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CURRENT RESEARCH ACTIVITIES

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University of Washington
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BIOLOGICAL OCEANOGRAPHY

Research in biological oceanography is under the direction of G. C. Anderson, K. Banse, T. S. English, B. W. Frost, D. P. Henry, V. W. Kaczynski, J. C. Lewin, M. M. Pamatmat, J. P. Thomas, and D. F. Winter.

Puget Sound

Plankton studies. Results of a study to measure the horizontal distribution of phytoplankton in Puget Sound during spring indicated that the phytoplankton bloom consists of a series of discrete patches of high phytoplankton biomass as estimated by *in vivo* chlorophyll *a* measurement. The areas were separated by regions of relatively low phytoplankton biomass. The size, distribution, and movement of patches is apparently controlled primarily by the surface currents within Puget Sound. Patches appeared to form in at least two locations (off Restoration Point at the south end of Bainbridge Island, and off Brown's Point near Tacoma) where the stability of the water column was high. Patches were isolated by tidal action and had a net northward movement toward the sill at Admiralty Inlet. Some patches appeared to move across the sill into the Strait of Juan de Fuca during neap tides rather than being mixed to depth by tidal action at the sill. The disappearance of the blooms from the Sound may also be related to increased tidal flushing resulting in decreased stability of the water column during periods of spring tides. (Munson)

Organic matter budget of Puget Sound. A multi-disciplinary project has been initiated which has as its objective the development of a numerical model describing biomass variations in Puget Sound as functions of seasonal and environmental changes. The success with which the first-generation model represents plankton density variations in space and time will be tested against data acquired at a station near mid-channel in the main basin of Puget Sound, off Point Jefferson, during the spring and early summer of 1966. The relevant data include standard hydrographic observations and measurements of chlorophyll, nutrient concentrations, and production rates as functions of depth.

The project has been subdivided into two main phases: the hydrographic and the biological phases. The first of these involves the construction of an approximate analytic representation of circulation and mixing in the main basin of the Sound. The characteristic pattern of flow in the main basin is that of a positive, fjord-type estuary, modified in the present instance by effects induced by tidal motions and mixing over the major sills. The relative simplicity of quasi-steady state models recommends their use in the first-generation studies. Ultimately, the details of the circulation dynamics will depend upon time through transient variations in tidal action, fresh-water runoff, and wind stress.

The second phase of the project is concerned primarily with metabolic processes in algae and their relationship to available nutrients and to available sunlight. For example, we are examining measured nutrient concentrations and the chlorophyll and productivity data to elucidate the relationship between nutrients, specific productivity, and light intensity.

When the two main phases of the first-generation effort are completed, the hydrographic analysis will be combined with quantitative descriptions of the relevant biological processes to complete a system of equations which determine the variations of algal populations in space and time. Solutions of the system will be tested against the 1966 data as described above. Supplementary field data will probably be acquired to resolve uncertainties in theoretical descriptions. (Winter, Banse, Anderson)

Scattering-layer studies. The biological significance of sound-scattering layers in Puget Sound is being investigated by: (1) an evaluation of the species composition and abundance of organisms associated with a diffuse, diurnally migrating layer detected acoustically at 100 kHz; and (2) a continued examination of the ecology of layered pelagic fish populations. Monthly cruises in southern, central, and northern Puget Sound involve underway sonic surveying with selected stations occupied for vertical tows (1-m and 2-m closing nets) for zooplankton samples and opening and closing horizontal net tows for micronekton collections. In addition to continuously monitoring the echo sounder, acoustic information is being recorded on magnetic tape for signal processing between cruises. Hydrographic data is being collected at specified locations. (English, Cooney, Maynard, Halstead)

Salmonid predator-prey relationships. Prior to the development of the Washington State salmonid hatchery program, Puget Sound had a resident population of Coho salmon. By 1969 the magnitude of the hatchery releases had reached 1,400,000 lb. of young salmon and steelhead trout; however, the resident Coho population had practically disappeared. Short-term food stresses might be occurring due to the time and magnitude of localized releases. A study is underway to determine the interaction of the salmonid predators (especially salmon) with their zooplankton prey and to gain insight into whether a food stress for the salmon is occurring.

All salmon are known to feed especially on zooplankton, and fish in general are known to be highly selective in their feeding behavior. Our approach is based on following the population dynamics of selected zooplankton species, as determined by stomach analysis of the young salmon in the Puget Sound study areas. The Washington State Department of Fisheries is supplying the specific salmon release information (species, dates, numbers, and weights) and is collecting young salmon and quantitative zooplankton samples from the same localities for analysis. Quantitative zooplankton samples taken in Carr Inlet during 1969 for another project are being reanalyzed.

We now have partial lifetables of four cohorts of *Euphausia pacifica* in Carr Inlet for 1969. The spring cohort suffered 74.8% mortality between 22 May and 16 June 1969. During this period, 14,240 kg of young salmon were released into Carr Inlet via Minter Creek. The zooplankton standing stock decreased from 39.49 to 25.77 g/m^2 (wet weight) even though most of the zooplankton species were actively growing and several were reproducing at this time. Gut analysis of a small sample of yearling Coho and Chinook salmon confirmed that these species fed on zooplankton (which includes (*Euphausia pacifica*) at this stage of their life cycle in Puget Sound.

Juvenile chum and pink salmon (under 6 cm) also were analyzed for food items, which were compared with zooplankton samples at the same localities--

i.e., shallow inshore waters. This is the first known gut analysis for this young stage in salt water; more mature fish are known to feed on zooplankton. The results were surprising: the juvenile chum and pink salmon were feeding primarily on epibenthic species. Although the analysis is incomplete at this time, there appears to be little correlation with the zooplankton samples. (Kaczynski, Clayton)

Oxygen consumption by the seabed. We have continued to improve, test, and use the shipboard method for measuring oxygen consumption by the seabed. A series of comparisons with *in situ* bell-jar measurements showed that the shipboard results were the same as those obtained *in situ* in both total uptake and partitioned rates (chemical oxidation and respiration). That the accuracy of the shipboard estimates is the same as the *in situ* estimates in the deep sea remains to be shown. The results of experiments on the effect of hydrostatic pressure on the rates of uptake by sediment cores from 2,700 m or more are still ambiguous. More experiments are planned for 1971 with samples from Kurile and Aleutian trenches.

The baseline study of benthic oxygen consumption in Puget Sound has been completed. Twenty-three stations were sampled quarterly; experiments were performed at 5, 10, and 15 C. Results show significant differences and changes in oxygen consumption due to temperature, season, and stations. We now have convincing evidence that the seasonal cycle of oxygen consumption at all stations is independent of the temperature cycle; but, being coincident with the temperature cycle which has a positive effect, the amplitude is bigger than it would otherwise be. The cycle shows a minimum in January; it rises through April, reaches a maximum in July, and then declines through October to January. Chemical oxidation shows the same seasonal fluctuation indicating that although a purely inorganic chemical reaction was being measured, these rates are rather intimately associated with anaerobic metabolism which gives rise in the first place to the reduced substances that are oxidized. This also would mean that anaerobic metabolism in the sediment could be undergoing an annual cycle. For the first time, we found a correlation between the concentration of reduced substances in the sediment and the rates of inorganic chemical oxidation.

We are still unable to find a significant correlation between total oxygen uptake and any environmental factor. It appears that in Puget Sound in January the size and metabolism of the benthic community is governed by the organic matter in the sediment plus the flux of organic matter during that season. By July the rates at the different stations have risen to varying degrees according to the additional supply of organic matter which differ from place to place. The summer data from the continental terrace of Washington and Oregon also give supporting evidence for our hypothesis that the oxygen consumption by the seabed is not only governed by the organic matter content of the sediment but also influenced by the flux of organic matter to the bottom which varies with depth. (Pamatmat)

Benthos communities. During spring 1969, 140 quantitative bottom samples were collected by 0.1 m^2 grab sampler at 48 stations in Puget Sound. The purpose was to apply modern statistical methods to the animals larger than 1 mm, delineate communities, and relate these to environmental measure-

ments. Factor analysis had been used successfully to study samples taken in 1967 and 1968 on the shelf off Washington; because of the more complicated physical environment in Puget Sound, it was not obvious that the approach would work here as well.

All the crustaceans, bivalves, and echinoderms (160 species) have been identified. The thirty most frequently occurring species were subjected to factor analysis in R- and Q-mode to determine the groupings of the species and the distribution of the communities, respectively. Tentatively, six species groups have been identified that are associated with the three first factors, explaining 44% of the total variance. The first factor seems to represent coarseness of the sediment as measured by the mean particle size; the second factor seems to represent the effect of depth. The third factor is difficult to interpret.

Community identification as determined by the Q-mode of factor analysis results in four groups of stations: muddy bottoms in shallow water, gravelly or coarse sandy bottoms, sandy bottoms, and muddy bottoms in deep water. However, there are many stations of intermediate factor loadings, and most stations have high loadings to more than one factor even after rotation. Therefore, classification of benthos communities as discrete units in Puget Sound may not be realistic (contrary to the situation on the continental shelf off Washington), but ordination in a space of four identifiable factors representing 50% of the total variance seems to be a fruitful approach.

Species diversity and dominance are being determined by several methods. The highest diversity seems to occur on stations with gravel or coarse sand and on the muddy stations in deep water, and the lowest diversity on sandy bottom and on the muddy bottom in shallow water. The diversity at six stations that had been studied during 1963-1964 was nearly identical to the previous results, which indicates considerable stability in the structure of the Puget Sound benthos communities. (Lie)

Biomass of benthic infauna. After sorting the collections from the same 48 stations into Pelecypoda, Polychaeta, Echinodermata, Crustacea, Gastropoda, Pennatulacea, and Miscellaneous, and setting aside large and rare organisms, wet weights were determined and converted into ash-free dry weights. A mean ash-free dry weight of 13.64 g/m^2 was obtained for the sum of all taxonomic groups for all stations.

Mean weights for the stations were tested against salinity, depth, mean particle size, and per cent of sediment nitrogen by multiple regression analysis. Biomass proved to be most strongly correlated to the nitrogen content, with a simple correlation coefficient of 0.365 (significant at $P = 0.01$). Biomass correlated to mean particle size with a coefficient of 0.314 (significant at $P = 0.05$). Biomass was not correlated to salinity or depth. Kendall's rank correlation methods were also applied to biomass and environmental data.

The distribution of biomass was described conventionally in terms of sediment type and depth. Eight categories were discussed: the shallow mud community; the deep mud community; the sandy mud community; the muddy sand community; the deep sand community; the gravel sand community; and a

mixed mud, sand,and gravel community.

Seasonal and/or yearly changes in biomass, if any, will be assessed at four of the stations by utilizing data by Nichols and Dawson. (Dawson)

Population dynamics and energetics of a benthic polychaete species. In a study of the role of benthic deposit feeders in the energetics of and turnover of organic matter in the seabed, energy flow through a numerically important species population is being assessed. *Pectinaria californiensis*, a deposit-feeding polychaete dominant both in numbers and biomass in the deep, soft mud of the main basin of Puget Sound, is commonly found also in shallow mud and sandy mud in a variety of locations in Puget Sound. Monthly samples taken at five stations representing three habitats in Puget Sound are being used to determine size, distribution, growth, mortality, and reproductive capacity. Laboratory studies are underway to measure rates of respiration, feeding, removal of organic matter (nitrogen, carbon) from sediment and release of dissolved waste products (ammonia, urea, total free amino acids). Some assessment of the energetic importance of this species population relative to that of larger but rarer coexisting species populations will be made. (Nichols)

Biology of the Columbia River Effluent Area

Studies of the deep subsurface chlorophyll maximum. Work has continued on the studies of the deep chlorophyll layer. The layer is present not only in the Columbia River effluent but is apparently trans-Pacific between latitudes 35 to 45°N approximately. In the Columbia River area, the layer underlies the plume at a depth of about 60 m, where concentrations of chlorophyll range from 1 to 3 mg m^{-3} chlorophyll *a*.

