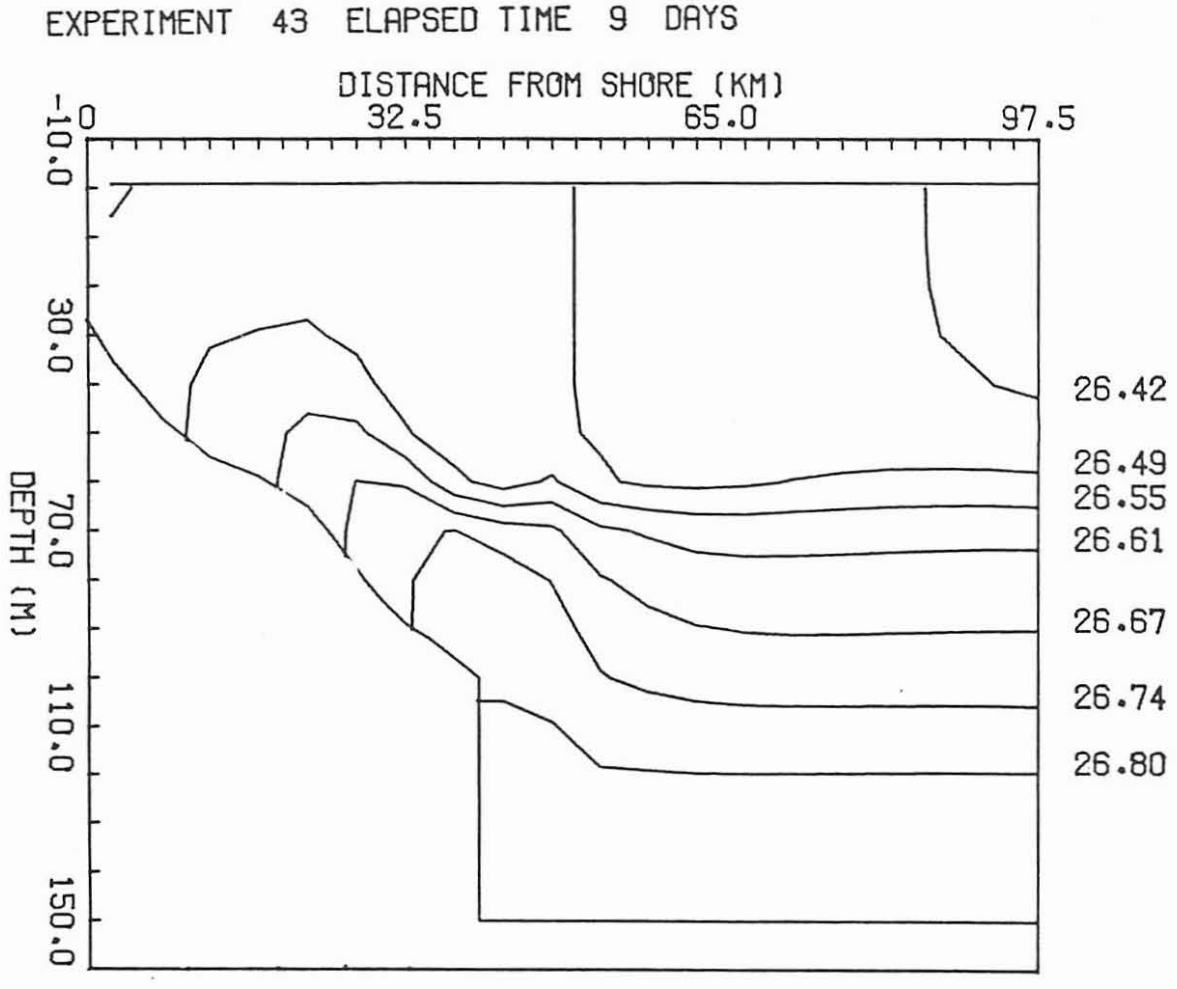
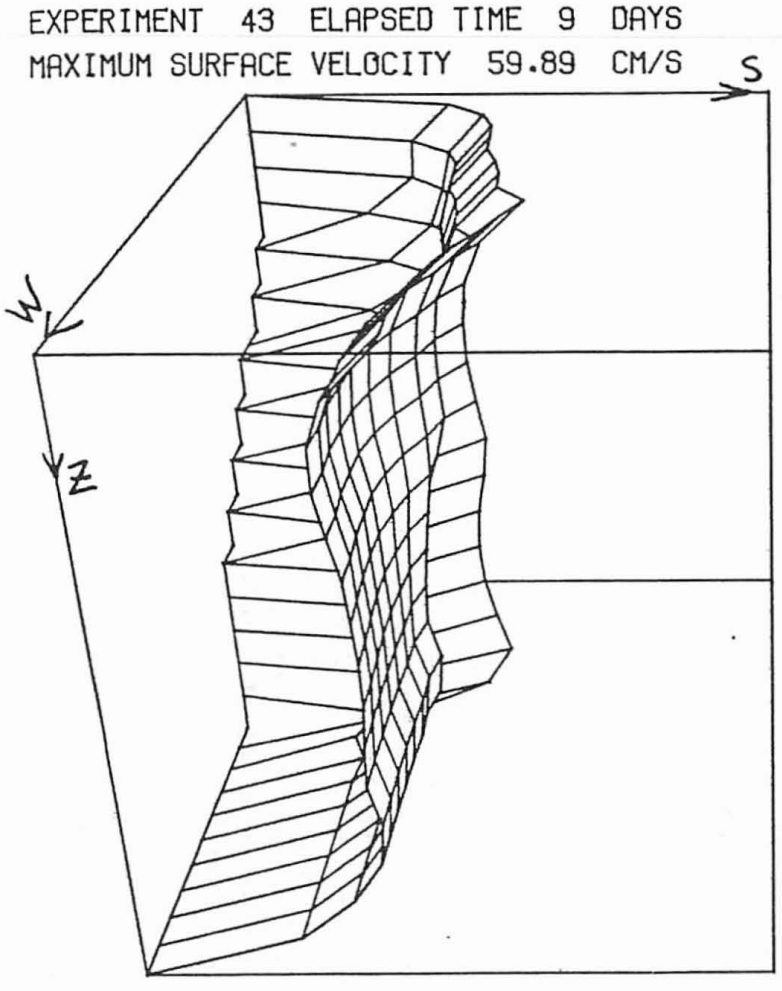
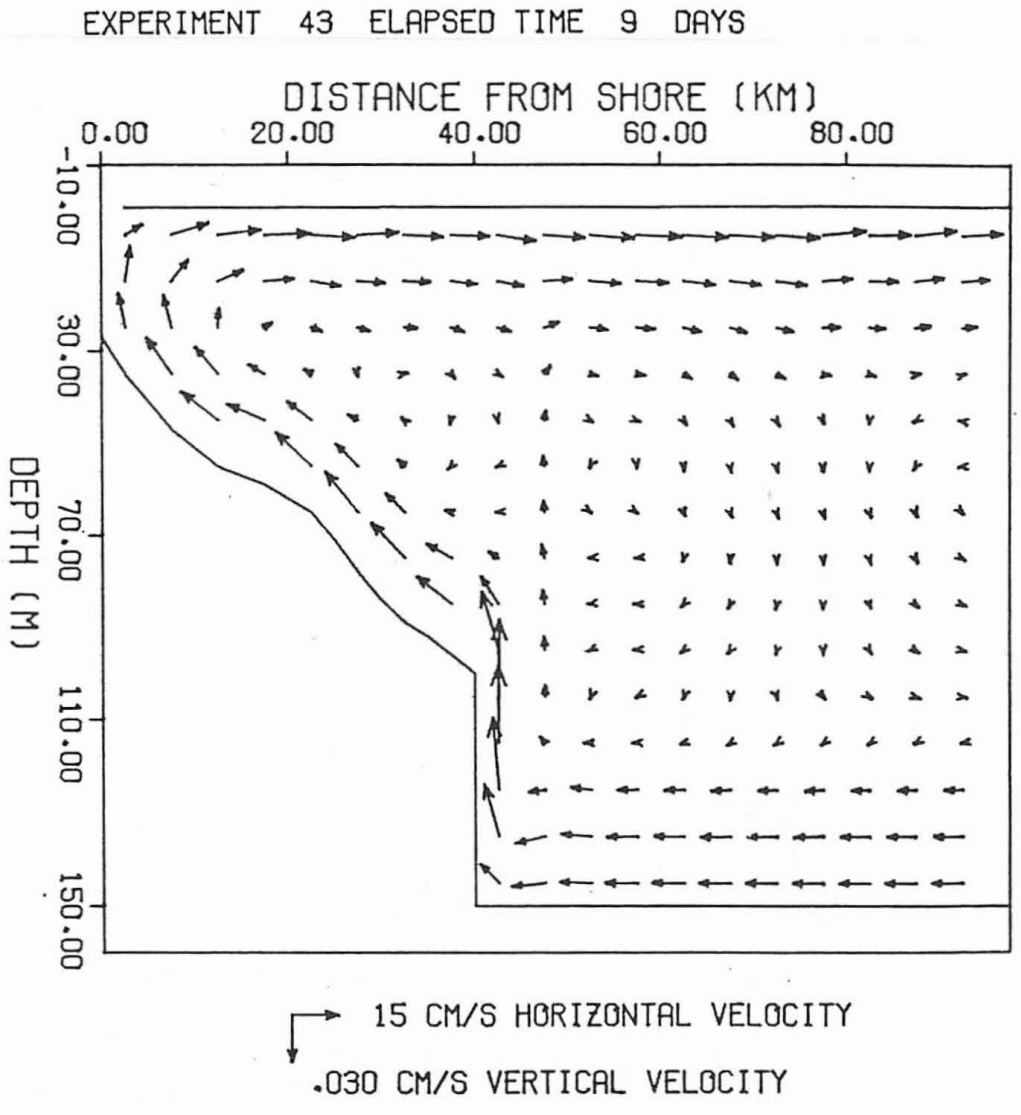


Figure 3. Effect of shelf-like topography, northwest Africa, 26° 21' N.

a. Density distribution after nine days strong wind from the north.



b. Longshore velocities (3-dimensional plot)



c. Cross-shelf velocities

VI. Estuarine Processes

Research in this element is directed toward understanding the processes occurring in these semienclosed bodies where the seawater is appreciably diluted by mixing with the inflowing river water. These processes are unique by virtue of strong gravitational convection, strong tidal currents, and/or large net flows due to river inflows. Such areas are high in biological productivity and for this and other reasons important to man. Quantifying the processes governing the system is scientifically interesting and practically very important.

A. Near-Surface Circulation in Fjords

It is characteristic of fjord flow that the most vigorous circulation takes place in a brackish water zone near the surface. In fjords with appreciable freshwater input, the flow is generally characterized by one or two reversals in horizontal current direction. The surfaces of no mean motion define the boundaries of two or three circulation zones whose structures change in response to changes in wind and run-off intensity. When most of the freshwater comes from river discharge near the head of the inlet, in the absence of winds, the circulation tends to be a two-zone system in which the uppermost zone moves persistently seaward above a landward-moving deeper zone of saltier water. The salinity of the uppermost zone tends to increase in the direction of the mean current due to entrainment of denser, more saline water from the zone below.

One of our primary objectives is the development of an approximate analytical representation of gravitational convection and density structure in the near-surface flow regime. The utility of similarity techniques has been explored in the hope that relatively simple description would emerge for the quasi-steady, nontidal component of fjord circulation. We have made progress with a similarity analysis based on the use of exponential functions of the longitudinal coordinate of the fjord. Approximate solutions for the velocity field and density distribution have been obtained and the results applied to near-surface zones, i.e., above sill depth, of segments of Hood Canal (Figure 4) and the central basin of Puget Sound.

An important shortcoming in the above models arises from inadequate knowledge of the turbulent exchange processes acting in these highly stratified surface layers. Complementary to studies of this problem by direct observations of turbulence in stratified fluids, we are investigating the applicability of various functional relationships for eddy coefficients in terms of the density and velocity profiles which control the turbulent processes to data obtained under a variety of fjord flow conditions. An improved representation for these coefficients will enable significantly better theoretical models of the near-surface circulation in fjords. (Winter, Rattray)

B. Mathematical Studies

In addition to similarity analysis, two other mathematical approaches are being examined for use in modeling steady-state gravitational

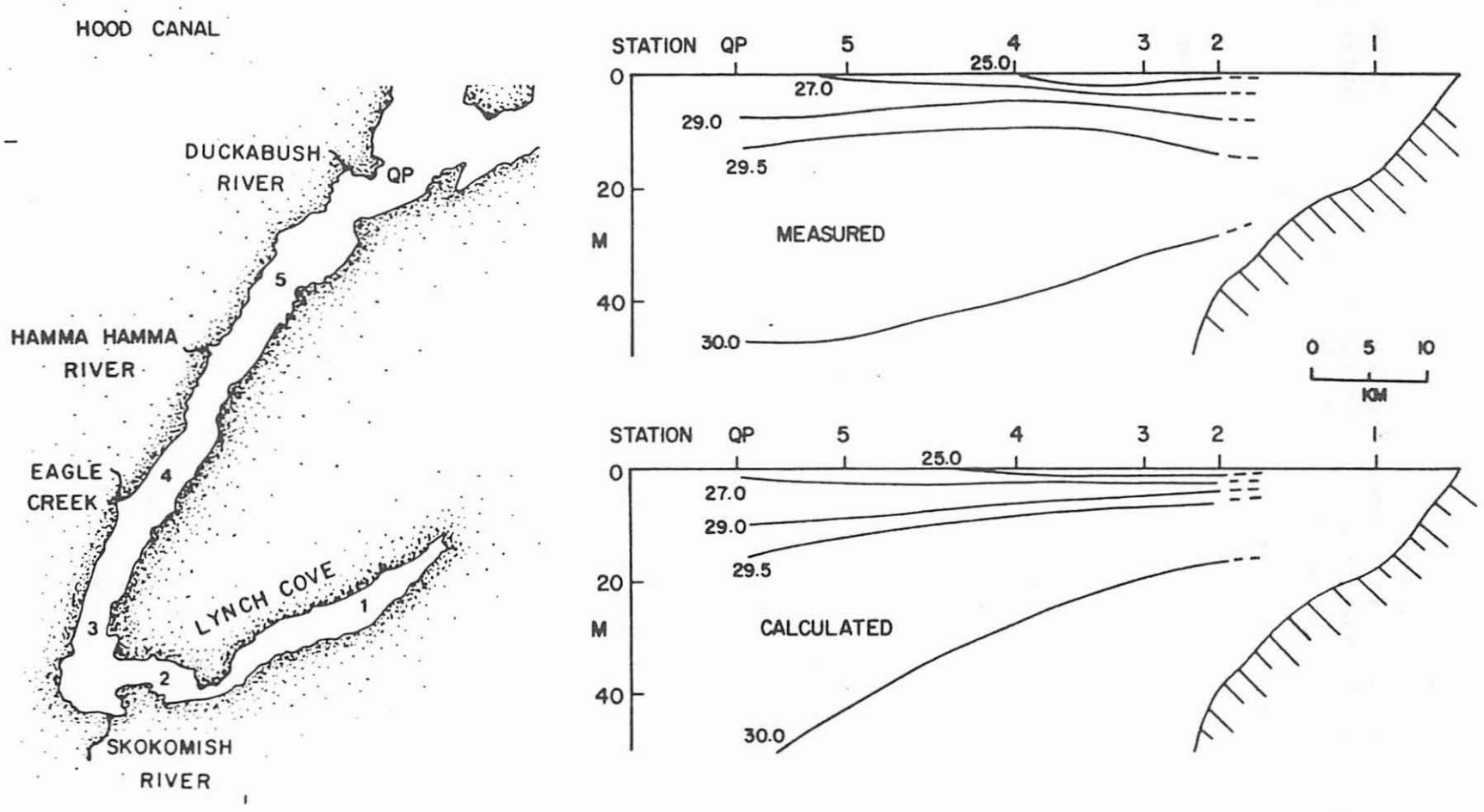


Figure 4. Comparison of measured and calculated salinity distributions in Hood Canal.

convection and wind-driven flow in stratified inlets. The first approach involves a two-zone flow representation which differs from earlier layered models in two important respects: (1) Effects of common bathymetric features (sills and channel constrictions) can be calculated and (2) turbulent and/or advective transport between zones is included in the formulation. The second approach involves a variant of the method of weighted residuals in which the dependent flow variables (density, velocity components, and free surface height) are continuous functions of depth and axial distance along the inlet axis. Both techniques are being used to calculate velocity and density fields over extensive segments of local inlets. The results from each approach appear to be consistent with one another and with observations to the extent allowed by the approximations invoked. The total computation time required for each procedure is quite small (a fraction of a minute on the CDC 6400). These same mathematical techniques, used here to describe estuarine hydrodynamics, can be adapted to modeling biological and chemical processes in inlet waters.

A second phase of this project has as its objective the efficient computation of tidal currents in estuaries. To determine time-dependent currents in a partially or well-mixed estuary, corresponding to a prescribed tidal input, it is customary to use numerical time-stepping procedures to solve the governing equations. A matter of practical concern is the excessive computer time which is often required by this process. We are presently developing an alternative method, in which modal decomposition is used; the nonlinear terms are included by use of iteration. Each iterative step uses a finite element formulation to solve an associated variational problem. Considerations of complex boundary conditions, accuracy, and stability are presently under investigation in this project. For a number of estuary problems of practical interest, it appears that this new approach will lead to a large saving in computer time. (Winter; C.E. Pearson, Department of Aeronautics and Astronautics)

C. Circulation and Exchange Rates in Puget Sound

Current records that were obtained at nine depths in Port Susan, near Everett, Washington, show both a correlation between the wind and some of the currents and a predominant three-layered mean flow (Figure 5). Based on these observations, and because of the low river runoff into Port Susan, a wind-driven, two-layered model was created to explain the currents. The river discharge did not contribute to the dynamics of the model but was assumed to maintain the two-layered nature of the system, with a less dense top layer.

This model predicted both a mean flow with three layers of water moving in opposing directions and a multilayered flow at a period of about 60 hours, the period of the dominant winds. Furthermore, the amplitudes of the currents as a function of depth that were predicted by the model are in good agreement with the data. Changes in the modeled currents in response to changes in the thickness of the near-surface, low density layer are also in qualitative agreement with the measurements. (Lam)

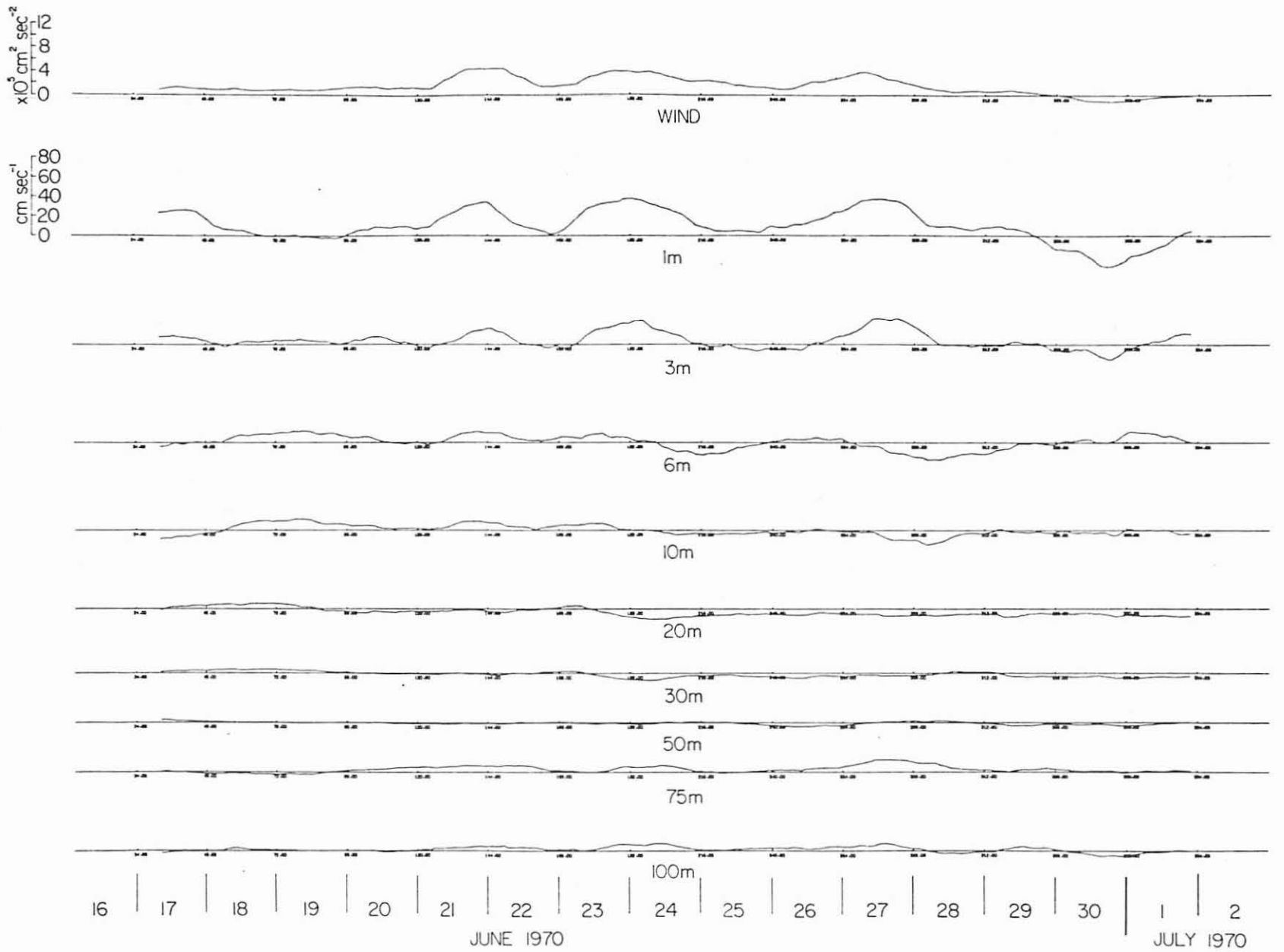


Figure 5. Times series of axial wind stress and current speeds in Port Susan, Washington. Daily or higher frequencies have been filtered from the data.

The program to investigate the dynamics of Puget Sound, conducted by the Pacific Marine Environmental Laboratory during winter in 1972 and 1973, has been expanded. Currents and water properties were measured at several levels from a subsurface mooring at the same site (near West Point, main basin) as the previous studies for the year beginning in September 1975. The mooring was replaced at 2-3 month intervals during which time an STD section was occupied from Tacoma to beyond Port Townsend. Winds were monitored at West Point. These data, as well as previous data, are being analyzed to determine the net long-term circulation and mixing characteristics throughout the water column. A two-dimensional model of the sound as a fjord-type estuary is being formulated to simulate the major flow characteristics of the central basin. (Cannon, Galt)

A new program to study the dynamics of the Strait of Juan de Fuca was initiated by the Pacific Marine Environmental Laboratory in 1976. For approximately a month, currents were measured in a section across the strait and related STD and wind measurements were taken. The results of the study are being analyzed. (Cannon)

A one-year current meter deployment in Hood Canal will be completed in February 1977. This study will provide data on eddy formation by promontories. (Shi [Larsen])

D. Exchange Processes in Estuaries

The circulation and water and salt exchanges in estuaries are being investigated in several interrelated studies. These include studies of estuarian straits, the influence of sills, and studies applicable to the middle reaches of estuaries.

A cooperative investigation with the Department of Environment, Canada, took advantage of their extensive current-meter coverage in a cross section of the Strait of Juan de Fuca to jointly run longitudinal and lateral density profiles over a number of tidal cycles. The data are being analyzed to determine the dynamic and salt balances under the given external conditions. (Dworski, Rattray)

The importance of the tidal motion in the horizontal diffusion of salt for tidal estuaries is well recognized; however, there are no theories that adequately relate the salt flux to the tide. Preliminary calculations suggest that in certain cases a significant contribution to this salt flux can occur in the bottom boundary layer, but that the actual transport will depend critically on the nature of the boundary layer. This phenomenon is being investigated by combining the theoretical prediction with an experimental program to both guide and validate the theory. A preliminary joint experiment was carried out in the Strait of Juan de Fuca, in cooperation with the Pacific Marine Environmental Laboratory, in which both velocity and salinity profiles were measured at a high sampling rate over an interval of 3.6 days. Analysis and interpretation of the data are continuing. (Dworski, Galt, Hamilton, Irish, Larsen, Rattray)

Theoretical studies are under way to determine the effects of non-rectangular cross section and channel curvature on the circulation, salinity distribution, and exchange processes in estuaries. The solution will be obtained by expansion in terms of an appropriate parameter, with the case of large vertical mixing to be the first considered.

Theoretical calculations have indicated that the transport of salt by tidal currents in a partially mixed estuary has a strong vertical dependence; in fact, the transport might be seaward near the bottom. Lateral boundaries induce a similar behavior with minimal landward salt transport near shore and greater transport in the main channel.

We are investigating the effect that these boundary layer phenomena may have on inducing a lateral circulation within the estuary. Additional causes of lateral circulation result from a dynamic interaction with bottom topography. Near shore eddy formation in the Hood Canal entrance, although not a partially mixed estuary, is being studied. We are attempting to measure the vorticity input to the main stream as it depends on tide range for a particular channel configuration. Additional studies have been initiated with the cooperation of scientists in Japan. Their interest lies in explaining the salt balance in the Seto Inland Sea. (Shi [Larsen])

A field study of Peel Inlet, Western Australia, is being carried out to measure exchange rates between the large shallow inland sea and the open Indian Ocean. (Larsen)

E. Salt Wedge Estuaries

A theoretical study giving the circulation and salt wedge configuration in a class IV estuary has been completed for a model estuary of rectangular cross section with a constant bottom slope. Comparison between theory and observation is favorable for the Mississippi and Duwamish rivers.

An experimental program to measure the turbulent salt flux in the Duwamish River under a number of flow conditions ranging from a salt wedge to a moderately mixed estuary has been conducted. The observed conditions for salt wedge breakdown are being compared with the theoretical studies.

During the past year equipment including a small floating research platform has been assembled. From this platform are suspended hot film probes that are capable of resolving frequencies of up to 25 kHz. The first field test in January 1977 established that the system was noise free and that we will be able to measure turbulence intensities in the vicinity of strong density discontinuities such as are found in salt wedges. Knowledge of the true nature of the turbulent intensity will support or deny an assumption in the theoretical model by Mitsuda. (Mitsuda [Larsen])

F. Stability of Estuarine Flows

Mean velocity-density combinations that are typical for different types of estuarine flows (salt wedge, coastal plain estuary) are being

investigated for stability. It has been found that two major effects emerge for this kind of family: (1) Increasing the position of displacement of the maximum density gradient from the position of maximum shear results in unstable modes with larger amplication rates for the same values of the Richardson number; (2) The proper combination of the free-surface condition with the mean profile-density results in larger values of the wave numbers than is usual for oscillations. (Criminale, Hamilton)

VII. Sediment Transport

The purpose of this element is to elucidate the phenomena of sediment movement in the marine environment. Investigations include theoretical studies of the dynamics of boundary-layer flows and associate grain movement; field experiments of natural flow conditions relating to sediment motion; and descriptive studies of the sedimentary processes in various marine environments (see also V).

