2 June 1972, Volume 176, Number 4038 SCIENCE

Implications of a Systems Approach to Oceanography

Studies of marine biomes involve both rapid data analysis and group cooperation at sea.

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Contemporary data acquisition and computer systems on board ships enable oceanographers to examine data on a large number of variables while at sea. This ability to rapidly examine the changing parameters of a marine ecosystem, through either continuous monitoring or cooperative experiments aboard ship, has led groups of oceanographers to consider undertaking holistic studies of marine ecosystems. Sufficient data on the distribution of system variables can be processed fast enough for individual oceanographers to interact at sea rather than 2 years later, to plan group experiments while in the study area, and to begin to use simulation models as tools for the synthesis of incoming data.

Approximately every 10 years, mathematical models have been used to study marine ecosystems; this phenomenon may reflect an increase in the ability to gather data as well as a periodic need for synthesis. Until recently, however, models have stressed either individual populations or individual processes. The early models, based on individual laboratory populations, were developed in the 1920's (*1*) and 1930's (*2*) and were transferred to the preliminary oceanographic studies of the 1940's (*3*) as data on marine ecosystems became available. In the 1950's, an interim period of slide rules and hand calculators, more detailed models (*4*) were constructed as more data were generated on the metabolic rates of marine organisms.

Although field studies of ecosystems were carried out in the 1950's (*5*), the lack of generally accessible high-speed computers restricted modeling efforts to population studies. The population models of the 1950's were transferred for the first time in the 1960's (*6*) to analog computers capable of running small-scale simulation models. As the scope and requirements of systems ecology, or studies of total ecosystems, became apparent (*7*), a shift was made to the digital computers of the 1970's. These computers made possible complex models of multiple population interaction (*8*), fishery management (*9*), and nutrient flow within several trophic levels (*10*). The ability to simulate has perhaps now caught up with the ability to measure total ecosystems.

Studies of total marine ecosystems were advocated as many as 40 years ago by the late W. C. Allee (*11*).

> One of the more intelligent of our university presidents once said that Ecology seemed to be the study of the sty with the pig left out. Modern studies of oceanography have seemed to me to deserve, at times, the same definition. The ocean's sty is so complicated and vast and beautiful that it is not to be wondered that it attracts attention as compared with the less obvious oceanic pig. Fortunately, the emphasis given in the present symposium [1933] shows that the latter is not being entirely neglected even though as yet, no one seems able to see the whole pig. If as a result of my remarks you are tempted to think that I have my attention fixed so low as to be able to see the pig's feet only, I assure you that the defect is more apparent than real, and is caused by the great ease of focusing on the littoral animal communities of the bottom, than upon those of the entire waters. . . . The subdivision of littoral regions into faunal provinces . . . suggest[s] the biomes of modern workers. . . . Analysis of this complex challenges our best individual and cooperative power. Failure to recognize the essential unity of this animal-plant-environment relationship retards progress in oceanic studies . . . and consideration of their properties will help us to . . . perhaps throw some light upon the problems now awaiting solution in marine ecology.

Our environmental problems are even greater now (*12*) than they were in 1933, but the implementation of systems studies has had to await the development of an adequate technology and sufficient interest in a systems approach to oceanography.

Marine Biomes

The easily accessible intertidal regions have been well described (*13*), and energy budgets of both organisms and communities have been prepared for areas such as mangrove forests (*14*), salt marshes (*15*), and rocky coasts (*16*). The distribution of marine benthic communities has also been extensively studied (*17*), and some marine ecologists have concentrated on individual pelagic communities (*18*). Few oceanographers, however, have addressed themselves to studies of total marine ecosystems on a scale comparable to studies of the terrestrial biomes of grassland, tundra, desert, deciduous forest, coniferous forest, and tropical forest (*19*). Efforts to build simulation models as part of a systems approach to upwelling ecosystems (*20*) have led to questions about total marine ecosystems and whether or not the ecosystems of these coastal upwell-

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Table 1. Estimated potential yield of fish per year in upwelling ecosystems (*78*).

