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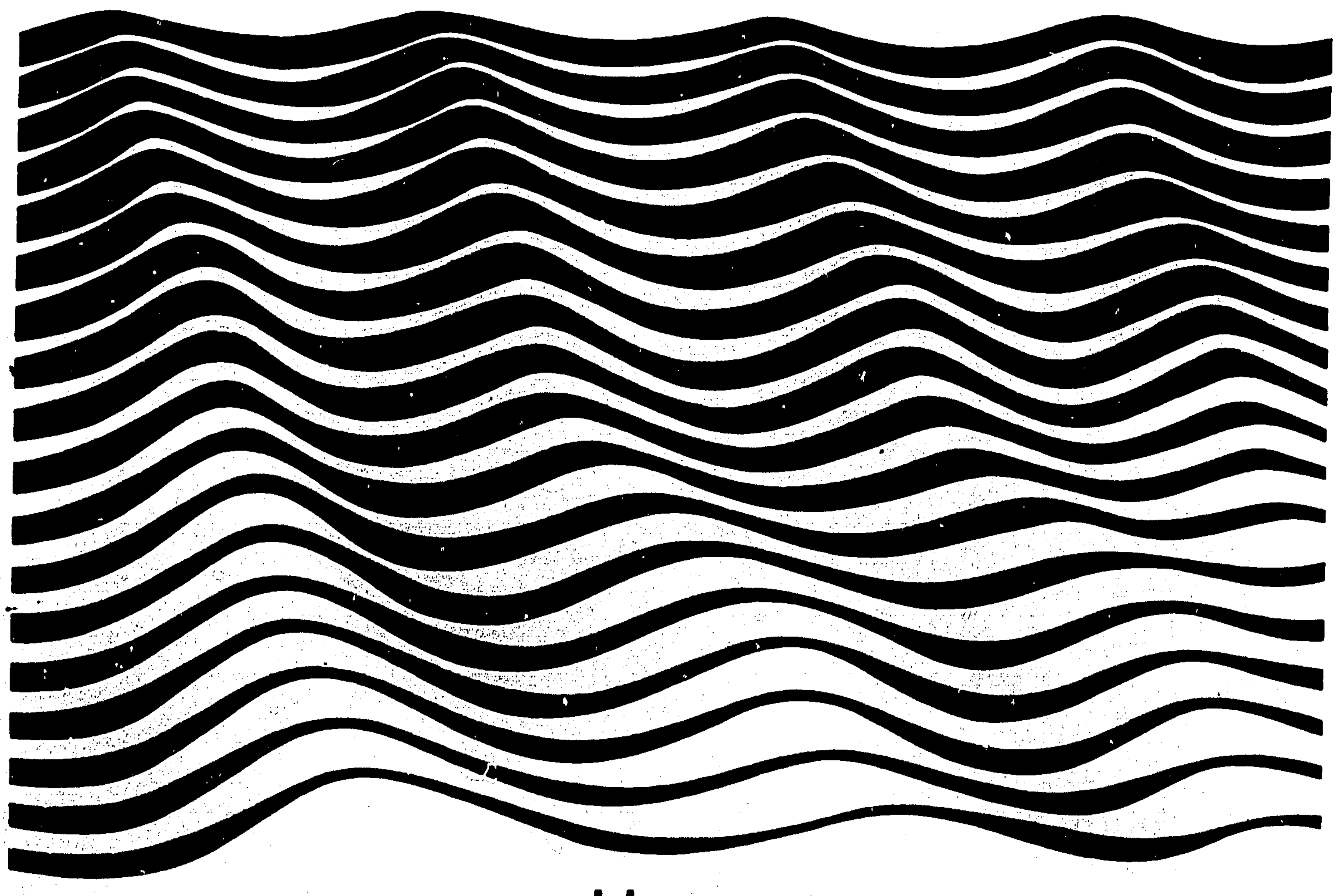
Monitoring life in the ocean

Report of working group 29
on monitoring in
biological oceanography

La Jolla, 1970
Plymouth, 1972



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SCOR-ACMRR-UNESCO-IBP/PM

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"Most of all, work on simplifying and distilling your objectives. Cato boiled his down to three words* - and by saying them over and over eventually wiped out the competition."

Robert Townsend, 1970.

* "Delenda est Carthago"

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Preface

The effects of increasing technological stress upon populations of marine animals and plants have become a cause for increasing concern, perhaps especially because of the possible feedbacks from such effects, if they prove to be real, to our own health, economic welfare and enjoyment of a healthy environment. Sea birds, our best "miners' canary", give us a very strong signal but one out of which it is not easy to extract and understand the information content: what are we to make, for instance, of the collapse in only a few years of the brown pelican populations on the California coast - reasonably well demonstrated to be caused by organochlorine contamination of their environment - when we also know of the irregular, but not infrequent, and even more dramatic population declines of the same species on the Peruvian coast - but, in this case, shown to be due to the natural effects of the onset of El Nino conditions in the Peru Current.

Such problems, and the underlying concern, have suggested that we reappraise the status of our long-term monitoring programs of life in the ocean; many of these programs begun purely as research projects in support of biological oceanography, or in support of other objectives such as fishery management, have now acquired a new importance in the search for indicators of the effects of technological stress in the oceans.

In response, several international organisations (see Chapter VI) concerned with marine affairs have cooperated in this review of the status of the technology and strategy of monitoring in biological oceanography; it is hoped that this review will assist people who are concerned with policy and design of ocean monitoring programs to evaluate new proposals made to them, to initiate new projects themselves, and to support the continuation of current programs. This review was written mostly with the needs of people in high-technology areas in mind, in order to introduce them to the practical problems inherent in work at sea with which they may not be familiar; but it is hoped that it will not be ignored by, for instance, scientists from developing countries or from low-technology areas, who might reasonably infer from this report that relatively advanced technology is required for environmental measurement, data acquisition and data analysis and presentation. With respect to ocean buoys, satellites and their like, this is obviously correct. However, sophistication and gadgetry are no substitute for a well conceived and executed series of observations. The generalizations which have been made with respect to accuracy and frequency of observation apply equally from the most simple to the most complex system of data acquisition. This review does not consider the kinds of observations which could be made with a minimum of equipment from near shore stations; however, it can be stated that essential criteria for any program of observations is that they are carried out systematically, with awareness of the problems associated with their collection and analysis and always with clearly defined objectives. Automated data collection and analysis is a welcome additional asset to a programme but without the foregoing criteria being satisfied it becomes a meaningless expenditure.