A. Wave-Sediment Interaction

The goal of this program is to delineate the physical and geological factors responsible for various sediment types found on continental shelves. Seagoing equipment has been upgraded so that detailed data on waves and currents may be correlated with photographs of the bottom and transmissometer measurements. The new system which employs a microprocesser control has had two successful field trials in Puget Sound. The initial sea deployment is scheduled for March 1977, followed by field trials during the summer so that modifications of the equipment may be made, if needed, in preparation for the major thrust during the winter 1977-1978. We plan to monitor conditions at locations on the Washington Continental Shelf that contain different sediment types. The threshold conditions for sediment resuspension will be examined at each location. (Larsen, Sternberg)

B. Modern Sediment Accumulation on the Washington Continental Shelf

This project is a study of sedimentation on the Washington shelf, and involves an examination of the relationship between modern sediment accumulation and oceanic processes. The specific objectives are to establish a modern sediment budget for the Washington shelf and to evaluate existing theoretical models of Holocene sedimentation. A Pb^{210} radioactive dating technique is being used to determine modern sediment accumulation rates over the past 100 years, and to delineate trends in accumulation. To evaluate sedimentation trends over the past 10,000 years, shallow seismic reflection profiles (3.5 kHz) are being employed. Also being investigated is the influence of the major sedimentary processes (physical and biological) on the accumulation of modern Washington shelf sediments, which involves the detailed examination of sedimentary structures, bottom currents, and benthic biology at specific sites. (Nittrouer [Sternberg], Jumars)

C. Investigation of Bottom Currents and Associate Sediment Movement in Westernport Bay, Australia

In October 1974 a study was initiated in cooperation with the Geology Department of Melbourne University, Australia, to investigate sedimentary processes in Westernport Bay, a complex tidal embayment adjacent to Melbourne, Australia. The measurement program consisted of nine one-week stations to record bottom currents, bed configuration, relative turbidity, waves, and tides occurring within the major channels and the entrance to Westernport Bay. Seabed drifters were also used to elucidate the net flow and sediment dispersal paths within the bay and adjacent continental shelf.

These data have provided estimates of the frequency of bottom sediment movement, mode of transport, dispersal routes, and mass transport of bedload at various sites throughout the bay. The results have been used to evaluate the impact of several harbor dredging proposals. The study program is continuing in Westernport Bay and also is being expanded to include other coastal embayments in Victoria, Australia. (Sternberg)

D. Theoretical Studies

In conjunction with the turbulent boundary layer and coastal circulation experiments that are described in other sections (see IV *B*, V *A*) and with lectures being prepared for advanced sediment transport courses, the fluid mechanical foundations of sediment transport theory are being examined. At the present time the focus is on the following aspects: bedload transport under conditions of low to moderate concentration, the interaction of the bedload layer with the non-sediment transporting flow above it, the transition from bedload to suspended load transport, and the concentration profile in the immediate vicinity of the bed under suspended load conditions. The method being used employs the sediment-fluid momentum equations in conjunction with mass conservation expressions for each component and is analogous to, but more general than, the approach followed by P.R. Owen in his investigation of saltation of uniform grains in air. (McLean, Smith)

VIII. Marine Stratigraphy

Marine stratigraphy involves description, correlation, and interpretation of sediments and sedimentary rocks of the deep sea and continental margins. Information gleaned from this field is applied to the study of global tectonics, geological and climatic history, the evolution of planktonic life forms, and the economic potential of shelf and deep-sea areas, among other subjects.

A. Role of the Kobuk and Kaltag Faults in the Tectonic Evolution of Western Alaska

Data from marine geophysical studies in the northern Bering Sea and southern Chukchi Sea have been used to trace the offshore extensions of two of the major transcurrent faults in northern Alaska. The Kaltag fault extends for more than 300 km offshore beneath St. Matthew Basin south of St. Lawrence Island. Offset along the onshore segment exceeds 120 km (right-lateral) since Cretaceous time. The existence of the Kobuk fault has only recently been proven. Its offshore extension can be traced for more than 170 km east of Kotzebue Sound beneath Hope Basin, and offset along this large fault has been in a left-lateral sense. A tectonic model is being derived which attempts to explain the role of these great transcurrent faults in the light of known facts regarding regional geology and tectonics in western Alaska and eastern Siberia. The model places several constraints on relative movements between the two continents and evolution of the Arctic Basin. (Holmes)

B. Silicoflagellate and Radiolarian Studies

The research program for the study of siliceous mocrofossils has been continued with the main effort being toward the establishment of the silico-flagellate biostratigraphy of the North Pacific Ocean.

The analysis of selected core sediments from Legs 5, 6, 16, 17, and 18 of the Deep Sea Drilling Project in the eastern North Pacific were completed. By far the best succession of this group of microfossils was observed from the continuously cored Site 173, off Cape Mendocino, California. Diversified calcareous nannoplankton, diatoms, radiolarians, and planktonic foraminifera assemblages recorded in nearly all samples, which ranged from Early Miocene to Recent, provide the basis for delineating the geological range of taxa. The microflora and fauna distinguished in the samples represent a mixture of cold-water and warm-water species, thereby bridging the high and low latitude assemblages. Additionally this deep-sea sequence from Site 173 should serve as a basis for attempting correlation with California Tertiary land sections. The results of the investigation were presented (1-CPNS) at the First International Congress on Pacific Neogene Stratigraphy in Tokyo, Japan, in May 1976.

A similar study of the western North Pacific region has been undertaken in 1976. Included as one of the major objectives is the detailed examination of outcrop samples from several Late Cenozoic-type sections of Japan collected during the two U.S.-Japan Cooperative Programs, and their correlation with the deep-sea biostratigraphic zonation of the North Pacific.

Through participation in the Dry Valley Drilling Project in Antarctica, 264 cored samples from seven drilled holes were obtained. Silicoflagellates and radiolarians were found in cores from Holes 8, 9 and 10 in the New Harbor area of McMurdo Sound. These occurrences are being evaluated with the results of similar studies on diatoms and foraminifera, as well as oxygen isotope and microfabric analyses of sediments, to interpret the geological history of Antarctica.

Investigations of Late Mesozoic radiolarian assemblages have been continued: more samples from the San Juan Islands and various localities throughout southeast Asia have been obtained. Since sufficient specimens of diversified forms have been recovered, detailed microscopic examination including observation under the scanning electron microscope are being carried out. The results of the study would provide a needed age-framework for sediments associated with the ophiolite suites, which in turn would have an impact on previous tectonic interpretation of the respective areas. (Ling)

C. Paleontologic Synthesis of Cenozoic Deep-Sea Data

Research during the first two years was mainly concerned with small-scale projects involving limited resources and a small group of individuals. Subsequently the program comprised a number of individuals who directed their major efforts toward large-scale projects, including the tentative establishment of a computer-based paleontological data bank. The initial purpose of the data bank was to advance research on nannofossil stratigraphy at the University of Washington but outside encouragement led to a proposal, recently submitted to the National Science Foundation, to establish a permanent data bank for all fossil information collected by the Deep Sea Drilling Project (DSDP).

The present program is intimately concerned with paleoenvironmental problems as they relate to the fossil record. In many instances it is possible to test environmental models by examining this record, and the program has made significant contributions to automated production of paleoenvironmental maps, using techniques that are easily adaptable to many contemporary environmental problems. This work is carried out in close collaboration with Scripps Institution of Oceanography sedimentologists who are developing a lithological data bank for DSDP cores, and University of Miami scientists who are constructing a data bank of world tectonic data for use in paleoenvironmental models based on the present environment.

The major successes in stratigraphy and marine micropaleontology have come in the area of automating and computerizing calcareous nannofossil biostratigraphy, using cores and published information about them provided by the DSDP. Initial conclusions are that (1) at any level of probability the biostratigraphic resolution in any given area (local or global) can be doubled using an internally consistent body of data when processed within a probabilistic framework; (2) sequences change appreciably among differing oceanic, climatic, and water-depth regimes; (3) higher biostratigraphic resolution is obtainable at lower rather than at higher latitudes.

The benefit of processing paleontologic data by computer is that for the first time in paleontology the minimum acceptable results may be specified in order to estimate the amount of work necessary to accomplish the project before starting it. Conversely, it is also possible to estimate the type of results a given amount of investigation can be expected to produce.

Recently a series of 60 maps of the Pacific Ocean were produced using the combined data for the paleontological and lithological data banks. These maps show the accumulation rates in $g/cm^2/10^3yr$ for the carbonate, silica, detrital components, and the total of those three fractions for three million year intervals back to 45 million years. Calculating rates in the above units avoids the complications of compaction of sediment with burial and allows, for the first time, a reasonable history of the fluxes of these components through time. (Worsley and students)

IX. Coastal and Shelf Sedimentology

The purpose of this element is to investigate the sedimentological nature of estuarine and continental shelf environments. Studies include the origin and classification of sediments, distribution of sediment types, rates of deposition, and interpretations of the geological history of shallow marine environments.

A. Post-Wisconsin Transgressive Sequence

A study of the section of unconsolidated sediment on the continental shelves of the western Laptev, East Siberian, Chukchi, and Bering seas is nearing completion. The findings of fifteen years of examination of the surface sediments and stratigraphy of these continental shelves have been published, are in press, or are in rough manuscript form. The results provide the first relatively complete picture of post-Wisconsin transgressive sea sedimentation under arctic and subarctic conditions. The unconsolidated sediment sequence is generally less than 25 meters thick over much of the shelf beneath this shallow, broad, epicontinental-type sea. The thinness of the sequence, the brief time span (mostly post-Wisconsin) of the sequence, and the presence of pronounced marker horizons in the section make the area an excellent model for the study of the sedimentary sequences from transgressive seas. Subbottom acoustic reflection profiles and analysis of sediment collected from both the surface and at depth in the post-Wisconsin sequence reveal significant detail on the modern sedimentary environment and the environments of deposition during transgressive sea level. These environments range from the classic basal sands through nearshore and offshore marine facies; they can be seen to interfinger with stillstand river deltaic deposits and deposits that appear to be previously undescribed marine "deltaic" which are related to unidirectional rather than tidal flow.

Ultimately this investigation will permit comparison of the transgressive and modern sedimentary sequences on shelves open to the Arctic Ocean (the Chukchi Sea is bordered on the north by a sill separating it from the Arctic Ocean) and the open waters of the Bering Sea. Additionally it is our intent to seek further understanding of the details of latitudinal variation of sediments and sedimentary environments by comparison of the arctic regions to the west of the Chukchi Sea and the subarctic regions of the Bering Sea with the Chukchi Sea. As the study progresses southward it would be possible to tie-in with Russian studies of the southwestern Bering Sea shelf and Niino and Emery's studies extending from the western Kamchatka Peninsula to the Gulf of Thailand. It is also the intent to refine the dates for, and variation of, post-Wisconsin sea level and to define the southern limits of the possible paths of migration across the Bering Land Bridge and the time and rate of closure of the bridge. (Creager, McManus, Holmes)

B. Recent Sediments of Puget Sound and the Outer Continental Shelf

The character and distribution of suspended particulate matter and of specific components of surface bottom sediments in the central basin of Puget Sound and on the outer continental shelf is being examined. The initial experiment was designed to determine an "optical signature"

for suspended particulates associated with outfall wastes and to distinguish these from naturally occurring river input and marine detritus. Continuing studies attempting to establish links between the mineralogy and chemistry of the surficial bottom sediments and the distribution of these parameters in the suspended particulate matter are being conducted. (R.E. Burns; E.T. Baker, Pacific Marine Environmental Laboratory)

X. Micropaleontology of Sediments

The program is directed toward a better understanding of the major siliceous and calcareous components of marine sediments. The taxonomy, evolution, ecology, and distribution of each major group of organisms, in space and time, are being investigated.

Investigations of Late Mesozoic radiolarian assemblages from the outcrop samples associated with ophiolites exposed on Vancouver Island, Canada, the San Juan Islands, Washington, and islands throughout southeast Asia are continuing.

The study was initiated with the cooperation of personnel from the University and the Geological Survey of Malaysia, several universities of Japan, and the Geological Sciences Department, University of Washington. The main objectives are to obtain fossil evidence for the age of the sediments and to furnish a guide for the interpretation of the tectonic history of the concerned areas.

Thus far, the main effort has been to recover as many specimens as possible from samples of different lithologies. Detailed examination of these microfossils, including observations under the scanning electron microscope, has been initiated. Sufficient specimens of diversified forms are now on hand so that it should be possible, when the study is completed, to define the age of the deposits more positively. (Ling)

XI. Global Tectonics

This program involves the use of marine geophysical techniques in the study of the large-scale tectonic processes. Historically, the method is not very old (post-World War II), but it has already resulted in a great unifying theory for geophysics and geology: the plate tectonics explanation of continental drift. The new concepts have already revolutionized research on earthquake prediction and regional prospecting for minerals and oil.

A. Thermal-Tectonics of Plate Boundaries

Attempts are being made to integrate the results of heat flow and topographic, seismic-reflection and seismic-refraction measurements with physical models of both sea-floor spreading and lithosphere subduction. Considerable success has been achieved in explaining the phenomena at spreading centers, including the systematic decrease of topographic height with age, the thermomechanical processes responsible for the characteristic structures in Ophiolite suites (ocean floor exposed on land) and acoustic-velocity anisotropy in the mantle. Similar studies are in progress on the mechanics of subduction zones, using a somewhat more limited library of data, but set against a background of more primitive geomechanical models. (Lister)

B. Driving Forces of Plate Tectonics

In conjunction with a Geophysics course, some theoretical work is being done on the greatest outstanding problem of global geophysics. If we understood the forces that drive the plates, we would have a valuable clue to the dynamic processes deep in the mantle, since an understanding of the history of plate motion by means of the dynamics involved implies a general picture of the internal workings of the mantle. Obvious important phenomena are the absorption of subducted plates and the generation of new "hot spots" and rift zones. At present, the integration of geochemical data into the physical picture is one of the main weaknesses in the field, but some progress is being made on the purely physical side. (Lister)

C. Geophysical Studies of the East Pacific Rise

Detailed seismic and magnetic studies of the East Pacific Rise have been undertaken on the Cocos plate (17°N) and in the Gulf of California (22°N). Results from the Cocos plate experiment indicate a thickening of the crust with age that could be due to a hydration of the uppermost mantle producing low velocity material. The Gulf of California work was primarily to survey a site for a deep IPOD hole. In the course of this survey it was found that the East Pacific Rise off Baja California has an axial valley and that this valley is probably underlain by a small magma chamber. Analysis of these data is continuing. (Lewis)

D. Geophysical Studies of East Pacific Trenches

Our interest have extended recently to trenches and a highly successful experiment was conducted off Peru in June 1976. This was

a joint experiment involving Peruvians and North Americans. Our part was the deployment of ocean bottom seismometers and the firing of shots for our instruments and land stations. Some of the results of this experiment have been submitted for publication. (Lewis)

In 1978 we will be undertaking a study of the Washington-Oregon margin to see if trench structure exists here. (Lewis; S.W. Smith, Geophysics Program)

XII. Genesis of the Oceanic Crust

This element, another aspect of marine geophysical investigation, seeks to determine the structure of the oceanic crust itself and how this varies with time after its creation. Besides the inherent scientific interest of this as yet unsolved problem, there are potentially important deductions to be made about ridge crest thermal and mineralization processes. Magnetic and seismic studies under way will help determine the structure and geological history of the oceanic crust.

A. Geothermal Circulation in the Oceanic Crust

One of the most important new fields in marine science is the study of the chemical interaction between seawater and the continually renewed rocks of the oceanic crust. The geophysical study involves (1) tracing the patterns of the convection cells and (2) estimating the temperature of the circulating waters. The former, by means of suitable laboratory-experimental and theoretical work, can provide some evidence on the depth of the circulation of seawater; the latter some direct evidence of the conditions under which chemical exchange takes place. Both investigations have been given some sound backing by extensive theoretical work on the mechanics of water penetration into hot rock. A recent advance in field instrumentation (Figure 6) has produced the first long continuous profiles of closely-spaced heat flow measurements. These confirm the dramatic and pervasive nature of hydrothermal circulation in young oceanic crust, and provide a strong impetus for further theoretical and laboratory work. (Lister)

B. Fine Structure of the Oceanic Crust

A fruitful avenue of research to study the fine structure of the oceanic crust is being undertaken. To improve the tools for examining the fine structure, a deep tow multichannel refraction-reflection system will be developed in 1977 under ONR support. The seismic velocities found with this tool will then be related to the physical properties of ophiolites and IPOD core samples obtained by N.I. Christensen. (Lewis; N.I. Christensen, Geophysics Program)

C. A Paleomagnetic, Rock Magnetic, and Opaque Mineralogy Study of Drill Cores from the Mid-Atlantic Ridge

Intensive magnetic and opaque mineralogy studies of the drill core material recovered during DSDP Leg 45 which penetrated 576 meters of igneous oceanic crust on the Mid-Atlantic Ridge have been initiated. The purpose of these studies is to determine the origin and evolution of linear marine magnetic anomalies as well as the general structure of the oceanic crust. Special attention is being focused on specific problems such as the identification of paleohydrothermal zones, the implications of the presence of several magnetic polarity units in a single drill core, identification of tectonic rotation of crustal sections, and correlation of geochemistry and magnetics data to provide constraints on possible models of mid-ocean ridge magma chambers. Additional samples obtained by

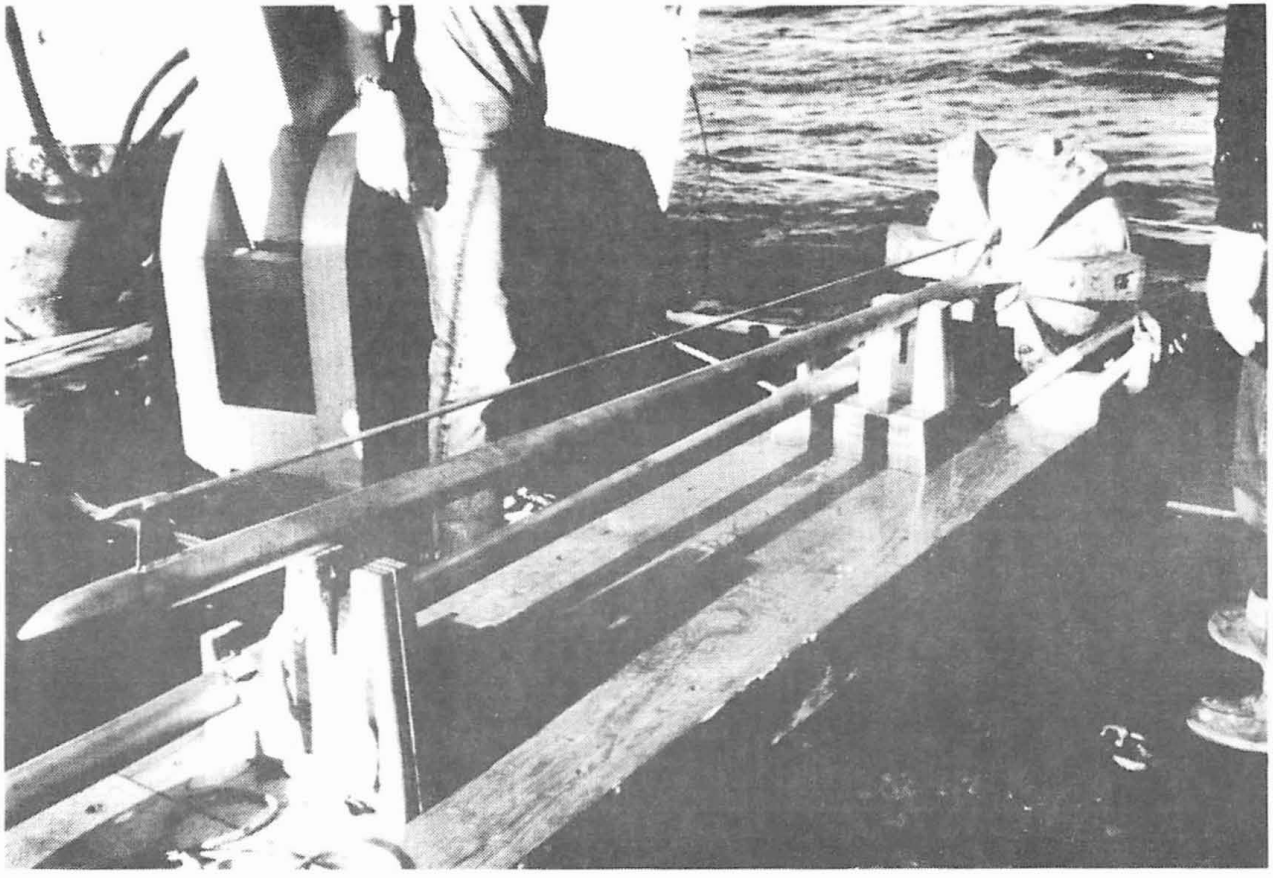


Figure 6. A new mechanical configuration for a probe to measure heat flow through the sediments on the ocean floor; temperature sensors are in the thin bar to achieve fast response. The probe is maintained under strong tension to resist bending when pulled out of the sediment. Data is transmitted to the ship via an acoustic link and is available in real time.

submersible from the FAMOUS area of the Mid-Atlantic Ridge and from DSDP Legs 16 and 34 in the Nazca Plate are also being used in these studies. (H.P. Johnson, Merrill)

D. Long-Term Anomalies in the Paleomagnetic Field

Cooperative work between the University of Washington and the Australian National University is under way to consider long-term (millions of years) deviations from the time-average paleomagnetic field from a geocentric axial dipole field. Such deviations reflect large-scale inhomogeneities in the lower mantle and/or core. Furthermore the deviations, if found significant, would require major reconsideration of a considerable body of paleomagnetic work. (Merrill)

E. Magnetochemical Studies of Marine Sediments

Geochemical studies, including trace metal and rare earth element analyses, are being combined with rock magnetic studies to help determine the magnetic and chemical history of deep-sea sediments. (Merrill, H.P. Johnson)

F. Miscellaneous Rock Magnetic Studies

A considerable effort is being made in an attempt to understand the origin of remanent magnetization in minerals and rocks. This effort includes both theoretical and experimental work and represents a long-term commitment on the part of magnetists at the University. Some studies being conducted are: the properties of remanence in single domain, pseudosingle domain, and multidomain grains; chemical remanent magnetization; the origin of drying remanent magnetization. (Merrill, H.P. Johnson)

XIII. Analytical Chemistry of Seawater

All the research aspects of chemical oceanography require an accurate description of the chemical field--a problem in analysis. Analytical methods adequate to the task are required and often must be developed and adopted specifically to marine problems or developed *de novo*.

A. Enzyme Studies

1. Effect of temperature

A comparison was made between different phytoplankton species in an attempt to measure and elucidate in the laboratory their adaptation to various ocean temperatures. The temperature at which *in vitro* inactivation of the electron transport system begins was measured for eleven species. The average inactivation temperature was between 18° and 23°C, but outstanding exceptions with inactivation temperatures as high as 43°C were noted for a tide pool species, *Dunaliella tertiolecta*. Despite the differences in inactivation temperatures, the experimental values for the energies of activation of the electron transport system for all eleven phytoplankton species studied were very similar and averaged 12 Kcal/mole. (Ahmed)

2. Electron transport system calibration

Zooplankton: Respiration rates and the activity of the respiratory electron transport system have been measured for three species of freshwater zooplankton and natural assemblages of freshwater zooplankton. As with marine zooplankton, the correlation between the two parameters is high. There is no statistical difference between the ETS/R ratio for marine zooplankton and that of freshwater zooplankton. It is concluded that the ETS/R ratio published for marine zooplankton is also valid for their freshwater counterparts. (Devol)

Bacteria: The relationship between oxygen consumption, ETS, and ATP in cultures of three species of marine bacteria are being continued. R/ETS and ETS/ATP ratios increase during the transition from the log phase of growth to the senescent phase. They level off at 0.476 ± 0.023 and 0.21 ± 0.012 $\mu l\ O_2 hr^{-1} (ng\ ATP)^{-1}$, respectively. The applicability of these relationships to deep-sea bacteria is being investigated. (J.P. Christensen [Devol])

Relationship between ETS activity and denitrification: The ETS assay will also measure electron flow through the cytochrome system of bacteria using inorganic nitrate as an oxidizing agent. For five unidentified marine bacteria isolated from local fjords and grown anaerobically, a good correlation between ETS activity and denitrification role has been observed. Since variations may exist in the ratio of ETS activity to denitrification rate similar to those found for bacterial oxygen consumption these studies are being continued and eventually will include different growth phases of eight to ten species of marine bacteria.

Using ETS activity data obtained on Cruises TT 066 and TT 076 and the relationship between ETS activity and the rate of denitrification determined in the laboratory, the rate of denitrification in the eastern tropical North Pacific has been estimated as 2×10^{13} gN/yr and 1.6×10^{13}. Similar data from Saanich Inlet indicate the denitrification rate there to be about 6.8×10^{8} gN/yr. (Devol)

Comparison of ETS activity with standard hydrographic techniques: The rates of respiration as estimated from ETS activity are being compared to rates estimated from observed changes in oxygen concentration in the deep waters of Narrows Inlet, British Columbia. At present the rates estimated from ETS activity are somewhat lower than those observed. However, the flux of oxygen into the sediments remains to be estimated. (Smethie [Devol])

B. Chromium Speciation in Marine Waters

Dissolved chromium in marine waters exists in many forms, depending on pH, E_H, and the concentration of many other ions. It is thought that Cr exists in two major oxidation states, Cr(III) and Cr(VI). A slightly oxidizing environment can convert one state to the other, similar to that for Mn(II) and Mn(IV). However, in a reducing environment, Mn(II) is soluble while Cr(III) forms hydrolysis species which are readily absorbed by sediments. For oxidizing conditions, Mn(IV) is not mobile, forming oxide coatings, while Cr(VI) is mobile as the $CrO_4^{=}$ anion. It is reasoned that the opposite nature of the dissolved species with respect to the redox potential may aid in understanding the marine chemistry of Mn and of nodule formation.

A second feature of Cr(III) is that the exchange rate for waters of hydration is very slow, with a half life of about 2 days. It is speculated that reactions involving Cr(III) may be hindered by the slow exchange of waters of hydration. This rate may dictate which hydrolysis and oxidation species are found.

