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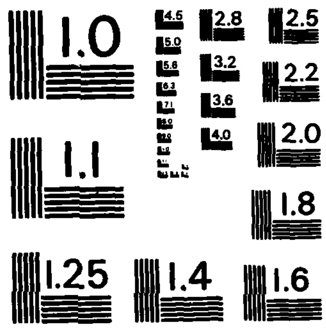

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Two Special Issues in Satellite Oceanography

Ocean Dynamics and Biological Oceanography

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Ocean Dynamics and Biological Oceanography

Ocean Sciences Board
Commission on Physical Sciences, Mathematics,
and Resources
National Research Council

NATIONAL ACADEMY PRESS
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

Because of some recent major advances in the prescription of the technical requirements for satellite oceanography (e.g., the TOPEX Science Working Group report[1] and the report of the NRC Space Science Board, A Strategy for Earth Science from Space in the 1980's, Part I: Solid Earth and Oceans[2] and recent technological advances (e.g., the coastal zone color scanner), the Ocean Sciences Board decided to prepare the two brief papers in this report that highlight significant and urgent problems in relation to satellite oceanography. We hope that they will be useful in the further development of satellies as important tools for ocean science.

John H. Steele, Chairman
Ocean Sciences Board

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INTRODUCTION

The potential value of satellite measurements to oceanographic studies has been demonstrated. However, to achieve fully the great potential of data from space as a tool for studying ocean science problems, it will be necessary to develop closely coupled programs using all the methods available to study the physics, chemistry, and biology of the sea. In particular, measurements in the ocean are essential for the interpretation of satellite measurements on the surface.

This report highlights two areas--ocean dynamics and biological oceanography--that we believe are ripe for special emphasis. The excitement and potential of the new satellite technology already show in some of the recent oceanographic literature, and they have spurred reports and recommendations by other units of the National Research Council. For example, a recent report by the Committee on Earth Sciences of the Space Science Board (<u>A Strategy for Earth Science from Space in the 1980's, Part I: Solid Earth and Oceans</u>) specifies the uses of altimetry for ocean-dynamics studies. We add our endorsement to that report from the perspective of the oceanographic community and add our emphasis that such studies will also require in situ measurements. Indeed, the integration of measurements of physical and biological processes in the ocean with global satellite measurements is central to the understanding of critical long-term questions such as resources and the CO_2 and NO_x cycles in the biosphere.

Long lead times are required for the establishment of new satellite programs. Therefore, in order to achieve the enormous and unique potential of this new technology we must take steps now to plan for the new programs and arrange for multiagency support of the needed research and development. We hope that the two reports presented here will help to stimulate this process.

EXECUTIVE SUMMARY

General

Satellites can provide unique, global data that, in combination with other *in situ* data, are likely to result in major advances in the ocean sciences. The two ocean-science fields most likely to be advanced through the use of satellite-acquired data are ocean dynamics (global ocean circulation) and biological oceanography.

Ocean Dynamics

The highest priorities for a study of ocean dynamics from space are to measure the spatial and temporal variability of sea-surface elevation, to measure the mean sea-surface elevation relative to the geoid, and to determine the wind stress over the ocean. Such measurements are feasible only by using satellite technology, are required globally and at frequent intervals, and should last at least 3 to 5 years. Substantial supplemental *in situ* measurements will be needed in order to interpret and study the satellite data adequately.

Biological Oceanography

Understanding of important processes in biological oceanography can be advanced significantly by the application of satellite and other remote-sensing technologies via a coherent, long-term (5-10 years) program. A combined color/temperature scanner is an essential element of such a program. Supplemental aircraft-based and *in situ* sensors will be required in order to utilize and interpret the satellite data adequately.

1. OCEAN DYNAMICS FROM SPACE--OPPORTUNITIES AND PRIORITIES

I. Introduction

Satellite measurements now appear for the first time to be able to yield the global distribution of geostrophic surface currents, sea-surface temperatures, and wind stress. These data, when combined with subsurface density and current measurements, will provide a synoptic view of both the mean and time-dependent general ocean circulation. The description of the circulation, the surface temperature, and the surface wind is fundamental to our understanding of the role of the ocean in climate dynamics and the effects of the ocean on fish stocks, pollutants, marine transportation, offshore operations, and national defense.

A number of recent reports[1-8] have focused on these issues and addressed the technical needs, the background, and the future plans of the United States and other countries. The international interest in the science to be accomplished is high. It is thus important that the appropriate spaceborne systems be launched by the late 1980's in order that they can be in phase with international programs now under way such as the World Climate Research Program.