The recommendations arising out of this review may be briefly summarised here. They are the following:

- That the importance of maintaining already ongoing monitoring programmes in the ocean is of paramount importance.
- That global and regional reviews should now be made of the data output from such ongoing programmes.
- That several areas of promising technology require the stimulation of special working parties.
- That progress in this field moves so rapidly that reviews such as the present one must be repeated at two to five year intervals.

I - INTRODUCTION

The WG felt that it was essential to consider the question of the general nature of biological variability in the ocean, as the statistical problems inherent in any monitoring system are fundamental to its cost-effectiveness and are dependent on the relationships between the scales of biological variability and the selected scales of sampling or sensing, both in space and time.

Biologists have been acutely aware of what is currently termed variability since the earliest days of quantitative marine biology but it is only in recent years that the systematic study of this variability has begun. The following paragraphs may serve to illustrate, in rather simple terms, the complexity of the problems facing quantitative marine ecologists, especially in attempting to monitor trends and rate changes in the ocean.

Physical variables in the ocean vary with time at a fixed point in space mainly as a result of water movement of various scales by means of advection and diffusion. Biological variables vary as a result of the same processes, but also according to factors inherent in biological material, which may be independent of physical water movements, or may enhance or reduce their effects.

Animals, and motile plants, aggregate at various scales of size, they migrate in two planes and in various scales of time, they reproduce, encyst, die and they are harvested by man. Such are only a few of the causes for the great variability with time inherent in serial observations made by marine ecologists, and which are a major cause of their preoccupation with statistical methods.

Aggregation patterns in marine animals may be active or passive, and range over several orders of magnitude on the metric scale; planktonic crustacea may aggregate for social or reproductive purposes into clusters of the order of centimeters or tens of centimeters in scale, or may be aggregated by density layers or circulation cells in the mixed layer on a scale of metres or tens of metres. Thus, any net haul taken in an apparently homogeneous mixed-layer of the ocean may be replicated only within rather wide limits. Pelagic larvae of benthic invertebrates may be passively distributed by ocean currents and adults derived from such larvae are aggregated on an apparently homogeneous sea floor according to the manner in which they were distributed by the currents.

Fish may live solitarily, when they can be considered, for measurement purposes, as rather rare particles in sea water; they are sometimes caught by sampling instruments, sometimes not (even according to the degree of sophistication of fish and fisherman); fish may also aggregate in schools varying in size from several individuals to several million individuals and these schools may appear to be randomly distributed or aggregated in a homogeneous medium, so that they are detected by one measurement, missed by the next.

The distribution of organisms in the sea also varies with time, on several scales. Day and night measurements at one location of the presence and numbers of biota may give very different values because of diel vertical migration in the open ocean, or because of diel variation in the behaviour of benthic or demersal organisms.

Life cycles of organisms cause them to be recorded or measured at a location in some seasons, but not in others; seasonal variability may be gradual and correlated rather closely with physical variables such as temperature, or it may be abrupt, as when an organism emerges from cysts, reproduces and re-encysts, (or some parallel phenomenon) during a restricted part of the yearly cycle of events in the ocean.

Longer term climatic variability in the ocean, as for instance the waxing and waning of sea temperature in high latitudes, has profound effects on the nature of biota present and measureable at any location, at similar seasons from year to year. The scales of time involved here may range from decades to several tens of decades. The major climatic recessions on the geological time scale may be ignored for practical purposes, but must be recognized as the major component of the environment of which those variations measureable on the human time scale are minor components.

It was in the context of this variability (which, as Table 1 suggests, stretches over at least 15 orders of magnitude) of animals and plants in the ocean that the WG undertook its tasks.

Table 1

0.1	micrometer	
1	micrometer	Phytoplankton
10	micrometer	
100	micrometer	
1	millimeter	
10	millimeter	Forage organisms
100	millimeter	
1	meter	
10	meter	Fish school diameter, aggregations of invertebrates.
100	meter	
1	kilometer	Aggregations of invertebrates
10	kilometer	and vertebrates.
100	kilometer	
1000	kilometer	Distribution limits and
10000	kilometer	migrations

II - OBJECTIVES

The technical literature on ocean monitoring is replete with superficial statements of objectives and plans. One trend is the familiar generalisation concerning the benefits to be derived from global monitoring of, for example, surface chlorophyll from near-space satellites - "so that our fishing fleets may be directed to the productive regions of the ocean". Another trend appears as an uncritical, extended list of variables that seem feasible to monitor from (eg) an ocean data buoy and from which no short-list of actually useful candidate variables is indicated. For this reason some time was spent discussing realistic objectives of potential programs designed to monitor variables in the ocean of relevance to marine life. Without such a review of objectives, it would not be possible to be selective.

A. BIOLOGICAL OCEANOGRAPHY

Two elements of biological oceanography were examined to assess the utility of monitoring: species indicators of oceanic change and testing of production models. Time series data in the former is necessary to evaluate the probability of indicator species incidence. In the latter case, an effective production model can be expected to reproduce time series information and eventually yield predictions on various scales of space and time.

Indication of oceanic variations resulting from long-term trends or sudden changes in the marine climate or from man's activities affecting the ocean may be derived from biological indicators used to locate shallow water masses and to trace their movement, or to reveal the effects of pollution and to attempt to separate these effects from those caused by natural events.

However, the routine use of biological species as indicators of water masses is uncommon, for several reasons. To obtain data from plankton samples is both slow and costly, and usable information is usually unavailable until long after the event. In contrast, modern electronic sensors of physical and chemical properties of sea water are capable of very rapid generation and processing of data. Even when indicator species have been carefully selected, extrapolation from one region to another is usually unsatisfactory. Boundaries of species in some parts of their range may not coincide with any other obvious oceanographic features, perhaps due to non-linearity of response to environmental variables.

Further, physiological races of a single species may react quite differently to the environment, be distributed quite differently, and yet be morphologically distinguishable only by special techniques. For these and similar reasons, the use of biological indicators can probably be applied most readily in situations where the monitoring of major, occasional events (such as the 1958/60 events in the California Current) is the object of the programme, or where frontal conditions in the ocean provide rather clear-cut species boundaries which can readily be monitored (as in the Kuroshio-Oyashio and the Gulf Stream/Labrador Current situations). However, with diligence and in special operational situations the method might be applied to detect rather subtle changes in relatively homogeneous areas of the oceans. It is in these situations that the method may be most useful in distinguishing between the effects of natural environmental changes and pollution.