The deep chlorophyll maximum is not found north of about 45 to 48°N latitude where nutrients do not become depleted in surface waters. To the south, the maximum layer gradually deepens and disappears by about 35°N latitude. Similarly, the depth of nutrient-depleted waters deepens in a southerly direction until the nutrient depletion exceeds 100 m south of 35°N. This suggests that the nitrate supply controls the depth of the maximum but light penetration becomes the controlling factor when the depth of favorable nutrient supply exceeds 75 to 100 m. (Anderson)

Microscopic examination has been made of a few of the samples from the deep chlorophyll layer, and these have been compared with samples from surface waters. Not only is the concentration of cells much greater in the deep layer, but also the species composition is very different. Preliminary results indicate that a single species tends to dominate in the layer; for example *Halosphaera* sp. was dominant in 1969, whereas *Rhizosolenia alata* was dominant in 1968. (Booth)

All of the results during this past year have strengthened our prior conclusions that the maximum layer is due to phytoplankton growth at the depth of greatest chlorophyll concentration (*in situ* formation), a mechanism that was for the most part hardly considered in earlier studies of deep chlorophyll maxima. Our conclusions, however, do not preclude the operation of other mechanisms of formation previously discussed by other workers.

Irrespective of the mechanism of formation, the fact remains that the deep phytoplankton maximum contributes significantly to the primary production of the area and is therefore of importance to consideration of production processes within the area.

An R/V *Alpha Helix* cruise to the area in August 1970 provided information on the patchy nature of the chlorophyll layer. A single patch was followed for a period of several days and the horizontal and vertical shape was determined. Compared with previous years, the chlorophyll maximum was deeper (75 m) and not as strongly developed. Reasons for the difference are being investigated. (Thomas)

Zooplankton samples were collected in recent years to determine the importance of the subsurface phytoplankton maximum to herbivorous zooplankton. These samples, collected with Clarke-Bumpus nets and with a pump, were examined for abundances of most species of copepods. The results suggest that grazing copepods concentrate at different depths, depending on the availability of food as indicated by concentrations of chlorophyll. In May 1969, when most phytoplankton production was in waters near the surface and before the seasonal appearance of the subsurface phytoplankton maximum, immatures and adults of the numerically dominant grazers (*Calanus pacificus, Pseudocalanus minutus,* and *Clausocalanus* sp.) were aggregated in the upper 50 m. In July and August the same species of grazers, predominantly in immature stages, were concentrated between 40 and 70 m at the same depth of the phytoplankton maximum, which was well developed. In contrast to this pattern for herbivorous species, other copepods known to be carnivorous (e.g., *Corycaeus* sp., *Lucicutia* sp., and *Metridia* sp.) did not aggregate in layers of high phytoplankton production. (Frost, Peterson, Anderson)

Zooplankton. We are attempting to determine the cause (or causes) of the absence of a phytoplankton bloom, and consequently low primary production, in the Columbia River effluent area in 1963. To examine one possibility, differences in the zooplankton biomass and/or species composition, we have determined the quantitative distribution of zooplankton during 1961, 1962 and 1963, and have evaluated the effects of major environmental factors--such as depths, seasons, years, and locations (Columbia River plume, ambient seawater, and inshore environment). Analyses are based on statistical treatment of data on dry weights and estimated zooplankton biomass for about 850 samples obtained by towing Clarke-Bumpus samplers with fine-mesh nets.

Zooplankton biomass was found to be significantly less during 1963 than in 1961 and 1962. This low value could possibly be a reflection of low primary production in that year. Besides physical factors such as amount of mixing, incident radiation, and nutrient concentration, increased grazing pressure of large oceanic copepods can also result in lower production of phytoplankton. This problem can be solved after species analysis of zooplankton samples for 1963.

We also found that the plume environment represents an extension of the neritic region in the open ocean and is characterized by the presence of typically inshore species in large numbers. The ambient regime, in

addition to small common copepods, contains larger and typically oceanic species such as *Calanus plumchrus, Calanus cristatus,* and the subspecies of *Eucalanus bungii*. Therefore, there is more zooplankton biomass in the ambient waters than in the plume. In the inshore region, seasonal variation of zooplankton abundance is markedly subdued. Furthermore, there is more zooplankton biomass in this region during autumn and winter than in ambient or plume regions because of higher primary production due to greater stability in the water column and net onshore transport of water which helps to accumulate biological populations near shore.

The distribution of phytoplankton biomass, as chlorophyll *a* concentration, and primary productivity are now being studied. Seasonal, yearly, and local differences will be evaluated. Determination of the species composition of zooplankton samples for 1963 will complete the study; it then will be possible to describe phytoplankton-zooplankton relationship in this region on a quantitative basis. (Jawed)

Biological Prediction of the Spring Bloom in the Northeast Pacific

From February through June 1970, data were collected on research and commercial vessels as part of a continuing program to test mathematical models for predicting the timing and level of production of the spring phytoplankton bloom in the Northeast Pacific. In cooperation with this program, the Faculty of Fisheries, Hokkaido University, sampled for chlorophyll and plant nutrients, and made measurements of attenuation coefficients during a trans-Pacific crossing in June and July 1970. The data are providing a description of the seasonal and annual distribution of temperature, insolation, plant nutrients, chlorophyll, and primary production over a large area of the subarctic North Pacific Ocean.

In collaboration with T. R. Parsons, Nanaimo, the ability of the Steele-Menzel model to predict primary production was tested using data collected from the North Pacific Ocean. The agreement between calculated primary production and that measured by ^{14}C uptake was good. In addition, the model may be used to provide information on seasonal changes in the type of primary producers. To check this, work with preserved quantitative phytoplankton samples collected from the commercial vessels is now in progress. This includes the identification, enumeration, and biomass estimates of diatoms, dinoflagellates, coccolithophorid flagellates, silico-flagellates, ciliates, tintinnids, and foraminifera species. Composite samples are also being examined in order to differentiate five areas of the North Pacific in regard to the relative importance of the taxonomic groups. (Anderson, Munson, Booth)

Dissolved Organic Matter Released from Phytoplankton

An investigation is underway to determine the biological significance of dissolved organic matter (DOM) in the euphotic layer of the oceans. Research involves measuring the release of DOM from natural populations of phytoplankton, and developing a method to determine assimilation and biological oxidation rates of phytoplankton-derived DOM.

Few measurements of the release of DOM have been made, particularly in oceanic waters. Data collected off the southeastern coast of the United States suggest that as one proceeds from the highly productive estuaries of Georgia to the oligotrophic waters of the Sargasso Sea, the per cent of photoassimilated carbon released as DOM increases to where it nearly equals particulate primary productivity. In addition, there is some evidence from Sargasso Sea observations that the rates of release of DOM from phytoplankton vary diurnally, During the 1971 R/V *Thompson* North Pacific crossing and cruises off the Columbia River, we will determine rates of release and test a method for measuring rates of assimilation and biological oxidation. (Thomas)

Release of DOM has also been measured in eutrophic and oligotrophic areas of the Northeast Pacific Ocean as well as during different stages of a phytoplankton bloom enclosed in a large plastic cylinder in Puget Sound. In both the Sound and offshore areas, a close correlation was found between the production of particulate organic matter and the release of dissolved organic matter. In fact the regression equation expressing this relationship was similar in both studies. (Anderson, Zeutschel)

Primary Productivity and Energy Flow in the Arctic Ocean

An intensive sampling program is being conducted from Fletcher's Ice Island (T-3) in order to describe the annual cycle of phytoplankton in the Arctic Ocean and to develop a model combining light, other environmental variables, phytoplankton standing stock, primary productivity, and zooplankton grazing. Carbon-14 uptake is being measured at constant illumination and *in situ* at selected depths. Cell counts are being made with an inverted microscope. Zooplankton is being sampled by 2-m vertical closing nets. (English, Lewis, Ferguson)

Physiological and Ecological Studies of Marine Diatoms

Several projects are being carried out on the physiology and ecology of marine diatoms. The diatom populations occurring in the surf zone along the Olympic Peninsula are being studied. Massive blooms of diatoms occur in this particular habitat during autumn, winter, and spring and constitute the major food of the razor clams which inhabit these beaches. Studies are being made in the field with the natural populations in order to determine their photosynthetic rates, respiration rates, rates of nutrient uptake, total biomass, how the cells are distributed in the surf zone, and correlation between diatom growth and nutrient effluent from the Columbia River. In addition, physiological studies in the laboratory will reveal how the two major species (*Chaetocerus armatum* and *Asterionella socialis*) are uniquely suited for life in the surf zone.

Various diatom species, as well as other algae, that excrete high amounts of extracellular polysaccharide into culture medium are being cultured for a Sea Grant project. The chemical nature of the extracellular material is being studied by Forest Resources to determine uses for these new polymeric materials. Other projects on availability of iron to phytoplankton species, role of boron in diatom growth, and heterotrophic growth of marine pennate diatoms are being continued. (Lewin)

Studies on Microzooplankton

Studies are being conducted to obtain a good estimate of the relative importance of the microzooplankton in the energy budget of a marine area such as Puget Sound. To accomplish this, organisms are needed for laboratory work that are easily handled and are representative of those found in the field. Such parameters as growth, reproduction, respiration, grazing rates and assimilation coefficients may be measured and applied to field data.

A large gymnostomatid ciliate, isolated from waters around Friday Harbor, Washington, was temporarily chosen when culturing tintinnids proved difficult. It grew best on the cultures of *Thalassiosira fluviatilis*, either in mixtures with other cells or in monoalgal cultures. The haemocytometer has been used for cell counts. Doubling times for populations with high food density were about 36 hr at 20 C and 60 hr at 15 C.

Marine rotifers are reported to be common in Puget Sound during spring and summer months. Brief attempts have been made to culture two of the more common species (*Synchaeta* sp., *Trichocera* sp.) on various algae, so far without success. However, another marine monogont rotifer, *Brachionus plicatilis* (originally isolated from the Salton Sea), was obtained. It does not reproduce (or only slowly) at 15 C but grows well at 20 C. Doubling time at this temperature in cultures of *Dunaliella tertiolecta* was about 22 hr (cell concentrations of 50×10^4 cells/ml) to 31 hr (cell concentrations of 15×10^4 cells/ml). Female-egg ratios are also higher on the average for rotifers in the higher concentration of food cells. Although the data were extremely variable, average grazing rates (at 20 C, food concentrations of 15×10^4 cells/ml) were estimated to be about 800 cells per ml per female per day. (Dewey)

Studies of Planktonic Copepods

To enhance our understanding of quantitative trophic interactions between phytoplankton and herbivorous copepods, we are studying the population dynamics and feeding ecology of species of planktonic copepods that occur both in the Columbia River effluent area and in Puget Sound. Populations of *Pseudocalanus minutus* have been maintained in the laboratory at 10 and 15 C; rates of development, generation times, and egg production were measured. Potential population growth of *Pseudocalanus* in different temperature and food regimes is being investigated. *Calanus pacificus* was cultured in the laboratory and produced one complete generation. Adult populations of *Calanus* consisted entirely of females and individuals lacked oil sacs. Oil sac development seems critical for survival of males, but not for females. We are testing the effect of type and supply of food on production of oil sacs in *Calanus*.

Feeding rates and feeding behavior of *Calanus* are being studied. We are particularly interested in temporal variation of ingestion rates at very low (natural) densities of phytoplankton. Experiments are done both with batch cultures of phytoplankton and with chemostat effluents. We are also developing methods involving liquid scintillation counting to obtain estimates of secondary production in laboratory populations of *Calanus*.

A long-term study of the systematics and zoogeography of marine epipelagic organisms is continuing. Males of the sibling species pair, *Calanus finmarchicus* and *C. glacialis*, were re-examined to assess the significance of differences between two similar species of *Calanus* occurring in Puget Sound. It appears that two North Pacific species of *Calanus*, those occurring in Puget Sound, are cognates of the North Atlantic species, *C. finmarchicus* and *C. helgolandicus*. (Frost, Maguire, Vidal, Cohen)

Studies on Carnivorous Amphipods

The paucity of studies on material or energy budgets for marine carnivorous zooplankton and consequent poor knowledge of their growth efficiencies make the determination of the importance of carnivores in marine food chains approximate at best, even when determinations of their biomass and productivity can be made. With this problem in mind, a carbon and nitrogen budget for the pelagic amphipod, *Calliopius laeviusculus*, raised under controlled conditions, is being attempted. Work to date indicates that this species can be reared in the laboratory from the time of release of young (approximately 50 µg dry weight) to adulthood (+5.0 mg dry weight). Young readily feed on phytoplankton but can also ingest animal material. Juveniles and adults are capable of an entirely carnivorous diet, and a large adult will capture and consume as many as 10 copepodite V of *Calanus* sp. per day. Food type and food size preference are being examined. An investigation of the effects of food concentration and temperature on growth rate and efficiency will be initiated. Respiration and excretion will be periodically determined over the life span, and all molts and eggs will be collected. Analyses will then give a complete carbon and nitrogen budget for various stages of the life span of the amphipod. Some similar work but to a more limited degree will be done on another amphipod, probably *Cyphocaris challengeri*, for comparative purposes.