Area	Effective period of upwelling over the whole ecosystem (months)	Pelagic fish (10^6 tons)	Demersal fish (10^6 tons)	Whales (10^6 tons)
Peru-Chile	12	11.5	0.6	
Angola–South Africa	9	3.9	1.1	
Dakar-Casablanca	8–9	3.0	0.7	
Baja California–Cape Mendocino	7–8	3.5	0.4	
Arabian Sea	6	3.5	0.7	
Oregon-Washington	3–4	0.8	0.6	
Gulf of Panama	3–4	0.2	0.1	
Antarctica	3–4			1.6

ing areas constitute collectively a marine biome. Are there food chains of persistent communities in these areas that can be recognized as a separate entity over sufficient geographic (climatic) and temporal (geological) scales to have evolutionary implications as to its structure, function, and maintenance?

The upwelling ecosystems are easily recognized, for the effects of coastal upwelling appear not only in the biota of the immediate marine environment, but in the geology of the sea floor and in the climate, geology, and communities of ecosystems in adjacent land areas as well. A number of features (*21, 22*) characterize the upwelling biome: (i) an almost complete lack of rain in the adjacent terrestrial ecosystems, resulting in a coastal desert community; (ii) moderate humidity with frequent fog; (iii) high concentrations of nutrients and organisms, with typical pelagic, intertidal, and benthic communities, as well as an emphasis on pelagic rather than demersal fisheries; (iv) a large bird population and, consequently, an accumulation of guano deposits on the islands they inhabit; (v) a periodic mass mortality of marine organisms caused either by dinoflagellate blooms or anoxic conditions; (vi) deposits on the sea floor of sediments of high organic content and characteristic accretions of phosphate; and (vii) deposits on the land of sediments characteristic of a very dry climate (for example, sand and salt).

With respect to the pelagic component of an upwelling biome, the same kinds of diatomaceous phytoplankton and clupeid fishes are found in the major upwelling areas along the coasts of Peru, California, Arabia, and northwest and southwest Africa. That immense fisheries are supported by these ecosystems has been attributed to the fact that energy transfer is more efficient in short food chains such as these than in long food chains (*23*). Some organisms, such as *Euphausia pacifica*, are carnivores in the longer food chain of an oceanic ecosystem (*24*) and herbivores in the shorter food chain of a coastal ecosystem (*25*). A number of people have noted that clupeid fishes are found only near coasts (*26*), but none of them has been able to provide a hypothesis as to why these fishes are there or why some are herbivores in the short food chains of upwelling ecosystems.

Plumes, or eddies of cold water drifting offshore, are characteristic of upwelling areas (*27, 28*). Two of these ecosystems, off Peru and northwest Africa, have been studied thus far in the International Biological Program, "Dynamics of biological production in upwelling ecosystems," and it has been found that nutrients and chlorophyll are distributed in the same pattern as the temperature plumes in these areas. Early studies of the California ecosystem (*29*) indicate that the same relation exists there between phytoplankton and upwelled eddies of water. This variation in water temperature in upwelling areas may be a key to the evolution of the short, productive food chains.

Distributions of pilchard (*30*), herring (*31*), sardines (*32*), and anchoveta (*33*) appear to be associated with temperature gradients. This parameter may be important in maintaining dynamic speciation in the oceans (*34*). It is possible that these relatively primitive, very distinct teleost fish (*35*) have developed the ability to use the cold-water plumes characteristic of upwelling areas to locate, feed, and stay with the phytoplankton blooms in the upwelled water. Echograms have indicated dense schools of anchoveta in plumes off the coasts of Peru and Chile during weak periods of upwelling (*33, 36*). As the upwelling season intensifies (*37*), the plumes become more diffuse and the fish populations disperse along the entire coast (*38*). Similarly, schools of sardines and anchovies have been observed to migrate north (*39*) along the coasts of California and northwest Africa, following the seasonal movements of the cold isotherms of the upwelling centers (*40*).

On the basis of low diversity–high instability hypotheses (*41*), the low diversity of these pelagic components (*42*) would argue against the development of a persistent community in the upwelling areas. Low diversity–high instability theories purport that such communities, involving reputedly simple trophic relations, undergo time lag–induced oscillations in population density of sufficient magnitude to generate unstable behavior and possible extinction of individual species or communities. However, the low diversity upwelling ecosystems may contain control mechanisms other than the inherent food web complexity, which is presumed to be a buffer to perturbations of high diversity ecosystems. If these upwelling ecosystems contain sufficient feedback links or interactions to reduce population oscillations (such as grazing stress dependent on food density, or temporal isolation of trophic levels through spatial heterogeneity of the upwelling area), then they may still constitute a marine biome.