Testing of production models can only be thoroughly performed with time series data from comprehensive monitoring programs. Considerable progress has already been made in the northern Pacific in this regard (McAllister, 1969; Parsons and Anderson, 1970; Parsons, Giovando and LeBrasseur, 1966); two rather simple models of the primary production cycle have been validated, and it has been shown to be possible to monitor primary production from ships-of-opportunity using one of them.

In the N.E. Pacific it has been shown that variations in the biomass of zooplankton indicates the level of production by the phytoplankton whose stock remains constant under grazing pressure, and it has also been possible to correlate temporal and spatial progression of zooplankton biomass increase with similar progression of the critical depth as indicated by mixed layer depths, incident radiation and an assumed value for radiant energy at the compensation depth.

Further, American Mail Line ships plying between Seattle and Tokyo have been instrumented for a period of several years as follows: incident radiation (actinograph), mixed layer depth and temperature (XBT), chlorophyll-a (solvent extraction and spectrophotometry), nutrient salts (frozen samples), zooplankton (high speed sampler & sea water intake). Levels of primary production can be derived with a simple five-variable equation (Steele and Me el, 1962) for which sufficient data can be generated with this suite of instrumentation, the results have been validated using independent C^{14} (net) production data, providing allowances can be made for phytoplankton taxa having different productive rates and carbon/chlorophyll ratios.

B. MANAGEMENT OF OCEAN FISHERIES

The management of fisheries involves the monitoring of system variables (fish population indices of various kinds) and forcing functions (fishing effort and environmental change). These comprise the majority of the large-scale, long-term marine life monitoring operations that have so far been mounted. It was not the intention of the WG to review these operations directly, but rather to consider the ways in which systems which generated real-time (or short-delay) data on the environment in which commercial fish populations lived, might be useful to the community of people and agencies concerned with sea fisheries; fishermen, fish buyers and processors, fishery scientists, fishery managers, and so on. The importance of long time-series data from fisheries sources has been much overlooked by biological oceanographers in general.

If such a monitoring system resulted in an increase in our effectiveness in obtaining large quantities of real-time data from the ocean, and in disseminating these data to analytic centres, and thence in usable form (charts, reports and so on) to the fishery community, and if these products can be specially adjusted to the needs of this community, then the benefits to be derived might be threefold:

1. Tactical efficiency, and hence profitability, of fishing vessels may be increased because of the increased effectiveness of short-time-scale forecasting services which could be made available if governments wished to, or if industrial units were able to organize such services.

2. The futures market for fishery products would become more predictable through the application of long-term (3-6 months) climatic forecasts to seasonal fishery predictions, with the same caveats as for (1) above concerning the implementation of such forecasts.

3. The effectiveness of fishery management (or regulation) would be increased by an enhanced ability to forecast the strength of dominant age-classes expected to enter fisheries in subsequent seasons or years, such increased effectiveness promoting also an increased economic efficiency on the part of producers and processors.

It is not necessary to discuss in detail the various ways in which the tactical efficiency of fishing fleets could be improved by short-term predictions, since Hela and Laevastu (1970) have given an adequate review in their recent book, and because it is here that the non-fish biological output from a monitoring system might be least important; apart from locating or predicting high-forage areas in real-time, a monitoring system could perform this function in two ways: (1) by such means as satellite measurements of sea surface temperature, or from a network of data buoys, it could predict ocean features from which fish location and abundance predictions could be made and (2) by similar means, sea and weather condition predictions on fishing grounds could be made, to be used in conjunction with fish predictions.

This is all obvious and does not need expanding; what is perhaps not so obvious is whether or not we should now be encouraging an increase in the efficiency of our fishing fleets. There are two good arguments why this should be done, as a secondary aim of fishery science: (1) only by the development of economically sound fishing fleets can a degree of stability be introduced into a notoriously unstable industry and (2) an economically sound industry may be presumed better able to stand the effects of rational regulation than an inefficient, uneconomic industry. Therefore, provided it goes hand-in-hand with rational fisheries management, the first suggested benefit from a monitoring system seems to be valid.

The second suggested benefit, concerning operations of fish buyers and processors in the futures market is one which does not come at once to the minds of engineers and oceanographers: it simply means that fish buying, processing and maintaining an inventory has to be done against two sets of variables. One set is relatively well understood and predictable, being the seasonal and geographical fluctuations in demand for established products in world markets; the other set, the geographical and temporal variation in supply of the raw material and its price, are virtually unpredictable on the time scale which would be useful. Present attempts by industry in California to predict seasonal production of Peruvian fish-meal and Japanese albacore before the season's fishery attest to industries' interest in such predictions.

Finally, the third and possibly the most important benefit, requires comment. Present management models of the dynamics of exploited fish populations are still largely non-stochastic and management policies are encountering, in consequence, serious problems in some fisheries; imposed upon the effects of a fishery on fish stocks are the irregular effects of climatic conditions causing great variation in real abundance and in availability, and which are independent of fishing effects. To some extent the availability problem can be tackled, as it arises, by shorter or longer term tactical predictions of fish location and abundance transmitted to fishing vessels; but the problem of abundance, or age-class strength, is more basic, and harder to understand. It seems to stem, in the main, from varying recruitment success from year to year as larvae and juveniles find themselves in a better, or worse environment. There is a considerable literature on this problem and much of the effort of fish population dynamics is now directed towards its resolution. Once sufficient understanding of larval and juvenile ecology is reached, monitoring systems might materially assist the prediction of age-class abundance early enough to be useful in fishery management.

It is practicable for modelling purposes to consider some fish eggs and larvae as members of the plankton. In production models this inclusion should be extended to fish of sufficient age for recruitment to have been determined, and hence monitored. This may be the most important objective in the fisheries field for projected marine life monitoring programmes.

C. MONITORING MARINE POLLUTION

The effluents from man's industrial and agricultural activities, and other effects of the technological revolution are widely thought to be causing significant changes in the abundance and kinds of living organisms in the oceans. Public concern over this is now so high that plans for surveying and monitoring their effects are currently being made by many national and international agencies. The WG undertook to consider specifically only those aspects of monitoring that were relevant to pollution management through the identification, description and continual up-dating of the effects of trends and changes in the physical environment on the nature and distribution of life in the ocean.

It is perhaps insufficiently stressed in pollution monitoring and management schemes that changes in marine biota may be due not only to the effects of technological stress on marine organisms but also to the effects of climatic trends and changes in the physical environment of the oceanic biota. Systems for monitoring natural changes in the ocean must be instituted in parallel with pollution monitoring systems if we are to understand the causes of the observed changes.