A field program to determine the biomass and productivity of *Calliopius* in a semi-enclosed body of water is planned. This study, combined with the laboratory information, will permit an estimate of how much carbon and nitrogen is required to maintain the species. (Dagg)

Zooplankton Physiology

Experiments were performed on the oxygen consumption by two species of mysids, *Archaeomysis grebnitzkii* and *Neomysis awatschensis*. The effects of temperature, salinity, dissolved oxygen concentration, and duration of experiments were evaluated. The species do not show significant differences in their oxygen-consumption rates at different temperatures. The lethal lower limit of oxygen tension for both species is about 20 mm Hg. Both species show little effect of salinity and duration of experiments. (Jawed)

Taxonomic Studies

Barnacles. Systematic and zoogeographic studies of barnacles of the eastern Pacific Ocean are continuing. The study of the inter- and intraspecific relationships of species included in the "Revision of the *Balanus amphitrite* Complex" has been completed. Work on the occurrence of

complemental males in highly evolved barnacle species has revealed that this phenomenon is not restricted to a single subgenus of *Balanus* and that intensive investigation of several allied subgenera as well as detailed study of the life histories of both hermaphrodites and males is needed. (Henry)

Polychaetes. Work toward a key for the benthic polychaetes (exclusive of Archiannelida and Myzostomidae) of Washington and British Columbia continues. (Banse, Hobson)

Revision of records of species (and often of descriptions) of Phyllodocidae, Syllidae, Nereidae, Nephthyidae, and Sabellidae is completed and papers are being prepared. (Banse)

CHEMICAL OCEANOGRAPHY

Research in chemical oceanography is under the direction of R. C. Dugdale, M. L. Healy, T. T. Packard, S. Pavlou, F. A. Richards, and J. J. Walsh.

Dynamics of Biological Production in Upwelling Ecosystems

The initial cruise for investigating the dynamics of biological production in upwelling ecosystems, an integrated research program sponsored by the U. S. International Biological Program, was carried out in 1969 near Punta San Juan, Peru. This area appears to be surprisingly stable, taking the form of a plume of cold, nutrient-rich water rising close to shore and drifting offshore to the north. Within a sampling grid, maps were made showing the patterns of salinity, temperature, chlorophyll, phosphate, nitrate, and silicate at 3-m depth. Groups of investigators from the U.S., Peru, Spain, France, and Greece conducted experiments on the kinetics of such processes as the chelation of trace metals in upwelled water, the diurnal cycle of nitrate reductase, nitrate and ammonia uptake, and silica uptake in phytoplankton. The effects of the large anchoveta population on the recycling of nutrients were found to be substantial. (Dugdale)

PASTOUZO Cruise. The second IBP cruise, similar in design to the Peru cruise, was carried out on the R/V *Thompson* (TT-47) to study nutrient enrichment processes in the eastern Mediterranean Sea during February-March 1970. The Mediterranean is well suited for these experiments, since it is chronically in a state of extreme nutrient deficiency and can be expected to respond quickly to nutrient additions. The Petalion Gulf, east of Athens, was found to have virtually no source of nutrients in early spring, in contrast to Saronikos Gulf which receives the sewage effluent from Athens and its port, Piraeus.

Three arrays of current meters and thermographs were set in the Petalion Gulf so that with the onset of northerly winds, return flow toward the north would be measured near the bottom. Approximately 3 weeks of records were obtained. A computer simulation model has been constructed for the area; with the real wind data input to the model a substantial flow to the north is predicted. The season was unfavorable for detecting the effects of vertical transport, and few effects of the wind-driven circulation were observed.

A study of the effect of large nutrient additions was conducted in northern Saronikos Gulf. The *Thompson's* underway data system was used to study the patterns of nutrients and productivity resulting from the water circulation and sewage. As a result of the first set of maps of nutrients, chlorophyll, and temperature, experiments were carried out to relate the effect of ammonia concentration on nitrate uptake; the current hypothesis was confirmed in the field by this means. Greek scientists who participated in R/V *Thompson* cruise 47 have started an IBP project, in collaboration with the Upwelling Program, with the goal of producing simulation models of the two gulfs to aid in the management of pollution problems.

In cooperation with scientists from the Instituto de Investigaciones Pesqueras, Barcelona, underway data recording of nutrients and chlorophyll was undertaken between Athens and Barcelona, with special emphasis on the

Straits of Messina and the Straits of Bonifacio. The progressive enrichment in nutrients to be expected in the Mediterranean in an east to west direction was observed. Relatively high nutrient concentrations were observed, especially in the region east of Bonifacio, which is known to exhibit strong mixing in the winter and through which a storm with 60-knot winds had passed 2 days in advance of the *Thompson* crossing. Since stations with reliable chemistry from the different basins of the open Mediterranean have been virtually lacking, three hydrographic stations to the bottom were taken during the east-west crossing. Nutrient chemistry was carried out in duplicate for phosphate, silicate, nitrate, nitrite, and ammonia.

A working conference on the analysis of upwelling systems was held 24-25 March at the Instituto de Investigacion Pesqueras in Barcelona. Papers resulting from the conference will be published in February 1971 in a special issue of *Investigacion Pesqueras*. After the working session, a 2-day cruise from Barcelona to Castellon, Spain was made to map out the effect of the River Ebro on the nearby productivity and chemical regimes. (Dugdale, Walsh)

Simulation models. Development of preliminary biological simulation models of an upwelling area has been completed. One spatial model, based upon the Hyperion sewage outfall in California, predicts the development of a phytoplankton plume downstream and detached from the outfall itself (Dugdale, Whitledge). The parameters in another model can be adjusted to simulate the phytoplankton concentrations measured in the stable upwelling plume off Punta San Juan in Peru (Walsh, Dugdale). A submodel for nitrate uptake was validated using data from the Peru cruise and will be used in subsequent models (Dugdale). Although these models have been restricted severely in scope by the limitations of the IBM 1130 computer, preliminary results match observations of the real ocean. As these models are expanded for use on large computers, we may find that the apparent success has been the result of oversimplification and inadequate computer power.

Models in various stages of development are a Peru anchovy fishery model (Paulik); a numerical simulation model of the fluid dynamics of coastal upwelling (O'Brien, Florida State University); an ecological model with the capability of generating spatial resolution up to 60,000 spatial blocks and 40 variables (Walsh); and a model of the wind-driven "complete Ekman" system, including bottom stress, for velocities in coastal and enclosed regions (Hopkins). The University of Washington's Center for Quantitative Science serves as headquarters for the simulation modeling project directed by Dr. Gerald Paulik.

Phytoplankton and Herbivorous Zooplankton Processes

A continuous culture laboratory with a variety of automated analyses is being set up for bio-chemical studies of the kinetics of energy and nutrient flow through the first two levels of the marine ecosystem. This joint project involves algal chemostat experiments, studies of linked algal-zooplankton continuous cultures, tracer methods and enzymatic analysis, and simulation modeling studies. The culture system will include an automatic data recording and processing system with provisions for interfacing with digital computers. (Dugdale, Conway, Harrison, Curtis, Frost, Kaczynski, Packard, Pavlou, Walsh).

Enzymatic Determination of Rate Processes in Plankton Ecosystems

Studies of respiratory and nitrate assimilation processes are continuing. The sensitivity of the respiratory electron transport assay has been improved and the kinetics of the electron transport system (ETS) in two species of diatoms has been determined. The relationship between the ETS activity and the respiratory rate is presently under investigation in cooperation with V. Kaczynski. ETS studies on zooplankton are being carried out at the Friday Harbor Laboratories with members of the chemostat research group. In this project we are making simultaneous measurements of ammonia and phosphate excretion, ETS activity, and oxygen consumption on common members of the zooplankton community.

Size fractionation of the respiratory activity of plankton communities has continued with M. L. Healy. These studies show that the nanoplankton are the major consumers in the plankton smaller than 500 μ.

Investigations with nitrate reductase have shown that the enzyme is rapidly induced in phytoplankton by the presence of nitrate. The response to nitrate is related to the duration of prior nitrate starvation. Ammonia inhibits this induction and represses nitrate reductase. This repression phenomenon has been observed both in the laboratory and at sea. (Packard)

Studies of Oxygen-Deficient, Anoxic, and Sulfide-Bearing Marine Environments

Saanich Inlet. During 1970, cruises were made to Saanich Inlet, Vancouver Island, approximately every 6 weeks to document the changes accompanying the development of anoxic conditions and the production of sulfides. Emmission-spectrographic techniques were used to examine the effect the development of anoxic conditions has on trace metal concentrations in particulate matter. (Flourie)

Studies are now focused on short-period physical, chemical, and biological processes in Saanich Inlet, a system which appears to flush between July and October. Specific goals are: (1) determine the credibility of single station observations used to define yearly changes; (2) obtain an approximate profile of the horizontal changes in the chemical properties; (3) evaluate the importance of biological processes in controlling the distribution of non-conservative properties; (4) correlate the characteristic length scales of the chemical distributions with the length scales of the currents causing mixing in Saanich Inlet; and (5) estimate the time required to re-establish anoxic conditions after flushing.

During February 1971, an experiment will utilize the R/V *Thompson* and R/V *Onar* anchored a predetermined distance in Saanich Inlet. Chemical properties will be monitored continuously at the sulfide-oxygen interface; current observations will be correlated with chemical measurements. The experiment will run through one tidal period; the distance between the ships will be increased and measurements will be resumed for another tidal period. (J. Anderson, Devol)

PECAR cruise. Observations of nutrients, dissolved gases, and trace metals were made during R/V *Thompson* cruise 46, December 1969 - February 1970, to the eastern tropical Pacific, Caribbean and Black seas. Thirty-one stations were occupied to determine the areal extent of the denitrification process in the oxygen-minimum zone of the eastern tropical Pacific. Northeast of the Galapagos Islands, where the Cromwell Current becomes chemically indistinguishable from the oxygen-minimum zone of the eastern tropical Pacific, 10 stations were occupied to examine chemical changes occurring in the water mass. In this region the highly oxygenated water of the Cromwell Current loses oxygen and increases in nutrient concentrations. Chemical and physical data were collected in Golfo Dulce, the Cariaco Trench, and the Black Sea for anoxic environment studies. Other multi-disciplinary projects were carried out by the seven institutions participating in the cruise. (Richards)

Trace elements. The distribution of particulate manganese has been examined in Golfo Dulce, the Cariaco Trench, the Black Sea, and Lake Nitinat. In general the distribution of particulate manganese is the same in these basins. Thermodynamic calculations on oxidizing-reducing environments show that the particulate manganese distributions agree with thermodynamic principles. The results of these observations confirm that anoxic basins are a trap for manganese and iron. The existence of reprecipitated iron and manganese is a persistent feature at the interface above the anaerobic zone in anoxic basins. (Flourie, Healy)

Nitrate anomaly. The nitrate anomaly is a measure of the conversion of nitrite and nitrate to nitrogen gas by denitrifying bacteria. Because data from a number of R/V *Thompson* cruises to the northeastern tropical Pacific Ocean permit the calculation of this parameter, it is a useful tool for investigating denitrification in these low-oxygen waters. Data collected in December 1969 during R/V *Thompson* cruise 46 indicate that the minimum transport of nitrate anomaly out of the northeastern tropical Pacific is $\sim 10^{13}$ g/year. This value is of the same order of magnitude as some estimates of the total amount of denitrification in the ocean and indicates that the low-oxygen waters in the northeastern tropical Pacific are a major marine denitrification site. Data from R/V *Thompson* cruises 1, 35, 37, and 46 and some data from other institutions are being analyzed to improve our understanding of denitrification in this region. (Codispoti)

Anoxic respiration processes. Studies of anoxic respiration processes using environmental simulators have shown that in water collected from the oxygen-minimum zone of the eastern tropical Pacific, a large fraction of the nitrate is reduced to nitrite before the bacteria will use nitrite as the terminal electron acceptor. However, there is no striking accumulation of nitrite in water collected from the oxygen-deficient zone of Saanich Inlet. Two different bacteria may be responsible for denitrification in these areas. Further experiments are planned along with the development of an anoxic chemostat to identify the bacteria responsible for denitrification and to obtain denitrification rates. (Devol)