Chromium studies may be useful in understanding the history of modern sediments since buried Cr will be reduced to Cr(III), allowing adsorption and/or precipitation to occur. The immobile Cr should be an excellent time indicator of the beginning of certain types of industrialization such as those involved with plating, steel, photographic, and tanning activities.

If thermodynamics equilibrium occurs for Cr(III) and Cr(VI), the oxidized species should dominate in normal seawater. Results obtained from various analytical techniques disagree as to which state is favored. The discrepancy may be due to disequilibrium or to the lack of proper equilibrium constants. It is also likely that the various methods produce differences depending on how vigorously the species are attacked and altered and by how the samples are handled.

The first priority in our Cr study was to evaluate techniques capable of analyzing for Cr(III) in concentrations as low as 10 parts per trillion. Chelation with beta diketones have proven to be useful in forming stable, nonpolar forms of Cr(III). The chelated metal is

efficiently extracted from the water with benzene. The chelate is volatile, a feature which allows it to be passed through a gas chromatograph column. An argon plasma produced by a microwave generator was used to excite the Cr eluted from the column. An emission spectrophotometer was used to detect the Cr emission, resulting in a detection limit for the system of 10 parts per billion. A second approach using atomic absorption was evaluated by injecting the extracted Cr into a graphite furnace chamber. This system offered a detection limit of 10 parts per trillion.

Further studies are being carried out to evaluate the extraction chemistry by varying pH, E_H, and concentrations of Cr(III), Cr(VI), the chelating agent, and various sea salts. Adsorption of Cr(III) and Cr(VI) onto natural suspended matter and onto the walls of storage containers has been evaluated using Cr^{51} and a NaI scintillation detector. Results indicate that Cr(III) is lost from solution to glass containers faster than to nalgene containers. Cr(VI) did not appreciably adsorb in either glass or nalgene containers.

In the future, it is proposed to evaluate the thermodynamic equilibrium by varying parameters in experimental tests. Analysis of Cr(VI) will be evaluated using a different chelating agent (ammonium pyrolidine dithiocarbamate). From the various approaches, it is anticipated that speciation of Cr in ocean and pore waters will be further understood. (Cranston [Murray])

XIV. Chemical Indicators of Oceanographic Processes

A function of chemical oceanography is the use of chemical variables to elucidate oceanographic processes. Such studies as the characterization and tracing of water masses and the reconstruction of biological events by following spatial and temporal changes in biologically mediated chemical variables are examples of this kind of research.

A method of identification and tracing of a number of water masses has been formalized. Standard hydrographic observations are used to (1) identify the tracer concentrations in the source waters, (2) trace the water masses along density surfaces and estimate the error in the inferred distributions. The method has been used to determine the distributions of water masses between the Galapagos Islands and the coast of Ecuador during the fall of 1971. (J.J. Anderson, Richards)

XV. Chemical Controls and Consequences of Biological-Biochemical Processes

The limitation imposed on photosynthetic productivity in the oceans by the availability of light and plant nutrients is an historical problem in oceanography. Newer developments are revealing a large variety of chemical controls on biological functions. These include the complex questions of the role that trace materials, such as metals and trace organic compounds, play in biostimulation or toxification of marine communities; and their effects on such basic processes as photosynthesis, ATP formation, electron transport system activity (ETS), and nitrate reduction and denitrification.

A. Enzyme Assay Estimates

Enzyme assay techniques are being currently developed to measure the dissimilatory sulfate reduction in marine waters and sediments. Both adenyhyl sulfate reduction and the bisulfite reductase activities are under study. The purpose of this study is to determine the rate limiting step in the enzymatic dissimilatory (respiratory) reduction of sulfate. The marine bacteria in the water column and sediment samples from the anoxic Lake Nitinat and Saanich Inlet are to be harvested and analyzed for their capacity to enzymatically reduce sulfate. The level of enzymatic activity is to be compared with the more conventional methods that rely on the measurement of sulfide in the water column and sediment. The *in vitro* determination of sulfate reducing capacity is being supplemented with the *in situ* measurements. The *in situ* radioassay consists of the measurement of sulfate reduction capacity of a marine water or sediment sample grown on ^{35}S- sulfate as compared with the reducing capacity of an established line of *Desulphovibrio desulfuricans* culture grown under conditions similar to the *in situ* samples. These studies are expected to yield results that will make it possible to conduct "real-time" measurements of an important biological process in marine environments which so far has been studied only indirectly by end-product monitoring. (Ahmed)

The vertical gradient (dR/dz) of the oxygen consumption rate in the Costa Rica Dome, as estimated from electron transport system activity, at depths between 100 and 3000 m is better described by the equation $R = R_o\ e^{\alpha \ln z}$ than by the equation $R = R_o\ e^{-\alpha z}$ suggested by Wyrtki and Ben Yaakov. The horizontal gradients over the same depth range are variable and reach as high as 0.55 $\mu l\ O_2\ yr^{-1} l^{-1} km^{-1}$. This value is nearly the same as dR/dz between 2000 and 3000 m (1 $\mu l\ O_2\ yr^{-1} l^{-1} km^{-1}$). The direct measurement of these gradients tends to refute the argument that deep-sea metabolic activity is unvarying.

The vertical gradient in the ATP, the living fraction of the particulate organic carbon (POC) concentration, is described by the equation: $ATP_z = ATP_o\ e^{-\beta \ln z}$, that is, the same form as the equation for oxygen consumption. Furthermore, the constants α and β are similar in value ($\alpha = 0.89$ and $\beta = 0.81$), suggesting a close relationship between the two variables.

A preliminary analysis of data taken during the first DOMES cruise at about the same latitude but further west (120°-160°) than the Costa

Rica Dome indicates the same general trend in the 100-1000 m depth interval. During the second DOMES cruise (February-April 1976) ETS activities and ATP concentrations will be determined in the 1000-5000 m depth interval. From these data an equation describing the depth distribution will be determined and the constants compared to those of the Costa Rica Dome if applicable. (J.J. Anderson, Devol)

B. Limiting Oxygen Tensions

A chemostat has been designed with dissolved oxygen as a controllable parameter, thus allowing the growth rate of bacteria to be limited by a carbon source while providing independent control of dissolved oxygen. Oxygen tension is monitored using autoclavable electrodes. This type of control permits the simulation of oxygen-deficient environments within which the growth rate of organisms is carbon limited, which may be the case in the region of the secondary nitrite maximum in oxygen-deficient environments.

Nitrate-reducing and denitrifying bacteria have been isolated from several oxygen-deficient or anoxic marine environments. Chemostat studies are being carried out with these organisms to elucidate their physiological response to low oxygen concentrations by monitoring indices such as the level of respiratory enzyme activity, ETS, ATP, cell yield, and rates of oxygen and nitrate consumption. The resultant physiological data will allow us to interpret field data more intelligently and to model the processes responsible for the generation and maintenance of water masses with low concentrations of dissolved oxygen. (R.J. Ozretich)

The kinetics of oxygen uptake have been determined for nine species of marine bacteria. In general, kinetic constants agree with those that have been determined for terrestrial and enteric bacteria. The kinetic constants indicate that bacteria from the eastern tropical North Pacific have a higher affinity for dissolved oxygen than those from the oxygen minimum zone of Saanich Inlet, British Columbia. Thus the oxygen concentration at which these organisms switch from oxygen to nitrate respiration is probably lower in the eastern tropical North Pacific than in Saanich Inlet. This observation is supported by observed distributions of secondary nitrite in the two areas. (Devol)

Bacteria have been isolated from open ocean and nearshore oxygen-deficient or anoxic environments; the genera *Vibrio* and *Pseudomonas* have been identified. Two marine isolates and three type cultures have been grown in both batch and continuous cultures. Results from the continuous culture experiments indicate the following:

1) Nitrate reduction begins during a complex oxygen uptake rate to oxygen concentration relationship and after the oxygen concentration has been lowered to at least 10 μM. The oxygen level of initial nitrate reduction appears to be species dependent.

2) Cellular yield during anaerobiosis has been found to be less than aerobic growth but the percentage of reduction is species dependent.

3) The mean electron transport system activity is approximately 2.0 times higher during dissimulatory nitrate reduction than during aerobic growth.

4) Denitrification was observed in response to a complex, unresolved interaction of growth rate, and the nitrate and nitrite ion concentration.

Work is continuing with the objective of determining *in vitro* interactions of processes at low oxygen tensions which may help interpret field observations made in oxygen-depleted and anoxic environments. (R.J. Ozretich)

C. Role of Trace Metals and Their Speciation in Photosynthesis and Respiration

Efforts have been made to develop the analytical methods, as well as conduct laboratory and field studies, necessary to understand the role of trace metals in photosynthesis and respiration. These studies involve detailed examinations of trace metal speciation, particularly the capacity of seawater to chelate metal (copper) ions, and the characterization of the organic ligands.

The studies include determining the temporal-spatial distribution of organic chelating species and characterizing them by molecular weight and functional group analyses. Samples from surface, deep, and interstitial waters of Narrows Inlet and from the entire water column of Saanich Inlet, both in British Columbia, are being so analyzed. Voltammetric titrations indicated significant organic chelation only in samples from the upper 10 meters of Saanich Inlet in June. Gel filtration separations of organic matter from pore waters, surface waters, and anoxic waters showed that the complexing capacity of pore waters decreased with depth in the anoxic sediments of Narrows Inlet. Copper and, to a lesser extent, lead were complexed with organic matter with molecular weights ranging from 500 - 10,000 in pore waters from the upper part of the sediment. However, the complexing capacity of the deeper pore water was low. The surface waters of Saanich Inlet contained excess nonlabile organic ligands of high molecular weight. The material was of lower molecular weight than that from the pore waters. Anoxic waters contained no significant chelating material.

Organic fractions with a measurable chelating capacity are being studied to determine the rates of metal uptake, as well as to further characterize the possible ligand species, using high-speed liquid chromatography. (Healy)

D. Role of Humic Acids in Controlling the Bahavior of Trace Metals in Fjords

Apparent mixed stability constants are determined by combining humic acid extracts with copper, lead, and zinc. The extracts are obtained by passing water samples through a macroreticular polystyrene resin that will retain the humic substances. Different chemical groups of the humic extract are separated by gel filtration chromatography and serial elution.

Extracts of humic substances from Lake Nitinat waters (180 meters) and muds were found to contain an inert copper chelate in the fulvic acid fraction. Cadmium and lead were complexed to a much lesser extent. We are proceeding with these investigations to the point where the complexing properties of humic substances in several inlets can be compared. (Lieberman [Healy])

XVI. Kinetics and Thermodynamics of Chemical, Biochemical, and Geochemical Processes

This section encompasses research on fundamental reactions in seawater diffusive processes, and the chemical effects of specific conditions in the marine environment.

A. Large-Scale Chemical Oceanographic Processes

Current research is concentrating on denitrification in the eastern tropical Pacific Ocean, nutrient budgets for the Arctic Ocean, and the role of large-scale advection, particularly subsurface countercurrents, in controlling the chemical characteristics of upwelling source waters.

A paper dealing with the importance of horizontal processes in the denitrification zone of the eastern tropical North Pacific Ocean has been published recently, and a paper dealing with the importance of the Bering Strait exchange in nutrient fractionation between the oceans is being revised. Continuing studies include formulating reactive phosphorous and combined nitrogen budgets for the Arctic Ocean. A study of biogeneous silica deposition in the Arctic Ocean is in its initial stage, as is a study of the relationship between current shears and denitrification sites in the eastern tropical North Pacific. An investigation of denitrification off Peru will be conducted during JOINT II Coastal Upwelling Ecosystems Analysis (see XIX *B*). This effort includes a major survey of the waters off Peru during May 1977. (Codispoti)

B. A Multidisciplinary Eastern Tropical Experiment

An experimental program (METREX) has been designed to investigate the processes controlling the oxygen minimum and anaerobic nitrite features of the eastern tropical North Pacific. The oxygen minimum zone is a tongue centered along 15°N that extends from the coast of Central America to the central Pacific. The tongue is found below the thermocline to a depth of about 800 m. Inbedded in the oxygen minimum is a tongue of nitrite produced by the anaerobic bacterial respiration of nitrate. Both features are relatively stable in time and space.

Models are being developed for the oxygen and nitrite features. The oxygen tongue can be represented as a balance between horizontal diffusion and a respiration function that decreases exponentially from the coast of Central America. This model suggests that advection may be insignificant in controlling the distribution of these nonconservative properties. According to the model, three parameters are of importance: (1) the horizontal diffusion coefficient, (2) the maximum coastal repiration rate, and (3) the horizontal decrease of respiration away from the coast.

In the anaerobic nitrite model a balance is assumed between diffusion and nitrite production where the rate of nitrite production is dependent on its concentration. Important parameters in the nitrite model include: (1) diffusion coefficients, (2) maximum respiration rate of nitrate, (3) leakage rate of nitrite, and (4) a Michaelis-Menten

coefficient for the uptake of nitrite. The models will be further developed to include stochastic and seasonally varying forcing functions. Eventually the two models will be coupled so the distributions of oxygen and nitrite can be produced from mixing parameters, oxygen boundaries, and an organic matter distribution.

To test and refine the theories on the oxygen minimum zone and on anaerobic nitrite space, biochemical laboratory studies and multidisciplinary field experiments are being planned. The laboratory studies are designed to investigate the coefficeints associated with bacterial leakage and uptake of nitrite. Additionally, a filtering technique is being developed that will preconcentrate bacteria for immediate kinetic experiments.

The field program is being designed with dominant chemical, biological, and physical components. The chemical component will focus on defining (1) the nitrite model biochemical parameters in natural bacterial populations from the oxygen minimum zone, (2) the spatial distribution of respiration rate in the oxygen minimum zone, and (3) the detailed vertical profiles of the chemical parameters. The biological program is being designed to estimate the coupling between primary production in the surface layers and respiration rate in subsurface layers. Sediment traps will be used to measure the fluxes of particles of different composition and sizes.

The physical component will focus on determining the horizontal diffusion coefficients on scales appropriate for the oxygen minimum and anaerobic nitrite spaces. Additionally, the physical component will evaluate the mean current field to test the hypothesis that a tongue of nonconservative properties can be formed and maintained without advection. (J.J. Anderson, Richards; A. Okubo, State University of New York, Stoney Brook)

C. Vertical Profiles of Nonconservative Properties in the Euphotic Zone

About 75 continuous vertical profiles of nitrate, nitrite, ammonia, phosphate, silicate, oxygen, temperature, salinity, and chlorophyll have been made to a depth of 200 m, twice during 1976, at three locations in the eastern tropical North Pacific.

A statistical analysis is being made to determine the stability of the general features of the profiles and the variance about the mean profiles. Generally, the vertical profiles of nitrate, nitrite, and chlorophyll exhibit stability in time and space with a striking relationship among the vertical positions of these three profiles. Nitrite has a single maximum that is found in the nitrate gradient region; the chlorophyll maximum is apparently correlated with the maximum gradient in the nitrate profile and is above the nitrite peak. Ammonia is found above the nitrite peak and the distances of separation is apparently stable over a period of a few days and within a space of a few kilometers. The magnitude of the ammonia peak is highly variable in time while the peaks of chlorophyll, nitrite, and the gradient of nitrate are relatively stable. (J.J. Anderson, Devol)

A model has been developed to explain a coupling between the nitrate and chlorophyll distributions. Essentially the flux of nitrate into the photic zone is assumed to occur by upwelling so the nitrate gradient is proportional to its uptake rate, which in turn is related to the distribution of chlorophyll from the chlorophyll maximum to the bottom of the euphotic zone. A similar analysis is being developed to investigate the strong coupling between the distributions of nitrite, nitrate, and ammonia. (J.J. Anderson)

D. Chemical and Geochemical Studies off the Washington Coast

These studies offshore of the Columbia River are following four main lines of investigation:

1) surface chemistry of the scavenging of various species dissolved in seawater, especially As, by well characterized natural particulates;

2) uptake and transfer of several isotopes, starting with Po^{210}, by particularly well defined parts of the marine food web that we are in a unique position to study. (Po^{210} forms the major dose of internal radiation to a number of marine organisms, so its cycling through the environment and marine food web is important both in terms of its possible effects on the marine organisms and on human consumers of the marine organisms.)

3) Pb^{210} and Po^{210} in sediments offshore of the Columbia River, with the dual aims of learning more about these two natural radioisotopes in the sea and determining accumulation rates of Columbia River derived solids on the continental shelf and slope over the past 100 years. (The Pb^{210} technique has also provided sedimentation rates over the last 100 years in Lake Washington and Puget Sound to date the time when man's discharges of arsenic, mercury, and oil began to appear in the sediments.)

4) aliphatic and aromatic hydrocarbons in samples of phytoplankton, zooplankton, and neuston, and in sediment cores using the same sampling gear and analytical procedures as in the Puget Sound hydrocarbon studies (see XVIII B). (Carpenter and students)

1. Sorption-desorption studies of trace metals

The direction of our research has been influenced by the working hypothesis that the removal of many radioactive and nonradioactive elements from seawater is dominated by surface chemical reactions between dissolved species and particulate phases. Since the scavenging ability or surface chemical reactivity of different types of suspended solids varies greatly, a major part of our effort has been to develop and/or acquire the analytical instrumentation and expertise to adequately characterize the suspended matter naturally present in the Columbia River and rivers entering Puget Sound, in Puget Sound, and off the Washington coast, and to collect enough of this material for sorption-desorption-scavenging studies under controlled conditions.

We have acquired or developed over the past few years the ability to determine for suspended matter samples the following properties:

mineralogy by X-ray diffraction, organic carbon and nitrogen contents, major and minor element chemistry by nondestructive neutron activation and thin film energy dispersive X-ray fluorescence, and surface area by the BET technique of nitrogen gas adsorption. The combination of all these analytical capabilities allows us to work with concentrations of dissolved chemical species and suspended matter much closer to natural concentrations and to characterize the suspended matter much better than most other investigators.

Having developed these capabilities, we are now studying surface chemical scavenging reactions between a wide variety of radioactive and stable elements and the particulate phases naturally present in coastal and estuarine areas. The first sorption-desorption studies were for mercury because of the great interest in its environmental chemistry (Bothner and Carpenter, 1973). Following this, a series of sorption-desorption studies with arsenic and preliminary studies of the scavenging of dissolved lead by natural marine particulates using the 10.5 hour tracer Pb^{212} have been carried out.

Samples of the organic rich suspended particulates collected from Saanich Inlet in August sorbed only about 15% of the radioactive As^{74} arsenate, with 15-25% of the racer being sorbed within 2-3 weeks.

Additional studies of the sorption of the radioarsenate showed clearly that the ferric hydroxides have great affinity for dissolved arsenic; over 90% of the arsenate was taken up within 20 hours by the ferric hydroxides and, at most, 1-2% of this could be desorbed by placing the spiked solids in unspiked seawater with one half or one fifth the arsenic concentrations. The manganese oxides were comparable to the Puget Sound particulates and much less effective at scavenging the dissolved arsenic than the ferric hydroxides. Two marine ferromanganese nodules were also extremely effective scavengers of dissolved arsenate, and the arsenic they sorbed was not released in the desorption experiments. We believe that this behavior is due to their iron, rather than their manganese, compounds. The results of these experiments show rather clearly that hydrous iron oxides are much more effective than inorganic clays, manganese oxides, or organic rich suspended matter as scavengers of dissolved arsenic.

Every study to date indicates that the lead-210 introduced to the sea both via decay of Ra^{226} in the water column and by atmospheric precipitation is scavenged quickly to marine sediments, but the chemical reactions dominating the scavenging have not been identified. Initial experiments with natural assemblages of Puget Sound suspended matter and with Pb-212 tracer have revealed (not unexpectedly) more complex behavior with the natural particulates and tracer, both at concentrations much closer to natural levels than those used by Gadde and Laitinen (1975), who investigated the reactions of dissolved lead with synthetic hydrous iron and manganese oxides in fresh water. Sorption is apparently less rapid (but still fast on an oceanographic time-scale), less complete, and less reversible with the natural assemblages of particulates in seawater than with the synthetic hydrous metal oxides employed by Gadde and Laitinen. The effects of temperature, pH, salinity, etc. on the uptake and release of lead by these natural particulates still needs to be investigated. (Jahnke [Carpenter])

2. Sediment studies with lead-210

For several years we have been involved in identifying and tracing Columbia River derived solids in the water column and in the sediments on the Washington continental shelf, slope, and the submarine canyons indenting the slope. Recently most of our attention has been directed to the continental slope and the canyons indenting the slope. The chemistry and mineralogy of the suspended particulates, the clay mineralogy of bottom sediments, and the accumulation histories over the past 100 years and over the past 7000 years, with the lead-210 and ^{14}C techniques, respectively, have been studied. The lead-210 derived accumulation patterns support the idea that more sedimentary material is transported down these canyons to the deep sea than is transported over the shelf break and down the open continental slope. (Bennett [Carpenter])

3. Hydrocarbon studies

Samples of phytoplankton, zooplankton, neuston, and sediments were collected in August 1975 on three transects across the shelf off Washington. The sediment cores will be used to determine hydrocarbons at different depths and to determine the sediment accumulation rates over the last 100 years with the lead-210 technique. Our special corer with hydrostatically damped rate of penetration into the sediment to sample the sediment-water interface with the least possible disturbance was used. This corer takes four cores, each 1-2 feet long, and thus gives replicate samples going back in time.

Given the limited amount of data on hydrocarbons in all types of samples from both Puget Sound and the Washington shelf, it is most important to determine the quantities and types of hydrocarbons present in organisms first, sediments second, and in the water itself third. This is partly because it is the impact on the organisms which is of greatest concern, and partly because the analysis of hydrocarbons dissolved in seawater is still a very difficult task. Accordingly, during the first year we have concentrated our sampling and analytical programs on organisms and sediments; most studies of water samples will be undertaken in subsequent years. Since oil spills are more likely in Puget Sound, we are stressing first the analyses of samples from Puget Sound. The shelf samples will be analyzed as time permits. (Bennett, Prahl, Clark, Rosa, Bates [Carpenter, Hedges])

E. In Situ Adsorption Experiments

An *in situ* adsorption experiment on the deep sea floor and in the water column will be conducted in 1977 under the IDOE-NSF Ferromanganese Program (MANOP). Carefully characterized iron and manganese phases will be exposed to natural seawater, and the changes in properties and chemical composition that take place with time will be examined. This experiment will be the first direct attempt to test the hypothesis that adsorption of trace metals on hydrous metal oxides is the mechanism by which these metals are enriched in ferromanganese nodules. This experiment is being conducted in conjunction with P.G. Brewer (Woods Hole Oceanographic Institute) and R.G. Burns (Massachusetts Institute of Technology).

During the coming year we will synthesize and then characterize the synthetic iron and manganese oxides that are similar to the most important phases found in manganese nodules. These substrates will be characterized by X-ray diffraction surface area (by gas adsorption [B.E.T.]), and morphology (by S.E.M. and T.E.M.). The oxidation state of the manganese oxides and some magnetic properties will be determined. The zero point of charge will be determined by alkalimetric titrations. We will also measure adsorption isotherms for Co^{+2}, Cu^{+2}, and Mn^{+2} in the laboratory.

Following the *in situ* experiments we will repeat the characterization experiments and analyze the substrates for adsorbed trace metals to compare with the laboratory isotherms. (Balistrieri [Murray], Spell)

F. The Surface Chemistry of Goethite

The surface chemistry of goethite is being studied to evaluate its significance in trace metal uptake in ferromanganese nodules, marine sediments, and removal in estuarine systems.

Goethite has been synthetically prepared and identified by X-ray diffraction and S.E.M. The surface area was determined by the B.E.T. method.

Potentiometric titrations in NaCl and KCl at various ionic strengths determined the pH of zero point of charge [pH(zpc)] to be 7.55 ± 0.1. From this the relative surface change was calculated at the different ionic strengths. Using the method of Hohl and Stumm (1975), the equilibrium constants for the dissociation of the surface groups were obtained. The intrinsic constants (the equilibrium constants under "chargeless" conditions) for 0.1 M KCl are $pk_1 = 6.05$ and $pk_2 = 9.48$.

Adsorption of metals in 0.7 M NaCl was measured with the intent of calculating the equilibrium constant for the metal-goethite interaction. The alkaline earths, Mg, Ca, and Sr, show an increase in adsorption after the pH(zpc) indicating predominantly electrostatic attraction. The transition metal, Co, shows significant adsorption occurring at $\sim$ pH 6, indicating predominatly specific adsorption. The adsorption of Ni and Mn has yet to be completed.

Future work will be done to evaluate the importance of organics on the adsorption of metals on goethite. (Balistrieri [Murray])

G. Determinations of Rate Constants from Pore Water Data

Our approach has been to obtain kinetic information by modeling the vertical distributions of sedimentary organic matter, interstitial nutrients, porosity, and sedimentation rates. We use diffusion, advection, reaction equations to model our experimental data and evaluate kinetic parameters, and put limits on diffusion coefficients and adsorption equilibrium constants. Data from Saanich Inlet and Narrows Inlet where the sediments are extremely reducing (and biological mixing and/or irrigation are minimized) show that a simple steady-state condition exists and that the kinetics of oxidation of organic matter appear to

be first order with respect to usable organic matter. An interesting feature in Saanich Inlet is that the sediments show two distinct zones, an upper sulfate-reducing zone and a lower methane-producing zone. The kinetics of organic matter decomposition in both these zones appears to be first order, but the rate constant is approximately an order of magnitude slower in the lower methane-producing zone than in the upper sulfate-reducing zone. Data from central Puget Sound sediments show a much more complex situation where biological activity (i.e., irrigation of sediments by burrowing benthic organisms) is forming layers of oxidizing sediments between layers of mildly reducing sediments. We have qualitatively described the distribution of ammonia, nitrate, and nitrite in these sediments. We are planning to develop more sophisticated diagenetic models (including non-steadystate models) and use numerical methods to solve the appropriate differential equations in order to develop a better understanding of diagenesis in marine sediments. (Grundmanis [Murray])

H. Kinetics of Oxidation of Fe(II) in Seawater

No ferrous iron can be measured in Puget Sound seawater, yet in the pore waters of the sediments there is a high concentration of ferrous iron that is diffusing out of the sediments. This implies that the oxidation of Fe(II) to Fe(III) is extremely rapid. In order to determine how fast we have been measuring the kinetics of oxidation of Fe(II) in pore water samples, our *in situ* pore water sampler was used. A fifteen ml pore water sample was collected in the layer above that containing sulfide. The initial Fe(II) iron concentrations are in the range of 1 to 10 ppm. In these experiments the samples are injected into a reaction flask on board ship and the flask is bubbled with air to stabilized P_{O_2}. The pH is monitored continuously. Samples (4 ml) are drawn after different time intervals, filtered through 0.45 μ filters, and analyzed for ferrous iron. Assuming that the following rate law holds we have found that

$$\frac{dFe(II)}{dt} = K\,[Fe(II)]\,P_{O_2}\,[OH^-]^2 .$$

The calculated rate constant is constant for the first five minutes and averaged $8.9 \times 10^{11} \ell^2 mol^{-2} atm^{-1} min^{-1}$. The agreement between our measurements and those of others suggest that Fe(II) in the pore water is not tied up in strong ferrous-organic complexes. Strong organic complexers have been shown to slow the kinetics significantly so such an effect would be obvious in our results.