SCOR-GESAMP Working Group 39 has been established in order to identify guidelines for the study of marine ecosystems in relation to pollution, and so this topic is not considered in great detail in the present review.

III - PLATFORMS AND MODES OF OBSERVATION

Measurements of biologically important parameters from buoys and ships-of-opportunity will be most effective when combined with the more accurate and precise measurements taken by grid and transect surveys. A model of primary, secondary and fishery productivity for a region may need to include parameters estimated from historical data, and from currently deployed grid surveys, fixed buoys and ships-of-opportunity. In addition, data collected in one of these ways may suggest tactical changes in the sampling design of another method. For example, the historical data record can be used to suggest the range, accuracy and precision of measurement necessary for a parameter from a buoy - one buoy in an upwelling area may need a temperature range of 10°C with a precision of 1.0°C while another buoy in the center of a gyre may need only a 4° range but may require a precision of 0.1°. Similarly, the detection of mixed layer depth from ships is now frequently accomplished with a small number of temperature profiles per unit time and space. Continuous measurements of temperature profile from a buoy may suggest improved estimation procedures using randomized multiple drops of XBT's to confound periodic internal wave effects.

The rate of change of temperature at a fixed buoy moored in a slow current may suggest the necessary response time of an instrument to be towed at 20 knots in the same region, while data from towed instruments may suggest the optimum spacing of buoys for monitoring the motion of eddies, gyres, fronts and currents. It seems likely that the final determination of optimum rates and necessary precision of measurement will lead to a mixture of measurements from specialized research vessels, ships-of-opportunity and buoys. The speed with which we reach this optimum mix may well depend on the early strategic interaction of these various measuring devices deployed in differing scales of space and time. The WG considered ~~the principles~~ involved in monitoring life in the ocean from four kinds of platforms, and discussed combinations in which these might be deployed in integrated monitoring systems.

A. RESEARCH VESSELS

Oceanic research vessel designs are frequently compromised by the flexibility of missions they can carry out and cost of construction. They cannot be considered cost-effective for highly specified and simple monitoring measurements: rather, their role here seems to be in the design and testing of monitoring apparatus and the research necessary to define new oceanic features to be monitored. Many monitoring activities may permanently require ocean-going research vessels to supplement buoys, ships-of-opportunity, and satellites. In these instances it will be necessary to arrive at a minimum in design and staffing to carry out the most effective long-term monitoring role.

However, there are some exceptions to this generalisation; for instance, the long-term CalCOFI investigations designed to monitor the spawning stock of fish in the California Current, together with related biological and environmental system variables, for periods of several decades, has from its inception been mounted in research vessels. The objectives of this programme have been reached by a repetition of multi-ship plankton net surveys over a standard grid repeated monthly, quarterly or less frequently. This resembles the continual open-ended repetition of a rather simple oceanographic expedition over a relatively small (2000 km x 450 km) standard grid of stations. The work has been done from medium size (40-60 m) research vessels that have required in these cruises much smaller scientific parties and far less scientific instrumentation than on normal research cruises. This is the unsatisfactory solution imposed by the need to operate the surveys from a vessel able to keep the sea and sufficiently fast to be able to have a high probability of completing each planned survey; it is expensive, and precludes the use of research vessels, designed for other purposes, on more sophisticated missions.

B. SHIPS-OF-OPPORTUNITY

Routine scientific observations from commercial vessels plying their normal routes have long been used to monitor the ocean relatively cheaply; the advantages of the method are clearly that one can obtain regular data from the large areas of the ocean crossed by shipping lanes. Not so clearly, the disadvantages are numerous: although it is easy to obtain simple data that can be recorded automatically, or routinely by the ships' crew (and such is the basis of the greatest part of routine meteorological observations from the ocean), it is not so easy to make more complex observations because of a number of constraints to the mounting of complex instruments aboard merchant vessels, either to function unattended, or to be tended by an operator. Deck space is frequently at a premium, especially near the stern where it is convenient to mount instruments for overside operation, but which are also areas important in docking. Vessel schedules and routes, except for rather small numbers of lines, are to an extent flexible, and are rapidly becoming more so with the advent of container-ships, so that planning of the lines of observations may not be easy. The decline in the numbers of passenger-carrying ships on scheduled services is increasing this problem. The speed of ships is increasing rapidly, so that the operation of towed vehicles from merchant ships is becoming much more difficult; where speeds of 10-12 knots were not unusual in the past, speeds of 15-20 knots are to be expected now. The near future may see many 25 knot ships in routine operation.

Problems such as these face one very long-term biological programme using ships-of-opportunity; this is the IMER Continuous Plankton Recorder survey presently operating from Edinburgh, and which has been collecting data from the North East Atlantic for more than 25 years on a routine and regular basis. It is becoming more difficult to find ships which are willing and suitable to deploy this equipment, and switches of equipment from ship to ship are becoming increasingly frequent.

The objectives which might be achieved by monotoring programmes deployed aboard ships-of-opportunity are those that can be satisfied by a repeated 'centric-systematic-area-sampling' scheme (Milne, 1959), such as CalCOFI, in which repeated routine occupancy of stations by research vessels generates data taken to be representative of contiguous rectangles in the ocean. Repeated ships-of-opportunity crossings of rectangles may be used to produce comparable data but dependence of the operation on the schedules and vagaries of commercial ships means that desired data-sets can rarely be completely achieved. The IMER CPR surveys illustrate this problem very well, and suggest how it may in large part be resolved by statistical techniques (see p.26).

A ships-of-opportunity survey will normally involve repeated but widely spaced transects along more or less constant tracks, which will almost inevitably produce bias in estimates of temporal changes. In areas with relatively stable geographical regimes this may not be a serious problem in that the bias will be approximately constant and will not greatly effect interpretations in terms of relative temporal changes. In less stable areas it may be necessary to take particular care in planning the survey, if necessary supplementing it by strategically placed transects by research ships to detect any important geographical changes which are small compared with the spacings between the ships-of-opportunity tracks.

C. BUOYS AND OTHER STATIONARY PLATFORMS

The literature on the technology and proposed deployment of ocean data buoys is now rather large, but the actual deployments of buoy systems in the ocean is not yet very extensive. In all the plans for the data buoy systems that the WG has examined, the monitoring of biological variables is (for good reasons) almost completely neglected, probably mainly because of a lack of interest on the part of biologists in biological data which could perhaps be collected from these platforms. Some of the variables that might be measured are discussed below: the reasons for using a buoy or similar platform for such measurements range from the simple (because it was there, anyway) to the statistical (because a series of measurements taken from a single buoy may integrate variables over rather large areas of extrapolation). SCOR WG 28 (Air-sea Interaction) have proposed several prototype buoys for making simple physical measurements and have suggested that research in this area might be increased if such buoys were commercially available.