Organic matter in anoxic environments. Observations of dissolved and particulate organic carbon have been made in Saanich Inlet and Lake Nitinat, Vancouver Island; and in Golfo Dulce, the Cariaco Trench, and the Black Sea during R/V *Thompson* cruise 46. In general, concentrations of both dissolved

and particulate organic carbon are highest near the surface and decrease to low and fairly uniform concentrations at greater depths. The concentrations are not demonstrably greater in the sulfide-bearing waters than would be expected in otherwise comparable oxygenated water. The particulate organic carbon often increases near the bottom. The increases are generally consistent with possible near-bottom circulation, but they may be caused by the sampling equipment disturbing the bottom. Qualitative differences in the organic matter in anoxic and oxygen-bearing waters are under investigation. (Devol)

Trace Metal Studies

The transport of lead from the atmosphere to the sediments has been investigated in Lake Washington. Airborne lead appears to be accumulated on phytoplankton and eventually deposits in sediments. The contribution of winter circulation to the downward removal of lead will be studied on several cruises to Lake Washington during spring 1971. (Baier, Healy)

A program is underway to investigate the supply, transport, and fate of copper introduced into Puget Sound by industrial pollution. (Tatomer, Healy)

Water Mass Characterization and Circulation Studies by Chemical Parameters

A computer model has been developed to study the relationships between physical and biological processes and the distributions of chemical properties in the oceanic environment. A set of equations defining the distribution of oxygen, temperature, and salinity in three dimensions are put in matrix form and solved for the current field that is needed to produce the prescribed distributions. The input parameters, determined from observation, are the first and second spatial derivatives, the time derivatives of the three properties, and the biological oxygen change. Diffusion terms also must be supplied which closes the set of equations, thus allowing the current field to be uniquely defined. In this way, we can study the relationships between advection and diffusion.

Using this model, we have tested the equations relating horizontal diffusion to the length scale of the phenomenon under consideration, and have concluded that the horizontal spacing of discrete oceanic data relates directly to the length scale in the 4/3-power diffusion equation, $K = a\sigma^{\frac{1}{3}} l^{\frac{4}{3}}$. The effect of anisotropic vs. isotropic horizontal diffusion on the current field under specified oxygen, temperature, and salinity distributions has been studied. It appears that the direction of the calculated current is sensitive to horizontal anisotropicy, while the current speed is less sensitive. The model is also being used to determine the significance of horizontal to vertical diffusion and investigate the importance of errors in the derivation of chemical properties from analytical techniques.

We will test the model during cooperative studies with Oregon State University on an R/V *Yaquina* cruise in fall 1971 to the eastern tropical Pacific. Chemical data and characteristic oxygen consumption values will be obtained for different water masses in the region where the Cromwell Current is divided into north and south arms by the Galapagos Islands. The validity of calculated current speeds and directions, using chemical parameters, will be checked against direct current measurements obtained with drogues. (J. Anderson)

GEOLOGICAL OCEANOGRAPHY, MARINE GEOPHYSICS, AND GEOCHEMISTRY

Research in geological oceanography, marine geochemistry and geophysics is under the direction of L. C. Bennett, F. E. Burns, R. Carpenter, J. S. Creager, R. J. Echols, B. Lewis, H. Y. Ling, C. R. B. Lister, D. A. McManus, R. T. Merrill, D. J. Piper, J. D. Smith, R. W. Sternberg, and T. R. Worsley.

Sediment Transport Studies in the Marine Environment

Boundary-shear stress measurements have been made over various bed configurations--rocks, rippled and nonrippled sand--from a variety of oceanographic environments. Concurrent with these measurements, we have observed incipient sediment motion and ripple migration rates. Characteristic values of the drag coefficient (C_{100}) relating the mean velocity 1 m above the bed (U_{100}) to the boundary sheer stress (τ_0) have been determined for the various bed configurations. Both hydrodynamically rough and smooth environments have been encountered. The critical shear stress associated with initial grain motion is being determined for a wide variety of natural marine sediments in an effort to provide field evidence of the general conditions causing sediment motion in the sea. We also are estimating the mass transport of sediments resulting from tidal currents flowing in the vicinity of the seabed.

A version of the Bagnold mass-transport equation has been modified according to results obtained from the *in situ* measurements. The modified equation more adequately predicts bed-load transport than previous forms. Further analysis is being carried out on bed-load and current measurements made in Bering Strait during summer 1970.

A project is underway to study bottom currents and associated sediment transport on the Washington continental shelf. An instrument has been designed to rest on the sea floor and measure bottom currents and pressure fluctuations continuously for 30 days, as well as photograph the bed every 30 min. One prototype assembly has been built and is now being tested in Puget Sound. Three additional instruments are being constructed. During winter 1971, the instruments will be placed in an array on the central and outer shelf. Field measurements will be used to evaluate the spacial and temporal distribution of bottom currents on the continental shelf and the influence of these currents on the movement of sediment. (Sternberg)

Seismic and Acoustic Studies

The physical properties of earth materials determine the velocity of seismic waves and the degree of seismic-energy absorption. Even when earth materials cannot be sampled, seismic information can be used to study the properties of these materials. The range of sound velocity and attenuation in natural unconsolidated sediments is being studied by continuous seismic refraction methods and by direct measurement on cored sediments. Using sound-pulse reflections, we are measuring *in situ* acoustic absorption between 100 and 12000 Hz in unconsolidated sediments on the continental shelf and in abyssal plains of the North Pacific. (Bennett, Guntersen)

Shallow geological structures of the Washington continental shelf and beneath the inland waters of western Washington are being investigated by seismic reflection and refraction profiling coupled with magnetic field measurements, bottom sampling, and seabed photography. Our objectives are to (1) develop an understanding of the Tertiary and Holocene geologic history of the Washington continental margin in relation to recent theories of crustal deformation and sea-level fluctuations (Wissman); (2) study the effect of Pleistocene glaciation on the geology and bathymetry of Puget Sound and Strait of Juan de Fuca (Mayers); and (3) examine faulting and sediment transport processes and their possible effects on proposed engineering facilities in Puget Sound (Sylwester), on coastal beaches and bars (Bennett), and on the Nisqually delta (Stockman).

Information is being sought on all underwater photographs for inclusion in a world seabed photograph index proposed by the National Oceanographic Data Center. (Bennett, Ferjancic)

Turbidite Study

Investigations are continuing on the primarily turbidite sequence of sediments forming Nitinat Fan and filling the northern portion of Cascadia Basin between the continental margin of Washington and Vancouver Island, and Juan de Fuca Ridge about 250 miles offshore. The objectives of this study are: (1) select the statistically most significant variables of the near-surface Cascadia Basin sediment for determining turbidite provenance, dispersal routes, depositional environments, and chronology on a regional basis; (2) assess the local variability of each parameter; (3) reconstruct the geologic history of the total turbidite sequence in Cascadia Basin by deep-penetration seismic profiles; and (4) compare the preferred orientation of turbidite sediment texture with the local topography.

Over the last 3 years, 49 piston cores have been collected from Cascadia Basin and to the west of Juan de Fuca Ridge. In addition, 1026 miles of 4-kHz and 894 miles of air-gun seismic profiling have been run across the basin. Biostratigraphic and textural studies have been completed on all the cores collected. We have analyzed selected samples for total carbon and organic carbon content. Vertical variations in the clay mineralogy have been examined in six cores. Work has also been completed on a core-mounted gyroscope package which gives us the capability of taking oriented piston cores for magnetic susceptibility-sediment texture studies. The statistical analysis of the variables to date has centered on the textural analyses and on the biostratigraphic analysis of Radiolaria and foraminifera.

Biostratigraphic analysis based on foraminifera and Radiolaria counts has been used for basin-wide correlation of Holocene and Late Pleistocene sediment sequences. Holocene sedimentation has been most rapid east of Vancouver Valley (~20 cm/1000 years) and in the deep-sea channels (20-50 cm/1000 years) which traverse Cascadia Basin. West of Vancouver Valley, Holocene sedimentation has proceeded at a rate of less than 5 cm/1000 years.

Postglacial sediments in Cascadia Basin contain 1.5-2% total carbon, while the Late Pleistocene turbidites show only 0.5-0.75%. These Pleistocene sediments also contain less than 1% organic carbon, while the organic carbon content of the recent deposits is commonly 1-2%. The lower carbon content in Pleistocene deposits may be attributed to the increased rate of sedimentation during glacial periods and dilution of the carbonaceous material by terrigenous sediments. Conversely, the lower content may reflect a reduced influx of organic material during glacial time.

The clay mineralogy in Cascadia Basin shows a marked change across the Pleistocene-Recent boundary. The montmorillonite content increases (7-35%), while illite and chlorite-kaolinite decrease (45-30%) in progressing from glacial to postglacial deposits. This change may reflect a shift in source area or material. The Pleistocene chlorites show a higher degree of crystallinity than do the postglacial chlorites, indicating reduced chemical weathering during the late Pleistocene. (Carson, McManus)

Heat-Flow, Sedimentation, and Sea Floor Structure

A heat-flow measuring and high-resolution seismic profiling capability has been developed for investigating heat-flow distribution and bottom structure in the deep ocean. Almost all heat-flow measurements are now being made with a probe-type apparatus measuring sediment thermal conductivity *in situ* rather than with the more standard corer-outrigger apparatus. (Lister)

Results of a study of the heat-flow pattern on the western flank of Juan de Fuca Ridge have been surprising. Instead of rapid decay of heat-flow westward of the crest to typically subnormal flank values of 0.8 μ cals/cm^2-sec, a large area of subdued topography between 40 and 120 km has a six-measurement mean heat-flow of 6.4 μ cals/cm^2-sec. Furthermore, six new measurements east of the crest average to 7.1 μ cals/cm^2-sec, and yet the four values on the inner western flank (0-40 km) average to 2.4 μ cals/cm^2-sec.

It was established from a previous seismic profile across the area that the high heat-flow region on the western flank was unusual in having a smooth (though blocky) basement and almost perfect "snowfall" sediment cover. The availability of good bathymetry for the area demonstrates a further curious correlation: the highest values are all on top of knolls or ridges while any values situated in well-defined valleys or closed depressions are unusually low. The contrast of 50:1 in heat-flow across 25 km near 131°W is striking and could be considered an extreme example of the "valley effect." It is clear from the seismic profiling and bathymetric delineation, together with sediment deposition rates obtained from cores, that the topography and sedimentation cannot generate the observed anomaly patterns by refraction of conductive heat-flow or by slumping. This conclusion is further substantiated by the general lack of correlation between the heat-flow fluctuations east of the ridge crest with the subbottom structure observed on the coincident seismic profile.

The data obtained on this project point strongly to one possible explanation: that heat is primarily transported through the oceanic crustal layer by convective hydrothermal flow. In areas of incomplete sediment cover the

flow is partially open and the heat-flow measurements are systematically depressed; where sediment cover is substantially complete the surface conductive heat-flow reflects the cell pattern beneath which will automatically generate a topographic distribution opposite to that produced by conductive refraction. Implicit in this theory is the concept of greater bulk permeability in the jointed oceanic crustal layer than in the overlying sediment, a non-intuitive suggestion. A more complete description of this theory will be prepared for publication. (Lister)

On the R/V *Oceanographer* SEPAC Cruise, January to March 1970, an 800-km long high-resolution seismic profile was made across the entire crestal region of the E. Pacific Rise at 42°S, and two shorter profiles were completed at 38°S (Eastern Flank) and 36°S (Eastern flank - over the crest). A set of heat-flow measurements were made along the crestal part of the 36°S profile. On the way into Valparaiso, a short acoustic profile was run across the Chile Trench, and showed most unusual disturbed sediment structures on the trench floor. This is being interpreted in terms of trench-subsidence mechanisms. (Lister, Burns)

Seismic Refraction Studies

In the past decade we have gained a better understanding of the fine structure of the upper mantle under the continents, mostly by using seismic refraction techniques; yet little is known of the oceanic upper mantle. This knowledge will be critical in working out the physical processes involved in plate tectonics. The application of refraction techniques to this problem requires source-receiver distances of several hundred kilometers so as to record acoustic waves refracted to the depths of interest, i.e., down to 300 or 400 km. The efficient handling of data and ship time suggests the use of long-range telemetering buoys. Such buoys are presently under construction and will be given sea trials in summer 1971 with a preliminary upper mantle study in the Northeast Pacific. (Lewis)

Deep Sea Drilling Project: Leg 5

Twelve sites were drilled and 869 m of core were recovered on Leg 5 of the JOIDES Deep Sea Drilling Project--the 55-day cruise of the *Glomar Challenger* from San Diego to Honolulu in April-May 1969. The drilling program was designed to sample major east-west fracture zones of the Northeast Pacific to investigate the origin of the magnetic anomaly patterns and possible relative movement along the zones; and to recover continuous sedimentary sections along a longitudinal profile (140°W) to determine the history of the Equatorial Current System and the North Pacific Central Water masses. The publication *Initial Reports of the Deep Sea Drilling Project, Volume V,* covers the operational results of Leg 5. (McManus, Burns)

Radiolaria and Silicoflagellates from the North Pacific Ocean

During the past few years, we have conducted investigations from the eastern to the central part of the subarctic Pacific to determine the nature and pattern of distribution of siliceous microfossils and their role in the regimen of the deep-sea sediments of the North Pacific. Radiolaria from the

surface sediments have been recognized to show a definite biogeographic distribution pattern having close relationship with the general circulation of the watermass of the area. R/V *Thompson* cruise 49 to the western North Pacific was carried out during June-July 1970 to complete the general areal coverage for the entire subarctic Pacific Ocean. We are now investigating deep-sea sediment cores collected during the cruise.