II. Priorities for Measurement

The Committee on Earth Sciences of the Space Science Board[2] has prepared an accurate and comprehensive summary of the specific spaceborne measurements and of the necessary simultaneous in situ measurements required for describing ocean dynamics. The Ocean Sciences Board (OSB) has reviewed that summary from the somewhat different (and perhaps broader) perspective of the ocean sciences and concurs that attainable and primary objectives for the study of ocean dynamics from space are as follows:

1. To measure the spatial and temporal variability of the sea surface elevation,
2. To measure the mean sea-surface elevation relative to the geoid,
3. To determine the wind stress over the ocean, and
4. To measure sea-surface temperature.

The first three of these objectives are of highest priority, primarily because of the technical difficulties in temperature measurement. In addition, the OSB concurs that subsurface measurements required to complete the data set include information on near-surface circulation and subsurface density and current flow. The data from the measurements of sea-surface height, subsurface density and circulation, and wind stress when used in the dynamical equations of motion will allow us for the first time to have a global picture of the general circulation and its primary driving forces.

III. Surface-Pressure Distribution

The spaceborne altimeter provides the oceanographer with a global distribution of sea-surface height relative to the geoid. Use of independent geoid data then leads to surface-pressure gradients. Surface geostrophic velocities are calculated from the pressure gradients and can be used as the reference for integration of the observed density field for velocity at depth. The scheme is much like that used in meteorology meteorology to determine the wind field: there the surface pressure is defined by a network of barometers whose vertical location is determined by survey. These surface data, when combined with measurements in the air column above yield information on the total geostrophic wind field.

With the known surface-pressure gradients there is no need to rely on a more or less arbitrarily chosen "level of no motion" for velocity reference. There is abundant evidence that there are no broad levels of no motion in the sea but rather a complex three-dimensional distribution of velocity. Thus altimetry could be a major and fundamentally important step toward obtaining a true picture of the ocean circulation.

IV. The Geoid and Wind Stress

To measure time-dependent currents requires only monitoring the sea-surface height, since the geoid does not change over short times. To measure the mean pressure field also requires knowledge of the geoid. A new gravity-measuring satellite has been proposed and represents one means for providing this information. For the driving force, it appears that wind stress can be measured using a spaceborne radar scatterometer, although some work remains to lay a sound physical basis for interpretation of the stress measurements.

V. Sea-Surface Temperature

It is recognized that sea-surface temperature is an important variable, both for the ocean and as a boundary condition for atmospheric circulation. However, measurement of temperature has a lower priority for two reasons: (1) the accuracy of new measurement techniques has not yet been demonstrated to meet perceived needs, and (2) the general circulation must be described before the evolution of sea-surface temperature anomalies can be understood. It is necessary to evaluate rigorously how well the sea-surface temperature signal can be extracted from the microwave radiometer. The demonstrated accuracy of spaceborne sea-surface temperature systems still remains inadequate to resolve the signals as observed by direct measurement. Oceanographers need accuracies of from 0.1 to 0.5^{o}C, but current capability has uncertainties of from 1 to 2^{o}C. Much of this uncertainty comes from surface foams, water vapor, and liquid in the path of the radient energy. The new multichannel sensors may be capable of much improved accuracies.

VI. In Situ Measurements Needed

Since the satellite altimetry and geoid data give only a pressure field at the surface, it is clear that determination of the subsurface circulation and property distribution of the ocean are also essential elements of a global circulation measurement program. Such measurements cannot be made from satellites (although satellite data-collection systems are needed) but are feasible from ships and moored or drifting instruments. A major program of in situ measurements will be required for collecting the necessary data in the ocean while the satellite makes its measurements at the ocean surface. Examples of such studies include temperature and salinity measurements in areas of the world ocean where such data are now lacking in order to provide the basic mean density field; time series of temperature, salinity, and chemical tracers; and large-scale measurements of deep and near-surface circulation, probably with surface buoys and subsurface neutrally buoyant floats.

VII. A Specific Mission--TOPEX

In view of the above considerations, and from a number of studies showing the capabilities of the existing altimetric and scatterometer data, it is clear that satelliteborne instrumentation must be the central focus of a global circulation experiment. The general priorities for satellite ocean circulation studies take specific form in the proposal for an Ocean Topography Experiment (TOPEX), proposed by a Science Working Group sponsored by the National Aeronautics and Space Administration (NASA). The TOPEX report[1] provides immediate tactics for implementing the general recommendations. The Science Working Group has made the most extensive study of this question and has carried out a detailed analysis of the errors involved and the instrumental needs.

In summary, the TOPEX group notes that a general circulation experiment requires a satellite capable of measuring its height above the mean sea-surface with an accuracy of 2 cm. This suggests a nominal circular orbit with a height of 1300 km to minimize air drag. In order to maximize ocean coverage, as well as to resolve optimally both zonal and meridional currents and to avoid tidal aliasing, the inclination is proposed to be near 65°. The subsatellite track would repeat within 1 km every 10 days to provide averages to reduce measurement noise.