The food chains of upwelling ecosystems do not appear to be controlled by predators, as are some terrestrial food chains (*43*); periods of low or high predator stress apparently do not change the structure of these food chains. When periods of El Niño, or incursions of warm water occur along the coast of Peru, the anchoveta move offshore or remain in the deeper, cold water; thus birds, their natural, major predators, are no longer able to feed on them (*38, 44*). However, there does not seem to be too much change in the anchoveta populations during these periods of low predator stress (*45*); the factor limiting the population of the avian predators may be nesting space (*46*) rather than the availability of food. In contrast, man has apparently preyed so intensively on sardines off the California coast that they may be replaced in their niche by anchovies

(*47*). Even so, there has been little apparent change in the clupeid component of the food chain of this ecosystem during at least the last 1000 years (*48*).

There are other feedback mechanisms, however, which may be responsible for maintaining the phytoplankton-clupeid communities. In the Peruvian ecosystem, nutrients are recycled directly in the form of anchoveta excretions (*49*). The value of a simulation model is quite clear in this case. An attempt to obtain a mass balance of nitrogen to account for the observed phytoplankton biomass (*50*) reinforced the idea that ammonium is an important source of nitrogen for phytoplankton (*51*). The measured uptake of ^{15}N-labeled nitrate did not account for all of the phytoplankton growth in the model; when the measured input of ammonium from fish gill excretions (*52*) was added to the nutrient uptake expression of the model, a mass balance was obtained.

Because of their large biomass, anchoveta are more important than zooplankton in regenerating nutrients off the coast of Peru (*50*). In addition, the anchoveta apparently experience a vertical, diel migration in the plume areas (*33*), and may follow a pattern of feeding in surface water at night and resting in the subsurface sources of upwelled water during the day. The possible nutrient "short circuit" and the diel alternation of grazing stress in the surface layer of a structured environment could be factors contributing to the stability and high productivity of these short food chains, at least in the Peruvian ecosystem. During periods of intense upwelling, when plumes are no longer distinct centers of herbivore populations and nutrient recycling, the phytoplankton biomass off Peru is approximately half as large as it is during the periods of weak upwelling (*53*).

The water circulation patterns of upwelling areas may provide indirect feedback loops. Subsurface countercurrents have been observed in the major upwelling areas (*54*), and a shallow, 25-meter current flowing south was found under the northward Ekman drift, off the coast of Peru (*55*). Experiments in which trace metals and chelators were added to this water (*56*) suggest that, if the source of upwelled water is the northern, "self-fertilized" section of the ecosystem, enrichment will not increase the growth of phytoplankton. However, if the source of upwelled water is offshore and to the south, where the productive Ekman layer no longer overlies it, then enrichment will enhance phytoplankton growth. The surface circulation may serve as an additional means of reseeding phytoplankton populations in the upwelling plumes. A warm eddy with a high concentration of chlorophyll appeared to be returning shoreward off Point San Juan, Peru (*20*). This flow may be a secondary source of phytoplankton; mixing occurs across the interface between the offshore and onshore plumes. These possible feedback loops suggest that phytoplankton production, at least off Peru, may be directly related to both the circulation and the herbivores of the upwelling ecosystem.

Peru's upwelling ecosystem is the richest in the world (Table 1). It is the only ecosystem in which the centers of upwelling do not appear to migrate up the coast and in which fish may be the dominant herbivore. As mentioned previously, the clupeids apparently follow the isotherms in at least two of the other major ecosystems, in which the pulse of energy migrates from the equator toward the poles. Fish are rheotactic (*57*), and it is possible that they swim against opposing currents in such upwelling ecosystems, not only as a response to temperature, but also in order to follow the centers of high productivity. If so, this behavior could be, in terms of evolution, a somewhat primitive feedback loop. Not all subpopulations of these clupeids migrate from one end of the ecosystem to the other (*58*), but there appears to be a minimum amount of total energy input distributed over the entire upwelling system, and perhaps a minimum num-