The study of Radiolaria from the deep Bering Sea surface sediments reveals that the fauna from the Bering Sea is somewhat different from the assemblage so far recognized in the central and eastern subarctic Pacific. The fauna from the Okhotsk Sea is being analyzed for comparison with those from the Bering Sea and northwestern Pacific.

The finding of the Miocene and Quaternary silicoflagellates from the central North Pacific deep-sea sediments has been published. As an outgrowth of the study, we are examining the deep-sea sediments to determine the stratigraphic range of silicoflagellate taxa from the upper Cretaceous to Recent. Samples from the Scripps collection serve as the nucleus for the study. Additional samples were received from the JOIDES Deep Sea Drilling Project and from some of the well-known land localities such as New Zealand, California, and Japan. We have observed an interesting Radiolaria and silicoflagellate assemblage from Miocene sediments of Japan. The stratigraphic position of these samples was clearly documented and the age dated by means of other planktonic microfossils, such as Radiolaria, foraminifera and calcareous nannofossils. We are now cross-correlating the geologic occurrence of silicoflagellate taxa in these samples. (Ling, McPherson)

Studies of Unconsolidated Sediments in the Chukchi and Bering Seas

During R/V *Thompson* cruise 51, August-September 1970, additional field data were collected in the Chukchi and Bering seas for studying the stratigraphic history of the sediments deposited during a major marine transgression across a continental shelf-coastal plain. The Chukchi-Bering sea continental shelf is an excellent model for studying transgressive sedimentary sequences because of its simplicity in sediment thickness, age, and marker horizons. The sediment, predicted to average no greater than 10 to 15 m in thickness, can be collected fully with presently available coring equipment where the sediment is soft; yet it is thick enough to provide detail of sedimentologic events over the 20,000-year Holocene transgression. Hopefully, TT-51 data will be useful in interpreting the paleogeography of the Bering Land Bridge and the times of inundation.

Shallow-penetrating continuous seismic profiling (using a 4-kHz system) permitted continuous monitoring of the changing thickness of unconsolidated sediment. The air gun and sparker were used alternately, depending upon the depth to basement. Continuous reduction of the data permitted tentative location of buried Pleistocene drainage channels. Much reduction and interpretation remains, however, because the upper 15 m of the sediments contained as many as six reflectors in some areas. Wherever the subbottom reflectors indicated a thickened section of unconsolidated sediment, the bottom was cored at least to the first major reflector and, where possible, through a number of reflectors. As was the case during past cruises, the suspected interfluves were covered by thinner sediment layers that were significantly more difficult to core

The area of the southern Bering Sea approximately delineated by the piston core locations is apparently covered by more recent coarser grained sands and silts, which make coring difficult to impossible and which reduce the amount of subbottom penetration of acoustic energy. The buried channels detected in the western and southern portions of the survey area were cored; the length of the piston core barrel was varied at each station until maximum penetration was attained. Van Veen grab samples were obtained and gravity cores were attempted at no greater than 56-km intervals along the cruise track in water less than 200-m deep in the southern Bering Sea. (Creager, Holmes, Morrison, Roberts, Knebel, Silverberg)

The Chukchi Sea portion of the cruise was made to delineate further the details of a marine "delta" discovered north of Bering Strait in 1967. Subbottom reflection profiles and piston cores were collected in the delta area, and two anchored current measuring stations were occupied to investigate sediment transport from the Bering to Chukchi seas. (Sternberg)

In a cooperative study with Dr. David Scholl of the U. S. Geological Survey, four subbottom profiling tracks were run across the continental slope south of the Pribilof Islands and samples were collected at three dredge stations. Since we were denied permission to collect bottom samples to the west of a median line separating Alaska and Siberia, only underway operations were carried out west of the line.

Foraminiferida of the Bering and Chukchi Seas

Studies are being carried out to understand the environmental significance of empty foraminiferal tests in bottom sediments for paleoenvironmental interpretation of ancient marine sediments deposited in high latitudes. During summer 1970, we obtained extensive collections of marginal marine Foraminiferida in the vicinity of Kotzebue, Alaska. The study of these samples is detailing changes in the living fauna along a marked salinity gradient and providing an estimate of the degree to which faunal boundaries, as reflected by populations of empty tests, are obscured by transportation of tests. We also are comparing standing stocks and assemblages of empty tests for the sublittoral zone of the southeastern Chukchi and northern Bering Seas. Because of the probable role strong bottom currents in the area have in transporting tests, the hydraulic properties of the tests of some dominant species are being examined (Kachel).

A further understanding of the ecology of marginal marine Foraminiferida in arctic environments will be sought by studying seasonal changes in populations. We will begin this study in 1971. (Echols, S. Barnes)

Calcareous Nannofossil Biostratigraphy and Paleoecology

Zonation. The JOIDES Deep Sea Drilling Project has demonstrated the unsurpassed value of calcareous nannofossils for rapid biostratigraphic age determinations. In collaboration with Dr. E. Martini of Frankfurt, Germany, we have developed a nannofossil zonation of the Neogene which has a resolution of about 1 my. This zonation was used successfully on Leg 7 and subsequent legs of JOIDES.

During 1970, a preliminary nannofossil subdivision of the previously unzoned Upper Jurassic-Lower Cretaceous interval was completed for the western Atlantic using cores obtained on Leg 1 of JOIDES. We now are investigating the unzoned Middle Jurassic interval. When this study is completed, there will exist a continuous formal zonation scheme for sediments younger than Triassic, since the Lower Jurassic has previously been zoned. The resolution of this scheme will be about 1 my. (Worsley, Cline)

Applied biostratigraphy. Oligocene-Eocene calcareous nannofossils from the Olympic Mountains are being analysed in a preliminary study which hopefully will provide a framework for correlation of Olympic sediments with offshore submarine outcrops off the Washington coast and elsewhere. (Worsley)

Paleoecology and paleoclimatology. When first employed as biostratigraphic age indicators, nannofossils were thought to have had little environmental restriction. This has subsequently been shown to be untrue, thus setting a practical limit to biostratigraphic resolution by current techniques which is rapidly being approached. Detailed studies are being conducted on the biogeographic and vertical ranges of important Maastrichtian (uppermost Cretaceous) nannofossils. This interval was chosen because the apparently synchronous nature of the Cretaceous-Tertiary unconformity provides a convenient worldwide datum for initial stratigraphic control. We are studying both JOIDES cores and terrestrially exposed marine sections from around the world. Preliminary results indicate the presence of strongly differentiated climatic belts for the Maastrichtian, a fact which helps explain the confused state of current biostratigraphic zonation for this interval. (Worsley, Mayers)

The Paleogene interval of New Jersey is being investigated. This area is critical because it provides one of the few sections containing abundant well-preserved calcareous nannofossils which is transitional between the tropical and polar realms. We should obtain interesting data on the ranges of important Lower Tertiary species near the biogeographic limits of their ranges. (Worsley, Armentrout, Gustavson)

Large-Scale Vertical Migration of Carbonate Compensation Depth

From JOIDES Deep Sea Drilling data, it is evident that many large-scale paleontological gaps exist in the strata beneath the deep ocean basins. The Mesozoic-Cenozoic gap is the most conspicuous of these, being found in all cores penetrating the Cretaceous. Like most others, this gap seems to be the result of submarine solution of carbonate rather than erosion of strata. Recent evidence indicates that such unconformities are the result of large-scale vertical migrations of carbonate compensation depth (CCD). At present, we are constructing a model that attempts to account for the ubiquitous terminal Mesozoic extinctions as having occurred because CCD migrated to the surface at that time, causing widespread imbalance of the Earth's CO_2-O_2 budget. (Worsley)

Clastic Sedimentation In Man-Made Lakes

In the summer of 1966 and 1967, 131 short cores were taken from shallow water over an active delta in Watts Bar TVA Lake, Tennessee. Lakes of this

type are subjected to daily oscillations in level of as much as 0.5 ft/day and have an annual cycle of about 6 ft. A study is in progress to determine whether the delta will impede navigation in the near future and what effect the osciallations of water level have upon particle-size distribution of the delta. The physical significance of the relationships between water depth, per cent organics, mean particle size, standard deviation, skewness, and kurtosis is being sought. (Worsley)

Marine Geochemistry Studies

The distributions of several elements in surface sediments and cores from the North Pacific are being measured in an effort to understand the sedimentary history of this region. Various sediment phases will be analyzed separately to evaluate stratigraphic and regional variations in the chemical composition of the abundant minerals. Since the JOIDES project drilled several holes in the Northeast Pacific in spring 1969, it will be possible to look at a much larger section of the sedimentary column than has been possible in the past. (Piper)

The role that marine organisms play in concentrating certain elements is being investigated. Samples of zooplankton, phytoplankton, water, and suspended matter collected in the near-shore environment off the Washington coast are being analyzed for trace elements. (Piper)

Other underway projects include chemical and geological studies of sediments between the Galapagos Islands (Carpenter); investigations of magnetic properties of manganese nodules (Carpenter, Crecelius, Johnson); and the study of the geochemical cycle of mercury in the Columbia River and adjacent marine environment (Carpenter, Bothner).

Paleomagnetic Studies

A large paleomagnetic laboratory has been constructed in which the following problems are being examined: a study of magnetic effects associated with low-temperature oxidation of magnetite and titanomagnetite (Johnson); rock magnetic studies of Laschamp samples--rock samples that presumably record the youngest magnetic field reversal event yet proposed (Johnson, Levi, Whitney); paleomagnetism of Cobb Seamount (Merrill); rock magnetic studies of the Twin Sisters Dunite (Kinoshita); study of the microscopic coercive force spectrum of thermo-remanent magnetization in multidomain magnetite (Levi); preliminary paleomagnetic studies on Cretaceous plutons west of the San Andreas Fault (Whitney); and a study of a reversal transition zone in a Jurassic pluton in California. (Whitney, Merrill)

Nonuniform Boundary-Layer Flow and Sediment Transport Studies

The elucidation of many geomorphological and sedimentological processes requires an understanding of both the mechanics of erosion and sediment transport and the mechanics of turbulent flow near uneven natural boundaries. Through a variety of projects several aspects of these two problems are currently under investigation.

Proper study of a two-phase flow system such as the sediment-water system requires numerous carefully made measurements of the interaction between the local flow and the dilute phase under various specified mean flow conditions. At present accurate measurements of this type cannot be made in the field, so experimental studies of the mechanics of erosion and sediment transport are being carried out in a small laboratory flume. Concentration is on the evaluation of the lift and drag due to a turbulent shear flow on sediment particles of various sizes relative to the size of the bed material, both when the particles are setting on the bed and when they are suspended but in the neighborhood of the bed. Simultaneous theoretical calculations are being made on these problems.