Ocean Weather Ships, light-ships and offshore oil-rigs can be considered special variants of data buoys and although few in number are perhaps more useful to the biologists. Many years of biological data have accumulated from weather ships - in the N.E. Pacific and N.E. Atlantic in particular. Of especial interest is the presence on board of scientifically trained personnel able to make routine observations: the

Canadian and French weather ships, at least, have special accommodation aboard for an oceanographic party to be carried in addition to the normal complement of meterorologists. While weather ships remain in service they should be used to the fullest possible extent. Extremely valuable lengthy time series of standard plankton samples have been taken from some stations and the value of such series is increasingly appreciated.

It is not easy to suggest how ocean data buoys may be deployed in the future to answer real problems that pose themselves independently of the existence of buoys: that is, how buoys may become more than solutions in search of a problem. The WG examined (see below) the reality of two previously suggested applications in fishery science but it was felt that it is in the indirect mode, by measuring physical variables in the ocean known or suspected to be keys to biological variation, that buoys will find their most important application.

The model of skipjack tuna migration in the eastern Pacific Ocean proposed recently by Williams (p.32) exemplifies this. The model has three possible solutions to the problem of why the young fish migrating from spawning grounds in the open ocean, several thousand miles offshore, partition themselves in the observed number between the Central & South American fishery areas and the Mexican fishery area. It is suggested that the variability in the timing strength and location of the eastward termination of the Equatorial Counter Currents may determine this partition. This model, supported by data now being collected, could form the basis of a prediction of skipjack migration if the week-to-week situation at this eastward termination of the Counter Currents could be monitored, either by an array of buoys or perhaps by inference from satellite or airborne remote sensor data.

D. NEAR-SPACE SATELLITES

The literature of remote sensing is large, especially in the form of symposia at which contributions tend to be repetitive - while the actual deployment of remote sensors is rather limited. The potential advantages of this mode of monitoring have been sufficiently stated in many other places but it remains to be demonstrated that the sensing techniques that have been shown to be theoretically feasible can actually be deployed operationally. The simplest oceanographic variable, sea surface temperature, has yet to be monitored from space on a sustained basis with a satisfactory data output, despite the very considerable development work that has been done, and despite repeated feasibility studies which have produced excellent ground-truth support for sea-surface temperature charts obtained from satellites. The major problems remaining before this technique will be a useful routine are partitioned between spacecraft instrumentation (eg serious tape-deck noise in earlier instruments) and environmental difficulties, mostly concerned with the amount and distribution of water vapour in the air column, cloudiness, and sea surface state. Solutions of the problems do not appear to be immediately in sight, and monitoring of this variable is unlikely to be satisfactory and routine in the immediate future.

This is a field where there is considerable pressure from industry and engineers on the scientific community, and on the governmental science agencies, to participate; because of this pressure, it is not easy to obtain a thoroughly objective evaluation of probabilities of success, and to determine the magnitude of the development funds needed to perfect and deploy the apparently feasible instrumentation. A secondary effect of the aerospace initiative to develop new sophisticated equipment is to cause us to neglect almost entirely a potentially much easier, but less elegant, solution to remote monitoring of surface observables in the ocean. The question of using 'aircraft-of-opportunity' is wholly neglected, yet the jet-routes crossing the oceans regularly, frequently and widely would seem to offer very attractive possibilities for monitoring the locations of ocean fronts, and temperature and chlorophyll gradients (see also p.50).

IV - MONITORING STRATEGY & STATISTICAL DESIGN PROBLEMS

There are strategic and statistical problems which are common to all monitoring programmes, whatever their objectives, but which are specific to that part of the biological system which is being monitored. These problems mostly concern the ranges of values to be expected for each candidate variable to be monitored, the expected rates of change of these values with time, horizontal distance and with depth. The selection of rational levels of accuracy* and precision* in the observations is also considered in this chapter. However, we first consider some general problems of survey design.

A. GENERAL DESIGN PROBLEMS

At the strategic level (eg selection of variables) it is necessary to consider the way in which the required information will be obtained from field observations. These observations provide data from which will be generated one or more quantitative variables containing the required information which has to be observed against a background of error variation. It is necessary to decide what variables are to be measured, the coordinates of the variables, the required resolution along these coordinates and the desired amplitude of the variability. These can be summarised as the type, form and the quantity of the information.

1. The Type of Information. This is a critical factor in the design of monitoring surveys, particularly where automated observation methods are used. On the one hand, it is not cost effective to measure too many variables, while on the other, gaps in time-series can never be filled in later. Resource limitations play an important part in the process of making such decisions. Is it better to devote limited resources to a detailed analysis of a few samples or to employ a higher level of abstraction in a more widespread survey? At a high level of abstraction (eg biomass determination) the risk is that the wrong kinds of information are obtained to meet the objectives of the survey. At a low level of abstraction (eg species counts) the risk is that not enough observations can be made.

Chapter V indicates that methods are available for some variables, or could be developed, suitable for a range of levels of abstraction. In such cases there is the possibility of integrating the results from observations at more than one level.

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*The WG has found a considerable lack of understanding concerning the use of the terms accuracy and precision, both among its own members and its correspondents. We have used the terms throughout this report in the following manner: in the language of target shooting, a precision describes the internal scatter of a group of shots aimed at a mark and accuracy describes how far from the mark was the centre of the group.

For example, it may be possible to use high density results from a high level of abstraction to serve as a guide to interpolating between less dense low abstraction level observations. The results from an automated high abstraction level observation system could be used to control the frequency of observations of a low level method by an automatic feed-back mechanism. Such methods are probably most generally applicable in situations where information is needed on the timing of events and for event-marking requirements, such as fronts or blooms.

2. The Form of the Information. It is necessary to decide on the resolution required in the field observations. Some guidance on this is given below, particularly in relation to temporal variations. In designing a survey it may be necessary to carry out pilot studies in order to determine rates of temporal and spatial variation to assist in assessing the resolution required for the survey. Also at this stage it is necessary to consider the statistical or other analytical procedures that will be involved in deriving usable results from the field observations.