The experiment would have to last at least from 3 to 5 years in order to begin to describe the interannual variability of ocean circulation. This is of special interest in understanding air-sea interaction in the tropics, where the interannual variability dominates the seasonal effects.

Two other sets of satellite measurements are also required for the mission: the wind stress and the geoid. Since the surface currents of the ocean are driven primarily by the winds, TOPEX requires timely measurements of the global oceanic surface wind field. Such measurement could be made by a scatterometer of the type currently planned for the Navy's NROSS satellite, a satellite that is planned to be in orbit in 1988. The Satellite Surface Stress Working Group report[6] presents a scientific rationale for ocean-surface stress measurements and provides the detailed requirements for such a satellite system. The winds must be obtained over the TOPEX operating period as concurrently as possible so that the interactions can be established.

An accurate geoid is required not only for the calculation of the mean circulation but also for the accurate determination of the satellite's orbit. The special-purpose gravity-measuring mission, GRAVSAT, has accuracies compatible with those required by TOPEX. The improved knowledge of the geoid sought from the GRAVSAT mission need not precede the launch of TOPEX because the geoid data can be used retrospectively. However, in order to extract mean circulation information in a timely way, it is clearly desirable that the six-month-long GRAVSAT mission be flown sometime before the end of the TOPEX mission.

Finally, particular attention must be paid to the problems of dealing with satellite data in general. The handling of the 3-month SEASAT data set revealed the need for adequate, dedicated computers and properly evaluated and developed algorithms to be in place before the satellite is launched. In view of these lessons, as soon as component space sensors have been identified, we recommend that work be started to develop techniques for maximizing the usefulness of the data and that a complete data-handling system be in operation at the time of launch.

VIII. Timing of Altimetric Experiments

In terms of timing, it is important that any altimetric mission have a maximum period of overlap with other national and international field programs. For example, TOPEX could be a key element in the global climate programs now being discussed in the international scientific community. In turn, the climate programs will be supporting a number of *in situ* observations useful for calibrating, interpreting, and complementing the ocean-topography measurements. To enhance the mutual benefits, the altimetric plans should maintain close ties with the developing climate plans. Since many of these programs will be under way in the mid to late 1980s, it is important to proceed with altimetric plans now. The OSB recommends that NASA make a commitment to proceed with such a mission now.

The European Space Agency has committed funds for an altimetric mission to be flown in 1987, and there is a plan for a Japanese altimetric satellite in the late 1980s. A number of meteorological satellites for the World Climate Research Program are being proposed now for the late 1980s. The Joint Scientific Committee/Committee on Climate Change and the Ocean meeting in Chilton, U.K.[4] supported the recommendations of the TOPEX group and noted that at the end of the 1980s a number of satellites making oceanographic measurements could be simultaneously in orbit. The meeting urged that close coordination between the different national space agencies be arranged so that the best possible overall scientific returns can be achieved.

Internationally, oceanographers are now planning a World Ocean Circulation Experiment (WOCE), as part of the World Climate Research Program. The central component of the WOCE would be altimeter measurements. Such an experiment would use support from many countries for *in situ* measurements of density and circulation; there is much international interest in starting this program as soon as feasible to coincide with World Climate Research Program plans. Such an experiment would present the same opportunities for oceanographers that the first GARP global experiment did for meteorologists.

IX. Global Positioning System

In addition to the altimeter studies, it may be possible to use the new very-long-baseline interferometry techniques of the Global Positioning

System (GPS) to establish absolute sea level at island sea level stations. The island sea level measurements, which must be used in a relative sense now, would be absolute. The impact on our description of the ocean circulation could be considerable. In addition, the GPS, by providing absolute position and velocity for ships, will allow measurements of water velocity relative to the ships to be referenced to the Earth's coordinate frame. It is thus essential that general studies for improving the accuracy of the GPS continue and that the full accuracy of the GPS be made available to oceanographers.

X. Summary and Recommendations

1. Ocean surface topography measurements are of high priority for describing the global ocean circulation and could be done by satellite altimetry.

2. Wind stress and geoid measurements from satellite are also essential parts of general ocean circulation studies.

3. In situ measurements are crucial to any satellite-based general ocean circulation experiment.

4. Several groups, most recently the Committee on Earth Sciences of the Space Science Board, have made the above recommendations. The Ocean Sciences Board, from the perspective of the ocean sciences, concurs in those general recommendations.

5. The specific TOPEX experiment provides immediate tactics to implement the recommendations for a general ocean circulation experiment. The Ocean Sciences Board recommends that National Aeronautics and Space Administration make a commitment to an altimetric experiment, either TOPEX or one like it.

6. The launch and operation of the altimetric mission should be phased to take advantage of international planning for oceanographic and meteorological satellites as part of the World Climate Research Program currently planned for the late 1980s.

7. Study should be made of the use of high-resolution global positioning system data as a possible complement to altimetry.