In addition to understanding the mechanics of the sediment phase and its local interaction with the fluid phase, it is necessary to be able to predict the local fluid flow from overall parameters such as mean pressure gradients. In sedimentological and geomorphological problems the flow of greatest interest is that near the boundary; whereas in most hydraulic and physical oceanographic studies the flow in this region is of secondary importance. This situation has resulted in a dearth of detailed knowledge about natural turbulent boundary layer flows – especially those over the uneven boundaries that predominate in nature. At present more is known about the sediment mechanics than is known about the velocity, pressure, and stress fields near boundaries in nonuniform turbulent flows. Studies being conducted to rectify this situation include: theoretical prediction of the flow over small amplitude topography in rotating and non-rotating frames of reference, measurement of the mean flow and fluctuating velocity field in two-dimensional nonuniform flow in the laboratory, measurement of the mean flow and fluctuating velocity field over sand waves in the Columbia River, measurements of the structure of turbulence and stress distribution in tidal flow in Puget Sound, and measurement of the flow over pressure ridges under the ice in the Arctic Ocean. (Smith)

PHYSICAL OCEANOGRAPHY AND MARINE HYDRODYNAMICS

Research in physical oceanography and marine hydrodynamics is under the direction of K. Aagaard, C. A. Barnes, L. K. Coachman, W. O. Criminale, Jr., A. C. Duxbury, T. Ewart, L. H. Larsen F. A. Lee, S. Martin, H. O. Mofjeld, M. Rattray, Jr. and G. I. Roden

Physical Oceanography of Puget Sound and Adjacent Areas

Many of the bays and sounds contiguous to the Northeast Pacific from Washington to Alaska vary in depth from 100 to 300 m and have a predominantly three-layer system that is in many respects similar in both properties and circulation to corresponding features in the major oceans. Studies are being carried out in the inland and coastal waters of Puget Sound and adjacent areas, which in many instances serve as excellent models for phenomena in the open sea. The goal of these studies is to provide a better quantitative description of water structure and circulation, the short- and long-term processes that affect the structure and circulation, the mass and energy budgets, and response of the waters to pertinent forces and changes in boundary conditions.

During 1970, intensive oceanographic studies were carried out in Port Susan and from Saratoga Passage to Deception Pass. The objective was to obtain detailed information needed for developing a quantitative model of the circulation and distribution of properties in these regions. Technical reports on the circulation of Port Susan and on direct current measurements in northern Puget Sound are in preparation. These investigations and related theoretical studies should lead to sufficient understanding of the circulation as a function of a minimum of parameters so that monitoring may be carried out for practical applications. (Cannon, Barnes, Rattray)

Current measurements were made in Juan de Fuca Canyon in February 1970. Preliminary analyses show that at the bottom, in 250 m of water, averaged current speeds of 0.5 knot persist over 10 days directed out the canyon and over the next 12 days directed toward the coast. (Cannon)

Dabob Bay--Hood Canal. The study of medium-scale water parcels in Dabob Bay (20 x 4 x 0.2 km) has shown these parcels to have variable dimensions (frequently < 10-100 m thick, up to 2 km wide, and 2-10 km long) and volume (10^7-10^9 m^3 or roughly 0.1-10 tidal prisms), and to have relatively uniform characteristics defined by closed isopleths of conservative and non-conservative properties (temperature, salinity, oxygen, and nutrients). Injection of intruding water into regions of relatively cold and low-salinity resident water gives characteristic vertical density profiles and temperature-salinity distributions that may persist up to 1 month. Hydrostatic instability frequently associated with the formation of smaller parcels (<1 tidal prism) may persist for several days. Parcel volume decay rates correspond to vertical eddy diffusivities of 1-4 cm^2/sec, with initial values just after formation of 20 cm^2/sec. The necessary local condition for formation appears to be a sill in the depth range of small vertical density gradients and low internal Froude number. Oxygen-utilization rates decrease with depth from 70 x 10^{-4} mg-atoms/liter/day in a relative static zone below the main pycnocline to 20 x 10^{-4} in the larger parcels at intermediate depths and 10 x 10^{-4} below the 120-m sill depth. (Ebbesmeyer)

The Skagit Bay study. Water properties and circulation in Skagit Bay near Deception Pass--which contributes approximately 2% of the water exchange between Puget Sound and seaward approaches, contrasted to 98% through Admiralty Inlet--are being studied in connection with a proposed nuclear power plant. Winds, runoff, surface (tidal) and pycnocline (non-tidal) oscillations in the main Puget Sound basin, and mass properties in the approaches and basin contribute to the circulation patterns. Erratic flow observed in Deception Pass in earlier work and the persistence of a scoured channel across the front of the Skagit River delta--the local sediment source where the tides meet at a statistical null point in current--suggest that oscillations of the pycnocline may be a major contribution to both scouring and the anomalous flow through Deception Pass. This project will provide information on water levels (11 sites), winds (6 stations on or near water), water mass properties in the main Puget Sound basin and immediate approaches, and currents for selected periods and locations. Beyond defining the local circulation, these measurements should show why pycnocline oscillations occur and the extent to which the various factors including pycnocline oscillations contribute to anomalous flows in a double entrance basin. (Barnes, Collias, Lincoln, Cannon, Smith, Rosebrook, Hammond, Somerton, Ewart)

Index of Puget Sound data. An index has been prepared for over 12,000 conventional oceanographic stations occupied in Puget Sound, Strait of Juan de Fuca, and the San Juan Island region from 1932-1966. Station data were collected by our Department, and its precursor the Oceanographic Laboratories, the Pacific Oceanographic Group (Nanaimo, B. C.), and the Washington State Department of Fisheries. This information has been coded as to publication or storage location and may be retrieved by cruise, time, water characteristics, or station locations which are presented graphically. The index was published as a joint effort of the Department, the Washington Sea Grant Program, and the Washington State Department of Natural Resources. (Collias)

Atlas of water properties of Puget Sound and vicinity. An atlas of water properties of the Puget Sound region, based on observations made during 1952 through 1954, is being prepared for publication. The atlas, with partial support under Sea Grant for publication, will include data on the following parameters: temperature, salinity, density, dissolved oxygen, and inorganic phosphate. These data are being prepared as vertical profiles in a form suitable for final presentation. In addition to the above profiles, temperature-salinity diagrams and time variations of properties for selected stations will be included. Supplementary information regarding major factors influencing water properties will be included as plots or in tabular form as appropriate. (Collias)

Puget Sound bibliography. Under the Washington State Sea Grant Program, an annotated bibliography of available literature pertaining to the Puget Sound marine environment is in preparation. For the bibliography we have combined and updated information from the Department of Oceanographys three-volume literature survey, *Puget Sound and Approaches, A Literature Survey*, 1953 and 1954 (out of print) and from the 1968 survey by George Ditsworth, *Environmental Factors in Coastal and Estuarine Waters*. Each reference cited in the bibliography has been assigned a thirteen-digit code word that is computer

compatible. Using the code-word system, information can be retrieved by any combination of the following: author, date of publication, Puget Sound subregion, land and water use, drainage basin, oceanographic data classification. The bibliography will be stored on random disk file for computer processing at the Department of Oceanography and the State of Washington Department of Natural Resources. The Department of Oceanography, in cooperation with the Division of Marine Resources and Department of Natural Resources, will maintain a continuous updating program. (Duxbury, Collias)

Columbia River Studies

A major environmental study was started in 1961 to determine the properties, distribution, and movement of Columbia River water and its dissolved and suspended load in the Northeast Pacific Ocean and to establish a base for predicting the general behavior of river water at sea. The area of primary interest includes the river and the coastal and ocean waters from San Francisco at 38°N to Vancouver Island at 49°N, and seaward some 600 km. Highlights of physical, chemical, geochemical, geological, and biological investigations carried out during the past 10 years by the University of Washington, Oregon State University, Battelle Memorial Institute, and Bureau of Commercial Fisheries are summarized in the AEC book *Bioenvironmental Studies of the Columbia River Estuary and Adjacent Ocean Regions*, D. L. Alverson and A. T. Pruter, ed. (in press). Contributed chapters from our Department include: "The Circulation and Selected Properties of the Columbia River Effluent at Sea" by Barnes, Duxbury, and Morse; "Variability of Salinity and Nutrients off the Columbia River Mouth" by Duxbury; "Summer River-Ocean Nutrient Relationships" by Conomos, Gross, Barnes, and Richards; "Summer River-Ocean Suspended Particulate Matter Relationships" by Conomos and Gross; "Aspects of Marine Phytoplankton Studies Near the Columbia River, With Special Reference to a Subsurface Chlorophyll Maximum" by Anderson; "Bottom Topography and Sediment Texture Near the Columbia River Mouth" by McManus; "Distribution of Organic Carbon in Surface Sediment, Northeast Pacific Ocean" by Gross, Carey, Fowler, and Kulm; "The Distribution of Microbiogenic Sediment Near the Mouth of the Columbia River" by Harman; "The Distribution of Pelagic Copepoda off the Coast of Washington and Oregon during 1961 and 1962" by Peterson; and "Sediment-Associated Radionuclides from the Columbia River" by Gross.

Seabed drifter studies. The effluent of the Columbia River, as it moves and mixes at sea, has been traced north along the Washington coast in winter and southwest off the coast some 900 km in summer; a lower salinity is used as the primary index of river water. Information from seabed drifters (plastic disks 18 cm in diameter, fitted with a 55-cm-long tail weighted to give the assembly slight negative buoyancy) further substantiates the reported near-bottom water movement over the shelf. This movement has been related to the general circulation patterns of the effluent area.

Drifters released on the inner continental shelf at water depths less than 40 m moved dominantly towards the coast, apparently under the influence of waves and wind-induced upwellings associated with northerly winds. Typical speeds ranged from 0.7 to 2.5 km/day. From releases at depths from 40 to over 90 m, the predominant movement was northward at typical speeds of 1 to 2 km/day. Many entered the Strait of Juan de Fuca, some were recovered on

the west coast of Vancouver Island, one was recovered in Queen Charlotte Sound, and two were recovered in Southeast Alaska near Ketchikan. The longer distances and speeds were 710 km at 0.8 km/day and 1140 km/day. The Strait of Juan de Fuca apparently enhances northerly near-bottom flow south of its entrance and locally retards northerly near-bottom flow north of its entrance. The pattern of bottom flow near the entrance to the Strait of Juan de Fuca appears to be somewhat similar to that near the Columbia River mouth. The distributions of water properties and sediments, movement of seabed drifters, direct current measurements, and radionuclide-tracer studies provide a substantial body of information. This information establishes a consistant pattern of the seasonal trend and short-period variability of the distribution and dispersion of Columbia River water and its dissolved and suspended load. (Morse, Barnes)

D Direct current measurements. Movements, temperatures, and pressures of the shelf waters near the Columbia River mouth were measured during 1967-1969. Data analysis and interpretation have been completed, and results will be reported in a Ph.D. dissertation and two technical reports. The measurements were obtained from self-recording instruments placed on submerged taut-wire moors; the primary moorage site was located next to a Coast Guard buoy installed at 46°25'N, 124°20'W in 78 m of water. The observations indicate a highly varying velocity field, consisting of two main components corresponding to movements driven by the local wind stress and those driven by the tidal surface elevation. The wind-driven circulation is of major importance to the disposition of the waters in the surface and bottom layers. For example, at midshelf (3 m off the bottom) the water flowed north and slightly offshore over most of the year, attained speeds of up to 70 cm/sec during storms, and seldom remained below 5 cm/sec for more than a tidal cycle. The anticipated residence over the shelf bottom of a freely moving sedimentary particle introduced into the coastal system from the Columbia River could be only several major storms. An approximate solution to the analytic problem was found that incorporated a wind-driven surface layer, a surface slope current, and a bottom frictional layer. By comparing this solution with the observed velocities, useful generalizations on the circulation were made. The straight barotropic tidal velocities were about 10 cm/sec, although the energy at the tidal frequency varies considerably. Several methods of treating the tide on the shelf have been presented that assist in separating the tidal component from the total velocity field. (Hopkins)

Studies were carried out during summer 1970 to extend Hopkins' work. The direct current measurements were designed to investigate horizontal coherence of currents along and across the continental shelf during a period of few weeks. (Smith, Cannon, LeBlanc)

Model and local variability studies. A numerical model initially formulated by Prof. Leonid Zhukov is being refined and improved for application to the Washington-Oregon coastal region. The grid extends from 42° to 48°N and from shore seaward to about 390 km. The mathematics and physical reasoning behind the model have been changed so that a generalized set of model equations can be used. Simplification of the model is done at later stages of analyses, rather than in the primary equations, so that the effect of simplifying assumptions on the model can be evaluated. Viscous and mixing coefficients are retained as variables in x,y,z space and are not assumed to be constants.