Using our average rate constant we calculate that the half life of Fe(II) in Puget Sound seawater at pH 8.0 is 3.9 minutes.

These experiments will be extended to include studies of the kinetics of oxidation of Mn(II). (Gill, Ravines [Murray])

I. Ammonium-Sediment Interactions

Experiments to determine the amount and rate of ammonium uptake and release by hemipelagic sediments are being conducted. These experiments

will determine the role of clay type, metal oxy-hydroxide coatings, and organics on the uptake mechanism.

This experimental work hopefully will answer such questions as: does ammonium adsorption on sediments and standard clays obey the Langmuir isotherm; is the adsorption reversible; how fast does it sorb/desorb; what effects do metal oxy-hydroxide coatings, clay type, and organics have on ammonium adsorption; does ion exchange with other cations effect the equilibrium concentration of ammonium in the sediments? (Boatman [Murray])

XVII. Marine Geochemical Studies

The main objective is to understand the chemical reactions that bottom and suspended sediments undergo in the marine environment. These studies include the mode of formation of manganese nodules, the effects of submarine volcanism on the chemical and mineralogical composition of marine sediments, the role of solid phases and organic ligands in controlling the distribution of trace metals and other chemicals in the ocean, the relationship of hydrocarbons in sediments to processes in the overlying water, and the role of mineralogical species in controlling the magnetic properties of the sediments.

A. Iron in Puget Sound

The distribution of dissolved iron, ferrous iron, and acid-reducing agent soluble iron in the main basin of Puget Sound and its tributaries is being investigated. Our studies so far show that essentially all measurable iron in Puget Sound can be removed by filtration through 0.8 μm membrane filters, thus dissolved iron must be less than about 20 nM (our limit of detection). This concentration is consistent with the hypothesis that dissolved iron in Puget Sound is controlled by inorganic solubility of hydrous ferric oxide. We also can detect no ferrous iron in Puget Sound. This is due to the rapid kinetics of oxidation of Fe(II). Our measured rate constant for the kinetics of oxidation suggests that strong ferrous-organic matter complexes do not exist in Puget Sound pore waters.

The distribution of acid soluble iron appears to be controlled by inputs from the rivers and the sediments. Only a small fraction of the river load makes it through the estuaries because the magnitude of the surface concentrations is smaller than predicted based on the calculated river flux. The "dissolved" iron in the rivers is actually fine colloidal particles that coagulate before the salinity exceeds 5 $^{o}/_{oo}$. There are high concentrations of Fe(II) in the pore waters apparently in equilibrium with siderite. The flux calculated using the iron gradient in the pore water is insufficient to account for the increase in acid soluble iron with increasing depth in Puget Sound. The flux of iron must be due to rapid regeneration occurring at the sediment-water interface. The ferrous iron diffusing out of the sediments is rapidly oxidized on contact with oxygenated seawater, and the resulting iron oxide particles are mixed in the water column by tidal currents. (Gill, Ravines [Murray])

B. Trace Metals in Puget Sound

We are currently investigating the distribution of dissolved and acid soluble Mn, Cu, Ni, Zn, and Cd in Puget Sound. Samples have been collected at seven stations located along the axis of the main basin of Puget Sound. Suspended matter samples (0.4 μ) were collected and the filtered water transferred to carefully cleaned polyethylene bottles. Unfiltered samples were acidified to about pH 2 with an acid-reducing reagent previously extracted of trace metals. Similar samples will be collected from the local rivers during periods of high and low flow.

The dissolved samples are being analyzed by batch extraction using Chelex-100 ion exchange resin. The suspended matter samples will be analyzed at the United States Geological Survey by D.Z. Piper.

The results from three stations completed to date suggest that the concentrations of dissolved trace metals are remarkably uniform and that the values do not differ much from those of open ocean seawater. Mn is the only element that has a higher concentration, and its distribution is similar to that of acid soluble iron.

Samples will be collected from the Washington shelf and slope and off the Mexican coast during the coming year. These samples will cover the nearshore environment and the water column in regions where there is a well developed oxygen-minimum. (Ravines [Murray], Spell)

C. Arsenic in Puget Sound

A budget of arsenic fluxes in Puget Sound is being developed with the aim of determining the rate of movement of arsenic through the four Puget Sound subbasins and the ultimate fate of both natural and anthropogenic arsenic introduced to Puget Sound. This information is needed to be able to predict the concentrations of arsenic with time in different parts of Puget Sound, given various natural and anthropogenic inputs at different places around the Sound. The major anthropogenic arsenic source is the ASARCO copper smelter located in Tacoma, Washington, that discharges large amounts of arsenic in liquid wastes directly into Puget Sound and which also emits large amounts of arsenic into the atmosphere from its smokestack.

The arsenic discharged in liquid wastes directly to the Sound is rather quickly diluted to background concentrations by vigorous tidal mixing in the neighborhood of the discharge. However, the studies on arsenic concentrations in samples of atmospheric precipitation have revealed that the second largest input flux of arsenic to Puget Sound is most likely atmospheric precipitations. The atmospheric arsenic emissions from the Tacoma smelter are clearly evident in arsenic rich dust and rains collected in Seattle 35 km downwind of the 600-foot high smokestack of this smelter.

In addition to determining total arsenic concentrations in waters of the Puget Sound region, we have also begun studies of the chemical form in which it is present, using techniques developed by Braman and coworkers at the University of South Florida. Most of the arsenic in the normal oxidizing seawater of Puget Sound is clearly arsenate, the thermodynamically stable form. The discharges from the Tacoma smelter are largely arsenite, however, and arsenite is much more toxic to most marine organisms than arsenate. (Engblom, Crecelius [Carpenter], M.L. Peterson)

D. Mercury in Bellingham Bay

We have been studying the amounts of mercury in sediments in Bellingham Bay, to the north of Puget Sound, as a function of time since the mercury discharge to the bay from a chlor-alkali plant was stopped

in 1970. This is the only field study to our knowledge that is determining the rate at which an estuarine system responds to the cessation of mercury pollution.

Our first publication on the geochemistry of mercury in Bellingham Bay showed that the sediments were not a permanent sink for the mercury that was discharged by the chlor-alkali plant and initially deposited in nearby bottom sediments. The time required for mercury concentrations in these sediments to decrease by a factor of two after the industrial input was essentially eliminated was about 1.3 years, suprisingly short. Mercury concentrations, that had decreased steadily since 1970 at one station in Bellingham Bay, jumped suddenly in 1974, apparently because some severe storms and deliberate dredging operations resuspended some of the mercury rich sediment in the immediate area of this discharge and caused it to be transported out to some parts of the bay. We are following the fate of this new spike of mercury to see how its behavior compares with that of the initial spike.

An aerated bell jar apparatus was used in Bellingham Bay to make the first direct field measurements of the rates at which mercury is moving from contaminated oxidizing and reducing sediments to the overlying seawater. In the reducing sediments a readily measurable flux of 2×10^{-5} ng total Hg/cm^2/sec was measured, presumably in response to a strong concentration gradient of dissolved mercury between interstitial and overlying seawaters. The form of the mercury released from these sediments was nonvolatile, so it was not species like elemental mercury or volatile organomercury compounds such as the expected methyl or dimethyl mercury. No flux of dissolved or volatile mercury across the sediment-water interface was measurable for the oxidizing sediments, possibly because both interstitial and overlying seawaters had similar mercury concentrations.

Preliminary tests have shown that the bell jar apparatus will be useful in determining fluxes of nutrients and arsenic and other chemical species across the sediment-water interface from both oxidizing and reducing sediments of Puget Sound. (Carpenter, Bothner, M.L. Peterson)

E. Pore Water Intercalibrations

Three different techniques are being used to study the pore water chemistry in Puget Sound. Murray uses an *in situ* sampler that was designed by Sayles, Mangelsdorf, Wilson and Hume at Woods Hole Oceanographic Institute. Emerson uses an *in situ* sampler known as the "peeper" and also collects samples by centrifuging segments of core. The "peeper" samples are collected by equilibrating distilled water in cavities with the pore water. The equilibration occurs across dialysis membranes and 0.45 μ Gellman filters.

Two intercalibration experiments have been completed, one in Lake Washington and one in Quartermaster Harbor in Puget Sound. The samples from both stations were analyzed for Ph, H_2S, alkalinity, NO_3^-, NO_2^-, NH_4^+, PO_4^{-3}, Fe Mn, Si, and Cl^-. These results show that all three sampling

methods produce similarly shaped profiles and the depth of maxima in the profiles occurs at the same depth. Some problems such as the distribution of Fe and NO_3^- remain to be solved. (Jahnke, Grundmanis [Murray, Emerson])

F. Nitrification and Denitrification in Puget Sound Sediments

A large part of our studies of the pore waters in Puget Sound sediments has centered on transformations in the nitrogen system. Denitrification in low oxygen areas, such as Puget Sound sediments, has been identified as the major sink for fixed nitrogen from the world ocean.

An example of our data for NO_3^-, NO_2^-, and NH_4^+ from three stations is shown in Figure 7. In all cases the concentration of interstitial NO_3^- decreases with increasing depth but a maximum is present at intermediate depths (20-30 cm). Nitrite shows two small maxima. The lower maximum at each station corresponds to the NO_3^- maximum. Ammonia generally increases with depth; however, there is a minimum at intermediate depths in all three cases.

There must be a nitrate source in these sediments and this must be autotrophic nitrification--the oxidation of ammonia to nitrite to nitrate. The NO_2^- and NH_4^+ profiles are consistent with this hypothesis. As molecular oxygen is required for nitrification, we hypothesize that the O_2 is provided by the injection of bottom water at intermediate depths by burrowing benthic organisms. In sediments collected with box cores there are several animals that could be responsible for the injection of aerated bottom water. They include maldanid polychaete worms and somewhat larger animals, the hohothurian *Molpadia intermedia*, which were found in the sediments between 10 and 40 cm.

We are continuing our investigations of this irrigation mechanism and will enlarge our analyses to include N_2 gas. (Grundmanis [Murray])

G. Dissolved Gases in Pore Water

Many of the chemical processes occurring in the diagenesis of organic matter in marine sediments involve gaseous reactants and/or products. For example, dissolved oxygen is used up rapidly during aerobic diagenesis. When oxygen concentrations reach very low values denitrification occurs with the production of molecular nitrogen. Sulfate reduction, which occurs with diagenetic sequence after denitrification, produces hydrogen sulfide. All three of these processes produce carbon dioxide as organic matter is degraded. Below the zone of sulfate reduction, carbon dioxide is reduced to methane gas. To understand these various sedimentary processes, it is essential to measure the distribution of these dissolved gases in the interstitial water. Very little work has been done on interstititat water gases due to problems of contamination and/or losses due to retrieval of cores and the processing involved to separate the interstitial water from the solid sedimentary components.

Our approach to this problem is to use an *in situ* sampling probe that enters the sediments, separates the interstitial water by filtration,

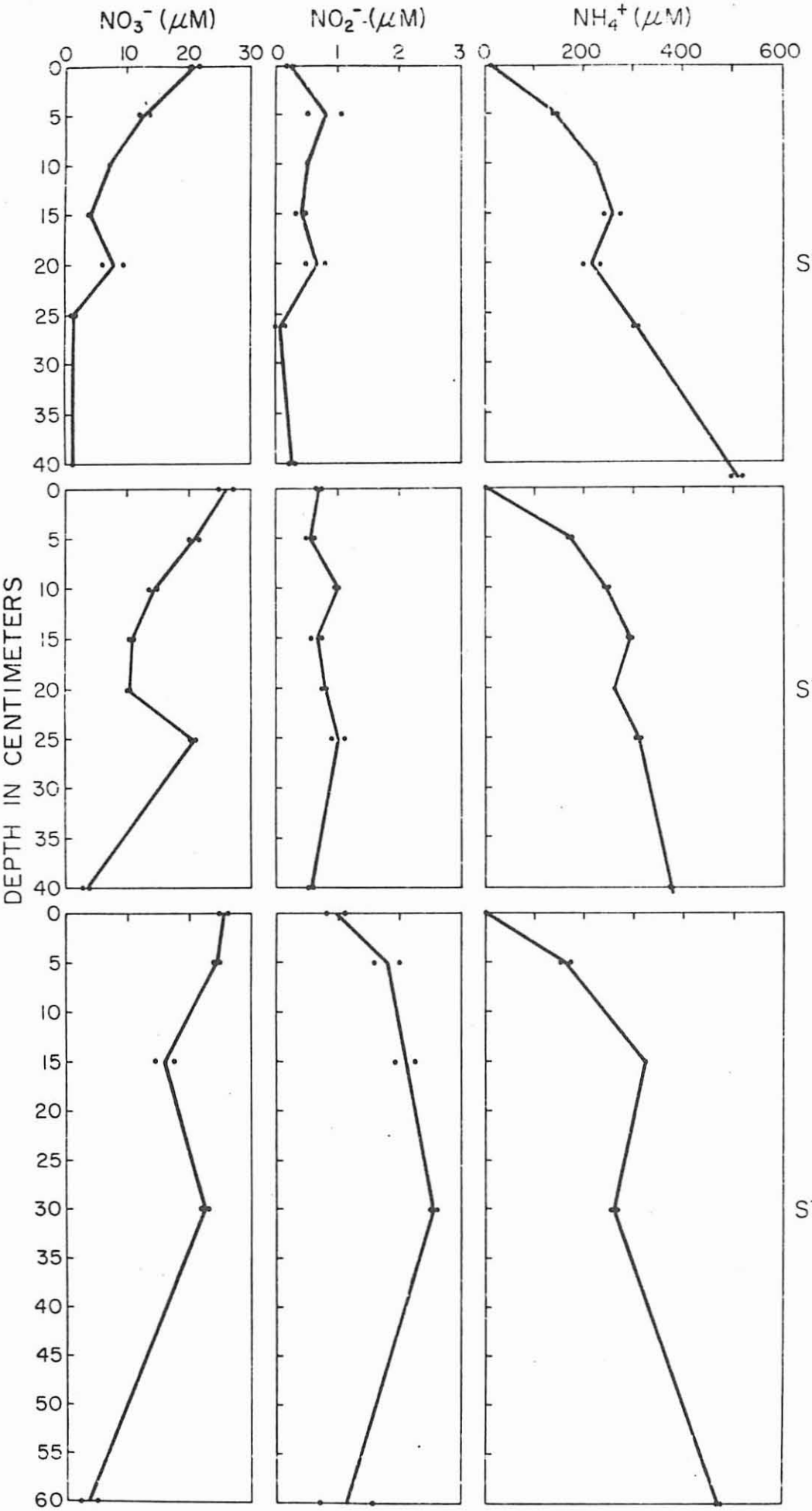


Figure 7. Interstitial nitrate, nitrite, and ammonia, 3 stations, Puget Sound.

and recovers the filtered water samples sealed from atmospheric contamination. As our present sampler is not gas tight, we are in the process of building and testing a gas-tight sampler for these studies. We are also developing shipboard analytical methods for the removal, separation, and measurement of O_2, Ar, N_2, CH_4, CO_2, and H_2S. The first four gases will be measured on a 1-2 ml sample using helium stripping followed by separation on spherocarb solid support in a Hewlett-Packard gas chromatograph equipped with a Carle microthermistor detector (for increased sensitivity). The separation of Ar from O_2 has traditionally been a problem. We plan to use subambient temperature programming to achieve this separation. CO_2 and H_2S will be measured on a smaller sample which will be acidified prior to helium stripping to convert $CO_3^{=}$ and HCO_3^{-} to CO_2 and $S^{=}$ and HS^{-} to H_2S. These two gases will also be separated on spherocarb solid support. We are planning to use the gas sampler and analytical system to evaluate the extent of diagenesis in the hemipelagic sediments in the following areas: Gulf of Alaska, off Washington, Oregon, and Central America. (Grundmanis [Murray])

H. Estimates of Sediment Mixing from Pore Water Radon Concentrations

During the past year we began making radon measurements on *in situ* pore water samples. Radon-222 (half life = 3.85 days) is an inert gas and is produced by the decay of radium 226 (half life = 1622 years) in the sediment. The concentration of radon in the pore water is maintained by a balance between production and decay except near the surface of the sediment where there is a radon deficit due to diffusion of radon into the overlying water. Radon can diffuse by molecular processes approximately 2 cm before it decays. Thus deficits occurring below 2 cm indicate some sort of mixing process. At two stations in Puget Sound (main basin and Hood Canal) we observed radon deficits as deep as 25 cm. At one station there was a distinct radon minimum at 25 cm which correlated with extensive burrowing at this depth (documented by box coring) and with a silicate minimum and nitrate maximum in the pore water. We are making measurements of the radon production rate on cores taken from these locations and with this information will be able to accurately calculate the radon deficit. Since the decay rate of radon is known, it will then be possible to estimate the rate of irrigation of the pore water due to bioturbation or other mixing processes. (Smethie [Murray])

XVIII. Chemical Studies of Marine Environments

These studies are designed to elucidate the chemistry of specific marine environments. In the past we have investigated the accumulation of the products of organic decomposition in anoxic marine systems; the solubility of iron sulfide and the distribution of trace metals in sulfide-bearing marine environments; and the distribution of particulate manganese in the oceans and specifically at the O_2-H_2S interface in sulfide-bearing basins and fjords. These and related studies, including studies of hydrocarbons in local environments, are continuing.

A. Low Molecular Weight Hydrocarbons in Alaskan Waters

As a continuing effort in the Outer Continental Shelf Environmental Assessment Program (OCSEAP), the temporal and spatial distributions of the dissolved aliphatic C_1-C_4 hydrocarbons are being determined as a part of the petroleum hydrocarbon baseline. Special emphasis is being paid to the $C_{2:0}/C_{2:1}$, $C_{3:0}/C_{3:1}$ ratios for the purpose of distinguishing biogenic and petrogenic hydrocarbons.

The analysis is carried out by He stripping the dissolved components, concentrating on a cold trap at -296°C, followed by GC-FID detection.

Recent observations in the Bering Sea and the Gulf of Alaska indicate that the distribution of methane is strongly controlled by benthic processes and the degree and type of mixing that occur on the shelf. Concentrations of ethylene and propylene are related to primary productivity.

Future studies will emphasize water column and sedimentary sources of these hydrocarbons. Analysis for low molecular weight aromatics will be implemented in regions characterized by natural petroleum leakage. (Cline)

B. Hydrocarbons in Puget Sound and off the Washington Coast

A program of studies of aliphatic and aromatic hydrocarbons in organisms, sediments, and waters of Puget Sound and the Washington shelf north of the Columbia River was begun in summer 1975 (see XVI *D*). Overall goals in this research are to increase our understanding of:

1) the distribution of aliphatic, aromatic, and sulfur-containing molecules in organisms, sediments, and waters of this region at the present time while the distribution is still primarily due to natural processes. (Such information on background concentrations is vital in recognizing the extent and effects of subsequent inputs of oil, yet it is almost completely lacking at this time for this part of the ocean.)
2) the composition and relative importance of the transfer of land-derived hydrocarbons to this part of the ocean by river input, sewage discharges, and atmospheric rainout, compared to biosynthesis by marine organisms. (We feel that

any interpretation of the observed distribution patterns we obtain will depend on the completeness with which we understand both the composition and magnitudes of the various possible sources. Analyses of the oxidation products of lignin compounds are being made by J.I. Hedges to determine the sources and relative amounts of land derived organic matter in sediment cores from the study area.)

3) the transfer of certain of these hydrocarbons between some parts of the marine food web. (Our initial gas chromatographs of organisms and sediments from Puget Sound and the Washington coast have revealed some unexpectedly large peaks at unusual carbon numbers and we are very much interested in determining the sources and fates of these molecules. We also have some unique opportunities to study certain well defined parts of the food web.)

These are clearly large and complicated problems which we are attacking with a variety of techniques, but only after collecting and preserving the samples with care to minimize contamination. Then following the appropriate sample extraction and cleanup procedures, we are applying the techniques of gas chromatography, ultraviolet fluorescence spectroscopy, high pressure liquid chromatography, mass spectroscopy, and radiocarbon and C^{13}/C^{12} determinations. J. Hedges is supervising the gas chromatography studies, R. Carpenter the liquid chromatography and UV fluorescence studies; A.W. Fairhall is supervising the radiocarbon and C^{13}/C^{12} studies.

Seasonal samplings of phytoplankton, zooplankton, and neuston have been conducted at about 40 stations in Puget Sound. These stations were chosen partly to provide geographical coverage of the region and partly because B.W. Frost has already made two seasonal collections of zooplankton at many of the stations as a start at defining the geographical and seasonal distribution of zooplankton. Additional stations are closely spaced in the Anacortes and Cherry Point/Ferndale areas north of Bellingham, which are the sites of the major refineries that will be receiving the Alaskan crude oil and are thus areas most likely to be subjected to oil spills. (Carpenter, Hedges, and students; A.W. Fairhall, Department of Chemistry)

Studies have been initiated into the distribution and composition of adsorbed petroleum hydrocarbons on suspended matter in northern Puget Sound. Regions of interest include Cherry Point/Ferndale refineries, Skagit and Frazers rivers, and the inner Strait of Juan de Fuca.

Large quantities of suspended matter are being taken with a continuous flow centrifuge in which gram quantities of material may be obtained. This work is also being supplemented with hydrocarbon adsorption studies involving locally derived detrital sediments. The n-alkane analysis will be carried out at the Pacific Marine Environmental Laboratory; aromatic analysis at the NOAA Analytical Laboratory using GC-MS procedures.

This study is relevant to the question of possible ingestion of oiled particles by planktonic and benthic organisms. Sampling is continuing and analysis of the data is under way. (Cline)

C. Sulfate Reduction in Anoxic Fjords

A radiochemical method for the direct measurement of sulfate reduction is being developed. Preliminary results indicate that the rate of sulfate reduction in the upper few cm of sediments in Lake Nitinat, an anoxic fjord, is about 12 x 10^{-6}µg at s $cm^{-2}sec^{-1}$. This compares well with a published estimate of the flux of sulfide out of Lake Nitinat sediments of 8 x 10^{-6}µg at s $cm^{-2}sec^{-1}$. Sulfate reduction rates also have been determined for the Lake Nitinat water column. Although these rates are near the present detection limit of the method, the profile is qualitatively similar to profiles reported for the Black Sea. After the method has been satisfactorily developed, sulfate reduction rates will be used in conjunction with other data to construct a mathematical model of the anoxic process in local anoxic fjords. (Devol)

D. Short-Chain Fatty Acids in Oxic and Anoxic Systems

We are developing a method for determining the C_2-C_5 normal and branched fatty acids in seawater and marine sediments. The method involves separating the acids from seawater by vacuum distillation followed by evaporation to achieve a 100-fold concentration. A gas chromatograph equipped with flame ionization detectors is used for the quantitative determination of these acids in prepared samples.

Field samples have been collected from sulfide-containing waters (Lake Nitinat and Narrows Inlet, British Columbia) and from waters oxygenated throughout (Dabob Bay, Washington). These samples will be analyzed for the C_2-C_5 fatty acids. From these measurements, the concentrations and distributions of these acids will be determined, and a comparison will be made between oxic and anoxic systems.

We are also investigating methods of storing field samples prior to analysis. (Kingsbury [Richards])

XIX. Biome Studies and Marine Ecosystems Analysis

This program is designed to advance the field of marine ecology through coordinated, in depth, interdisciplinary investigations of specific marine ecosystems. From the viewpoint of this program the marine ecosystems are conceived, in an extension of the classical trophic level concept, as multicomponent systems that transfer processes which relate to the components. The key to understanding the dynamics of these systems is the understanding of the spatial and temporal distributions of the components and the rates at which the transfer processes operate.

A. Plankton Metabolism in Lake Washington

Data for 1974-1975 and 1976 on the seasonal cycles of productivity, respiratory enzyme activity, and chlorophyll in Lake Washington have been analyzed. All show similar trends; however, maximum chlorophyll concentrations are attained in May or June while productivity and respiratory enzyme activity show maxima about one month later.

Changes in phytoplankton carbon were estimated from chlorophyll concentrations; loss rates were calculated by subtracting productivity from estimated biomass changes. Specific loss rates (loss rate divided by biomass) ranged from zero to 0.5 d^{-1}, in general much lower than those reported for Castle Lake, California. Phytoplankton night respiration and zooplankton grazing rates were estimated from respiratory enzyme activity and used to correct daily production rates. When corrected production rates along with an assumed sinking rate of 0.4 m/d were used, specific loss rates ranged from -0.09 to 0.2 d^{-1} and averaged 0.03 d^{-1}. In contrast to other lakes, Lake Washington loss rates are low, and it is not necessary to invoke physiological death to reconcile productivity data with observed phytoplankton biomass changes.

Rates of phosphate recycling by zooplankton in the euphotic zones of lakes Washington and Findley have been calculated from stoichiometric ratios, and respiration rates estimated from ETS activity. During the summer stratification in Lake Washington remineralization, based on the calculated rate, supplies 40 to 60% of the phytoplankton phosphorous requirements as estimated from ^{14}C uptake. Assuming that phytoplankton night respiration uses carbohydrates as the energy source and correcting ^{14}C uptake for night respiration, the percentage of production supported by zooplankton phosphorous remineralization increases to 60 to 80%. The trends are similar in Lake Findley, but late in the ice-free season zooplankton can support all the production. Additional sources of phosphorous are being investigated. (Devol)

B. Coastal Upwelling Ecosystems Analysis

The CUEA program, sponsored by IDOE, is based upon a systems approach to the study of biological production in upwelling regions. Within the physical and biological subdivisions, principal investigators from ten institutions are engaged in component projects. Our component deals with the chemical aspects of the hydrographic fields encountered

during the CUEA experiments. JOINT-I, the first integrated major field exercise, was carried out off the northwest coast of Africa in February-June 1974. American, French, Spanish, Polish, Mauritanian, and East German research vessels participated. A National Center for Atmospheric Research (NCAR) aircraft, based in Nouadhibou, made sea surface temperature and meteorological measurements. During 1975, a report on the *Atlantis-II*-JOINT-I hydrographic data was published. Initial analyses of these data were presented at the 1975 and 1976 annual meetings of the American Society of Limnology and Oceanography. A technical report on the *Atlantis-II* sections was completed in 1976 and a paper emphasizing and explaining the nutrient distributions during JOINT-I is nearing completion.