2. SATELLITE BIOLOGICAL OCEANOGRAPHY: A NEW POTENTIAL

I. Introduction

Remote sensing from space can play a major role in our continuing efforts to understand the important processes in biological oceanography. The information that we can derive from space will arise from data not only on the biota per se but in addition on the physical systems within which the organisms occur; and, in fact, one of the extraordinary features of remote sensing in oceanography is its ability to view these two aspects *simultaneously on relevant* spatial scales.

It is also clear that the information from satellites is essentially and literally superficial and that in order to be most useful it must be combined with information on processes at both the surface and depth in the ocean. Once again, this is true for the biology as well as for the physics: some of the same questions that arise in the future use of altimetry and microwave radiometry arise in the potential of color sensing. Further, remote sensing from space is just one aspect of remote sensing that, as with the study of the physical systems, should include measurements made by instruments within the ocean that sense properties and permit inference regarding events that occur at a distance from the instrument. Thus information from satellites must be viewed in the context both of our corresponding understanding of the physical systems and in terms of simultaneous development and application of techniques for increased observation within the ocean itself.

II. Problems in Ocean Biology

The distribution of life in the oceans is variable at essentially all space and time scales. It is difficult to consider the system as having an average structure with superposed variability. In practice, however, biological oceanographers often focus their investigation on two major aspects of the system: (1) energy and/or material flux and (2) the variability in distributions of populations at various trophic levels. Any comprehensive view of the system must combine these aspects into one conceptual picture.

A. Energy and/or Material Flux

These fluxes from primary producers to higher trophic levels include several states loosely defined as plants, herbivores, and carnivores. At the same time, however, energy and material change spatially and temporally, and these movements can be considered in vertical and horizontal dimensions. This division is artificial but is useful in both defining certain of our problems and identifying areas where major advances are occurring.

1. Vertical Flux

Particulate matter moves through trophic levels and at the same time can move downward through the water from its surface-layer source. Consumption and dissolution result in decreased concentrations of organic material with depth. However, this simplistic view is being greatly transformed by the results of measurements using sediment traps, which indicate that there is an unexpectedly high flux rate of large particles, mainly fecal pellets, that transfer matter rapidly and with some seasonal structure to great depths in the ocean. These results have obvious importance for our understanding of the total carbon flux in the ocean, but the extrapolation of detailed studies in particular locations will require an understanding of the horizontal and temporal variation in production of organic carbon in the upper layers and its initial transformation in that region.

2. Horizontal Flux

The downward flux depends not only on the primary production but also on the nature of the transformation of this material by the herbivores. To extrapolate from our measurements to a carbon flux for large areas of the oceans we need to know not only the primary production averaged over relatively large areas but also the efficiency of transformation to the higher trophic levels. These problems involve the cycling of nutrients in the upper layer and the net upward movement of inorganic nutrients to replace the net downward movement of organic particles. Within this system primary production measurements are an essential component but not the complete answer. <u>Data on chlorophyll</u>

in the euphotic zone averaged over large areas in space and time will be an essential element for our development of these large-scale patterns of energy flux but by themselves will be insufficient to meet the needs of fisheries and climatic studies. We definitely need better information on the relation between primary production and chlorophyll, on the transfer of energy and matter through the food web, and on the vertical and horizontal redistribution of organic material that results from these transfers.

The rate of primary production depends on, among other factors, the intensity of incident radiation and the depth of the upper mixed layer. Cloud cover can provide some index of radiation, and wind stress is an important parameter in mixed-layer dynamics. Thus these types of satellite data may provide input to general theoretical models of production cycles that can be tested at specific locations.

B. Variability

The horizontal and vertical variations in plants, herbivores, and carnivores depend in part on their relation to physical parameters and in part on biological interactions. The separation of these two causal factors (and their recombination) requires the study of both vertical and horizontal distributions.

1. Vertical Distributions

In most of the world oceans, there are persistent subsurface maxima in chlorophyll. This chlorophyll maximum is a widely recognized feature whose exact origin(s) and fate(s) are not fully understood. Nor is its role in primary production and in herbivore feeding fully integrated with our physical and chemical understanding of water column processes. (Although this chlorophyll maximum can cover a depth region of a few tens of meters, it does have considerable fine structure on the scale of meters or less that may be related to both the physical microstructure and biological processes.) This midwater maximum can outcrop at the surface in the vicinity of fronts and presents one of the most interesting features of the combined horizontal and vertical variability prevalent not only in coastal but in open-ocean regions. Further, the position and intensity of the midwater maximum is highly dependent on the structure of the thermocline and thus particularly sensitive to changes in this structure caused, for example, by sudden storms. Clearly, these spatial and temporal variations in chlorophyll in the ocean have an important three-dimensional structure that cannot be ignored.