A written description of the model mathematics and boundary conditions required for application of the model to the coastal region is now complete. Programming of the model is also finished and several runs have been made that predict the changes in the thermohaline field in 15-day time steps. The model results are available in numerical and contour plots of the salinity, temperature, horizontal velocity vectors, and vertical velocity fields for each time step. The results are now being verified by comparing model-predicted thermohaline distributions against monthly observed distributions from 1961. The task of tuning the model to make it yield changes commensurate with those observed is underway. The next task will be to investigate the relative importance of the model parameters and to simplify the model if possible.

Another study examined the local changes in salt content of a volume of water defined by a 10-station grid off the Washington coast. Salinity samples were taken in this area four times at 5-m depth increments from the surface to 40-m depth over a 12-day period. The salinity data was integrated over each 5-m layer to determine the total salt content for each layer and its changes between sampling periods. The local change of salt as integrated over each layer was judged to be related primarily to advective processes driven by the local wind stress. The local change in the salt content of the 0- to 5-m layer was found to reach 0.1% of its total content and occur within a 35-hr period. Changes over shorter time scales could not be evaluated due to the time required to sample the 10-station network by ship.

A study of the short-term local variation in salinity at a single station and its relationship to variability in nutrients in a region affected by the Columbia River has been completed. (Duxbury)

Hydrographic atlas of Columbia River effluent. Over 2000 preliminary contour drawings prepared for the hydrographic atlas of the Columbia River outflow area have been combined into approximately 200 final drawings of the horizontal seasonal distributions of temperature, salinity, density, and dissolved oxygen at 13 standard depths. Final drafting is in progress. Distribution patterns and their incremental values are indicated by a line pattern that produces a quasi-gray scale. The preliminary drawings for each cruise that were prepared in the compilation process provide a potential for useful atlas supplements for the individual cruises. (McGary)

North Pacific Transition Zone Studies

The transition zone between the subarctic and subtropical water masses is one of the major oceanographic features of the North Pacific. This zone extends from Japan to Mexico, a distance of over 10,000 km, and has an average width of 1000 km. During the past 2 years, significant progress has been made in understanding the transition zone characteristics in the central and eastern Pacific.

It is known, for example, that the width of the transition zone and the intensity of the temperature and salinity gradients at the boundary depend upon the wind stress field, the vertical stability, and upon the horizontal advection of density and salinity. The region of the northern boundary in

winter and spring represents a stability gap, where hydrostatic stabilities are lower by a factor of two than in the adjoining water masses to the north and south. The northern boundary is also marked by the appearance of large temperature inversions and the surfacing of the deep sound channel during the colder part of the year.

During March-May 1971, a field study of the thermohaline structure in the northwestern Pacific will be made. The R/V *Thomas G. Thompson* will make three crossings of the transition zone between Japan and the Date Line. The northwestern Pacific is characterized by the convergence of two large current systems—the warm and high salinity Kuroshio, and the cold and low salinity Oyashio. Where the two currents meet, sharp temperature and salinity gradients and numerous inversions are found. The observations will be used to test thermodynamic theory as well as turbulence theory. (Roden)

Physical Oceanography of the Arctic Ocean and Adjacent Seas

Central Arctic Ocean. This continuing program emphasizes direct current measurements, direct stress measurements in the ice-water boundary layer, and "geostrophic experiments" using three appropriately spaced stations. During March-April 1970 the Department collaborated with the Polar Continental Shelf Project, Department of Energy, Mines and Resources, in a pilot study for the Arctic Ice Dynamics Joint Experiment (AIDJEX) in order to explore techniques for measuring water stress on the ice and ice deformation. Measurements of time-dependent velocity and Reynolds stress fields at one location under the ice were made with the mechanical current meters developed by J. D. Smith. Fifteen meters in orthogonal triplets at five locations down to 18 m beneath the ice were used. Good records were obtained over a 4-day period during which a storm passed by with significant relative ice-water motion. Divers were used to deploy the meters and map the under-ice topography.

Mean flow within and beneath the boundary layer were recorded using three different models of Braincon current meters. Navigational control was by the Decca-Lambda system of PCSP. Concurrently, records of current at 40-m depth (bottom of the Ekman layer and above pycnocline) for longer than 1 week to examine coherence in the current field were obtained from pairs of meters with horizontal separation of 1.5 miles and 10 miles. A pair spaced at 20 nautical miles produced only 3 days of record because the 20-mile satellite station, threatened by ice breakup, had to be abandoned.

To measure the approach to geostrophy of the Arctic Ocean flow, synoptic hydrographic casts to 500 m were attempted at three stations spaced in a triangle with legs of approximately 10, 20, 30 nautical miles. Only one three-station cast was obtained (20-mile station abandoned). Ten paired synoptic stations spaced over 1 week, at 10-mile spacing, were obtained.

Gross deformation of the 10-20-30-mile triangle of stations was followed through position fixing of the stations with Decca-Lambda. The main camp was positioned on the average 15 times per day and the satellite stations twice per day.

A second study during spring 1971, again in collaboration with the Polar Continental Shelf Project, is in the final stages of preparation.

During the summers of 1967-69, about 620 days of current records were obtained between 150 and 1500 m from Fletcher's Ice Island (T-3). Measurements of the drift track were made with a satellite navigator. The voluminous data have been reduced, corrected, smoothed, and interpolated to produce records suitable for time series analysis. Such analysis, employing spectral techniques and digital filters, has been completed. Important characteristic periodicities in the motion are clearly identifiable, but as is usual with geophysical time series, it appears that an unambiguous deterministic interpretation of the measurements will be extremely difficult. (Coachman, Aagaard Tripp)

Bering Strait. Bering Strait is an extremely complex region in which the classical oceanographic techniques, e.g., water mass analysis, are of limited usefulness. The distributions of water properties are best described by appropriately chosen means and variances. Similarly, our current-measurement time series show an impressive amount of fine structure in the power and coherence spectra; the digitally filtered records exhibit complex modulation. The area appears to be one in which a number of tidal and second-class waves experience multiple partial reflections. An extensive paper in monograph form, presenting our view of the general physical oceanography of the region, is in preparation. (Coachman, Aagaard, Tripp, Rosenberg)

Bering Sea. A comprehensive study of the physical oceanography of the Bering Sea was initiated in 1969. Although the general pattern of circulatio in the Bering Sea seems established, there are many unresolved questions abou the circulation and water-mass distributions and their variations. Present laboratory work includes the re-evaluation and further analysis of the water masses, using all available data, and numerical calculation of the wind-drive transports from the atmospheric pressure distribution.

The first cruise (TT-41) during summer 1969 provided data for quantitative estimates of the circulation and for determining the appropriate reference level for dynamic computations. Information was obtained on the surface intermediate, and deep-water exchange with the North Pacific between Cape Africa, Siberia, and Attu Island, Alaska, during R/V *Thompson* cruise 50 in July-August 1970. Eight drogues were successfully tracked using radar transponders and the ship's satellite navigation system. While drogues were being followed, a grid of STD stations were taken encompassing the drogue tracks. Precision bathymetric records were collected over most of the cruise track.

Extensive drogue studies will be carried out in the western Bering Sea during a 1-month R/V *Thompson* cruise in summer 1971. (Coachman, Aagaard, Hughes, Barteau)

Baffin Bay - North Water. To understand and forecast the large semi-permanent polynya of northern Baffin Bay (the North Open Water), the Arctic Institute of North America is coordinating a study of many years standing, involving the Department of Oceanography and several other groups from the U and Canada. Quantitative estimates of Baffin Bay - Arctic Ocean exchange an Baffin Bay bottom-water formation are also being sought.

A 3-week summer cruise by the USCGC *Westwind* was made in 1970. The attempt to recover the current meters moored in Smith Sound in 1969 was unsuccessful; however, detailed sections of STD and hydrographic stations were accomplished over the entire North Water. Some current records were also obtained from eastern Lancaster Sound.

It is clear that winter observations are needed for a better understanding of the North Water. A comprehensive field experiment has been planned to obtain the pertinent oceanographic, meteorological, and climatological measurements necessary over an annual cycle. The experiment would utilize the USCGC *Eastwind* as a mobile meteorological and oceanographic platform in the North Water and three land-based stations around the perimeter. The situation seems favorable for beginning the experiment in summer 1971. (Coachman)

Greenland and Norwegian seas. The major circulation features of the Greenland and Norwegian seas are quantitatively explainable as wind-driven, due allowance being made for bathymetric flow modification. A very curious result is the apparent failure of the western boundary current to respond to reversals of the wind stress enduring for up to 5 months.

A modest extension of our studies of the connections between the Arctic Ocean and the surrounding seas was made summer 1970 in the form of much needed hydrographic and current measurements in the Barents Sea. This was done from the USCGC *Southwind* in cooperation with the University of Alaska. Two 24-hour current stations were obtained.

We expect to be anchoring current meters in the Greenland-Spitsbergen Passage during summer 1971 as the initial step in an extensive and intensive study of water exchange in the northern seas. Special emphasis will be placed on the Arctic Basin - Greenland Sea exchange. (Aagaard)

Investigations in the Northeastern Arabian Sea

The Arabian Sea shelf of Pakistan and India is covered by cool, poorly oxygenated subsurface water during the southwest monsoon; actual upwelling off southwest India starts at the time of onset of the monsoon and lasts for about 5 months. No observations were previously published that showed whether the onset of upsloping in the northern area is related to the arrival of the monsoon.

Bathythermograph sections were made by the *Oceanographer* in June 1967 on and near the continental shelf west of Goa, and west and northwest of Bombay, before and after the onset of the monsoonal rains. During the entire period a rise of isotherms below the mixed layer over the levels observed in May in other years was found. This was especially so in the southern and central part of the area; near Bombay, 35 km from shore, temperatures of 26 C were met at 40 m. However, the very shallow depth reached regularly by much cooler water from July through November had not nearly been attained. It is concluded that seasonal upsloping begins off Goa always before June. It is argued that it is likely to be the case off Bombay, too, but the few

available observations do not support this. Marked raise of isopycnals towards the coast before the arrival of the southwest monsoon can be expected in the north off Veraval.

A trough of the thermocline, approximately 20 m deep in 1967, is a regular feature during the pre-monsoonal months on the outer shelf west and northwest of Bombay. (Banse)

MARINE HYDRODYNAMICS

Wave Propagation

Continental shelf-generated internal tides. The basic model of internal tide generation (Rattray, Dworski, Kovala) is being extended on several fronts. Numerical techniques for handling more realistic density distributions are being developed (Dworski, Rattray) and numerical techniques for the summation of slowly convergent Fourier Series are being investigated (Larsen). The development of more realistic models will lead to additional insight into the complicated modal structure of internal tides over the continental slopes. A model with a sloping continental shelf is being studied (Prinsenberg, Rattray). Friction also plays an important role in modifying the internal-wave field because the high modes are rapidly damped. The role of friction in the basic internal-tide model is to broaden the structure of the internal-tide beam propagating seaward from the region of fluid above the continental shelf break (Wilmot, Rattray).