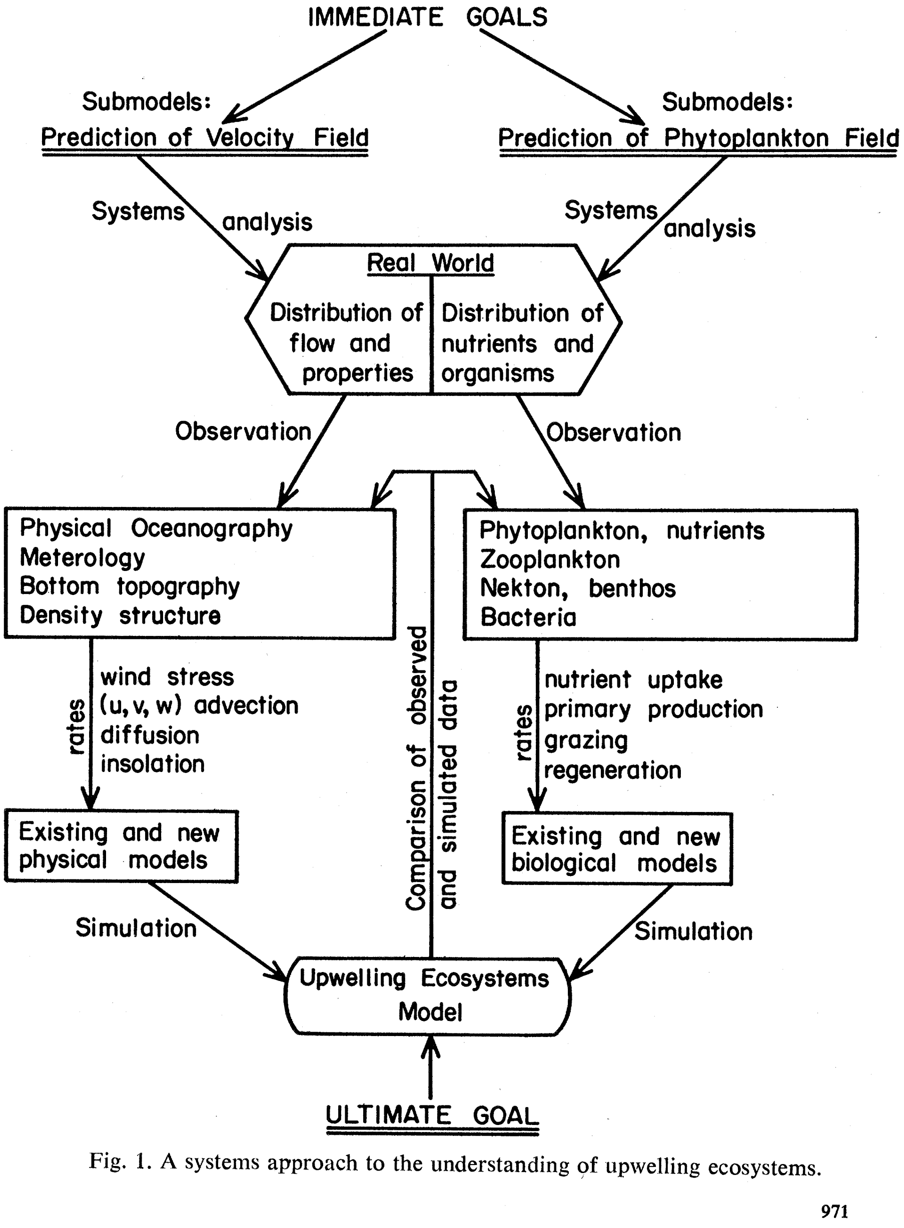

Fig. 1. A systems approach to the understanding of upwelling ecosystems.

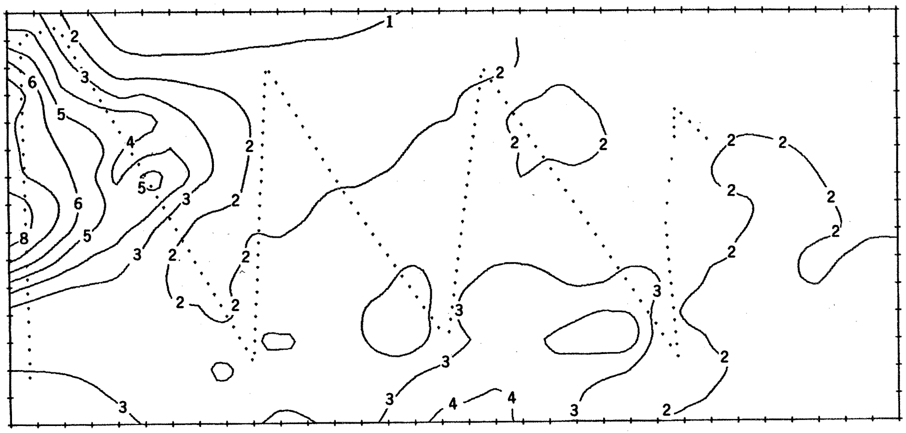

Fig. 2. A map produced by a seagoing computer of the surface chlorophyll distribution (measured in micrograms per liter) off Point San Juan, Peru.