2. Horizontal Variability

Although the vertical structure is important, it is apparent that knowledge of the horizontal pattern of distribution is of equal importance in coming to an understanding of both the distribution and the population dynamics of phytoplankton, zooplankton, and fish. The variability that we observe occurs on a great range of scales in space and time, and the interactions between trophic levels also involve interactions between different space and time scales.

Some idea of the conceptual and logistic problems can be obtained from a simplified representation of possible characteristic scales for

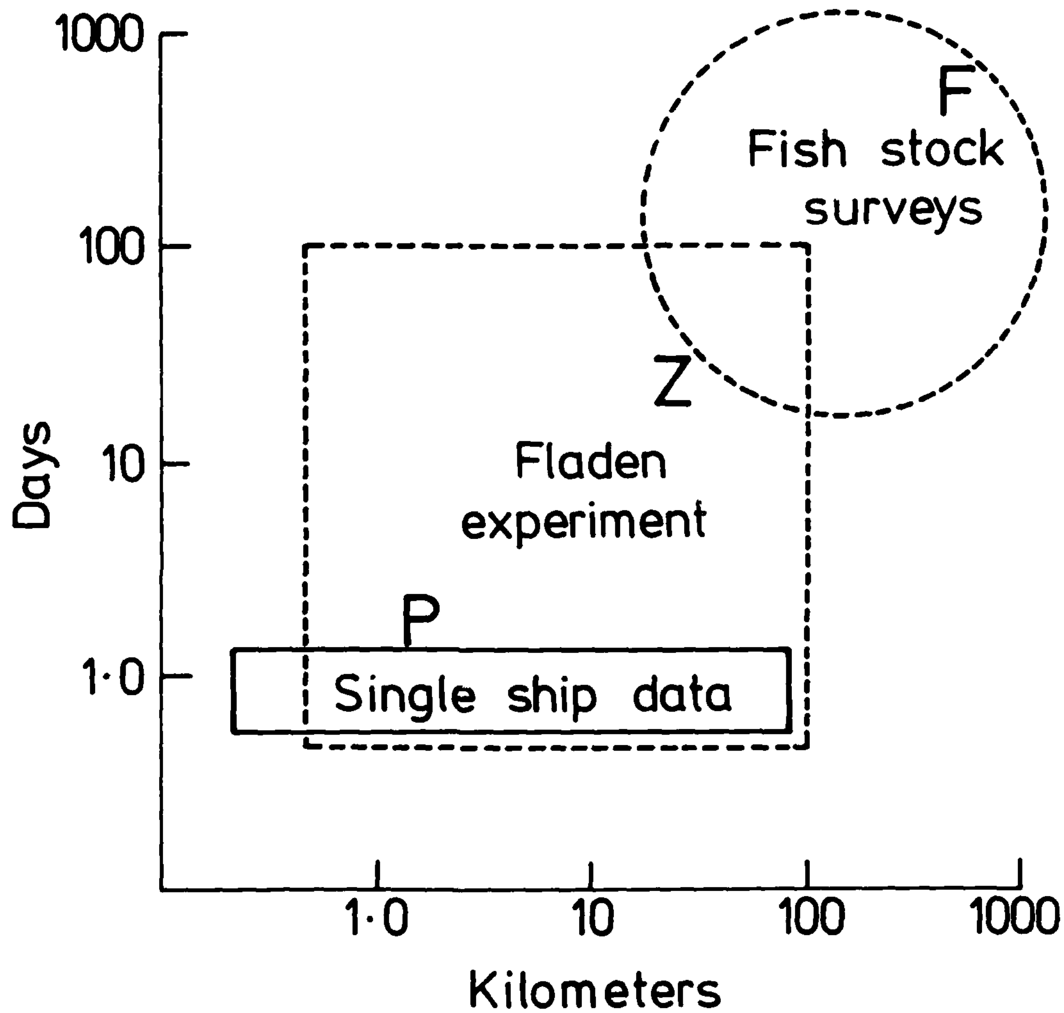

FIGURE 1 A simplified representation of typical time and space scales associated with plants (P), herbivorous zooplankton (Z), and pelagic fish (F). An indication of the sp*ce and time scales covered by various types of sampling programs.

three trophic components (Figure 1) in the context of a continental shelf food chain. The life spans of phytoplankton, copepods, and pelagic fish such as herring are of the order of 1-10, 30-100, and 600-2000 days, respectively. It has been proposed that the minimum scales at which phytoplankton growth can maintain such structure in the face of horizontal turbulent dispersion is of the order of a few kilometers. Scales of zooplankton patches appear to occur at tens of kilometers. For pelagic fish such as herring the scale of the annual migration cycle is of the order of 1000 km. To understand the dynamics of these populations, comprehensive sampling programs and theoretical studies must be concerned with the interactions along the diagonal of Figure 1. A comprehensive sampling program is obviously impossible logistically, and we have to content ourselves with obtaining data on the chosen spatial scale and repeating these observations as frequently as possible. The classical survey used for fish-stock assessment would sample at stations with a 50-100-km grid and repeat the program, if possible, 3-6 times per year over several years to give 50-100-day spacing. It can be seen (Figure 1) that with such sampling, only the minimum periods correspond to expected herbivore (zooplankton) variability, the result of which is apparently random data for this trophic level.