Multifactorial designs probably provide the most general data structure for analytical purposes. The simplest of all such structures is a table with each column representing a station, or the average for numbers of stations in defined areas, and with each row representing a species or other taxonomic entity. Such structures can be elaborated by, for example, generating a series of tables for specific time periods, usually months or years. Any multifactorial design implies a fairly rigid data structure with observations available for regular time intervals and uniform spatial patterns. Occasional missing values can usually be accommodated either by interpolation or by suitable procedures in analysis but irregular spatial and temporal patterns are difficult to deal with without considerable loss of resolution.

3. The Quantity of Information. The results derived from a survey will contain information about specified variables in terms of a set of coordinates with defined resolutions along the spatial and/or temporal axes. All will contain a proportion of error variation, but in nearly all instances natural variation will be large compared with any "instrumental" error, though this natural variation cannot normally be measured at all precisely. In attempting to assess the quantity of information required it is necessary to think in such terms as signal-to-noise ratio and variance ratio.

In this context, there are two main classes of variables: those where the cost of increasing the resolution in time or space is not limiting and those where the resolution is limited by the capacity of the instrument or by the effort required to analyse the samples. In the former case the signal-to-noise ratio can be assessed adequately by examining the coherence of observations at a resolution less than that required operationally.

The most complex case of resolution-limited observations are collections of organisms. Where sampling replication is impossible, there does not appear to be any universal or simple solution to the problem of assessing the accuracy of variables derived from such observations. Apart from trial-and-error, which presupposes assessment by analysis of the results by means of coherence within a multivariate structure or by fitting to a pre-existing model, the method which appears to be the most promising is a computer simulation of the survey in analogue or digital form. The requirements for such a simulation are a model which can be used to generate the frequency distribution of the values of the observations within time and space scales set by the defined resolutions required for the system variables, and a set or sets of mean values representative of the range and form of their variability. These values might be obtained partly by carrying out a pilot survey using the methods planned for the definitive survey, or partly by analogy with previous surveys.

One of the primary reasons for this approach to survey design is so that the sensitivity of the end result to each variable may be in time determined and sampling effort adjusted accordingly. For each variable one of the first matters to be determined is to what degree adjacent measurements in time or space are independent or coherent.

Coherence, in the content of biological variability, implies that any pair of observations are lined by more or less complex systems of rate processes: the closer the pair the greater the dependence of one on the other. This is true for spatial as well as temporal variation.

Coherence has important implications for sampling strategy. To take the simplest possible case, a linearly coherent variable can be defined precisely by two measurements. In practice, the measurements are subject to error variation and normally there is no *a priori* evidence on the nature of the coherence in the variable. A range of sampling strategies can be applied. At one extreme a large number of observations can be made at relatively infrequent intervals or spacings to achieve, by averaging, fairly precise estimates at these intervals; or, at the other extreme the sampling can be distributed evenly in space or time to give estimates of as many data on the variable as possible but with less precision.

In many situations multivariate observations can be made with the possibility of coherence within a family of variables which can provide information on the form of the individual variables.

The choice of sampling strategy in a given situation depends on the nature of the coherence within the variable, the extent of coherence between variables in multivariate situations, and the magnitude of error variations.

B. PRIMARY PRODUCTION

A set of eight variables has been selected as those most likely to be required to be monitored when this ecological sub-system is involved in any programme having objectives concerned with production models, probably especially those designed to assess changes in the quantity and quality of the standing stock of phytoplankton to indicate trends in climatic and pollution effects.

1. Irradiance and Day-length. In primary production studies one is usually interested primarily in the total quantity of photosynthetically active radiant energy available in a given period of time (review by Strickland, 1958). This is approximately 0.5 of the energy absorbed by a black body on the surface of the earth. Both long and short wave radiation is absorbed rather quickly by sea water so below the sea surface most of the total radiant energy is in the visible portion of the spectrum (Jerlov, 1957), and is almost all photosynthetically active. The most practical measurement of irradiance is the integral of irradiance and day-length, yielding a measurement with the units of energy per day. The relationship between total irradiance and primary production is not linear, rather there is an intermediate threshold level above which increasing levels of irradiance do not yield increasing quantities of primary production. Irradiance levels can vary quite markedly, especially on cloudy days. The most useful method of monitoring irradiance would be to measure and record incident radiation either continuously or to accumulate incoming radiation as integrals over 0.5 to 1.0 hour intervals.

The expected range of irradiance to be measured is from the minimum level for photosynthesis to about 700 langlies/day at the sea surface, and maximal rates of change with depth are of the order of 10^2/m; irradiance for present purposes should be measured within 5%. SCOR WG 15 (Photosynthetic Radiant Energy) have undertaken the task of devising simple instrumentation for workers using ^{14}C primary productivity measurements.

2. Attenuation Coefficient. WG 15 has investigated the types of instrumentation and techniques necessary to obtain estimates of attenuation of light in the ocean which determines the depth to which primary production occurs and, in addition, the optical properties of the oceans have been broadly classified. The results of these activities suggest that we are now in a reasonably satisfactory position to outline design specifications for a monitoring programme.

Expendable bathyphotometers are under development (Striffler, Woods Hole Oceanographic Institution), based on modifications of the standard XBT, and which can be deployed both from the sea surface and from aircraft. Further development and refinement of this technique could yield a powerful tool for monitoring purposes.

3. Stability and Mixed Layer Depth (MLD). The monitoring of stability and MLD is important for two reasons. The first is that productivity can proceed only when there is some degree of stability, and in areas that show seasonality the establishment of a pycnocline is associated with bloom conditions (eg Sverdrup, 1952); thus, the start of stabilization is an event marker. The second reason is that the degree of stability will regulate the total quantity of nutrients available, which then regulates the maximal size of the phytoplankton standing crop. However, not enough is known about vertical stability in absolute terms in relation to primary production to quote realistic specifications; vertical temperature profiles can provide useful information about relative changes in vertical stability and MLD. Temperature should be measured to an accuracy of 0.1°C and continuous profiles or intensive measurements at 3 - 5 m intervals covering the upper 250 m are desirable. In temperate regions with a marked spring bloom a high frequency of measurement at not less than one profile every three to four days, and perhaps in some cases much more frequently, is required during the period when the thermocline is being formed.

4. Temperature and Salinity. These parameters are only of indirect importance to studies of primary production, having utility primarily as the determinents of the density field, and hence of stability, the significance of which was discussed above. In a monitoring programme they are likely to be measured with sufficient accuracy and precision as part of the general programme.

5. Nutrients and Water Chemistry. For present purposes, chemical elements and compounds fall into two groups: (i) as determinants of primary production, and (ii) as products and/or reactants of primary production.