ber of feedback loops, required to maintain the phytoplankton-clupeid communities. The 6-month period of monsoon-induced upwelling along the African and Indian coasts of the Arabian Sea (*59*) may be the minimum amount of energy required to maintain a large clupeid fishery. The Washington-Oregon extension of the California ecosystem is relatively poor, perhaps because of either the short upwelling season or heavy inputs of fresh water from rivers, and supports salmon, a small herring fishery, and an equally important demersal fishery (*60*), in contrast to other upwelling ecosystems. The Gulf of Panama's clupeid stocks are even smaller and are not supported solely by upwelling, for during some periods of the year the anchoveta are iliophagous, feeding on the benthic algae of the mud flats (*61*). The phytoplankton of the Antarctic upwelling ecosystem is even less diverse than that of subtropical upwelling systems (*28*). Although upwelling provides adequate nutrients, this ecosystem receives only 3 to 4 months of radiant energy (*62*), which is evidently an insufficient input to allow for a food chain involving clupeid fish.

The above material is admittedly speculative and is intended to be a general holistic consideration of what might be some of the functions of both spatial heterogeneity and the role of low diversity elements of a pelagic food chain in maintaining a persistent community. Certain intertidal animals (*63*) and plants (*21*) are characteristic of the upwelling ecosystems, and the benthic communities are typically a low diversity (*64*) and high productivity (*65*) component as well. Not all ecosystems may need high diversity in order to be stable and persistent, and not all precepts of terrestrial ecology may be valid in marine ecosystems. The upwelling ecosystems, because of their similar climatological and geological features and their similar biological and physical structure, may tentatively be considered to constitute a marine biome analogous to a terrestrial biome.

The complexity and length of the food chain determines the appearance and behavior of an ecosystem (*66*). If the short food chains of upwelling ecosystems *do* constitute a marine biome, then one might expect to recognize biomes in the longer, more complex food chains of other marine ecosystems. An upwelling biome would be relatively easier to study, but perhaps outwelling (*67*) ecosystems [that is, those non-upwelling coastal ecosystems, coral reef ecosystems (*68*), polar ecosystems (*69*), and oceanic ecosystems (*70*)] might be considered marine biomes to be studied in the future as well.

Implementation and Implications of a Systems Approach

If there is an upwelling biome, what would the study of these ecosystems involve? The systems approach used in the International Biological Program studies of upwelling ecosystems is illustrated in Fig. 1. Interaction of environmental data, experimental work, data analysis, and simulation models is essential for investigation of total ecosystems. The flow of information is cyclic where a simulation model's initial inability to adequately describe experimental and field results is necessary feedback for ongoing work. Constructing a model of an upwelling ecosystem is the best method of channeling information within subprograms and of maintaining the continuity of data required for the various process submodels (*71*) that make up the ecosystem model. The interactions among the physical, chemical, and biological components of the program are shown in Fig. 1. Existing submodels are compared with the real world, and the discrepancies that occur with each pass through the cycle are used in designing the next set of field and laboratory efforts, in improving the next set of process submodels, and in updating the system model.

The adoption of this approach implies a new way to view oceanography and a new way to do oceanography. The field and theoretical results of studies on upwelling ecosystems over the last 3 years have demonstrated the necessity for experimental oceanography based on computers capable of rapid data analysis and on simulation modeling both aboard ship and ashore. Requirements for a computing facility aboard ship are particularly stringent, for the system must be capable of acquiring data in real time, of data editing of both underway and batch input, of graphic display of historical data, of presentation of ongoing laboratory experiments aboard ship, and of running simulation models.