JOINT-II, an integrated study of upwelling off Peru, is in progress. At completion, approximately six United States and three foreign vessels will have participated. NCAR aircraft have and will continue to carry out sea surface mapping; and a number of meteorological stations have been established along the Peruvian coast. Preliminary results will be presented at a meeting of the American Society of Limnology and Oceanography scheduled for June 1977. A data report dealing with some of the initial JOINT-II hydrographic data has been completed and a technical report based on sections prepared from this data nears completion. (Codispoti)

XX. Plankton Production

A material part of the efforts of biological oceanographers, in the field and in the laboratory, is directed at primary and secondary production of the plankton. The goals are to describe, explain, and predict the rate of production of organic matter in space and time, and the resulting distributions and abundance of organisms. The methods used for the plankton are quite different from those employed on the seabed, because the same plankton populations cannot be regularly revisited. Other studies of plankton production are summarized in XIX.

A comprehensive effort concerns the area off the coast of Washington, with emphasis on the continental shelf; these studies will be correlated with investigations on circulation, sediment transport, and geochemistry of the same area.

A. Coastal Waters off Washington and Oregon

1. Subsurface chlorophyll maximum

The subsurface chlorophyll maximum found off the shelf of Washington and Oregon continues to attract our strong interest. During 1975, three cruises to investigate the processes leading to its formation and maintenance were carried out and in 1976, one cruise.

Our previous investigations have shown that during the summer months a subsurface maximum of chlorophyll is a major biological feature of the North Pacific Ocean at intermediate latitudes. Beyond the continental slope off the coast of Washington and Oregon, the layer is found typically, at 55-65 m, between the seasonal pycnocline and the permanent halocline; chlorophyll concentration may be three to ten times as high as in the layers above. Although the maximum may be well below the depth where 1% of the surface light is found (this depth traditionally being taken to be the bottom of the euphotic zone), up to one half of the daily primary production per square meter is due to the phytoplankton associated with the subsurface maximum layer. A large part of the observed increase of pigment may be due to *in situ* growth of the phytoplankton but other mechanisms such as increase in cellular chlorophyll and sinking of cells from above must be considered. Although estimates have shown up to a ten-fold increase in chlorophyll, only about a three- to fourfold increase in cell carbon occurs within the layer. Previous studies on phytoplankton in the area of the Columbia River effluent overlooked the chlorophyll maximum, which, however, cannot be neglected in assessing the possible pathways of organic matter in the region.

In the water above the continental shelf, contiguous to the area of upwelling off Oregon, another quite local subsurface maximum of chlorophyll occurs which may, in part, be caused by advection of surface water seaward along the sloping isopycnals. (G.C. Anderson)

Phytoplankton enumeration: Formalin-preserved phytoplankton samples collected along a section off the Oregon coast at 44°40'N latitude during July 1968 have been examined microscopically to determine the

phytoplankton distribution. Of special interest is the composition of the population found within the oceanic subsurface chlorophyll maximum layer that has been described for that area. The populations in the subsurface chlorophyll maximum layer did not appear to differ significantly from those in the overlying waters. Slight shifts in the percentage composition by number and by carbon of the individual phytoplankton taxa in deep and shallow samples were noted at times. However, no significantly abundant species nor taxa was restricted to samples from the chlorophyll maximum layer; rather, most species were found at depths both above and within the subsurface chlorophyll layer along the section.

Since 1974, the major area of our research has shifted northward to the Washington continental shelf and slope. Selected samples from stations along a section at 47°07'N are being enumerated to ascertain the dominant types of phytoplankton in order to interpret certain observed features of the chlorophyll and primary productivity distributions. (Postel, G.C. Anderson, Perry)

Compensation light intensity: The high rates of photosynthesis measured in and below the deep chlorophyll maximum show that the 1% of surface light depth is not a reliable indicator of the depth of the euphotic zone and that commonly quoted values for compensation light intensity are probably too high for oceanic phytoplankton in the northeast Pacific. However, it may be argued that the algae in the subsurface chlorophyll layer are highly shade-adapted (as we have observed ourselves) and may not be characteristic of oceanic phytoplankton in general. Also, our earlier *in situ* measurements of photosynthesis were made over the daylight period (sunrise to sunset) and therefore did not allow for loss of ^{14}C-tagged organic matter by respiration at night. Consequently, we occupied a station to the north of the area where the subsurface maximum is found and made *in situ* measurements to depths below the 1% light level for 24 hours as well as for the daylight period. The ^{14}C uptake values from 24-hour incubations were slightly less than those from daylight incubation but were nevertheless measurable to below the 1% light depth.

It appears from our measurements that compensation depths are deeper than earlier estimates for large areas of the ocean, including areas where subsurface maxima of phytoplankton are absent. We are aware that the depth at which ^{14}C uptake reaches zero is somewhat below the 24-hour compensation depth because the method is likely to yield a measurement between net and gross production. We also recognize that the bottom of the photic zone is likely to be tied to a range of absolute light intensities rather than to percentages of surface light. Therefore, in a hypothetical situation with seasonally constant extinction coefficients, the compensation depth would be at shallower absolute depths in winter than in summer, as well as at shallower light depths, i.e., depth expressed as percentage of surface light. The field work is continuing using a quantum meter which is sensitive to levels of light below the 0.1% depth in summertime. (G.C. Anderson)

Nitrogen metabolism of coastal phytoplankton: The nitrogenous nutrition of phytoplankton assemblages in the waters off the coast of Washington are being investigated using ^{15}N-nitrogen tracer techniques.

Past studies in nutrient-poor waters have shown that ammonia is an important source of nitrogen. Present studies are designed to assess the proportionate utilization of nitrate and regenerated nitrogen compounds in coastal water during an annual cycle. The nitrogen assimilation data also provide a second approximation (in addition to ^{14}C carbon production estimates) of phytoplankton growth rates in coastal waters. (Postel, G.C. Anderson, Perry)

Net- and nanoplankton nitrogen metabolism: Nitrogen assimilation for different sizes of phytoplankton is also being determined in the field. Size-class separation affords a method of investigating phytoplankton processes on the level of functional groups. Observations on the biomass (chlorophyll a), carbon production, and carbon assimilation per unit chlorophyll a of the net- (>20 μm) and nanoplankton (<20 μm) show that the large cells vary more in their relative representation and activity in the plankton. Fractionation is accomplished by passing a sample that had been incubated with a ^{15}N-nitrogen labeled compound through high-porosity Nitex netting. Similar measurements of ^{14}C-carbon incorporation permit the examination of C/N assimilation ratios for different size classes. (Perry, Postel)

Glucose determination in seawater: A new microanalytical technique for the measurement of glucose in seawater was developed in 1976. This method, which involves an enzymatic amplification step, permits the determination of nanomolar concentrations of glucose in seawater. At present, this method is being employed to assess the spatial and temporal distribution of glucose in coastal waters. This information is germane to investigations of heterotrophy in the ocean. (Perry)

Carbon metabolism of marine phytoplankton: A laboratory study of carbon metabolism in a North Pacific diatom will attempt to resolve two related problems in analyzing primary productivity data from the field: (1) While carbon fixation and chlorophyll may be routinely measured, living phytoplankton carbon concentration cannot be measured, nor estimated from chlorophyll, with sufficient accuracy to provide ecologically useful values of mass-specific carbon fixation as a measure of cell-division rate. (2) While the trends of adaptation of the dependence of phytosynthesis on light intensity are known, there is no theoretical model to describe quantitatively this process for use in a large-scale similation model. In addition, although there is evidence of a hyperbolic relationship between intracellular concentration of a nutrient and the cell-division rate under limitation by that nutrient, this relationship has not been investigated for intracellular carbon under light-limited growth.

A single diatom will be grown under conditions of constant temperature and excess nutrients to isolate the responses of carbon per cell, chlorophyll per cell, photosynthetic parameters, and cell-division rate in steady-state (continuous light) cultures to changes in light intensity. Steady-state cultures will be obtained through light-limited continuous culture. The resulting data will be used to validate a preliminary theoretical model which has realistically simulated, light-adaptive behavior, and to estimate parameters of that model. (Strickland [G.C. Anderson])

2. Microzooplankton

The distribution of microzooplankton with respect to subsurface chlorophyll maxima found off the Washington coast during summer 1974 has been studied. One-liter samples of seawater were obtained from selected depths at a series of stations extending outward from the Washington coast beyond the continental shelf.

Ciliates were numerically the most dominant group. A significant increase in ciliate numbers was observed in the region of peak chlorophyll concentration in oceanic waters. Positive correlations were found between ciliate numbers and estimates of phytoplankton biomass. In continental shelf waters, however, the relationship between ciliates and phytoplankton was not as distinct. This may be explained on the basis of fractionation experiments which showed that larger phytoplankton cells made up a greater proportion of the total plant biomass in the nearshore region than seaward of the shelf break. The lack of a clear relationship between chlorophyll and ciliates in nearshore waters indicates that much of the phytoplankton biomass was not available to ciliates since many of the individual plant cells were too large to be ingested.

Metazoans, such as nauplii and post-naupliar copepods, were also counted. These tended to be concentrated in the zone of maximum chlorophyll content, but usually the number of specimens observed was too small to be statistically reliable. A manuscript is in preparation. (G.C. Anderson; Chester, Pacific Marine Environmental Laboratory)

3. Plant pigments

The determination of plant pigments in the sea and the use of these measurements as indices of biological processes continues. A research program has been designed toward a "pigment budget" of the water column. Efforts are concentrated on chlorophyll *a* and its metabolic products. Primary reasons for this are: (1) Energy utilized in the photosynthetic process must pass through the chl *a* molecule. (2) Techniques available to measure chl *a* and related pigments are more advanced and precise than methods that could be used for the measurement of other plant pigments. Also, the other pigments are not studied at present either because their ecological significance is uncertain; or, if they are potentially useful for interpretation of ecological phenomena, the information is more readily obtained in another manner.

Naturally occurring chlorophyll *a*-like pigments include chlorophyllide *a*, phaeophytin *a*, and phaeophorbide *a*. The first member, chlorophyllide *a*, can be found in the surface layers only. Traces of phaeophytin *a* can be found throughout the water column. By and large, the most abundant species is phaeophobide *a* which is present throughout the water column and in the underlying sediments. All three and the parent chlorophyll *a* can be separated and identified by a combination of chromatography and either spectrophotometry or spectrofluorometry. Quantification of any one member of the group is to some degree uncertain since techniques in use do not differentiate between chlorophyll and chlorophyllide groups. Evidence from chromatography indicates that chlorophyll and phaeophorbide are relatively much more abundant than chlorophyllide

and phaeophytin within the water column.

Production of the different species appears to be variable. Chlorophyllide is a precursor in the normal synthesis of chlorophyll but its presence in pigment samples may at times be an artifact of the technique, especially if extraction is carried out over an extended period of time, since chlorophyllase does not seem to be inactivated in acetone. Neither phaeophytin or phaeophorbide can be produced by placing algal cultures in the dark. Chlorophyll *a*, however, is readily degraded to phaeophorbide by passage through the gut of an herbivore. Phaeophytin appears in the pseudofeces of mollusks but not in fecal pellets. Presumably, it is produced from the parent chlorophyll if the algal cell is killed in a specific manner.

Because the sole source of phaeophorbide in the ocean appears to be herbivore grazing, its distribution should be relatable to phytoplankton-herbivore interaction. Complications arise from sinks for phaeophorbide produced in the water column. Phaeophorbide is light labile; consequently, fecal material produced and retained in the upper portions of the euphotic zone will be photo-oxidized. Larger fecal pellets, however, settle rapidly and are dispersed throughout the water column making sampling more difficult.

The present sampling is conducted in conjunction with zooplankton studies off the coasts of Washington and Oregon. Concurrent laboratory studies are described in XXII *D*.

Two techniques are currently under development to increase the specificity of pigment measurement in the field. The first, spectrofluorometry, can increase specificity for the chlorophylls *a*, *b*, and *c* when present in mixtures which also include the degradation products of chl *a*. Degradation products of chl *b* and *c* have not been identified in natural samples. The technique that appears most promising seems to be to scan the emission spectra before and after acidification when excited at four different wavelengths. Initial sea experience indicates that this method is almost as sensitive as the routine fluorometric procedure, but requires approximately five to seven minutes to complete the analysis, significantly longer than the routine technique.

The second technique, high pressure liquid chromatography, affords the possibility of separating the plant pigments in a sample thereby yielding better specificity. Numerous solvent systems were investigated and a "safe" one for shipboard use, two parts acetone to five parts iso-octane, yielded satisfactory separation of most of the pigments, but the more strongly absorbed ones, chlorophyll *c*, phaeophorbides, and chlorophyllidies are still retained on the column. Other solvent systems are being explored so that complete separation can be effected. This total system has been checked at sea and experience gained will be useful in the future. (Lorenzen)

4. Phytoplankton dynamics

A numerical two-dimensional (i.e., time and depth) model of primary production in the Pacific Ocean off Washington is used as an in-

vestigative tool to identify and quantify the physical and biological processes that govern the spring and summer variations in the vertical distribution of phytoplankton in the offshore zone. The study focuses on the development of one of the more prominent features of the region, namely, the subsurface chlorophyll maximum. The presence of this layer over extensive areas of the ocean can be expected to have a considerable effect on related biological and chemical characteristics, e.g., total biological production, distribution of nutrients, and oxygen.

The dependent variables in the model are the concentrations of chlorophyll *a*, nitrate-nitrogen, and ammonium-nitrogen. Since we assume that average horizontal gradients of both nutrients and phytoplankton are small, the dominant transport processes are vertical turbulence and sinking of algal cells. The biological terms are algal gross production, algal respiration, and zooplankton grazing for the phytoplankton equation, and selective uptake and regeneration for the nitrogen equations. The computation of light intensity includes the self-shading effect and seasonal as well as daily variations of the day-length and the incident radiation. Most of the parameters and forcing functions vary with time and depth.

The resulting set of coupled, nonlinear, integro-partial, differential equations is solved by using an iterative, semi-implicit, finite-difference method. Our experience indicates that considerable care must be given to the numerical technique applied to this problem.

The results of a long-term simulation over spring and summer months represent the main features of both the biological and chemical data. According to the model, the development and subsequent deepening of the subsurface chlorophyll maximum is attributable to *in situ* production, as well as differential sinking associated with nutrient depletion. The vertical distribution of nutrients in summertime is a consequence of biological processes. The rate of development of the subsurface chlorophyll maximum is determined in part by zooplankton grazing. A detailed description of this study is in press. (Jamart [Winter, Banse, G.C. Anderson, and Lam])

Several numerical experiments were performed over the period of the simulation, e.g., the formation and deepening of the subsurface chlorophyll maximum . The results of this sensitivity analysis show that the dynamics of the phenomenon is fairly independent of the exact values of most parameters (within reasonable limits). For the set of mathematical representations and assumptions describing the present model, the sensitivity analysis also supports the following hypothesis: The phytoplankton-nitrogen system, as it responds to zooplankton and light intensity, evolves in such a way that the amount of carbon ingested by herbivores is mainly determined by the resources available to primary producers. Physical constraints (e.g., sinking rate) affect the utilization of those resources. It appears that, in some dynamical sense, the chlorophyll distribution adjusts in time and depth so as to optimize the transfer of carbon to secondary producers. (Jamart [Winter, Banse])

One of the objectives of the modeling effort was to investigate in greater detail certain of the biological submodels in the numerical

primary production model. Specifically, we proposed to investigate further the dependence of gross production on external environmental factors and also to examine the functional representations of the metabolic processes in the numerical model. For example, in the model simulations, we have found that the vertical distribution of chlorophyll is sensitive to assumptions regarding the optimum light intensity (I_{opt}). The work of Steele (1962) suggests that the optimum light intensity is proportional to the cellular carbon-to-chlorophyll ratio (C/chl). Since this ratio is extremely difficult to measure in the field, it is necessary for modeling purposes to relate C/chl to more readily measurable quantities. Thus, in the submodel, we have utilized the light flux and nutrient regime to which the phytoplankton was exposed to estimate both C/chl and I_{opt}.

In the modeling of production, we have assumed that the functional form of growth production could be represented by a product of two terms, one depending on light intensity and the other on the external nutrient concentration. The functional relationship of production to external nutrients was assumed to be hyperbolic. However, most of the available information on nitrogen is based on laboratory experiments mainly concerned with the relationship between external nutrient concentration and nutrient uptake. For modeling purposes, it is desirable to synthesize this information on nutrient uptake and internal control of cellular growth to obtain quasi-empirical relationships between external nutrient supply, light intensity, and production.

We have been working on two submodels to accomplish the above-mentioned synthesis. One model addresses the question of how plant growth is related to light and external nutrients. Specifically, we have developed an idealized mathematical model of cell growth that relates carbon production and cell division rate to the history of exposure to light energy and external nitrogen supplies. The model appears to reproduce certain trends observed in plant production and adaptation. The second mathematical submodel, developed to investigate some observations on short-term adaptations (Harris & Lott, 1973), examines the role of photo-respiration and its dependence on cellular glycolate. We are continuing our efforts in this general area and refining these submodels. The results to date encourage us in the belief that this line of investigation may yield some new perspective on phytoplankton growth and may ultimately provide some additional guidance on quantitative representations of algal metabolic processes in numerical models of marine ecosystems. (Lam)

5. Surf-zone diatom blooms

Persistent blooms of surf diatoms are a characteristic feature of the coastal environment of northern Oregon and southern Washington where they extend from the Columbia River mouth for 75 miles north to Port Grenville. The two surf diatom of major importance are *Chaetoceros armatum* and *Asterionella socialis*. Because of the abundant and regular supply of diatomaceous food, the razor clam populations reach their greatest productivity along these same surf-swept sandy beaches.

The regional and temporal occurrences of the blooms and the environmental factors that may influence them have been studied over a

six-year period (1971 through 1976), emphasizing the vicinity of Copalis Beach, Washington. Since we had previously demonstrated that nitrogen is the nutrient that may be in short supply during summer months, an analysis of the factors influencing the nitrate cycle in the surf environment was undertaken. Nitrate depletion in upper water layers beyond the breaker zone takes place in April of each year due to the spring phytoplankton bloom; in 1974 *Thalassiosira pacifica* was the species responsible for the bloom. This same nitrate-depleted water is also characteristic of the surf zone in April of each year (Figure 8).

Between mid-April and mid-October, reintroduction of nitrate into the surf zone depends on encroachment of oceanic deep water high in nitrate; in 1971 when there was only weak upwelling, nitrate in the surf remained depleted over an extended period (six months). Upwelling can be masked by the presence of freshwater discharge from rivers and streams (as in 1971, 1972, and 1974). In the summer of 1973, when the rate of river discharge was at an all-time record low, the nitrate concentration in surface samples was higher than at any other time during the study period (Figure 8).

Cell concentrations of both surf species were reduced in summer (Figure 9). *A. socialis* often disappeared completely in mid- or late summer and *C. armatium* showed symptoms of physiological stress. Annual cycles of abundance of each of the surf species seem to be repeated in more or less the same fashion from year-to-year, in spite of the very different patterns shown in nitrate concentration from summer-to-summer. This points to the importance of annomia as an alternate nitrogen source for surf diatoms, particularly during summer months. In particular, an analysis of the factors influencing the nitrate cycle (at Copalis Beach) from 1971 through 1975 has been completed and a manuscript prepared. The results indicate that nitrate is depleted in upper water layers beyond the breaker zone in April of each year due to spring phytoplankton blooms. In 1974, *Thalassiosira pacifica* was the species responsible. This nitrate depleted water is also characteristic of the surf zone in April of each year (Figure 8). Between mid-April and mid-October, reintroduction of nitrate into the surf region depended on encroachment of upwelled oceanic deep water; in 1971, when there was only weak upwelling, nitrate remained depleted over a six-month period. However, the upwelling can be masked during the spring run-off by the discharge of freshwater from rivers and streams into the surf environment. Thus, in summer of 1973, when river discharge was at a record low rate, nitrate concentration in the surf was highest. Cell concentrations of the surf diatom *Chaetoceros armatum* were less in summer, while *Asterionella socialis* disappeared completely in mid- or later summer (Figure 9).

We have been able to show that the major source of the ammonia supply in the surf zone is through recycling processes carried out by the large razor clam populations. Excretion rates of ammonia have been measured in beach experiments during the past year so that we now have information concerning the effect of clam size, physiological state of the clams, seasonal changes, etc. on excretion rates of ammonia. (Lewin and collaborators)

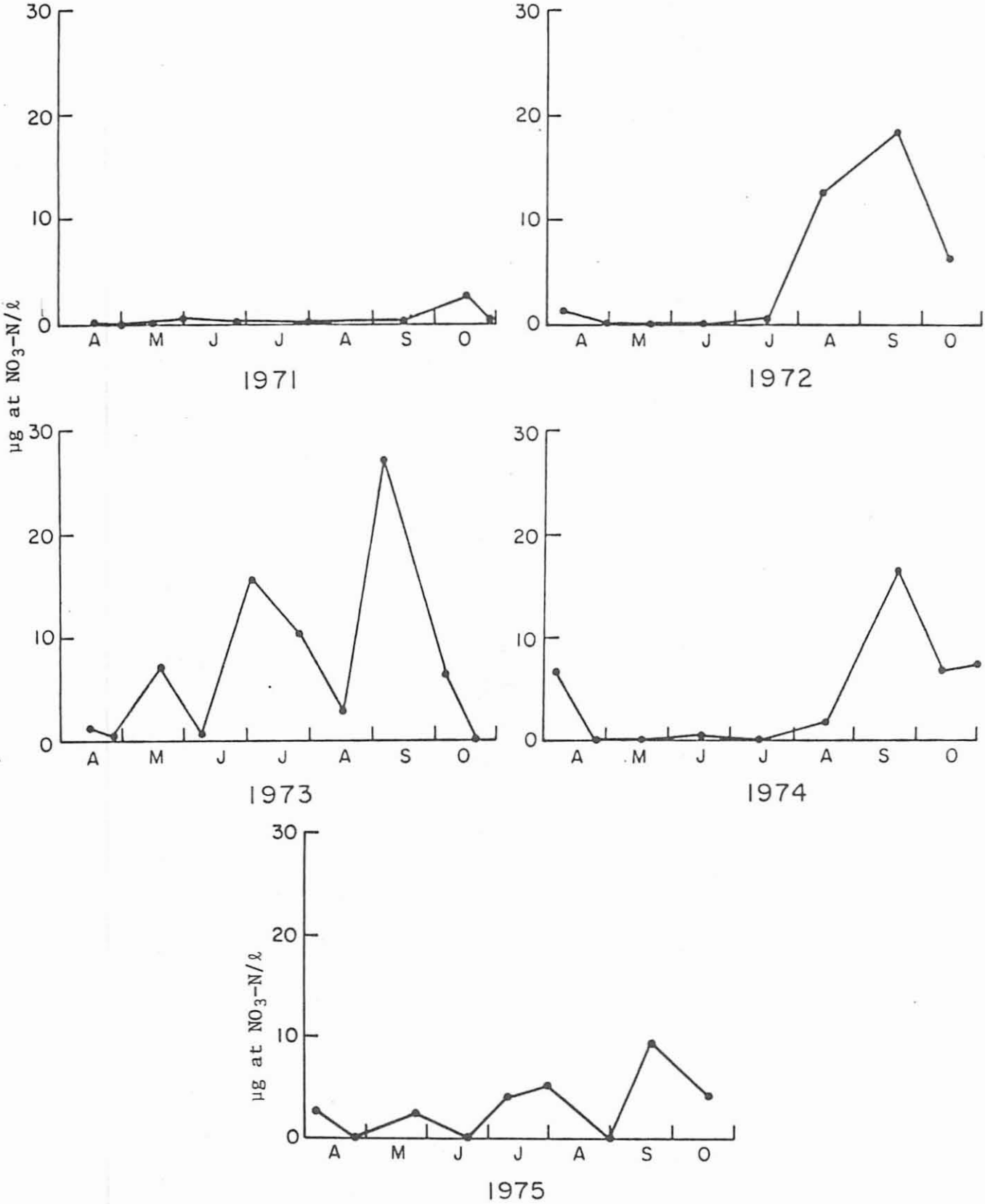


Figure 8. Distribution of nitrate during summer at Copalis Beach. (Each point represents average values of several samples during a 24-hour period.)

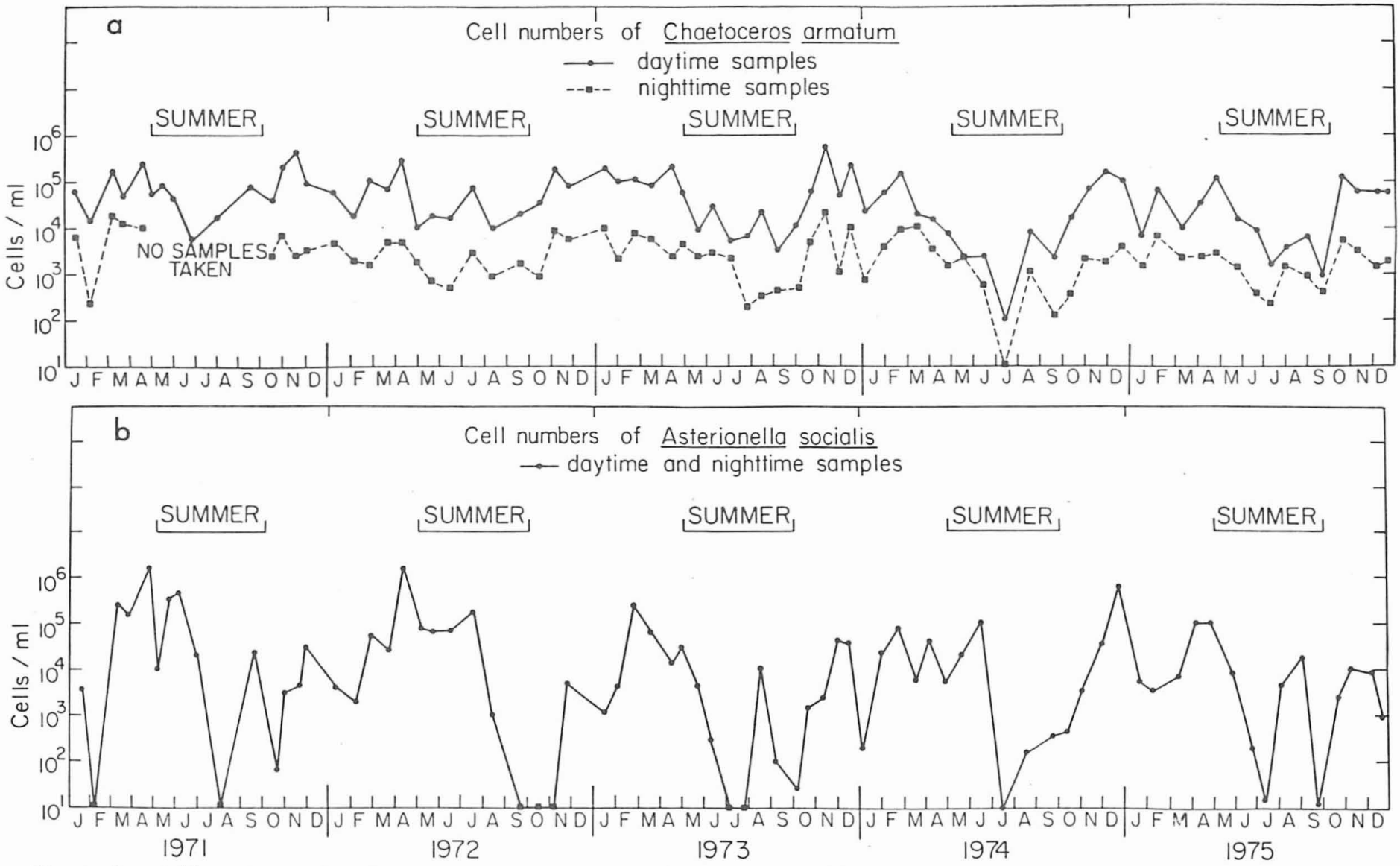


Figure 9. Cell numbers of major species of surf-zone diatoms at Copalis Beach during the period 1971-1975. (Each point represents average values of several samples during a 24-hour period.)