Experiments are being conducted off the west coast of Vancouver Island to observe the complex modal structure of the seaward propagating internal tides and to validate a theoretical description of the generation process. Deep-sea temperature-measuring systems have been designed and used to obtain long-term records from stations in and out of the internal tide beam. Data analysis has confirmed the existence of the internal tides, but the study of the cophase lines of the internal tide has not been completed due to somewhat noisy time-series records. We are carrying out laboratory experiments to gain a quantitative understanding of both internal wave instabilities and the role they play in oceanic mixing. Additional field work, again in cooperation with the Pacific Oceanographic Laboratories of NOAA, will be conducted in summer 1971. (Rattray, Barbee, Larsen, Martin, Dworski)

Internal waves. The role that internal waves play in increasing the vertical transfers across a shallow thermocline, particularly in upwelling regions, is being investigated. During R/V *Thompson* cruise 46, data were obtained from the Sea of Marmara, a shallow boundary between Mediterranean and Black sea waters and a region of strong vertical shear. Intense internal wave activity was found; during peak activity times the upward transfer of silicate was greatly enhanced. Although some questions exist because of the ship's drifting, we feel these data illustrate a situation in which the internal waves dominate the vertical transfer processes. Data are also available for the Costa Rica Dome upwelling region in the eastern tropical Pacific. We will use this information in planning experiments for investigating the problem of mixing and internal waves in areas of upwelling. (Larsen Carmack)

The breaking of internal waves on sloping beaches has been examined, and the Phillips criteria, based on the Kelvin-Helmholtz instability, as the mechanism causing breaking of the lowest-mode internal waves has been verified. Steepening is caused by a sloping bottom; however, before overturning can set in, the Kelvin-Helmholtz instability drains the energy from the wave. Some preliminary studies were made with miscible fluids where the limiting factor is a Richardson instability instead of the Kelvin-Helmholtz. (Larsen, Hall)

The stability of an internal wave of mode number 3 is being studied in the laboratory. We hope to discover the line in amplitude-frequency space above which the wave breaks down, and the waves to which the energy is transferred during breakdown. (Martin, Goodman)

Initial-value problems for the upper ocean. We are considering initial-value problems for the upper ocean under the combined effects of internal waves and shear-caused instabilities. The model is linear but general enough to allow any given pressure or velocity inputs at either the sea surface or within the thermocline. (Criminale, Bradt)

Ocean Circulation

The circulation is being investigated in a two-dimensional, zonally-uniform ocean approximating the conditions of the Antarctic Circumpolar Current. This model—which includes horizontal diffusion of heat, salt, and momentum—is composed of wind-driven and thermohaline-driven modes with Ekman boundary layers at the surface and bottom. An important result of this study is that the southern boundary has a passive role on the interior dynamics so that the large torque supplied by the surface wind stress must be balanced on the ocean bottom. This suggests that the three-dimensional effects due to the Drake Passage may play an important role in modifying the Antarctic circulation pattern. Mr. R. Overstreet at Dalhousie University is working on the final aspects of this problem.

Estuarine Circulation

A theoretical study giving the circulation and salt-wedge configuration in a salt-wedge estuary has been completed for a model estuary of rectangular cross section and constant depth. This study is being continued by extending the model to include an upstream slope of the bottom. (Rattray)

Another study on mixing-induced inlet circulations is nearing completion. A similarity solution has been obtained for the circulation and salinity distribution in a laterally homogeneous, tidally mixed inlet without fresh water inflow. (Hansen, Rattray)

Saline wedge stability. Numerical results for the linear problem of salt-wedge stability have been obtained; the criterion for maintenance of the wedge depends on the local Richardson number. We now are examining nonlinear effects. (Criminale, Lee)

Turbulence in stratified and rotating media. Experimental and theoretical research is being conducted on the problem of turbulence in a stratified or rotating fluid. Experimentally, we are studying the focusing of a beam of short internal waves generated by a circular wave generator. We hope to intensify the internal wave amplitudes in a systematic way, and thereby see at what point a transition to either turbulence or resonant breakdown occurs. (Martin, Greisman, Criminale)

Time-Dependent Motions of Large Scale

Research in this area has been concerned with the free oscillations in various oceans. The model of oceans having an equatorial boundary has been extended to a rectangular ocean in which the equator bisects the ocean into symmetric northern and southern halves. It has been possible to study free oscillations, not possible in the earlier model, whose velocities are meridional at the equator. Away from the equator both kinds of oscillations are governed by the same dynamics. (Mofjeld)

In studying long-period time-dependent motion in a polar ocean, the polar basin with a parabolic depth profile and vertical boundaries at a fixed latitude was considered. Both class 1 and class 2 waves were examined with respect to the influence of depth and friction on these waves (Farmer). This study is being extended in order to examine the effects of more general bathymetry on free oscillations in inland sea basins such as the Great Lakes (Hamlin).

The interaction of Rossby waves with a mean current such as the Gulf Stream is being investigated. A model has been developed in which the current flow is assumed parallel to a straight coast in an unstratified ocean of constant depth. With a rigid lid on the ocean the Rossby waves are plane waves which are assumed to be generated in the interior of the oceans and to propagate into the mean current. The interaction can be studied using a formulation adapted from the treatment by Longuet-Higgins and Stewart of the interaction between surface gravity waves and mean currents. Within the restrictions of a WKB approximation, the study indicates that Rossby waves whose wave numbers have a southward component are reflected by the stream and give up part of their energy to the current. Rossby waves whose wave numbers have a northward component penetrate the current until they are reflected and can in reflection reach a critical current velocity where the waves are totally absorbed. (Mofjeld)

Sea Surface Dynamics

Surface waves exhibit a weak nonlinear coupling that provides energy transfer between modes. The basic equations describing the coupling have been the subject of many papers; however, these equations also contain the information on the sideband instabilities of Stokes waves that were first noted by Benjamin and Fier. They considered the stability of a Stokes wave with respect to interactions with waves with wave numbers parallel to the fundamental. It appears that their study can be extended to incorporate stability with respect to nonparallel waves and to incorporate their analysi into the general interaction equations. (Larsen)

Sea Ice Physics

The way in which sea ice loses its salt is being investigated in the laboratory. In particular, we are studying the role of brine channels and ice stalactites, and are attempting to construct a mathematical model of the growth of both brine channels and stalactites. Theoretical studies complement the experimental work on desalination. (Martin, Criminale, Immerwahr, Cokelet)

We also are examining the role of ice-water-air interaction. Stress-strain modeling is under consideration in order to develop the dynamics for active ice flow. (Criminale, Josbeyer)

SAMPLING PROBLEMS AND SIMULATION TECHNIQUES IN OCEANOGRAPHIC RESEARCH

Development of interactive computer systems and simulation models for oceanographic research and education is under the direction of J. C. Kelley and L. H. Larsen.

Sampling Optimization Studies

In modern oceanographic research, the tendency is to measure an increasing number of variables. This requirement alone has stimulated the development of increasingly complex hardware systems for data acquisition and storage. The volume of data acquired and the demands for rapid analysis and presentation have been met by developing a number of large software systems for shipboard computers.

Hardware and software facilities have been developed for the Department; attention is now focused on the oceanographic sampling problem. We have developed the optimal solutions for sampling a single or several variables in the on-station mode. Both of these solutions ignore time-dependent effects. The "travelling-salesman" problem has a special solution to optimize the order in which stations are occupied. Basically this problem optimizes a path among a set of sites (stations). Given the locations of the sites, the time required at each one, and other information, we can determine how the travelling salesman—the ship in this case—can occupy those sites in the most efficient order by solving the "travelling-salesman" problem.

A method for monitoring high-order multivariate statistics in real time has been developed. The method involves tracing the path of principal components (eigenvectors) in the variable space. Special attention has been focused on developing significance tests and ways of displaying the loci of the real time eigenvector solutions in the hyperspace. (Kelley, Smyth)

Shipboard Computer System

The shipboard data acquisition and processing system is built around an IBM 1130 computer. Data acquisition is accomplished offline with a Hewlitt-Packard system with records on paper tape. The total system has been used in a wide variety of applications. Physical oceanographic applications include recording, analyzing, and presenting STD data in graphical and digital form as well as the routine presentation of hydrographic data. A facility is available for contouring surface data and for fitting regression surfaces to this data. New methods of graphical surface representation are being developed. For chemical work, a large-scale system for the analysis of data continuously recorded from Auto Analyzer outputs has been developed; the facility for contouring surface data can be directly used to present the output from this system. Programs for the analysis of data from a number of chemical experiments have been written for the system, and an extensive modeling system will be developed during the coming year for the simulation of upwelling and associated nutrient supply and productivity. In biological studies, programs for the analysis of data from oxygen-uptake experiments are available. For geological and geophysical work, we have developed systems

that will merge computed cruise tracks and time-series acoustic reflection data and present surface representations of the bottom and of sub bottom reflectors as well as isopach maps. (Kelley)

Computer Simulation Models

A project is underway to investigate some of the applications of simulation techniques for developing computer models of oceanographic phenomena. These models can provide insight into the phenomenon itself and be used in the educational process. Sampling a simulation model can be carried out under ideal environmental conditions, and full concentration can be focused on the scientific aspects of the sampling procedure. At sea the technological aspects often assume exaggerated significance, especially in the student's initial experience. The "true" answer is always known in the model and the student can compare his reproduction of the phenomenon based on data in his sample with the actual situation. In a relatively short time many students may interact with the computer effectively. (Kelley, Larsen)

Computer-Display Facility

An analogue computer and display system has been set up as a visual teaching aid for the undergraduate oceanography program. In lower-division courses it is being used to simulate and illustrate the dynamic behavior of natural processes in the marine environment. Projects include studies of chemical kinetics, biological systems, and nonlinear systems. The facility may be taken into the classroom and coupled to television monitors. (Larsen)

1971 OPERATING SCHEDULE FOR R/V *THOMAS G. THOMPSON*

After regular drydocking and overhaul, the R/V *Thomas G. Thompson* will make a cruise in February 1971 to Saanich Inlet, B. C. for chemical observations and current measurements. Studies to be carried out during a North Pacific expedition from March to mid-June are measurements of oxygen consumption in the seabed; observations of the thermohaline structure in the northwestern Pacific; and the collection of physical, chemical, and biological data for predicting the spring phytoplankton bloom in the subarctic North Pacific. The *Thompson's* summer schedule (July-October) includes a cruise for Columbia River effluent studies, a Bering Sea cruise for current and drogue studies, and one for geological and geophysical investigations off the Washington coast. Joint UW-OSU cruises on the R/V *Thompson* have been proposed for geological-geophysical and radiochemistry studies off the Washington-Oregon coast during October and December. During fall 1971, members of our Department also will be participating in the R/V *Yaquina* (OSU) cruise to the eastern tropical Pacific. The 1971 Operating Schedule for the R/V *Thompson* follows.

OPERATING SCHEDULE
R/V *THOMAS G. THOMPSON*
1 Nov 1970 - 31 Dec 1971

Dates	*Operating Days* *Sea*	*Outport*	*Support*	*Area*	*Senior Scientists*	*No. Sc. Party*	*Scientific Program*
1 Nov-31 Dec 70				Seattle	Bean		Overhaul
1 Jan-15 Feb 71				Seattle	Bean		Overhaul
16-22 Feb	7	0	NSF	Saanich Inlet	Healy	18	Chem Observations in Sulfide Environments
23-28 Feb				Seattle	Bean		Fit-Out
1-15 March	15	0	ONR NSF	Wash-Ore Coast Seattle-Hawaii	Pamatmat	8	O_2 Consumption Seabed Transit to Nawiliwili
16-18 March		3		Nawiliwili			
19 Mar-3 May	46		ONR	20°-45° N; 150°-180° E	Roden	14	Thermohaline Fine Structure
4-6 May		3		Hakodate			
7 May-15 June	40		ONR NSF	Modified GC Hakodate-Seattle	Anderson	20	Spring Phytoplankton Bloom; Zooplankton Studies; O_2 Consumption by Seabed; Trace-Metal Studies
16 June-5 July				Seattle	Bean		Turn-around
6-16 July	11	0	AEC NSF ONR	Off Columbia River	Anderson	15	Columbia River Studies; Seabed O_2 Consumption; Tide Prediction

16 July				Grays Harbor or Astoria			Offload
16-26 July	11	0	NSF	Transit to Dutch Harbor	Lewis	7	Seismic Refraction
26 July			NSF	Dutch Harbor			
26 Jul-22 Aug	27		NSF	Bering Sea	Coachman	12	STD & Drogue
23-24 Aug		2	NSF	Alaska Port (Kodiak)			
25 Aug-1 Oct	38		NSF	Nitinat Fan	McManus	18	Piston Coring, Subbottom Profiling, Plankton
2-17 Oct				Seattle			Turn-around
18-26 Oct	9		NSF	Wash-Ore Coast	Bennett (Joint Cruise OSU) - Cutshall	18	Seismic Reflection & Bottom Profiling; Magnetic Profiling; Radio-chemistry
26 Oct				Astoria			Turn-around
26 Oct-24 Nov	29		NSF	Blanco Fracture Zone	Lister	8	Heat-Flow Studies, Seismic Refraction
25 Nov-5 Dec				Seattle	Bean		Turn-around
6 Dec-18 Dec	13		NSF	Wash-Ore Coast	Bennett (Joint Cruise OSU) - Neshyba	18	Seismic Reflection & Bottom Profiling; Magnetic Profiling; Buoy Studies
19-31 Dec				Seattle	Bean		Turn-around