A real-time awareness of the ecosystem allows the systems oceanographer, while in the field, to plan tactical responses to temporal and spatial variations of upwelling ecosystems. The ability to view the ocean while one is there, rather than a year later, is essential to a systems approach. Figure 2, which shows the distribution of chlorophyll off Point San Juan, Peru, is an example of the maps of biological, chemical, and physical features that can be made while at sea. As the research vessel moves over the study area, seawater is pumped continously from a 3-meter depth through a series of temperature and salinity sensors, a fluorometer for determining the concentration of chlorophyll, and an Autoanalyzer array for analyzing nutrients. The data are reduced, interpolated, and contoured on a CalComp plotter—the ship's track is indicated by the crosses in Fig. 2 (*20*). These maps can then be used by oceanographers in the field for planning the next set of stations and experiments aboard ship and for comparison with the output of ongoing simulation models.

In addition to viewing what appears to be the real world, one must be able to view what is hypothesized to be the real world. Synthesis of data at sea is essential. Interpretations of simulation results cannot easily be based on reams of paper from a slow line printer or plotter, however, and the use of computer graphics terminals has been explored for fast presentations of both model output and different combinations of underway environmental data.

Figure 3 is a series of time-frame photographs taken of the output of a sewage outfall simulation model (*72*) that is displayed on a cathode ray graphics terminal interfaced to a laboratory computer. The vertical isopleths represent decreasing concentrations of ammonia downstream from a diffuser at the lower left-hand corner of each frame; the horizontal isopleths represent increasing concentrations of phytoplankton after 12, 24, 36, and 48 hours of simulated time. The vertical lines at the right of each frame are the boundary conditions for the ammonia and phytoplankton. The predicted growth of phytoplankton downstream from the sewage diffuser after 48 hours can be seen from one frame to the next in the growth of phytoplankton at right angles to the nutrient. As yet, this model is unvalidated, and field studies will be carried out in the near future. This simple model, however, serves as an example of the utility of fast graphic display.

Computer-animated movies (*73*) are another valuable means of condensing data, and a preliminary movie has been made by filming the output from the above sewage model. Visualizing the time-dependent behavior of system variables as abstracted by a simulation movie appears to be a powerful tool for studying the transient behavior of marine ecosystems. Computer graphics, whether in the form of plots, cathode ray tube display, animated movies, or a combination of the three, are essential at sea in an attempt to unravel the complexities of upwelling ecosystems.

As the ocean's processes become more visible, the capacity for scientists to interact at sea becomes much greater. More time is available for analyzing incoming data and one can begin to relate individual expertise to other activities aboard ship. The emphasis is then shifted away from going to sea to collect samples; instead, one can go to sea to perform environmental experiments. Such a changing emphasis implies increased group cooperation and the eventual redesigning of research vessels to house larger scientific groups.

Once true group cooperation is achieved, research vessels equipped for sophisticated experiments will probably follow. The concept of group cooperation is of more immediate importance, for it implies a subtle refocusing of individual scientific activities. No one person can study a total marine ecosystem, nor can the dynamics of the ecosystem be understood by each investigator doing his "own thing" independent of others. Group cooperation, however, cannot be achieved by listing a group of people on paper or by agreeing to agree on a multidisciplinary study in the same area (*74*). Joint goals must be defined—they must be truly interdisciplinary, lead to a solution to the questions posed, and, perhaps most important, reconcile the individual scientist's interests within the framework of the group effort. All disciplines must be equally important in the study or it must be clearly stated in the beginning which group is supposed to be performing the service function.

Further, group studies require more funding, and it must be remembered that these large sums of money carry