Using the fluorometer and other techniques, sampling is now possible at much smaller scales. By a combination of stationary and moving ships, a recent international effort (the Fladen experiment) studied a 100-km box for 100 days (Figure 1). About 20 ships were involved, and

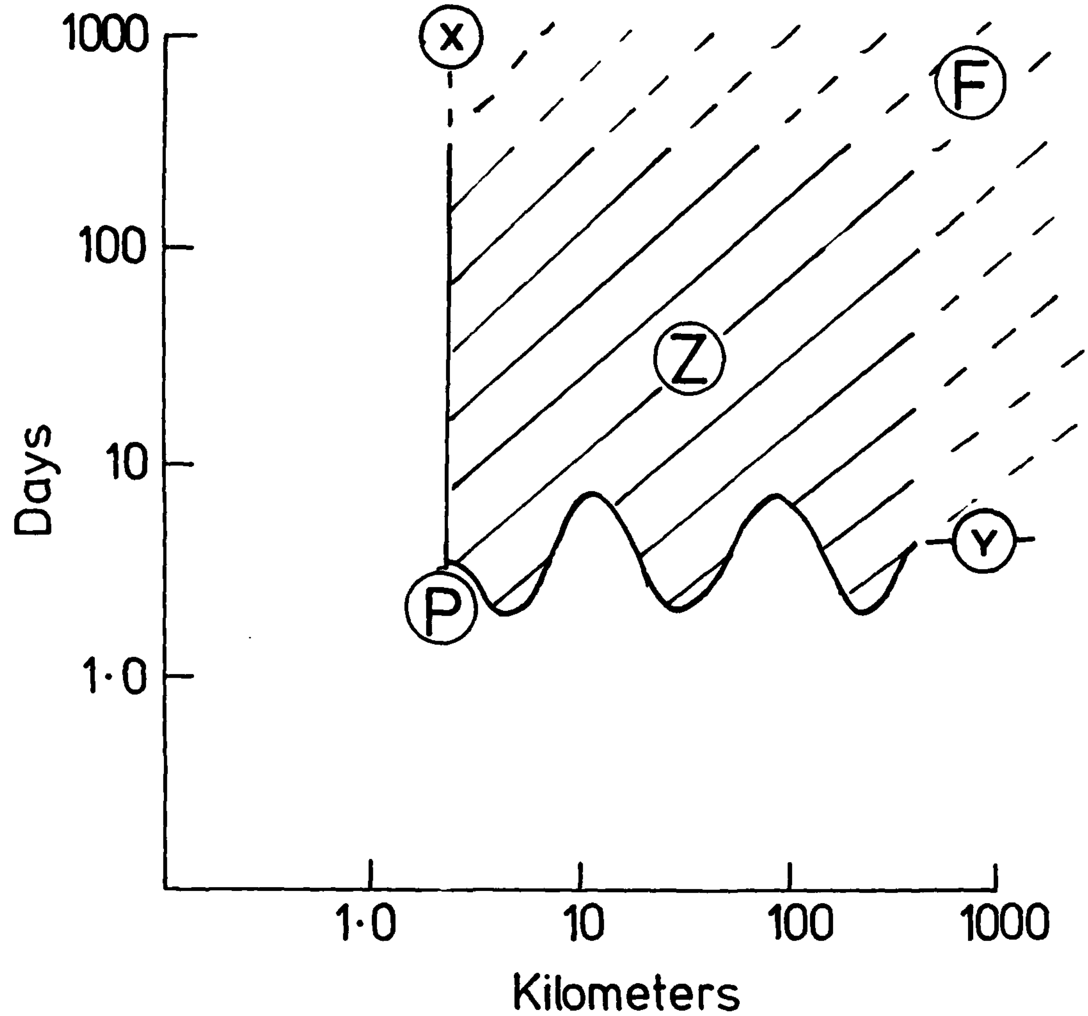

FIGURE 2 Schematic representation of the time and distance at which a color scanner will provide usable data.

clearly an effort of this magnitude is needed in order to study the interactions between the first two trophic levels of relevant temporal and spatial scales from surface vessels.

The immense advantages of remote sensing from satellite are illustrated in Figure 2, where we have superimposed on the same P-Z-F as are shown in Figure 1 the approximate scalar dimensions associated with a frame from the Coastal Zone Color Scanner (CZCS). For the minimum spatial dimensions, we have taken twice the pixel length as the usable data base. For the minimum temporal scale, the oscillatory line indicates the probable variability associated with data dependent on cloud cover, where the values could be between 2 and 10 days for repetition of data from a particular location.