The first category includes not only the major "nutrient" elements (eg nitrogen and phosphorus) but also elements present in sea water at trace concentrations (such as zinc, cobalt, iron). The second group includes oxygen, various organic compounds and carbon dioxide.

The use of nutrient measurements in productivity studies has had a long history (see Anderson, Parsons & Stephens, 1969; Stephens, 1970), but their future use, especially in a monitoring programme for primary production, is not certain. While the total quantity of nutrients present in the euphotic zone will provide a measure of the potential maximum standing stock of phytoplankton, it is of lesser importance for primary production rate estimates than is the flux of these elements through the plant population. Organic compounds released into the water column as a result of excretion by phytoplankton and products of zooplankton feeding activity are re-mineralized, and a proportion rapidly again taken up by the phytoplankton; this process may proceed at a very rapid rate, so that the amount of nutrient salts present at any given time, the only measure given by water analysis may not be an index of the turnover rate.

The chemical products of photosynthesis will probably not be monitored for primary production estimation, mainly because they enter into a number of other processes and are rapidly dissipated. For example, the detection of a change of 1.0 - 0.5 ml/l of CO_2 in sea water due either to photosynthesis or to respiration presents a rather formidable analytical task since there is normally 40-45 ml/l present and the change one wants to detect is probably within the range of the analytical error of available techniques.

6. Standing Stock of Phytoplankton. A number of data series from monitoring programmes are already in existence, indicating the importance of this measurement. These include:

Time series at a single location.

(a) Station "P" chlorophyll-a; N.E. Pacific, 11 years. (Stephens, MS 1970)
(b) Scripps Inst. Oceanogr. Pier net tows of diatoms; California Current.
(c) Great Lakes; water resources boards, 33 years. (Davis, 1964)
(d) Western English Channel; water colour, 40 years. (Russell et al, 1971)
(e) CalCOFI net samples; California Current, 20 years. (Smith, 1971)

Ships-of-Opportunity, transect series.

(f) Continuous Plankton Recorder; N.E. Atlantic, 23 years. (Robinson, 1970)
(g) Hokkaido University - Chlorophyll-a, 3 years. (Nakajima & Nishizawa, 1968)
(h) AML ships-of-opportunity, University of Washington; US-Japan chlorophyll-a, 5 years. (Anderson & Munson, 1972)
(i) Continuous underway *in vivo* chlorophyll-a, EASTROPAC, etc., c. 20,000 miles. (Love, 1972)

The spatial distribution of chlorophyll-a appears to be a much simpler case to monitor than cell counts and probably is more significant for primary production although, of course, cell counts contain more information in a statistical sense. Experience with the continuous *in vivo* chlorophyll tracks clearly indicates that chlorophyll-a at the surface, as measured by fluorometry, is effectively homogeneous over very large areas of the ocean, and that gradients are observed almost exclusively in regions also exhibiting hydrographic gradients; chlorophyll-a content is an integral of the interaction of both the biological and hydrographic history of the parcel of water under observation. The experience of the American Mail Line transects between the United States and Japan bears this out. After a switch from continuous monitoring to a programme with discrete samples every six hours there was no degradation in data quality. The data from the transects off Japan obtained by the University of Hokkaido also substantiates the observation that gradients are generally encountered in regions that are hydrographically complex.

Such observations have a direct bearing on the design of a sampling programme. Obviously a sampling grid would have to be closer spaced in regions known to be hydrographically complex, eg coastal and near-shore areas.

The frequency of sampling is also governed by other factors. The onset of the spring bloom may be quite rapid and the accelerated growth rate of the phytoplankton at this time may reduce ambient nutrient concentrations to the low "summer" levels in a period of less than two weeks, and this may also be reflected in chlorophyll-a levels on the same time scale. On the other hand, certain areas of the ocean, as illustrated by Station "P", do not experience an increase in chlorophyll-a levels as an expression of the spring increase, and the bloom appears to be limited by grazing. Here there is a relatively uniform level of chlorophyll-a throughout the year, and the phytoplankton "bloom" is expressed only as an increase in the rate of production, and an increase in biomass of the grazing zooplankton.

The estimated range in values is 0.03-30.0 mg chlorophyll-a/m^3, and rates of change of up to 2x/day, 10x/km in the horizontal plane and of 10x/10m in the vertical plane were likely to be encountered. Measurements should be made to the presently available levels of accuracy and precision which, with fluorometry, were of the order of ± 50% for in vivo data, and ± 10% for in vitro data. To be useful, the accuracy and precision of in vivo techniques must be appreciably improved.

7. Community Structure. For the purposes of monitoring primary production certain measures of community structure might be desirable in some cases. For instance, knowledge of the dominant species is important, especially if these can be related to maxima in the size distribution of photosynthesizing particles. Relative production rates of the component species would also be of interest, but perhaps the most important information that can be derived from community structure does not bear directly on productivity, but rather may reflect other processes, such as artificial eutrophication or natural changes in circulation patterns.

8. Carbon Assimilation. The net rate of carbon assimilation, though central in some production models, is a variable whose considerable problems of measurement are discussed elsewhere (p. 38) and which can probably be most usefully determined indirectly (see above) - this variable should usually be integrated over the euphotic zone, yielding values per unit area of sea surfaces. Rates will be found to vary in the range 1 mg - 1 gm C/day/m^2 and to have rates of change of up to about 25x per month at some places, of up to 10x per 100 miles horizontally and up to 10x per 10 m in the vertical sense. An accuracy and precision of ± 5% should be achievable.

C. SECONDARY PRODUCTION

The term "secondary producers" in this text will refer rather loosely to "marine zooplankton". The lack of precision in terminology is deliberate, reflecting the lack of knowledge of food requirements of some zooplankton, the variable food requirements of others, and the commonality of all zooplankton.

In seeking to identify the variables significant for monitoring secondary production it is to be noted that those listed include:- rate limiting effects associated with the organism and the environment, and behavioural responses as influenced by species interactions and by the environment and spatial distribution together with the feed-back or interactive effects between any combination of these variables. The choice of variables, their estimated range and likely effects are somewhat arbitrary; this reflects the present extent of knowledge about secondary production.

1. Day Length. It has been clearly established that light plays an important, if not fully understood, role in the diel vertical migration of zooplankton; other factors associated with light (eg water colour, polarization, turbidity), are also likely to modify the extent and duration of vertical migration, but these are regarded for this presentation as second-order effects and will not be discussed further. Day length, as such, need only be known with the accuracy to be obtained from nautical tables. There is a need to classify zooplankton as nocturnal grazers, diurnal grazers, continuous grazers and variations of the foregoing (McAllister, 1971) in relation to their reactions to illumination.