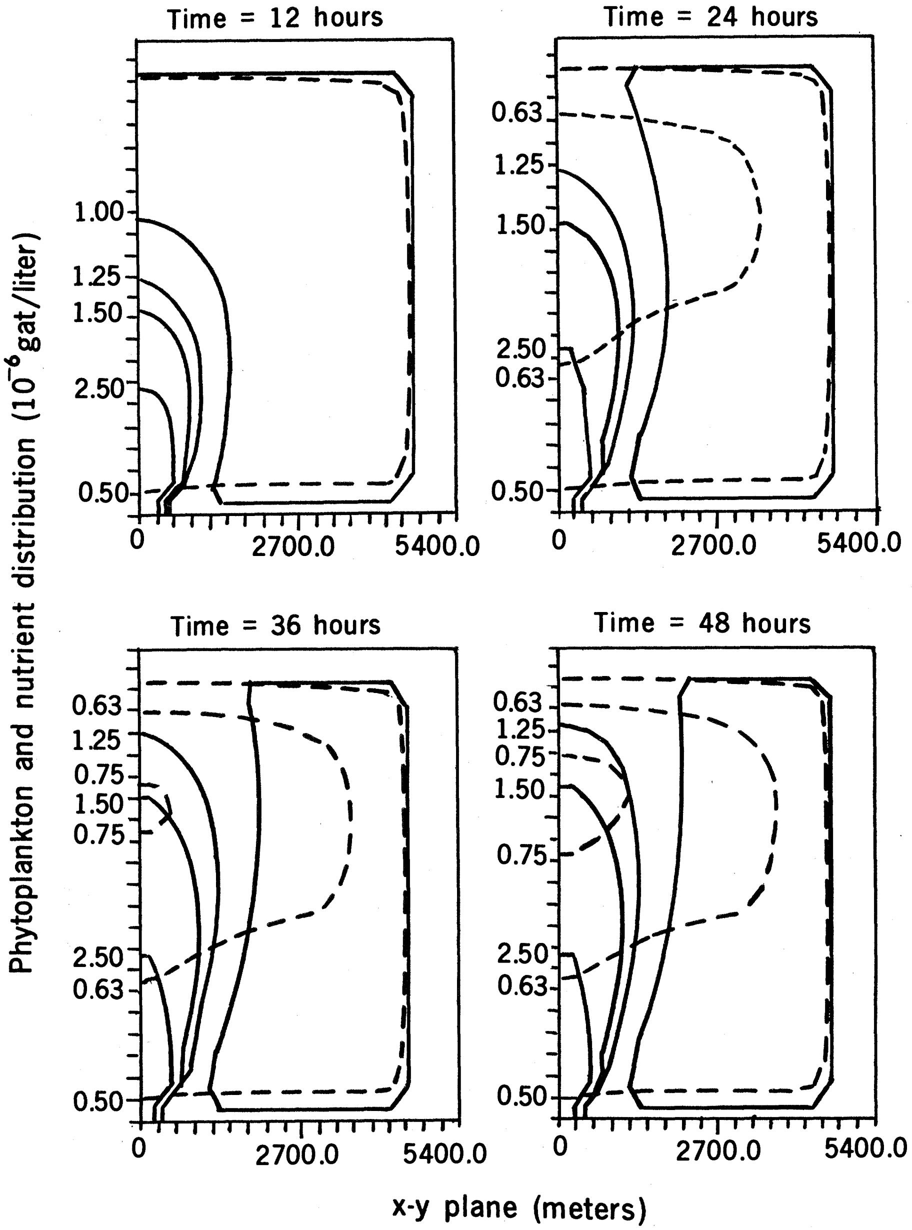

Fig. 3. A time sequence of the output of a simulation model of the phytoplankton (dashed line) and nutrient (solid line) concentrations (measured in 10^{-6} gram atomic weight per liter) in an *x-y* plane downstream from a hypothetical sewage diffuser, as displayed on a cathode ray graphics terminal.

with them the specter of agency-directed research, which is not necessarily the case in projects carried out by individual investigators. Indeed, most if not all practicing scientists have been trained in the prima donna school of individual competence, research, and recognition. Participation in large group exercises implies some loss of independence and increased bureaucracy. In the long run, the success of and the predictive payoff from true multidisciplinary research will depend to a large extent on the willingness of individual scientists to try to communicate and cooperate in this kind of research. As more funds for these multidisciplinary studies become available, the opportunities for group research will increase, and presumably society's reward structure for scientific activities will be stretched to include group as well as individual activities.

Prospectus

If there are marine biomes, if one adopts a systems approach, and if this is a manageable and personally rewarding activity, what kind of success can be expected from this approach to oceanography? There are those, of course, who feel that this is not a very fruitful approach: "One can play God, by calling forth a theoretical sea where specific species of phytoplankton grow and are fed upon by specified species of prey. One turns loose the computer and makes it predict the state of the universe in a given number of weeks" (*75*). Such skepticism is perhaps justified in the light of the panacea promised by some modelers (*76*) who have little data to test their prognostications.