The upper limit of the scale is taken as 400 km, corresponding to a detectable scale of variation within one frame, but the true upper limit depends on the relationship between the mean and the variance of chlorophyll distribution and the degree to which this can be represented in the calibration of the remote-sensed measurements from sea-surface observations. Recent CZCS data from coastal waters indicate that there is sufficient spatial variability in the chlorophyll distribution on the scale hundreds of meters to require highly precise spatial resolution of sea-surface observations. This will apply not only to the larger horizontal dimensions but especially to the longer-term time scales in waters for which the phytoplankton species that dominate the community change with time. We do not yet know exactly where these upper boundaries in space and time will lie, but, at the moment, it is apparent that to get truly "global" values, a carefully designed strategy for sea-surface observations will be required.

On Figure 2, X and Y indicate two physical processes that are important in influencing the spatial and temporal distribution of plankton. X corresponds to the cross-front dimension, which can be of the order of a kilometer and which for some fronts may extend over years. Y corresponds to weather events with a scale close to 1000 km and with periods of the order of 4-6 days. When these physical factors and the three biological components, P-Z-F, are looked at in the context of the scales of observation possible with a color scanner, it is apparent that the space-time area covered by this method extends over most but not all of the critical dimensions of the system.

Since the component for which we can approximate biomass with the color scanner--phytoplankton--lies on the boundary of the measurement range, it is essential to have alternative methods of extending the data set to smaller space and time scales so that observations from a satellite are not seriously aliased either in space or in time. Similarly, the events at fronts can be revealed by the satellite especially on the larger scale but need to be amplified by observations of the finer three-dimensional structure.

The zooplankton lie in the middle of the resolution range, and it is interesting that this is the position occupied by eddies in the schematic of energy distribution given by the TOPEX report.[1] The fish distributions, which can have an ultimate dependence on the phytoplankton, can also have a direct relationship with fronts and with weather conditions. Thus our understanding of the distributions of two of the components of the system, zooplankton and fish, may benefit greatly from information on wind stress, temperature, and altimetry (currents).

These comments emphasize the great value that the satellite measurements can have for our understanding of biological systems on a wide range of space and time scales. They also stress the importance of interrelating the biological and physical measurements, particularly for regions characterized by frontal systems and upwelling processes. In such situations, the horizontal variability in plant biomass is often great, and a semblance of synopticity is difficult to obtain solely from shipboard observations.

III. Future Requirements

This brief analysis indicates several main areas where further study of the problems involved in using satellite information are required.

1. *In situ* information. To complement the satellite data on color we need information *in situ* that covers both space and time scales as a function of depth, over ranges from fractions of a day to tens or hundreds of days and fractions of a kilometer to tens or hundreds of kilometers. Such information can be obtained by towed and moored fluorometers.

2. Linkage of biological and physical data. It is essential that biological data from remote sensing and within the ocean are closely linked with information on the physical environment. Temperature, particularly in upwelling regions, is useful in understanding changes

in chlorophyll distribution, and data on surface topography and internal current shear can contribute importantly to a more general interpretation of patterns and variability of plankton abundance.

3. Wide range of scales. Our understanding of the biological system both as a basic problem in science and also in relation to the more general questions of fisheries or carbon cycling, for example, require knowledge on the higher trophic levels. At present, data on planktonic herbivores and on fish stocks are acquired mainly through catches of the organisms by nets either for research or for commercial purposes. The use of acoustic techniques for the detection of fish schools has become common practice and an important new development is the quantification of these echo measurements both for fish and for plankton. The use of multifrequency techniques can even permit quantification of organisms in various size categories. Potentially, these measurements can be made both from moving ships using towed transducers and from moored systems. The great advantage of these dense methods of data collection is that they can cover a wide range of scales. Thus in terms of Figure 2, it should be possible to obtain vertical and horizontal sections across this diagram to be coincident with and complementary to the observations obtained from satellite sensors both for color and physical features of the environment.

4. Integrated systems. It has been stressed that the surface data on phytoplankton color and on physical features such as temperature need to be combined with subsurface measurements of these parameters and also of measurements of the higher trophic levels of plankton and

pelagic fish. The requirement is for an integrated data system that can provide these either from a moving ship or from a moored buoy. Such an integrated system would combine information on the physical environment from thermistors, possibly as a "chain"; from lidar (range-gated laser), which could provide information to 20-50-meters depth on phytoplankton concentration; and from acoustics, which could provide information on the medium-sized zooplankton. Preliminary definition of such a system has been carried out by the National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory (JPL).