6. Evaluation of chlorophyll measurements

The current interest in modeling and development in the field of biological oceanography has focused the need to evaluate practices used to acquire data since it is frequently necessary to pool data from different sources. One of the most frequently measured parameters in phytoplankton studies is the chlorophyll content of the water column. The past decade has seen the introduction of not only new techniques but of different specific absorption coefficients (used in equations to calculate pigment concentrations). In addition, practices vary in handling samples prior to analysis. An attempt has been made to evaluate the effect of using different techniques and sample handling procedures prior to analysis.

There are basically two sampling handling procedures and two techniques in widespread usage today. They are:

1) Immediate analysis after obtaining sample: Depending on various operational constraints pigment analysis can be carried out immediately after obtaining a sample. Investigators who analyze immediately usually use fluorometric techniques.

2) Analysis after storage: Operational constraints may make storage desirable. Investigators usually use spectrophotometric techniques on stored samples that previously were desiccated at reduced temperatures. The effect of storage seems to affect the final calculated pigment concentration with either spectrophotometric or fluorometric techniques to the same degree. Either drying or freezing or both bring about a reduction in calculated pigment content of 15-50%. Desiccation in a freezer is associated with the least "apparent loss" of pigment. Straight desiccation at room temperature is associated with the greatest loss and freezing is intermediate.

3) Spectrophotometric analysis: Pigment measurements have traditionally been carried out in aqueous-organic extracts of whole cells. Optical densities that are measured at different wave lengths are entered into equations and pigment concentrations calculated. The presence of chlorophyll degradation products can also be calculated by taking optical density readings before and after acidification.

4) Fluorometric analysis: Fluorometric techniques are significantly more sensitive than optical methods. Operationally they are faster because smaller volumes of water have to be handled and only two entities are estimated, chl *a* and phaeopigments.

Table 1

Summary analysis of different techniques for chlorophyll determination including correlation coefficients and, in parenthesis, the slopes of the least squares linear regression.

	SCOR/UNESCO	Strickland & Parsons	Spectro-chlorophyll	Fluoro-chlorophyll
SCOR/UNESCO	1	0.96 (1.18)	0.87 (1.19)	0.83 (0.57)
Strickland & Parsons		1	0.88 (1.01)	0.79 (0.45)
Spectro-chlorophyll			1	0.59 (0.29)
Fluoro-chlorophyll				1

A statistical analysis of chlorophyll determinations taken during cruise TT-091 (summer 1974) was undertaken to estimate the effects of the different methods of calculating pigment concentrations. In addition, paired samples, one of which was analyzed immediately and the other stored, were taken from the same water bottle. Three spectrophotometric methods and one fluorometric method was used. They include: (1) SCOR/UNESCO, (2) Strickland and Parsons, (3) spectro-chlorophyll less degradation products (Lorenzen) and (4) fluoro-chlorophyll less degradation products (Lorenzen). The results are summarized in Table 1. The correlation coefficients are satisfactory (above 0.7) except in the case of fluoro-chlorophyll vs. spectro-chlorophyll, but what is surprising is the variation in the amount of chlorophyll that is calculated using these different techniques. When compared with the fluoro-chlorophyll technique, which was carried out immediately, SCOR/UNESCO yielded values only 57% as large, Strickland and Parsons 45% as large, and spectro-chlorophyll only 29% as large. The latter three methods include the storage effect. On the other hand, the three optical techniques gave results which are more comparable. SCOR/UNESCO yielded values which are 118 and 119% larger than the other two methods, while the Strickland and Parsons and spectro-chlorophyll methods are directly comparable.

Analyses on the other sets of data are continuing. (Lorenzen)

B. Gulf of Alaska

This study is part of the large NOAA-sponsored Outer Continental Shelf Environmental Assessment Program (see XXVI *J*). Presently, we are compiling available baseline data, including measurements of phytoplankton distributions, nutrient supply, and hydrography, from

books, papers, technical and data reports, and from unpublished data at the University of Washington. A synthesis of this material will result in a description of the seasonal and geographic distribution of phytoplankton standing stock, production, and related physical and chemical factors. A numerical model which was developed for waters off the Washington coast is being adapted for use in the Gulf of Alaska (see XX *A* 4). Utilizing this model and the compiled baseline data, we are identifying the major factors involved in phytoplankton dynamics--knowledge which is necessary for the design and implementation of further field studies.

One of the longest time-series available is from the Canadian studies at station "Papa" (50°N, 145°W). However, to widen the data base, all pertinent data from the pelagic realm of the region of interest are being collected; these include 17 years of data from 114 cruises. The area will be divided into sectors, and analysis of variance will be used to describe the extent of the area in which generalizations from station "Papa" apply. Temporal variation of biological features and nutrients in the other areas will be described. In particular, the reported low biomass of the Alaskan gyre and the high productivity in the western sector of the study area will be investigated.

Published observations at station "Papa" indicate that chlorophyll concentration shows little seasonal change and that nitrate is always available in nonlimiting quantities. Furthermore, zooplankton biomass data have been available for many years. Based on this information, a numerical production model which did not depend on nutrients and which assumed that grazing pressure was an independent input was used. This model successfully reproduced the relatively uniform surface chlorophyll concentrations and also showed a peak in plant production during the spring, a feature that is consistent with the data. Using this model we found that the sensitivity of the results to changes in the different inputs is dependent on the time of year. We are pursuing these questions and simulating oil spills through changing the maximum plant growth rates and the grazing pressure. The resultant changes in the chlorophyll concentration are being compared with the standard case. (G.C. Anderson, Lam, Booth)

C. Radionuclide Pathways

Trace amounts of transuranic elements may be released to the aquatic environment during the preparation of fuel elements, the normal operation of nuclear reactors, and the processing of spent fuel elements; and also from atmospheric detonations of nuclear devices. However, observations on the behavior of transuranic elements in natural environments have not provided sufficient information for the prediction of the accumulation of transuranic elements by aquatic organisms.

In this study, the transfers of the transuranics, plutonium-237 ($t_{\frac{1}{2}}$ = 45.6 days) and americium-241 (long $t_{\frac{1}{2}}$), a decay product of ^{237}Pu, from water to two species of marine phytoplankton, *Monchrysis lutheri* and *Phaeodactylum tricornutum*, are examined. Possible processes of

accumulation are (1) adsorption onto cell surfaces, (2) diffusion through the cell membrane, (3) assimilation into the cells by active transport (requires biological energy), or (4) a combination of the three processes. By examining the rates of accumulation of these isotopes by live vs. dead algae (heat-killed) or 0° incubation), it is hoped to determine whether the mechanism is a biologically active or passive process. By measuring, at equilibrium, the activity on the algae vs. that left in the water, concentration factors will be obtained. (Equilibrium is defined as the time point when the distribution of activity between the algae, the filtrate, and the glass container is constant.) (Yen [G.C. Anderson])

D. Structure of Plankton Communities

Simulation models of marine plankton communities usually have described phytoplankton and herbivorous zooplankton in terms of biomass. The use of biomass obscures and oversimplifies a number of significant biological interactions, especially those which are related to species composition or size structure of trophic levels. However, species and size structure of phytoplankton appears to exert major influence over the structure and function of entire pelagic food webs. Moreover, theoretical studies of interactions among species of planktonic herbivores are impossible without specifying some species or size structure in the phytoplankton. Consequently, a new simulation model of a temperate ocean plankton community was developed that consists of 19 size classes of phytoplankton (cell diameters ranging from 2.5 to 161 μm) and 20 size classes of zooplankton (weights ranging from 0.1 to 106 μgC), the latter chosen to represent developmental stages of a small and large species of copepod, such as *Pseudocalanus* and *Calanus*, respectively. Fundamental physiological processes affecting the growth of phytoplankters and copepods are specified as functions of cell diameter and body weight, while predation on copepods is arbitrarily defined. Results of simulations graphically demonstrate (1) the significant role that size structure of phytoplankton plays in affecting the population dynamics of herbivores, (2) the importance of size-specific utilization of different sizes of phytoplankters by copepods, and (3) the strong effect of predation scheme (e.g., size-selective vs. nonsize-selective predation) on the dynamics and size structure of the plankton. Effects of simulated perturbations applied either at high or low trophic levels ramify throughout the food web. Results suggest that no single process (e.g., rate of supply of plant nutrient, nutrient uptake by phytoplankton, zooplankton feeding behavior, predation pattern on copepods) predominates in determining the dynamics and size structure of a plankton community. Investigations of the model are continuing. (Frost; J.H. Steele, Marine Laboratory, Arberdeen, Scotland)

E. Feeding Behavior of Herbivorous Planktonic Copepods

The goal of this project is to obtain a quantitative understanding of the feeding behavior of some herbivorous copepods which are important components of the plankton in Puget Sound and other temperate oceans. Experiments with species of *Calanus*, *Pseudocalanus*,

Temora, and *Acartia* were done to determine whether these filter-feeding copepods feed selectively or nonselectively when presented with mixtures of food particles varying in size composition and abundance. Results suggest that there are two types of filter-feeding copepods: conventional filter-feeders (characterized by *Calanus*, *Pseudocalanus*, and *Temora*) which are nonselective feeders, but may exhibit passive differential filtration of particle sizes, and seining filter-feeders (characterized by *Acartia*) which seem to actively select the most abundant available food particles. These two feeding strategies could have markedly different effects on the species composition and size structure of the phytoplankton, and therefore could greatly influence the dynamics of plankton communities.

Studies are continuing to determine the cause of significant seasonal variations in maximum filtration rates of *Calanus pacificus* in Puget Sound. Rates increase more than twofold from spring to summer, then decline in late autumn to levels comparable to spring values. Seasonal changes in filtration rate are correlated with changes in body size of copepods, but seem to be more closely associated casually with seasonal variations in the abundance of phytoplankton. Our observations are in accord with earlier accounts of seasonal changes in metabolism (respiration and excretion) found for several species of *Calanus* and other copepods. It appears that copepods are metabolically more active when phytoplankton is abundant and that high filtration rate is a correlate of this increased activity. (Runge [Frost])

F. Dynamics of Planktonic Herbivorous Copepods in Puget Sound

A field study was carried out for one year in the main basin of Puget Sound near Seattle and in Dabob Bay, a deep tributary basin of Hood Canal. The purpose of the study was to document seasonal trends in population sizes of the dominant planktonic copepods, *Calanus* spp. and *Pseudocalanus* spp. The two sites were chosen because of significant differences in the seasonal patterns of primary production; for example, the spring phytoplankton bloom occurs about two months earlier in Dabob Bay. Preliminary results indicate, however, that in both basins *Pseudocalanus* spp. begin reproducing long before the spring bloom of phytoplankton while reproduction of *Calanus* spp. occurs at the onset of the spring bloom. Moreover, within each genus there are major interspecific differences in patterns of life histories. Detailed studies of the populations in Dabob Bay are in progress. (Frost)

G. Control of Phytoplankton Growth by Grazing

Plankton communities in coastal and offshore waters of the subarctic Pacific Ocean are dominated by different species of grazers. Associated with this phenomenon are striking differences between coastal and offshore waters in the seasonal dynamics and pattern of utilization of primary production. For instance, in coastal waters large increases in standing crop of phytoplankton occur in spring or summer, but in offshore waters the phytoplankton standing crop is almost seasonally invariant, even though nutrients are always in excess.

The lack of phytoplankton blooms in offshore subarctic waters has been attributed to grazing by planktonic herbivores, in particular, the copepod species *Calanus plumchrus* and *C. cristatus*. Morphological studies, laboratory feeding experiments with *C. plumchrus*, and simulation model studies all provide support for the hypothesis that grazing copepods control phytoplankton growth in oceanic subarctic waters. In 1978, a field study will be conducted in oceanic waters to obtain direct evidence appropriate for testing the grazing hypothesis. Estimates of production rates for different size categories of phytoplankton will be made, and shipboard grazing experiments will be conducted with several major size-fractions of zooplankton (microzooplankton, small copepods, large copepods, euphausiid shrimps). Laboratory studies utilizing local populations of *C. plumchrus* are already in progress. (Frost)

H. Copepod Grazing Dynamics

A model that describes the feeding behavior of a copepod was based on the observation that there are three phases in the feeding response of adult females of *Calanus pacificus*. At low food concentrations they increase their filtration rate with increasing food supply until some maximum filtration rate is reached, maintain that maximum rate until a critical food density is exceeded, and then decrease their filtering rate while holding a constant ingestion rate for further increases in food concentration. In the model, the filtration and ingestion rates of a copepod were expressed as functions of the food concentration, the size of the food particles, and the body length of the animal. Figure 10 summarizes the filtering response predicted by the model for an animal with length, L, and filter area, A. The filter area is in turn dependent on the length of the animal and on the size of the food particles. We restricted ourselves to simple representations of the physical and biological phenomena in order to emphasize the basic concept of the model, energy optimization. Because of the success of the preliminary model, we are planning to extend the model by (1) incorporating more realistic descriptions of the filter and generalizing the equations in the model; (2) applying the results to obtain physiological constants for the animals from feeding experiments and to investigate the effects of a spectrum of food sizes on the feeding response; and (3) considering some questions about the competitive advantages of specific behaviors in the copepods. (Lam, Frost)

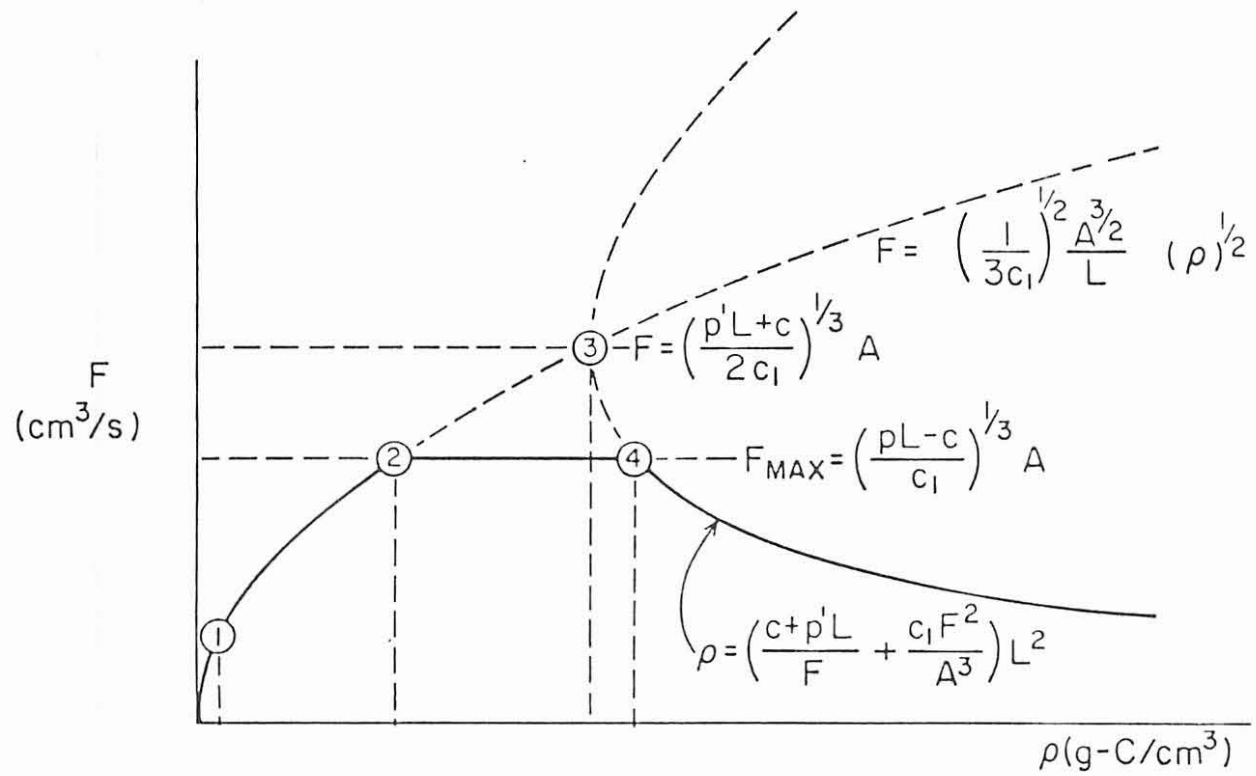


Figure 10. Modeled filtering response curve. L is the animal length, A is the animal's filter area and c, c_1, p, p' are physical and physiological constants.

XXI. Benthic Production

The objectives of this program are the same as those of plankton production, i.e., to describe, explain, and predict the rate of production of organic matter in space and time, and the resulting distribution of abundance of organisms. Biological processes in the seawater on the continental shelf, with its plankton, cannot be understood without taking the interaction with the seabed into account. Research in this field is not well advanced in the United States; however, it needs to be promoted not only for its intrinsic interest but because bottom organisms in many cases are more affected by, and therefore better indicators of, pollution than those of the plankton.

A. Dynamics and Production of an Interstitial Harpacticoid Copepod

Three intertidal sand beaches in Puget Sound were sampled during 1973 and 1974 at approximately ten-day intervals. Quantitative replicate core samples of the interstitital meiofauna populations were analyzed, with emphasis on the harpacticoid copepod community. This group of organisms reaches densities of $10^6/m^2$ during spring and early summer at MLLW stations, with lower densities (10^3-$10^5/m^2$) prevailing during the rest of the year. Nematodes outnumbered the harpacticoids during all times of the year by a factor of at least three. Gravid female harpacticoids are present throughout the year. One of the beaches is thixotropic at the lower tide levels, and viable populations of several harpacticoid species persist at depths of 40-50 cm within the sediment there. The interstitial harpacticoid community consists of approximately 20-30 species, depending upon beach location, sediment particle size, tidal elevation, and depth within the sand.

Huntemannia jadensis which was numerically dominant at the MLLW stations at all three beaches has been examined in detail for its abundance, age structure, and reproductive state. Cohorts were easily distinguished at each beach by following the abundance of the naupliar and copepodite stages through time. *H. jadensis* has only one generation per year. This finding was totally unexpected for a copepods of this size, as similarly-sized epibenthic species may have up to ten generations per year. Development from hatching to adult took two to three months in the field. Laboratory rearings of the organism at 8, 12, 15, and 20°C under excess food conditions were successful; the development time from hatching to the adult ranged from 45 to 95 days. Mortality was highest in the naupliar stages in both the natural population and in cultures.

Secondary production of *H. jadensis* was measured in terms of bodily carbon. An elemental analyzer was used for carbon determinations. Calculations of production according to the instantaneous growth method of Ricker, the Allen curve, and a modification of Winberg's method were in good agreement for any one beach, although values ranged between 0.6 and 1.7 $gC/m^2/yr$ for different beaches. P/B ratios ranged between 3.0 and 4.8. On a daily basis, production by this interstitial harpacticoid compares well with the few good estimates for production by planktonic copepods in temperate areas. (Feller [English])

B. Abundance Patterns and Dynamics of an Intertidal Amphipod

A study of the distribution, age structure, and reproduction of *Dogielinotus loquax* is being carried out. This amphipod inhabits a relatively narrow band in the upper intertidal at Ocean City Beach, Washington, a high-energy beach. Quantitative core samples, using a stratified random sampling scheme, have been taken at three to four week intervals for one year.

D. loquax produces in late summer resulting in a generation of overwintering adults that subsequently reproduce in the early spring. Lesser peaks of juvenile recruitment are also evidenced in late spring and early summer. Laboratory studies of egg development times will be correlated with the field data to provide estimates of birth and death rates. (Hughes [Banse, Jumars])

C. Long-Term Stability of Subtidal Bottom Fauna in Puget Sound

Puget Sound is one of the two or three marine (rather than estuarine) sites with published information on long-term stability of subtidal animal populations. We have intermittent records for some stations since 1963, where macrofauna (retained by a 1 mm screen) were sampled with the same gear; we also have made detailed studies of community structure, and, for short periods, of production of some of the dominant species.

Subsequently, three of the stations have been sampled biannually since May 1973 during the seasons when most species populations are composed of large specimens, and therefore the screen retains a considerable part of each population. As the environment at the sites is similar to the open shelf, information of a general nature is expected to result from a continuation of this project. Moreover, Puget Sound is the type locality for Sanders' Maritime Climate Boreal Community (in the context of the stability-time hypothesis), so that the data will be of general interest also for this reason.

The current five-year program stresses the dynamics of dominant species: variation of biomass and production estimates, and the possible relation of variations with, for example, presence or absence of competing species. It is hoped that subsequently estimates of the production by the entire macrobenthos can be attempted and that crude limits of confidence, based on observed natural cycles or trends, can be established. (Kisker; F.H. Nichols, U.S. Geological Survey, Menlo Park, California)

D. Soft-Bottom Benthos: Developing an Experimental Capability in the Field

The following of cohort growth and survival has been the only generally successful method applied to studies of the dynamics of soft-bottom (mud and sand) animal populations to date. This method is unable to resolve small-scale spatial variations and wholly unable to deal with populations not exhibiting clearly identifiable cohorts. The former problem impedes small-scale experimentation with factors suspected to influence growth or survival of populations, and the

latter difficulty excludes many ecologically interesting species. Experiments are being conducted with the introduction of tracers which can be used to provide "timing marks" in localized segments of benthic populations and thus to estimate local recruitment and mortality rates. Natural variability in these rates and responses to artificial perturbations are being assessed. (Jumars)

E. Resource Partitioning among Benthos

Studies continue into the interaction of spatial segregation and food-type selection in accounting for the extremely high species diversities among macrobenthos in some deep-sea areas. Gut-content analyses of deposit-feeding polychaetes from the San Diego Trough, Southern California Borderland, are being carried out to determine what physical characteristics of food particles are discriminated by individual species and whether the spectrum of particles selected by members of such species shows a dependence on location or on the proximity of closely related species. The intent is to identify necessary parameters in a realistic analytical model of resource partitioning among deep-sea macrobenthos.

Serological methods are being used to assess the reliability of direct microscopic examination in identifying animal gut contents. Antisera that are prepared for the macrofaunal species and meiofaunal taxa of a relatively simple intertidal community are subsequently used to determine the species' presence or absence in gut contents of other community members. These serological methods are compared with direct microscopic examination both in the field and under controlled laboratory conditions. (Jumars)

F. Deep-Sea Community Analysis

New or refined analytical methods for quantitative deep-sea faunal samples are being investigated as part of the DOMES Study (see XXVI *K*). Interest centers on finding or deriving methods able to extract the greatest amount of information on community structure and its pattern of variation under the conditions of high species diversity and low faunal density. Among other more traditional methods, spatial autocorrelation measures developed by geographers are being modified for this purpose. (Jumars)

XXII. Biology of Marine Organisms

Although being principally concerned with the temporal and spatial distributions of populations and the abundance of marine organisms, biological oceanography draws heavily on knowledge of the biology of marine organisms. Beyond this application, the biology of marine organisms is of intrinsic interest.

The inclusion of the research projects under this heading rather than under Biome Studies and Marine Ecosystems or Plankton and Benthic Production is somewhat arbitrary.

A. Laboratory Studies of Unicellular Algae

1. Heterotrophic growth

Work on facultatively heterotrophic diatoms continues. Species which normally grow by photosynthesis in the light but which can also grow in the dark utilizing organic compounds as energy and carbon source have certain ecological advantages. Thus, the results of such laboratory studies have implications for various ecological measurements in the field. Previously, growth and metabolic behavior for diatom species which utilize sugars (glucose) and organic acids (lactate, succinate) have been investigated. Currently, the emphasis is on those species that have the capability of multiplying in the dark by utilizing amino acids (predominantly glutamate) as substrates. Growth rates in the dark and in the light, rates of uptake of carbon compounds, and efficiency of utilization of compounds have been measured, and metabolic pathways determined.

Two papers reporting on the results of amino acid utilization have been published, and a third has been submitted for publication. A chapter reviewing the heterotrophic nutrition of marine diatoms was prepared for the new book, *Biology of Diatoms*, which is scheduled for release in February 1977. (Lewin; J. Hellebust, University of Toronto)

2. The clay coat of the surf diatom *Chaetoceros armatum*

During the past year, we have investigated the coat of tightly adhering clay particles (mixture of illite and montmorillonite) surrounding chains of *C. armatum* collected from its natural habitat at Copalis Beach, Washington. The clay plus silica frustules make up 63% of the diatoms. Cells grown in laboratory cultures have "sticky" surfaces which bind clay particles (2μ or less) to the cultures immediately after they are added. From scanning electron microscope studies, there is no evidence of any extracellular fibrillar organic material that could be responsible for binding the clay; rather the clay appears to adhere to and be cemented directly onto the frustular surfaces. Layers of clay particles then build up to form a thick and compact coat which retains its integrity upon treatment with hot nitric acid. Experiments on the nature and formation of the clay coat are continuing. (Lewin; J.R. Colvin, National Research Council, Ottawa)

3. Physiology of marine phytoplankton species grown under different light conditions

Growth rates and chlorophyll and protein concentrations (based on per cell) of several marine phytoplankton species grown under different light conditions, e.g., intensity, daylight, and light quality, are being studied. Comparisons are made between large and small species as well as between different phylogentic groups. Two of the most important groups, the diatoms and the dinoflagellates, are being given special attention. (Chan [Lewin])

4. Comparative studies of five species of *Ceratium*

Five dinoflagellate species of the genus *Ceratium: fusus, pentagonum, horridum, lineatum,* and *azoricum* have been cultured successfully in the laboratory. They are all isolates from the northeastern Pacific Ocean and from Puget Sound. Efforts are being made to obtain axenic cultures of these species. So far, bacteria-free cultures of *C. fusus* and *C. pentagonum* have been kept alive for more than two years. Comparative studies are being conducted on their nutrient requirements and salinity tolerance. (Chan [Lewin])

B. Organic Constituents of the Surf Diatom Chaetoceros armatum

The chemical composition of *C. armatum* from both field collections and cultured cells has been analyzed. Lipid comprises 67% of the organic matter and protein about 30% in cell material collected in its natural habitat. In cultured cells, there is less lipid and more protein. The high lipid and protein concentrations explain the nutritional value of this species as a food source for razor clams. The constituent fatty acids comprising the diatom organic matter and the razor clam tissue have been identified and comparisons made. A paper reporting these results is in preparation. (Lewin and collaborators)

C. Effect of UV-B Radiation on Marine Zooplankton (Pleuston) of Puget Sound

The effect of increased ultra-violet radiation on selected surface living zooplankton of Puget Sound will be evaluated. The flow-through natural (filtered) seawater system at the NOAA National Marine Fisheries Service Laboratory, Manchester, Washington, will be used to culture, test, and control organisms. Several replicates will be analyzed for each level of UV radiation: ambient, 10% increase, 25% increase, 40% increase. Survival will be the primary parameter, although, depending on species, feeding, molting, and growth rates may also be considered. Test organisms will include larval forms of commercial shrimps and mollusks (five to six species), copepods (three to four species), and other taxonomic groups as available. (Damkaer; D.B. Dey, Pacific Marine Environmental Laboratory)

D. Chlorophyll Degradation and Grazing Estimation

Laboratory studies have shown that a quantitative relationship exists between the amount of chlorophyll ingested by a herbivore and the amount of phaeophorbide, a chlorophyll degradation product, that appears

after the passage of the cells through the herbivore gut. The experiments showed that the conversion of chlorophyll to phaeophorbide was on the average 66% efficient on a weight basis and about 100% efficient on a molar basis. The specific fluorescence and specific absorption coefficients for phaeophorbide were found to be quite similar to those for phaeophytin. This similarity allows the use of previously published equations for the determination of phaeophytin in the determination of phaeophorbide concentrations.