Unfortunately, most of our environmental problems occur at the systems level of complexity (*77*) and these problems cannot be solved either by ignoring parts of the system, in a piecemeal approach, or by ignoring the entire system, in castigation of modelers. If mercury is being discharged into an estuary, one cannot necessarily determine the amount of it in benthos tissue by studying only phytoplankton, and a prediction of the distribution of mercury cannot be made without a working hypothesis or model. If models are put in their proper perspective as one of the necessary tools of studies of marine ecosystems, and if these models and their individual components are tested in the field, it should eventually be possible to use a family of systems models as a guide both to an understanding of the dynamics, and to the prediction and management of perturbations of marine coastal areas. Without a systems approach, it is not immediately clear that systems problems can be solved.

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79. I am deeply indebted to Richard Dugdale and James Kelley, who have contributed a great deal to this article. In a gestalt approach to oceanography it is hard sometimes to sort out individual ideas, but I will claim responsibility for the bad ones. This research was supported by NSF grants GB-8648 and GB-18568 and is Contribution No. 633, Department of Oceanography, University of Washington, Seattle 98105.

Third Lunar Science Conference

Primal igneous activity in the outer layers of the moon generated a feldspathic crust 40 kilometers thick.

Lunar Sample Analysis Planning Team

Two years ago the first scientific investigations of returned lunar samples were reported at the Apollo 11 Lunar Science Conference (*1*). Samples from the first mission to the moon had been in the hands of investigators for 3 months or less, and the picture of the moon that emerged at that time was necessarily restricted in scope. We learned that Tranquillity Base is underlain by basaltic rock that erupted onto the mare surface 3.7×10^9 years ago, rock that is generally similar to terrestrial basalts but with important differences: titanium and other refractory elements are enhanced in abundance, sodium and other volatile elements are depleted, and the water content and oxidation potential of the lunar basalt lava are orders of magnitude lower than those of analogous terrestrial lavas. The existence of other types of rock on the moon was only glimpsed, and the structure and evolution of the moon remained a mystery.

By now five round-trip missions to the moon (including the Soviet Luna 16) have returned some 176 kilograms of samples. Hundreds of man-years of scientific effort and thousands of pages of journal space have been devoted to investigation of the samples and to other aspects of the lunar problem. Our understanding of the moon has increased proportionately. The Third Lunar Science Conference, held at the National Aeronautics and Space Administration Manned Spacecraft Center in Houston from 10 to 13 January 1972, provided an opportunity to take stock of the advances made and problems outstanding (*2*).

Crust of the Moon

Unquestionably the most important gain made is that we now know there is a lunar crust: We know the principal types of rock that comprise it and, broadly speaking, their distribution over the surface of the moon. We know the thickness of the crust in one region.

There are three principal classes of crustal rock. One is mare basalt, rich in iron and sometimes titanium; the Tranquillity Base rocks are examples. Another is noritic rock (KREEP), rich in radioactive elements and refractory trace elements. The third is aluminum-rich anorthositic rocks (*3*). The most abundant lunar material of this class appears to be anorthositic gabbro, containing 70 percent plagioclase, although rocks with greater plagioclase content are also present.

All three rock types are represented among the large rock specimens collected by Apollo astronauts, but our confidence that these are the principal crustal rock types is based on the analysis and classification of thousands of glass and rock fragments in soil samples from the various landing sites. The soils, being mixtures of particles excavated, pulverized, and dispersed over the lunar surface by meteoroid impacts, are the best random samples of crustal material available. Minor numbers of particles having other compositions are also present in the soils: granitic and ultrabasic rock fragments, and glasses compositionally similar to howarditic meteorites.

We are informed of the surface distribution of basalt, norite, and anorthositic rock by two remote sensing instruments that the orbiting Apollo 15 Command and Service Module (CSM) trained on the moon. An x-ray spectrometer detected fluorescent magnesium, aluminum, and silicon x-rays generated on the lunar surface by impinging shortwave solar radiation, and reported variations in the x-ray intensity ratios Al/Si and Mg/Si along the ground track of the CSM. A gamma-ray spectrometer sensed the natural decay of potassium, uranium, and thorium in the lunar soil and reported the abundances of these elements (Fig. 1). The ground resolution in both experiments was about 150 kilometers in diameter. Generation of x-rays was confined to the upper millimeter of the soil layer; gamma rays from as deep as 10 to 20 centimeters in the soil were detected.

The Al/Si x-ray intensity profile

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