5. Consideration of major projects. The acquisition of a towed system providing measurements of physical properties, phytoplankton, and zooplankton by remote sensing in the water column would take several years, as would the deployment of a satellite incorporating a color sensor and the appropriate physical measurements of the ocean. To emphasize the value of these combined developments and to make explicit the specifications for each part of such a joint system, it is necessary to consider in more detail several projects in which these would form an essential part. We have stressed the need to re-evaluate the productivity of the open oceans and of certain major regions of coastal waters. As examples of areas requiring this re-evaluation, the mid-Pacific gyre and the Southern Ocean[7] pose questions of major basic and commercial importance. In connection with the management of coastal areas where fisheries or hydrocarbon developments can occur, there are several major regions of interest, including the southern

California Bight and Georges Bank/Gulf of Maine. We expect that for these areas (and for others), programs will be developed to increase our understanding of the production cycle. It would be valuable to include in these studies the capabilities of new systems for both remote sensing in the water column and remote sensing from space. Some aspects of this integration have been addressed in the Satellite Ocean Color Group report[8] and NASA and the National Oceanic and Atmospheric Administration (NOAA) are currently exploring the inclusion of an ocean color sensor on the NOAA H or I satellite.

IV. Summary and Recommendations

1. Remote sensing, defined as the ability to measure significant parameters at a distance from the measuring instrument, can contribute substantially to a revolution in our understanding of biological processes in the oceans. This is already apparent in physical oceanographic systems through the development of acoustic tomography and the potential of altimetry. There is a similar potential for biological oceanography in terms of lidar, acoustics, and satellite sensing of color. These methods taken together, and combined with physical measurements, can be truly synergistic in our field programs. This is especially true in gaining an understanding of the variability of the upper layers of the ocean as a mixed physical, biological system. We recommend that the development of all these methods of remote sensing be undertaken as a coherent program over a 5-10 year period by the National Aeronautics and Space Administration, the Navy Department, the

National Science Foundation, and the National Oceanic and Atmospheric Administration.

2. A combined color/temperature scanner is an essential element in this develoment and the cornerstone in determining the broad picture of variability at a large range of space and time scales (Figure 2). The interpretation of these measurements will require data on the physical environment that are on the same scales and in the same format to allow direct comparison. It is essential that the accuracy and sensitivity of the measurements be clearly defined, particularly in relation to the scales of Figure 2. We recommend that a commitment for a color/temperature sensor, such as that described in the Satellite Ocean Color Science Working Group report[8] to be available on a satellite in the period 1985-1990 be made by the National Aeronautics and Space Administration immediately. We recommend that current efforts continue with the existing data to establish the accuracy, sensitivity, and space and time scales for the use of these combined data. Either current or archived Color Zone Color Scanner imagery should be used when decisions are made regarding sampling strategy for any large study of ocean processes.

3. A strong aircraft-based remote-sensing capability is essential in studies of processes on the regional-mesoscale level. Such a capability can permit simultaneous measurements of sea-surface salinity (microwave/UHF) (with resolution suitable for estuarine plume studies), sea-surface temperature (infrared), and chlorophyll fluorescence and light attenuation (lidar profiling) over areas that are intermediate in

scale between shipboard or towed-instrument observations and satellite observations. This is particularly useful in relating biological to physical processes associated with upwelling, fronts, eddies, river, and estuarine plumes. Many biological oceanographers are highly enthusiastic about the potential of the National Aeronautics and Space Administration's (NASA's) instruments that measure such properties, and <u>NASA should take the lead in applying these aircraft-mounted systems to oceanographic studies</u>.

4. As a complement to the development of a satellite system, a towed sensor is needed that can remotely sense in the upper layer of the ocean, where biological activity is most concentrated (i.e., top 100 meters approximately). This sensor should have the capability to measure a major feature of the physical structure (temperature), obtain a measure of phytoplankton (flourescence), and derive estimates of major components of the herbivores and carnivores (multifrequency acoustics). Such a system will be of great general use for many aspects of biological oceanography, but is an essential component of the general studies of variability involving satellite sensing. Several funding agencies have a direct or indirect interest in this development. <u>We recommend that the National Aeronautics and Space Administration take the lead in a systems study of the requirements for such instrumentation and provide the support for construction of one or more prototypes involving towed and moored configurations</u>.

5. The systematic development of a suitable satellite package combined with appropriate <u>in situ</u> oceans sensors requires not only a

general definition of aims for instrument requirements for biological oceanography in the next 5-10 years but more specific and more detailed project development that provides the design criteria for both types of remote-sensing instrumentation. We recommend that, as part of the development of the instrumentation and as justification particularly for the satellite system, a small number (three to five) of projects be specified by the National Aeronautics and Space Administration in consultation with the ocean-science community that make optimum use of the new instrumentation in order to increase our basic understanding of ocean processes and also as examples of the application of such instruments to applied problems.

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