Present and planned research concerns the extension of the findings discussed above to the determination of herbivore grazing in the field. The majority of the field work has or will take place in Dabob Bay, a frequently studied fjord near Hood Canal, an arm of Puget Sound extending into the Olympic Peninsula, Washington. Monthly cruises of four to five days will be undertaken for approximately one year. An array of sediment traps will be set out upon arrival and retrieved just prior to leaving. The traps which are sent down closed are recovered closed so as to minimize washout of collected material. Production measurements using the ^{14}C technique will be carried out along with frequent measurements of the chlorophyll standing stock in order to estimate the amount of plant material both produced and lost in the euphotic zone above the sediment traps. The immediate goal is to establish a daily budget of production, standing stock changes, and pigment losses as measured by the sediment traps; and to estimate grazing losses through a consideration of the amount of chlorophyll which must have been consumed by herbivores to produce the amount of phaeophorbide found in the sediment traps. While on station both spatial and temporal profiling of *in vivo* chlorophyll concentration, profiling of salinity and temperature, measurements of submarine light by a quantum meter, and net plankton tows are also taken. The latter samples will be used for phyto- and zooplankton studies in the laboratory. (Shuman [Lorenzen])

E. Effect of Environmental Parameters on the Growth Rate of Herbivorous Copepods

Over 70 experiments designed to study the effects of temperature, food concentration, and size on the growth rate of the planktonic copepods *Calanus pacificus* and *Pseudocalanus* sp. have been completed. Growth rate was measured from copepodite I to adult under various combinations of the parameters.

There are strong interactions among all the parameters. For a given temperature and size of an organisms, the weight-specific growth rate increases with increasing food concentration up to maximum growth. As animal size increases, the food concentration up to maximum growth also increases but the rate of maximum growth decreases. As temperature decreases, the difference between the rates of maximum growth of small and large organisms diminished. Small organisms are affected to a larger extent, i.e., a decrease in temperature suppresses the growth rate of small organisms farther than that of large ones. The food concentration at which the rate of maximum growth is attained also decreases when temperature diminishes. A mathematical model to describe these interactions is being developed. (Vidal [Frost])

F. Laboratory Studies of Two Microzooplankton Species

The ingestion, respiration, and growth rates for the rotifer *Brachionus plicatilis* and the heterotrophic dinoflagellate *Noctiluca miliaris* were calculated using cultures grown on three different food species at several concentrations and at several temperatures. From these rates carbon budgets were calculated. In terms of body carbon the protozoan and the rotifer were of similar size, allowing the comparison of a unicellular organism with a multicellular one.

The effect of food concentration and of temperature on both microzooplankters was to increase ingestion, respiration, and growth rates. These rates also varied somewhat with food species.

The ingestion rate-food concentration curves for both rotifer and dinoflagellate were shown to be similar to those described by others for suspension-feeding crustaceans and for fish. However, the minimum food concentrations needed to support population growth of the microzooplankters were much higher than average concentrations usually found in natural waters. This may help to explain distributions of microzooplankton in the field.

Respiration rates for rotifers of a given body carbon were higher than those for equal-sized *N. miliaris* cells, but were not as great as would have been expected for poikilotherms scaled down to this size. Thus, metabolic rates of different kinds of microfauna cannot be extrapolated merely from rate-size relationships known for larger animals but must be measured directly.

The Q_{10} values for all rates were much greater for the rotifer than for the dinoflagellate. Growth rate was most affected by temperature change for both species, and respiration least affected. This explains the tendency for growth efficiencies to increase with temperature for these animals. Minimum food needed for growth was less for the rotifer than for the dinoflagellate, but when food concentration was high the ratio of growth to respiration for *N. miliaris* was greater.

Assimilation efficiencies for both microzooplankters (calculated from respiration + growth/ingestion) were comparable to values reported in the literature where the method of calculation was also "indirect", but were low in comparison to values found by subtraction of total egestion from total ingestion. Assimilation efficiency decreased with increasing food concentration for the rotifer. This was probably *not* due to a real change in digestive efficiency but rather reflected either an underestimate of total respiration cost or some other unmeasured carbon loss (such as "leakage").

The average net growth efficiencies for both rotifer and dinoflagellate were above the average values reported for poikilotherms, but were well within the range of values reported. This gives some support to the theory that microfauna have higher net growth efficiencies under optimal conditions than do larger forms. Results also suggest that the protozoan was more efficient than the metazoan in converting food to growth products under optimal conditions. However, whether differences between rotifer and dinoflagellate reported here reflect

real differences between uni- and multicellular forms or are only features peculiar to this specific comparison remains to be tested. (Dewey [Banse])

G. Small Metazoa: Respiration Rate and Species Size

In connection with the above project, a literature survey was made of the size dependence of the respiratory rate of unicellular organisms and small metazoans. This size dependence is usually described by the allometric equation $R = a W^b$ where R is respiration per animal, W the weight, and a and b are coefficients. The exponent is known to be near 0.75 for unicellular organisms as well as for multicellular animals and plants; however, a for unicellular organisms is almost an order of magnitude smaller than for metazoans; small metazoans, e.g., rotifers and free-living nematodes, were believed to show little or no size dependence of respiration, the exponent reportedly being near 0.95 or unity.

Using more and in part better data, our study confirms the coefficient a and the exponent b for unicellular animals and plants published previously by Hemmingsen. The now available measurements for small Metazoa show that also they tend to follow size relations with b close to 0.75 but with a values intermediate between those of unicellular forms and large Metazoa. Observations on annelids and arthropods indicate that the respriation rate of the small metazoans, which is low relative to that of other metazoans, depends on absolute size. We cannot support previously published phylogentic inferences. (Dewey [Banse])

H. Vertical Migration and Feeding Behavior of Mesopelagic Fish

Certain types of small mesopelagic fish are the primary cause of deep sound-scattering layers in the open ocean. To comprehend, for predictive purposes, the occurrence, intensity and vertical distribution of deep sound-scattering layers at a particular oceanic locality, what controls the distribution and abundance of mesopelagic fish must be known. A field study is being made of the feeding behavior of small mesopelagic fish from both migratory and nonmigratory scattering layers in the eastern subarctic Pacific Ocean. The study emphasizes the role that trophic interactions play in determining the vertical distribution of fish and in modulating diel vertical migrations which are performed by some species.

Field studies were done during summer at two localities, Station Q (51°N 135°W) and Station P (50°N 145°W). A variety of sampling programs was carried out at both localities to determine vertical distributions of mesopelagic fish and large species of zooplankton, and to establish when and where fish feed most intensively during the day-night cycle. At both stations the same three species of myctophid fish comprise 90% or more of the total mesopelagic fish captured in the upper 460 m. Two of the three numerically dominant species undertake diel vertical migrations over a depth range of 250 to 300 m. The third species remains below 220 m day and night.

Properties of the feeding behavior of each species of myctophid were adduced from analysis of stomach contents of fish collected

continuously throughout a 24 or 48 hour period. The two migratory myctophids feed most intensively in the surface layer at night, but also feed at low rates when in deep water during the daytime. Types of prey utilized by the two species were very similar. In contrast, the nonmigratory myctophid feeds almost exclusively during the daytime and there is extremely little overlap of its diet with that of the two migratory species.

A major objective of this study is to assess the impact of myctophid predation on the zooplankton community and to evaluate the importance of this group of consumers in the trophic structure of the subarctic pelagic community. (McCrone [Frost])

I. Species Size and Annual Turnover Rates of Field Populations of Animals

In ecosystem studies biological efforts in the field and laboratory are often allocated to concentrate on several dominant species. When it is desirable to have estimates of production rates for the other animal species, one commonly chooses an appropriate P/B rate (mean production rate/mean biomass) to apply to the standing stock measurements. The length of life has usually been used for selecting a P/B rate.

Following a suggestion by L. Dickie, published results of energy flow in field populations were plotted against the size of adults. Thirty-five aquatic and terrestrial invertebrates were emphasized, but fish and mammals were considered. We quantify that small species have substantially higher P/B rates than large species. Also we show that size has advantages over longevity as a scaling factor for the P/B rate.

The P/B rate of equilibrium populations can be used as a measure of the mean mortality rate. Small mammals obviously have higher mortality rates than invertebrates of the same size. Benthic (and possibly pelagic) field populations of small Metazoa (smaller than small chironomids and large pelagic copepods) clearly do not follow these rules, with P/B rates relatively too low.

Net growth efficiency (K_2) of populations cannot be shown to be dependent on adult size, longevity, or feeding type. (Mosher [Banse])

XXIII. Biogeography and Taxonomy

Biogeography deals with the distribution of organisms and is concerned not only with the phenomena at the present time but also with those of the past, thereby illuminating the origin and history of the fauna and flora. Biogeography, as well as most other aspects of biology, entails taxonomic work. The functions of taxonomy are threefold: identification, classification, and the study of species formation and of factors of evolution. Immediate objectives in biological oceanography, however, are often to solve pressing problems of identification in ecological or stratigraphic research.

A. Planar Island Colonization

Experiments on island colonization, using artificial panels, are presently under way at two Puget Sound sites. These experiments are designed to follow the patterns in colonization that result when marine invertebrates and algae colonize areas of limited size. The panels essentially are islands to their sessile adult biota; they are colonized by free-floating larvae which develop into nonmotile adults. Panels are suspended in the water column above the bottom. At intervals, they are removed temporarily from their moorings and observed in tanks aerated with seawater; then resubmerged at their original site for further colonization. From initial surveys of various types of indestructible panels, we have discovered a relation between the rate at which a panel fills up with colonists and the number of species present on it. Attention is now being focused on panels of different sizes, from a few square inches to a few square feet, to investigate the effect of island area on colonization. The panels will be treated in the same manner as those of the first experiment. (Schoener)

B. Nanoplankton Studies

Studies of the nanoplankton of the subarctic eastern Pacific from water samples collected between 132°W and 175°W and 45°N and 50°N are being conducted. A preliminary study was carried out on the distribution of the common nanoplankton species using the quantitative data of Munson (unpublished). Taxonomic studies of coccolithaphores have also been initiated. The taxonomic study will be based in part on the above collections and in part on specimens that multiplied in enrichment cultures using the technique of B.C. Booth described in a 1975 paper in *Limnology and Oceanography*, Vol. 20, No. 5. (Booth)

During the past year, we have completed an investigation of the small, pale green, spherical cells that appeared in enrichment cultures initiated by B.C. Booth. The organism has been placed in the class Chrysophyceae on the basis of fine structure of intracellular organelles; also the presence of chlorophylls *a* and *c*, diatoxanthin, diadinoxanthin, and fucoxanthin-like pigments suggest affinities with the Chrysophyceae. They differ from other members of the family, however, in several characters. Two of the pigments resemble but differ from true fucoxanthin; chlorophyll *c* is absent; and carotene is mostly α instead of β. An additional feature is that half of the chlorophyll *a* is in the form of chlorophyllide *a*.

A paper has been submitted for publication. (Lewin; R.E. Norris and B. Pearson, Department of Botany; S.W. Jeffrey, University of Sydney)

C. Benthic Polychaetous Annelids of British Columbia and Washington

Polychaetes obviously play an important role on the seabed. To facilitate ecological work on the group, keys for the approximately 220 known species of the so-called errantiate polychaetes have been completed for the waters of British Columbia and Washington, incorporating also records from Oregon (Banse and Hobson, 1974). The treated area forms a major section of the Oregonian Biogeographic Province which extends from Point Conception, California, to the Dixon Entrance region. In respect to polychaetes, the section is the best known part of the province, yet a considerable number of taxonomic revisions had to be made and, disturbingly, many new records were found during the course of the study on the keys. Currently, the second and last volume which will treat the approximately 260 species of sedentariate and archiannelid species from the same region is being prepared. (Banse; the late K.D. Hobson, Victoria, British Columbia)

D. Taxonomic Studies of Polychaetes

1. The Terebellidae

During the preparation of the keys for the second volume on benthic annelids, great difficulties were encountered with previous records, species descriptions, and synonymies in several families. One, the Terebellidae, has been largely neglected for about half a century in this zoogeographic province. Special emphasis had to be given to *Eupolymnia* Verrill, *Neoamphitrite* Hessle, *Neoleprea* Hessle, *Pista* Malgren, *Polycirrus* Grube, and *Scionides* Chamberlin. The problems among the Ampharetidae are similarly manifold. (Banse)

2. The Cirratulidae

Bipalpate species of Cirratulidae numerically dominate the macrofaunas of many, if not most, subtidal mud bottoms. The taxonomy of the group is particularly in need of revision because many older species descriptions encompass groups of species, some of which are sympatric. Statistical analyses of quantitative characters of setation and body tagmosis which are in progress begin to elucidate the differences and relationships among the species of *Tharyx, Chaetozone,* and *Caulleriella.* (Jumars)

E. Taxonomic Studies of Planktonic Copepods

Species of the calanoid copepod genus *Pseudocalanus* are important components of marine plankton in temperature, boreal, and arctic seas. There are four nominal species of *Pseudocalanus*, all described from the North Atlantic Ocean, but the published characterizations of these species are vague, and the validity of some of the species has been doubted. Portions of the original material of three nominal species (*P. minutus, P. gracilis, P. major*) obtained from zoological museums are currently being studied. Specimens of the fourth species, *P. elongatus*, were

obtained from the type locality. An extensive set of material, derived from plankton samples collected throughout temperate to polar waters of the Northern Hemisphere, will form the basis for a taxonomic revision of *Pseudocalanus*. (Frost)

XXIV. Marine Acoustics

This program has theoretical as well as applied aspects. One goal is to understand the effects of environmental variables on the transmission of sound in the sea. Phenomena being investigated include the sound-scattering layers that are formed by organisms and migrate diurnally and the causes of migration as there are other layers which do not move; the effect of internal waves and microstructure in the propagation of sound waves; and the propagation of sound waves both in the water and in the sedimentary layers.

A. Experiments on Acoustic Transmission and Ocean Structure

A program of field research, which is attempting to simultaneously study oceanic structure and acoustics has been started; it is directed toward understanding the mechanisms which give rise to fluctuations in the transmission path. To develop an understanding of the observed acoustic amplitude and phase fluctuations from the properties of the medium, we need to know the space- and time-scales of the index of refraction. Acoustic fluctuations occur from scattering by the inhomogeneities in the medium caused by turbulence, layering, and other variations from the mean-sound-velocity profile. Transmission fluctuations which are a function of time can be associated with the horizontal advection of these features caused by internal gravity waves.

The present work will study the correlation between fluctuations at two separated acoustic towers with the fluctuations of environmental parameters as measured from three moored arrays and two self-propelled vehicles. The correlation between fluctuations along the two parallel acoustic paths should depend on the coherence of the internal wave field at approximately the same horizontal separation. By measuring the various horizontal and vertical coherences from both the moored and towed spectra, it is hoped that the present theories of internal wave behavior can be tested and used to predict the acoustic scattering. Thus we test both acoustic and internal wave theories with one experiment.

During 1973 we completed the analysis of our open-ocean acoustic-transmission fluctuation experiment, which is viewed by many as a landmark in the understanding of the relationship between acoustic transmission and oceanic structure. Sound was transmitted over a 17-kilometer horizontal path between two seamounts located 275 miles west of Grays Harbor, Washington. The fluctuations observed in the experiment exhibit distinct behavior which is tentatively explained as the result of internal tidal and wave motion in the ocean. The results are of sufficient quality to allow a more detailed comparison between theory and experiment than has been possible previously. In 1974 we started a program to carry out a new set of experiments on acoustic transmission and oceanic structure. Two experiments have been planned. The major one, designated MATE (Midway Acoustic Transmission Experiment), is scheduled for June-July 1977 (see Figure 11); with the results, we hope to refine our models of the ocean's small-scale structure and processes. A preliminary experiment, designated PREMATE, was conducted in the Georgia Straits in June 1975 and data analysis is almost completed. Another experiment, designated MINI-MATE, was conducted in Dabob Bay in June 1976. This experiment produced good acoustic results which are now being analyzed.

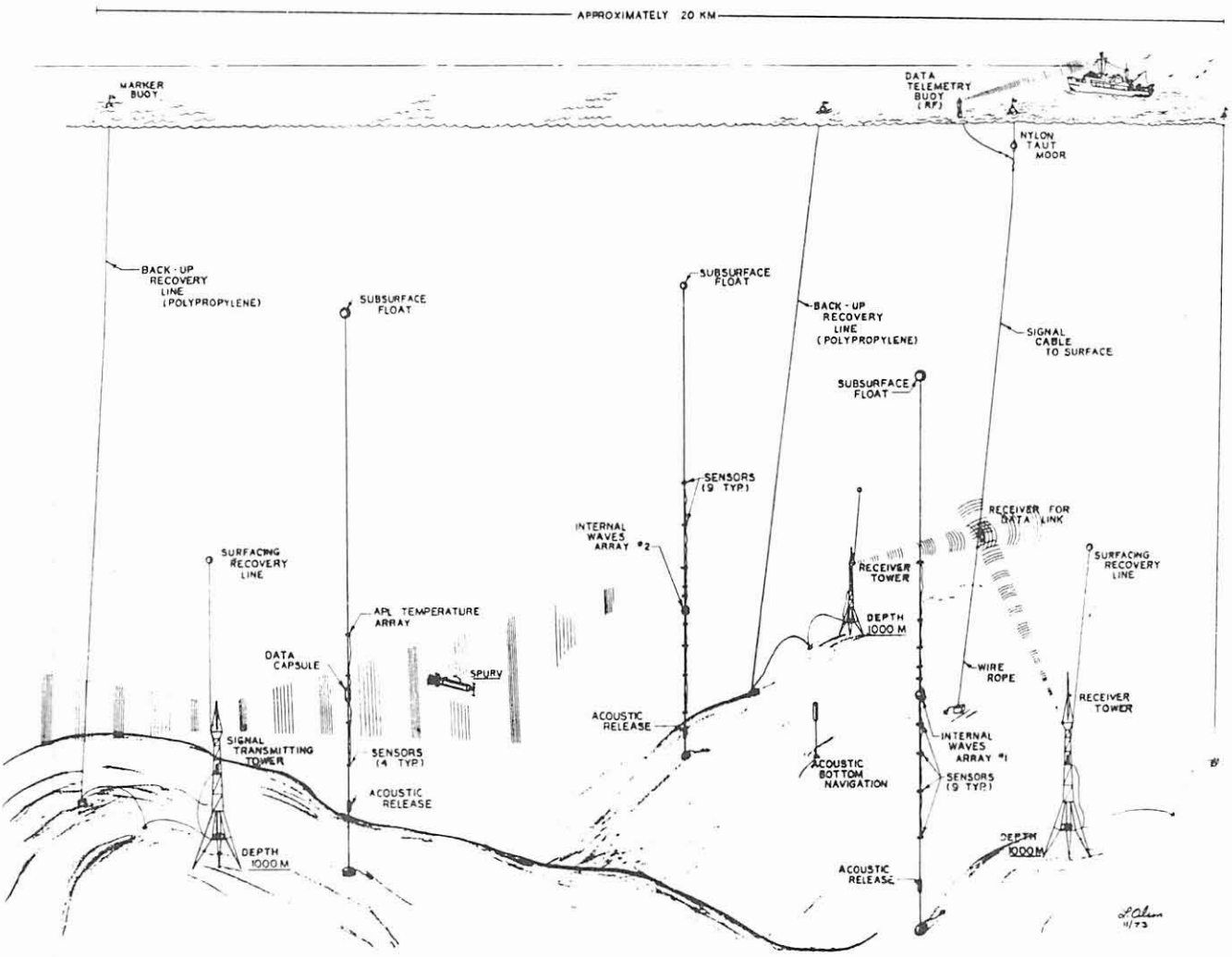


Figure 11. The Midway Acoustic Transmission Experiment (MATE) shown above combines several simultaneous but independent measurement programs.

MATE is essentially three experiments done simultaneously. First, acoustic transmission fluctuations will be measured over a 15-20 km path in a broad range of frequencies. These fluctuations are theoretically related to the temporal and spatial variations of the oceanic parameters in the transmission path. By measuring the acoustic fluctuations and the oceanic parameters simultaneously we can confirm the validity of available theoretical models. Second, spatial scales of oceanic structure will be measured by our Self Propelled Underwater Research Vehicle (SPURV); and, third, the temporal scales of oceanic parameters will be measured by moored instrument arrays. We intend to use three of the moored units which will be placed in the deep ocean to measure temperature, pressure, conductivity, and water velocity at a number of different depths and for durations up to one month. Hopefully, the data gathered from this extensive field program will allow us to describe the time variability of the ocean caused by internal waves. This, in turn, should provide the basis for a better understanding of the ocean's acoustic propagation characteristics. (Ewart, Irish, Desaubies)

B. Quantitative Acoustic Estimation of Zooplankton Distribution

Until recently, the use of acoustical methods for quantitative assessment of standing stock was largely limited to fish and other nekton. This research was undertaken to demonstrate and evaluate a quantitative acoustic method of assessing the standing stock of zooplanktonic and sound-scattering organisms. The time and space variability of standing stock for a mixed population of zooplankton was sampled in Port Susan, northern Puget Sound. Estimates of abundance in the sound-scattering layers were obtained using a quantitative acoustic system operating at 105 kHz. In order to provide an independent estimate of standing stock for comparison with acoustic estimates, samples were taken with electronically operated closing nets, which were towed horizontally and vertically. Of the five species or groups of species examined, the euphausid *Euphausia pacifica* was the only sound-scatterer that was consistently present in sufficient numbers to account for the observed scattering layers.

A comparison between net and acoustic methods of assessing standing stock demonstrated that the acoustic method provided speed and detail over the net method. The acoustic method also provides a means of estimating the total population of mixed-size scatterers. Euphausids ranging in size from 2mm to over 18 mm were censused by this method, even when abundances were as low as 2-3 m^3. On several occasions dense scattering layers were observed. Maximum abundances in such layers were acoustically estimated to be less than 1000 per m^3 and were generally less than 200-300 per m^3. Contour plots of standing stock in Port Susan revealed some persistent features in the spatial distribution. Large standing stock values (3000-5000 per m^2) were characteristically found at the head and mouth and lower values (less than 1500 per m^2) in the middle of the embayment. Day-to-day acoustic survey estimates varied by 12% to 14% while month-to-month estimates varied by 47%.

The evaluation of the acoustic system used in this study revealed that an optimization of such systems could be defined in terms of the

size and abundance of any zooplankter of interest. For targets of the size of euphausids, frequencies higher than 100 kHz will permit detection at the level of 2 or 3 per m^3; *Calanus*-sized organisms will require a minimum frequency of 200 kHz; and *Pseudocalanus*-sized organisms will require 400 kHz.

The improvement of acoustic data reduction and the greater use of acoustic methods of assessment as a routine field method are being investigated further. A dedicated minicomputer has been programmed for digitizing, analysis, and data presentation. The hardware used for analog recording in the field has been redesigned for solid state electronics and reduced power demands. The clarification of criteria for the improvement in quantitative acoustic systems also continues. (Macaulay [English])

XXV. Marine Resource Development

The purpose of this program element is to lay a firm scientific base upon which resources from the sea can be developed.

A. Methodology of Oil and Gas Resource Assessment

A pilot investigation of a novel geophysical approach to forecasting the oil and gas resources of unexplored or underexplored frontier basins from a statistical correlation between the producible oil and gas in reservoirs and a negative bias to the ratio of the filtered areally-weighted gravity anomaly to the toal basin volume has been conducted. The results of this investigation serve to focus attention on three subsidiary topics: the effect on clay-bearing rocks of the amount and kind of dispersed organic matter in a basin; the effect of differences in the amounts of migratory hydrocarbon fluids released from source organic matter on diagenetic changes in consolidating sedimentary rocks; and the feasibility of using the optical reflectance of dispersed vitrinite normalized for maximum rock temperature as a gauge of basin hydrocarbon richness. Research on these three topics is continuing. (Bennetts [McCulloh])

B. Compilation of Gravity Data for the Continental Margin of the United States

A systematic effort to compile all nonproprietary and unclassified gravity data for the entire United States continental margin (shelf, slope, and rise) continues. The ultimate goal is production of maps at 1:2,500,000 scale of both Free-Air and Bouguer anomalies of gravity. These will provide an extension of the Woollard and Joesting (1964) map covering the United States (exclusive of Alaska and Hawaii). This effort is expected to receive an important boost through industrial participation channeled through a Committee of the Society of Exploration Geophysicists. (McCulloh)

C. Interdependence of Marine Free-Air Anomalies of Gravity and Bathymetry

Much published work has defined rather well a systematic interdependence between mean Bouguer gravity anomalies and mean surface elevation for large areas on land. Evidence is sparse that a similar interdependence exists between mean Free-Air gravity anomalies and bathymetry for marine continental margin areas. The latter relationship is being defined through statistical correlations developed from published data on the eastern Arctic Ocean, the Aleutian slope and trench, the Southern California Borderland, the Gulf of California, and the northeastern Gulf of Mexico. (McCulloh)

D. Seismic Refraction Studies on the Gulf of Alaska

Seismic refraction measurements are being carried out in the eastern and western Gulf of Alaska Outer Continental Shelf areas in order to define the velocity structure and assist in the identification of rock types and geologic structures having economic significance. Sound sources

consist of large air gun arrays (up to 2000 in^3) as well as explosives (Tovex), and both sonoguoys and OBS's are used as receivers. Data were collected in the eastern Gulf of Alaska between Yakutat and Kayak Island in September-October 1974, and in the Kodiak area in July 1976. A second cruise off Kodiak is planned for June-July 1977. Use of receiver arrays will help to mitigate the effects of complex shelf structure between receiver and shot point, and common reflection point velocity gatherers will be used to extrapolate velocity structure across the shelf between refraction lines. An attempt will be made to correlate velocities with lithology and thus permit a geophysical characterization of economic basement. OBS measurements of naturally occurring seismicity will be used to investigate what appears to be an earthquake swarm beneath Albatross Bank. Preliminary study suggests the existence of a newly forming Benioff Zone beneath Albatross Bank. (Holmes)

XXVI. Applications of Oceanography

The purpose of this element is to provide the basic knowledge of oceanography and to adapt oceanographic tools for the solution of practical problems. Particular emphasis is placed on the development of predictive models of Puget Sound and adjacent waters for which it is necessary to first have a thorough knowledge of the oceanography of the area.

A. Forthcoming Publications

1. Oceanographic data, Washington continental shelf and margin

A chart that summarizes all of the oceanographic data to date is being prepared for the area between 46°-49° N and 124°-130° W. Particular attention is being given to geological and geophysical information. The chart will employ Mercator projection at a scale of approximately 1:1,000,000. Bathymetry, magnetics, and gravity will be shown, as well as bottom sampling stations and sample seismic reflection records. A complete list of references will be included. (Holmes)

2. Revision of Puget Sound bibliography

The 1971 *Bibliography of Literature: Puget Sound Marine Environment* has been revised; nearly 2,000 entires are included. The expected publication date is April 1977. (Collias, Duxbury)

3. Puget Sound surface currents

Photographs obtained from studies of the Puget Sound model have been assembled into camera ready copy for the impending publication of an atlas. Eight tide stages will be represented for four locations in Puget Sound. The results are qualitative; they will be of value, when used in conjunction with the *Tidal Current Tables, Pacific Coast...* published by the National Ocean Survey, in indicating the presence of eddies and other features beneficial to the boatman. (Collias, Lincoln, McGary)

4. Oceanography of Puget Sound

More than 40 oceanographers working on various aspects of the Puget Sound system, including 25 faculty and staff of the department, are collaborating on a book to be entitled *Puget Sound: Oceanography of the Inshore Waters of Washington*. It will be published by the University of Washington Press. All aspects of oceanography are being summarized and synthesized; overview chapters will integrate current knowledge to provide a picture of the Sound as a system. The treatise, with its comprehensive bibliographies, will serve as a basic document for scientific studies of the future and provide background information fundamental to demographic regional planning. (Coachman, coordinator; Richards, Henry, editors)

B. Puget Sound Tides

Discrepancies in the annual sea-level variations reported by various authors were noted when I was preparing an article for the Puget Sound book. Since raw data are available, an attempt will be made to resolve the relations between the fall intrusions of Pacific water and sea level. (Larsen)

C. Geological Hazards in Norton and Chirikov Basins, Northern Bering Sea

Seismic reflection data collected over the past nine years are being examined for evidence of faulting in the basin sediments which might present problems during any economic exploitation of these Outer Continental Shelf (OCS) areas. Recent field work was carried out in September 1976 and another cruise is planned for July 1977. Both high resolution and deep penetration records will be used to identify major faults and fault zones in the basins. Particular attention will be given to near surface faults and those which form scarps on the sea floor. Attempts will be made to date the fault movements, wherever possible, and to make a risk assessment of the areas in the basins containing evidence of significant fault activity. (J. Johnson [Holmes])

D. Geological Investigation of the Sedimentary Environment near the Mouth of the Columbia River

From an oceanographic point of view, the region near the mouth of the Columbia River is extremely complex. At any given time the flow in this region depends upon the relative magnitudes of tides, river run-off, wind-driven coastal currents, and wind waves. The situation is further complicated by the geometry of the river mouth and bar. Therefore, one must focus upon a particular facet of this complicated region if real progress is to be made in elucidating sediment transport phenomena. The present investigation is designed to determine the fate of dredged materials after disposal at designated sites in the vicinity of the river mouth. Disposal is usually accomplished in fair weather, whereas the dispersion of dredge material is associated with extreme events, such as winter storms or periods of significant wave activity. Our approach makes use of these considerations by concentrating on the flow near the seabed over the region of general interest.

Completion of the first two years of the program has shown that it is possible to recognize disposal sites used by the Corps of Engineers over some decades, both bathymetrically and through the use of textural and mineralogical properties of the disposed sediment. The natural sediment in the disposal sites has a mean diameter of 150 to 175 μm, making the two populations readily distinguishable.

Strong contrasts in mineralogy between the ambient sediment and the dredged material allows recognition of the dispersal pathways of the dredge spoils. Through the use of precise position and depth measurements a temporal and spatial history is being constructed of a controlled dump of 600,000 cubic yards of sediment emplaced during July-August 1975.

Ability to measure depth as precisely as one foot, together with the study of sediment properties, are permitting detailed tracking of the sediment as it disperses from the control site. Concurrent with the sedimentological and bathymetric investigations, measurements of suspended sediment, bedload content, and water mass properties have been made at the disposal sites. These data will help to define the hydraulic regime at the disposal sites. It is our long-range intent to relate observed changes in the deposits of dredged materials to the physical processes controlling dispersal.

The study will continue this year, but the field program will be confined to monitoring the temporal and spatial changes in the dredged sediment deposited at Site E (off the north jetty) and at Site G (1975 experimental one-time disposal south of the south jetty). (Borgeld [Creager, Sternberg])

E. Role of Particulate Matter in Transporting Toxic Pollutants

The present day composition of the oceans represents a complex balance among a number of environmental parameters both natural and artificial. Some of these parameters include, but are not limited to, the rates of supply and removal of substances to the oceans; the distributions and speciation of dissolved matter; the distributions and composition of particulate matter; the interactions of the biosphere with dissolved and particulate substances; advective and diffusive processes; and the amount of available light. A significant change in any of these parameters, either through natural processes or through man's activities, could upset their interactive balance and result in a significant alteration of the environment.

Particles suspended in seawater play a major role in regulating the chemical forms, distributions, and ultimate deposition of many marine pollutants. Some toxic elements in particulate form are transported to the oceans, where they are desorbed at the freshwater-seawater interface. Other elements (particularly petroleum hydrocarbons) are adsorbed onto the surfaces of suspended particles and are removed to the sediments as the particles settle.

In areas where the bottom environment is especially dynamic, near-bottom processes such as resuspension and transport of sediments may affect the ultimate deposition of pollutants. An understanding of the processes controlling the distribution, composition, and transport of suspended particulate matter is essential to the assessment of the fate of toxic pollutants in the marine environment.

Studies of the role of particulate matter in transporting toxic pollutants in the marine environment are being carried out under two programs. The Outer Continental Shelf Environmental Assessment Program (OCSEAP) for the coastal waters around Alaska is an attempt to determine baseline conditions before oil development on the continental shelf (see XXVI *J*). The objective of this study is to determine the seasonal variations of the distribution and chemical composition of suspended matter in the Gulf of Alaska and southeastern Bering Sea.

The Deep Ocean Mining Environmental Study (DOMES) program is an attempt to assess the effects of mining ferromanganese nodules on pelagic and benthic environments (see XXI *F* and XXVI *K*). The objective of the second study is to determine the high frequency (hourly) and low frequency (seasonally, yearly) variability in the distribution and chemical composition of particulate matter. (Feely)

F. Chemical Partitioning in Marine Ecosystems

Since 1972 we have been conducting a series of investigations designed to characterize the physical-chemical processes that control the distribution of trace organic compounds in coastal and estuarine ecosystems. These studies are supported by the Environmental Protection Agency and the Environmental Effects Laboratory of the U.S. Army Corps of Engineers. The long-term goals of this research are (1) to generate an *a priori* predictive capability of the distribution of environmentally stable but potentially hazardous organic chemicals among biotic and abiotic ecosystem components, based on fundamental chemical principles and easily measured ecosystem parameters, and (2) to assist the enforcing agencies in establishing environmental input and criteria requirements for open water discharge and dredge disposal operations.

We have been using polychlorinated biphenyls (PCB) as model compounds due to their ubiquity in Puget Sound, their low level detectability, and their stability; also they represent a series of chemically similar compounds that vary in toxicological and physical chemical characteristics. A brief description of the typical PCB residue levels in water, suspended particulate matter (SPM), and zooplankton in Puget Sound, and the measured component distribution ratios is presented below. The analytical methodology and a discussion of theoretical computations to derive an explicit expression for the PCB distribution in water and SPM is also discussed.

The predominant processes that control the distribution of an organic chemical in the marine environment are physical transport and dispersion and chemical interactions with biotic and abiotic components. These interactions may produce a reaction sequence with a multiplicity of intercomponent transfers and possible products of lower or higher stability and toxicity potential. Considering the complexity of most contaminant interactions with the various components of the ecosystem, it seems unlikely that the flow mechanism can be evaluated based on our current state of knowledge. Therefore, we have sought empirical parameters that can be easily measured in the marine environment and which reflect net effects of the complex intermediary transport and chemical transformation steps.

The net accumulation of an organic chemical on any interacting component of interest can be expressed as the product of its concentration in the dispersive medium multiplied by a proportionality constant. This empirical constant is defined as the component distribution ratio

$$K = \frac{C_{x(j)}}{C_{x(i)}}$$

where $C_{x(j)}$ and $C_{x(i)}$ are the residue concentrations of x in components j and i, respectively. For the purpose of this discussion, j is either SPM or zooplankton and i is the ambient water.

Data from Puget Sound is being used to test the applicability and universality of K to characterize the relative component concentrations. In addition to SPM and zooplankton collections, supporting hydrographic and biological data were collected and analyzed by standard chemical and biological oceanographic techniques.

A brief outline of the sampling and analytical methodology is presented below:

Whole water samples are collected in a 53-l stainless steel beer keg sampler at several sites in Puget Sound. One gallon water aliquots are stored in glass jugs under hexane. The remainder of the sample is passed through a glass fiber filter for SPM measurements, using a specially designed large volume filter system. The SPM-filter samples are stored frozen. Zooplankton are collected with a Juday closing net (312 μ mesh) modified to eliminate contamination from surface slicks and floatables. Both oblique and vertical net tows are conducted. The zooplankton samples are also stored frozen.

The chlorinated hydrocarbons are separated from the natural matrices by hydrocarbon solvent extraction. These extracts are cleaned of interfering organic compounds (e.g., lipids) by liquid-liquid partitioning, digestion with concentrated sulfuric acid, Florisil column chromatography, and ethanolic potassium hydroxide saponification. These procedures are used either alone or in various combinations. The extracts are analyzed by electron capture gas chromatography. Peak areas and retention times are recorded on a strip chart recorder and on a digital integrator. These data are reduced to the appropriate concentrations semi-automatically via a terminal and phone link to the campus computer. A technique has been developed to allow the quantification of the individual components of the complex gas chromatographic spectra of the PCB.

The data for all sample types show nearly identical spatial distributions of chlorobiphenyl residues within the Sound, with concentrations being highest in the Duwamish River-Elliott Bay region and decreasing to a relatively constant level in the remainder of the Sound. Water concentrations range from a high of 20-50 ppt in the Duwamish to a uniform level of approximately 2 ppt throughout the Sound. Similarly, SPM and zooplankton contain from 1.0 to 0.05 ppm (on a dry mass basis) and from 16 to 1.0 ppm (on a lipid mass basis), respectively.

Based on the above considerations, a preliminary theoretical derivation for K was attempted for the SOM water interactions. For a two-component transport involving the dispersive medium and a solid surface we have considered the following reaction scheme

$$X_W \underset{\leftarrow}{\overset{\rightarrow}{\rightleftharpoons}} X_S$$

where X_W and X_S represent the chemical X in the water and surface, respectively. Assuming chemical homogeneity, spherical packing on the surface, monolayer formation, and equilibrium conditions, we have

developed a theoretical expression for K as follows,

$$K = \frac{C_{x(S)}}{C_{x(W)}} = \frac{3 \times 10^3 \rho_W}{A^o_x r_X \rho_S \alpha^o_x} \gamma_{x(W)} \cdot \exp\left(-E_{S(x)}/RT\right)$$

where ρ_W and ρ_S are the water and SPM densities, respectively; r_S is the SPM particle radius; A^o_x is the specific molar area of X, α^o_x is its standard-state activity and $\gamma_{x(W)}$ is the aqueous activity coefficient. $E_{S(x)}$ is the energy of surface interaction between S and X. The terms of this equation have been evaluated for chlorobiphenyls of varying chlorine content and for natural SPM (phytoplankton and resuspended sediments). The calculated K was then compared with values obtained in laboratory uptake experiments and field measurements. The agreement among the data sets was good. Spatial and temporal means of the component distribution ratios, K, were also determined from the data. The K values for both SPM and zooplankton ($\sim 10^4$ and $\sim 10^6$, respectively) were virtually constant over the observed range of residue concentrations and the estimated uncertainty within all regions. Invariance with species composition was also observed for zooplankton. For both SPM and zooplankton, K increases with increasing degree of chlorination. The trends exhibited by the K quantities suggest that, at least for these chemicals in Puget Sound, an equilibrium partitioning mechanism is operable between the suspended phases examined and the ambient water.

The results from this preliminary theoretical treatment appear promising in establishing predictive capability for any compound for which the pertinent molecular porperties can be evaluated. It is hoped that this approach will provide a focus for discerning the critical molecular and ecosystem component parameters that govern the partitioning characteristics of a large number of xenobiotics discharged in the marine environment. The physical chemical models are now being refined and the second generation computations will be completed within 1977. (Dexter, Pavlou)

G. Interrelationships among Chemical, Physical, and Biological Parameters in the Puget Sound Main Basin

The aims of this study are: (1) to identify and quantify the sources of the nutrients, (2) to determine the budget of nutrients in the main basin of Puget Sound, expecially in the vicinity of the four major METRO sewage outfalls, Alki Point, West Point, Carkeek Park, and Richmond Beach, and (3) to provide a comparison of present-day conditions of nutrient concentrations and plankton off West Point with conditions in the mid-1960's.

Major exchanges of matter, such as nutrients and other salts, and fluxes of these properties involve the salt water sources, river and sewer discharges, biological activity, and direct precipitation. The emphasis will be to quantify these processes to determine the long-term effects of METRO's sewage outfalls on the main basin of Puget Sound. A major effort will be placed upon the interaction of nutrients and other factors with the biota.

A series of 22 cruises was conducted from November 1974 through 1975 to collect data at the same location (about mid-channel off Shilshole Bay) that was sampled in the mid-1960's. Nineteen cruises were made at three-week intervals. Measurements of temperature, salinity, density, dissolved oxygen, phosphate, nitrate, silicate, nitrite, and ammonia were made to determine the seasonal changes in water properties. Of the remaining three cruises, two were used for 39-hour time studies off West Point and one for the determination of nitrogen uptake. Analyses of the data will be completed in early 1977. (Richards, Collias)

In addition to the standard physical and chemical parameters listed above, the vertical chlorophyll distribution to 250 m was measured on all cruises and phytoplankton samples from each depth sampled were preserved for laboratory studies. During periods of daily sampling, simulated *in situ* primary productivity was determined for various light depths in the photic zone and vertical net hauls were taken within and below the photic zone (delineated by the 1% light depth) to measure zooplankton biomass. Photosynthesis vs. light intensity characteristics of the phytoplankton populations at the 100% and 10% light depths were also determined.

Two blocks of data were collected at the same location that was sampled in the mid-1960's. The first block of data was collected during a spring period (3 April to 13 June) when high river run-off and large plankton blooms are expected. During this time period, four weeks of daily sampling were carried out, preceded, and followed by a biweekly sampling schedule. A similar data series was collected in the late summer-early fall (1 August to 22 September) when low river run-off is normal. A three-week period of daily sampling was preceded and followed by periods of biweekly sampling. The low run-off period was not sampled in the previous 60's study.

Information collected in the mid-1960's indicated that phytoplankton processes in open water off Seattle were controlled largely by physical parameters and therefore would not be expected to be affected by the addition of nutrient salts. Since then, the sewage outfall at West Point has been in full operation, resulting in increased nutrient input to the main basin of Puget Sound. All samples have been processed, and a report is being prepared. (G.C. Anderson, W.K. Peterson, Postel, Campbell)

H. A Collection of Marine Algal Cultures

A large collection of cultures of marine algae (both planktonic and benthic forms) is maintained in the Department of Oceanography; considerable attention is devoted to the isolation of new cultures for the collection. The cultures are used both within the Department and elsewhere within the University; also, subcultures of many species are requested by other universities, government agencies, and private industry. With the growth of various aquaculture enterprises, there has been an increased demand for certain algal species to serve as food sources for larval and adult stages of various marine invertebrates. (Lewin)

I. Ecological Baseline and Monitoring Study in Port Gardner

This study grew out of mutual interests and concerns about potential future changes in the marine ecosystem of Port Gardner, northern Puget Sound and adjacent waters. Individuals and groups in the state and federal governments, the University, and industry repeatedly expressed interest in the possible magnitude and value of benefits to populations of marine organisms which could arise from pollution control enforcement actions. With the Environmental Protection Agency (EPA) and the State Department of Ecology, a joint study coordinating council has been established to review and define current investigations by the participating agencies.

A baseline study was begun in May 1973 to describe the marine environment and the populations of organisms in the study area before decrease in the concentration of sulfite waste liquor (SWL) from pulp mills could be effected by the proposed pollution-control installations and waste-load reductions. Currently a monitoring program adequate to detect significant related changes in the ecosystem so that the magnitude of the resultant benefits of waste treatment can be evaluated is being conducted. Monthly hydrographic cruises from May 1973 through July 1974 and, subsequently, bimonthly cruises were conducted. Chemical water-quality observations were made to provide a background of standard hydrographic parameters and of concentrations of SWL against which biological changes can be assessed. Dissolved oxygen and the inorganic nutrient ions of phosphate, silicate, nitrate, nitrite, and ammonia were also sampled on most cruises. Efforts will be made to develop an acceptable computation procedure to estimate total SWL in a volume representative of Port Gardner.

Quantitative data on bottom invertebrates collected in the same period have been correlated with distance from the mill's diffuser; the results demonstrate an increasing abundance of invertebrates along depth contours south of the deep water diffuser outfall. The significance of this information will not be known, however, until it can be compared with data collected after waste water-treatment controls have been accomplished. Two intensive sampling surveys were conducted in the mile southward from the deep water diffuser outfall to examine the relationships between distribution and abundance of benthic invertebrates and the statistical interactions of depth and distance from the outfall.

A sonic survey with a high frequency (105 kHz) echosounder was made monthly for the first year of the project and then bimonthly to assess the distribution and abundance of fishes and zooplankton acting as acoustic targets. Midwater nets were used at selected locations and depths to sample the concentrations of zooplankton forming widespread middepth sound-scattering layers. The most important result has been the identification of a water volume devoid of sonic targets at intermediate depth. Sonic targets can be found, however, at corresponding depths in other areas of Port Gardner and Puget Sound. The location of the void appears to correspond to high SWL concentrations in the plume from the deep-water diffuser outfall shared by the Scott and Weyerhaeuser pulp mills. Intensive sampling will be done

semimonthly to determine the extent, periodicity, and other properties of the void. Sonic observation, chemical water quality, and three oyster larval bioassays (done by the State Department of Fisheries) will be correlated.

A series of hauls at several depths with the research beam trawl to describe present populations and to detect major changes of specific composition and abundance in fishes, shrimps, and crabs were made monthly in 1975 at Port Gardner and bimonthly at two control stations. Duplicate hauls at depths of 5, 10, 20, 30, 40, 60, and 80 m are being made at all stations; 120 m is being sampled at two stations, and 150 m at one (Port Gardner). Similar series are being continued.

An initial beach survey southward from the Weyerhaeuser mill site to Mukilteo was made in 1973 to describe distributions and abundance of present populations of plants and animals so that gross changes corresponding to reductions in pulp mill effluents could be detected. An annual resurvey in 1974 and 1975 of the Port Gardner beach was made to document any major changes in plant and animal populations.

The Department of Ecology has investigated the distribution of juveniles of two salmon species and performed live box studies with these animals. The Department of Ecology has also made growth phase studies and bioassays using oyster embryos which will not be described here.

The first year of the study was primarily devoted to an intensive effort to obtain the most baseline observations possible within limitations of manpower and funding. Successive years are lengthening the biological baselines and are monitoring environmental changes. (English and co-workers)

J. Outer Continental Shelf Environmental Assessment Program

The OCSEAP program is sponsored by NOAA; the objectives are to (1) provide comprehensive environmental and biological data and information on the Alaska outer continental shelf lease area; (2) define the probable ecological impact of oil exploration, production, storage, and shipment on the outer continental shelf; (3) refine the understanding of key ecological dynamic processes; and (4) provide a basis for *a priori* predictive or diagnostic models of the ecosystem response to loading by petroleum and petroleum by-products. In addition to the studies cited below, see III *F* and *G*, XVIII *A*, XX *B*, XXVI *E*.

1. Phyto- and zooplankton of the Beaufort Sea

In the Beaufort Sea study, emphasis has been on the determination of seasonal density distribution and environmental requirements of phytoplankton and zooplankton in the nearshore area from Barrow to Prudhoe Bay and at an offshore site on an ice floe station. Nearshore field work was hampered by unfavorable ice conditions in August and September. Phytoplankton standing stock, chlorophyll *a*, primary productivity, and nutrient samples were collected from a float plane or a Boston Whaler using a Scott-Richards water bottle. Acoustic observations, using a Ross 200A Fine Line Echosounder system, were made

from the float plane. At the ice floe station (AIDJEX main camp), biological sampling was carried out from June through September. Biological sampling included ring net hauls for zooplankton and water bottle casts for phytoplankton standing stock, chlorophyll *a*, primary productivity, and nitrates. Light measurements were recorded for incoming radiation on the ice pack surface and observations were made on the state of melt of the ice surface. (English and co-workers)

2. Zooplankton of the Gulf of Alaska

The distribution and abundance of major species of zooplankton within the Gulf, on a seasonal and depth basis, is the main goal of this study.

Collections were made with closing nets hauled vertically through discrete layers and with obliquely towed bongo nets. The first samples were collected in October 1975 throughout Prince William Sound from the NOAA *Surveyor* and in the northern Gulf between Resurrection and Yakutat bays from the NOAA *Discoverer*. Some stations were occupied for more than one day to determine daily vertical migrations. On five subsequent cruises, on the *Discoverer* and the University of Alaska's *Acona*, collections were made primarily in Lower Cook Inlet, although on some cruises a transect was made across the open Gulf and into Prince William Sound. The samples are presently being analyzed for plankton-volume and species content.

Another aspect of the study is to describe the relative abundance of the many species of planktonic cyclopoid copepods. This important group is not usually considered on a species basis, sometimes being ignored altogether, because of taxonomic difficulties and the generally small individual size. However, cyclopoids are often numerically dominant, and their role in the ecosystem has yet to be properly evaluated. (Damkaer; G.A. Heron and D.B. Dey, Pacific Marine Environmental Laboratory)

3. Ichthyoplankton of the Gulf of Alaska

Primary emphasis in the Gulf of Alaska project has been to determine the seasonal density distribution and environmental requirements for principal species of ichthyoplankton. Other zooplankton mainly larger than copepods will also be studied. Samples were collected in Prince William Sound and the northern Gulf of Alaska in September-October from the NOAA *Surveyor*. Horizontal tows using the UW one meter NIO (Tucker) trawl and double oblique tows using a modified Brown-McGowan (Bongo) net were made. Continuous acoustic surveys used a Ross 200A Fine Line Echo-sounder system operating at 105 kHz. (English and co-workers)

4. Literature survey of plankton and aids to identification of fishes

A literature review of the phyto- and zooplankton in the Beaufort Sea and for ichthyoplankton in the Gulf of Alaska has been undertaken. A computer processing system that provides indexes for authors, key words, sources, and citations will be used. A bibliography of the available knowledge of the life histories of 15 fish species of

commercial value has been prepared. Lists of commercially valuable Alaskan species including fish, shrimp, clams, crabs, scallops, and abalone, as well as a list of Alaskan fishes with pelagic larvae, have also been prepared. A key to the pelagic fish eggs of Alaskan waters which includes 20 species of known commercial or possible commercial value has been constructed. (English and co-workers)

K. Deep Ocean Mining Environmental Study

The effects of suspended sediments on the oxygen minimum zone of the eastern tropical North Pacific is being investigated as part of the DOMES project. Deep-sea mining of manganese nodules may introduce bottom sediments into the subsurface layers and it is possible that these sediments will act as sites for bacterial growth which in turn may increase the respiration rates of oxygen and nitrate in the region, expanding the size and intensity of the oxygen-minimum zone. A combination of field, laboratory and model studies is being conducted to assess the response of the oxygen-minimum zone to mining activity.

Filed studies made in the DOMES area indicate that the growth of bacteria on particles is proportional to the log of the weight of particulate material added to a volume of water. It is postulated that sediment particles added to a volume of water immediately absorb a fraction of the dissolved organic matter in the water and then bacteria grow on the particles according to the concentration of organic matter adsorbed. With this mechanism the bulk growth rate is maximum for an intermediate concentration of particles in the water.

Laboratory studies are being designed to investigate this mechanism further and additional field studies may be carried out in an actual sediment plume in the DOMES area. A model is being developed that couples the soluble fields of oxygen and dissolved organic matter with the sediment plume. In the model the rate of bacterial growth and respiration is mediated by temperature and concentrations of oxygen and dissolved organic matter. The respiration in turn alters the oxygen and dissolved organic matter fields, and the growth of bacteria on the particles alters the sinking rate of the particles. (J.J. Anderson, R.J. Ozretich, R.A. Ozretich)

Field operations have now been completed. They were designed to provide the data needed to establish baseline information on existing environmental conditions, as well as to support concurrent research and modeling efforts. The field operations accommodated the requirements of the biological, chemical, physical, and geological investigations. Many measurements and samples are being used by several investigators; thus, the sampling program has been optimized to meet all needs (see also XXI *F*, XXVI *E*).

Data processing and analysis is progressing well. A "Preliminary Report" is in draft form and will be published in March 1977. The "Final Report" on Phase I is scheduled for completion in January 1978. Plans are now progressing for studying the first prototype mining test in May 1977, which marks the beginning of Phase II studies. (G.C. Anderson, R.E. Burns, Ozturgut)

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