2. Primary Production. The most likely requirements will be for information on the rate of primary production, the timing of changes in this rate and the duration of the productive season. At present there is insufficient information on herbivore feeding to be able to establish the precision with which primary production must be measured. However, this precision should be at least consistent with the herbivore species' generation time (see Table 2), their mode of feeding with respect to the growing season of phytoplankton, eg, Heinrich (1962), and also, with the diel feeding period.

3. Temperature. It is anticipated that temperature measurements associated with any monitoring programme will be sufficiently accurate for use in secondary production models, as temperature measurements with an accuracy of ± 1°C will be more than adequate for most areas.

The combined effects of temperature and the length of the productive season may control the generation time of organism thereby controlling secondary production. As an example Table 2 provides a list of calanoid copepods from polar to equatorial zones and their minimum generation time. One would expect the results of monitoring changes in temperature, combined with latitude, to explain some of the variation in secondary production.

TABLE 2 - Latitudinal variation in the generation time of *Calanus* and related genera

Species	Area	Temperature range	Min. generation time	Reference
1. *Calanus glacialis* *C. hyperboreus*	Ellesmere Island	~ 1°C	"several years"	Cairns, 1967
2. *Calanus glacialis*	Arctic ocean	surface : 0-12°C 20 m : ~0°C	365-730 days	Grainger, 1965
3. *Calanus plumchrus* *C. cristatas*	Gulf of Alaska	6 - 13°C	365 days	LeBrasseur, 1964
4. *Calanus finmarchicus*	Gulf of Maine	2 - 20°C	100-150 days	Fish, 1936
5. *Calanus finmarchicus*	Clyde Sea	7 - 16°C	45 days	Marshall & Orr, 1955
6. *Calanus pacificus*	California Current	10 - 16°C	28 days	Mullin & Brooks, 1967
7. *Calanoides carinatus*	Gulf of Guinea	20 - 25°C	14-21 days	Mensah, pers. comm.

Rapid temperature changes, due to spring warming (for instance) and evidenced by a poleward march of surface isotherms may or may not be a determinant of the distribution of organisms and therefore important to monitor; as, for instance, Berner & Reid (1961) have shown, the spring march of isotherms in the California Current has no effect on the distribution of some totally passively distributed organisms (Doliolum) while the same phenomenon, in the same area, has great significance in determining the distribution of large oceanic migratory fish, as Blackburn (1965) has shown.

4. Advection. Among physical parameters, advection, including geostrophic and Ekman circulation, is perhaps the most dynamic for it encompasses large and small scale events in both time and space. Tidal mixing may be of major importance in coastal areas while in the ocean internal waves may alter vertical distributions; less obvious, perhaps, is the retention or flushing of coastal waters as a result of shifts in centres of high and low pressure barometric fields. The latter is thought by Wickett (pers. comm.) to be responsible for the dispersal of coastal organisms into oceanic areas where they are frequently lost. For example, herring year-class strengths on the West Coast of Canada have been related to onshore-offshore transport; a great number of species of coastal organisms (stickleback in the Gulf of Alaska, threadfin off Costa Rica, red-crab off Baja, California occur as expatriates hundreds of miles from land by advective processes; in an extreme example, larvae of some species of coastal invertebrates are drifted across the Atlantic ocean (Thorson, 1961).

Rodewald (1960a-d) has analysed the fluctuations of the landings and availability of different commercially important fish stocks in the Barents Sea, Labrador area, and Icelandic waters in relation to the anomalies of winds. All his results indicate that anomalous water transport caused by large-scale variations of atmospheric pressure and winds determine the availability of a number of commercially important fish species, especially in northern waters where they are distributed close to the boundary of their normal range. By predicting the wind and pressure anomalies and the resulting anomalous currents, one would be able to predict the availability of fish in these fishing grounds.

5. Depth of Water. Generally, the water depth determines to some extent the rate at which variables or processes are likely to contribute to secondary production in any area; in coastal waters, where tidal mixing, heating, cooling, range of winds etc. undergo great variability both with respect to locality and season, meroplanktonic forms often dominate.

Perhaps more importantly, some of the species of mass-occurrence in highly productive areas (eg Calanus, Calanoides, Euphausia) require water of considerable depth to over-winter so that over the continental shelf some species are not able to maintain a year round population. In this way, bottom topography at some depth can affect production rates in surface waters and must be considered in monitoring such processes.

6. Standing Stock. The recent methodology of zooplankton sampling has been adequately described (Anon, 1968) and need not be reviewed again here; the present discussion will centre around zooplankton having their major dimension of 500μ or larger, this restriction in size reflecting limitations (such as mesh selectivity) associated with the commonly-used plankton nets.

Time-series of data, as sequences of continuous tracks or repeated point sampling over long periods, are available for some areas. Data from three of these sets have been plotted in a common format in Fig. 1. These diagrams provide examples of expected amplitudes of seasonal and annual fluctuations in standing stock in different situations. As might be expected, the two northern water areas (the North Sea and O.W.S. 'Papa') show a more consistent seasonal cycle of abundance than the data for California. Superimposed on the seasonal cycles, all three areas show coherence between the abundance in successive years. In the northern areas the year to year changes take the form of fairly clear trends in the amplitude of the seasonal cycles, while off the California coast there are more abrupt changes in abundance.

Examination of existing data of this kind can assist in the planning of sampling programmes to meet objectives involving the estimation of long-term fluctuations in standing stock. Monitoring on a finer scale in time and space, to determine local patchiness of the zooplankton, may be required in assessing its availability as food for planktivorous species of fish.

Figure 2 shows the extent of very short-term variability in total zooplankton biomass during different seasons at Ocean Station P. The dotted lines indicate period of bad weather when it was not possible to maintain the sampling schedule of one net haul per day. A & B are representative of the periods of the winter minimum and summer maximum respectively. During these periods the zooplankton biomass is relatively stable, and it is apparent that the frequency of sampling could be reduced without seriously affecting the estimate of the mean monthly zooplankton crop. In the winter (A), sampling could be reduced to once a week while in the summer (B) sampling once every four days would be sufficient. C and D show the variations in biomass at the beginning and end of the zooplankton bloom respectively, ie at a time when day-to-day variations in biomass may be quite large, while at the same time there is a perceptible upward or downward trend in the biomass values (particularly evident in D). During periods of the onset or decline of a zooplankton stock it is apparent that the frequency of sampling must be at a maximum level and that loss of

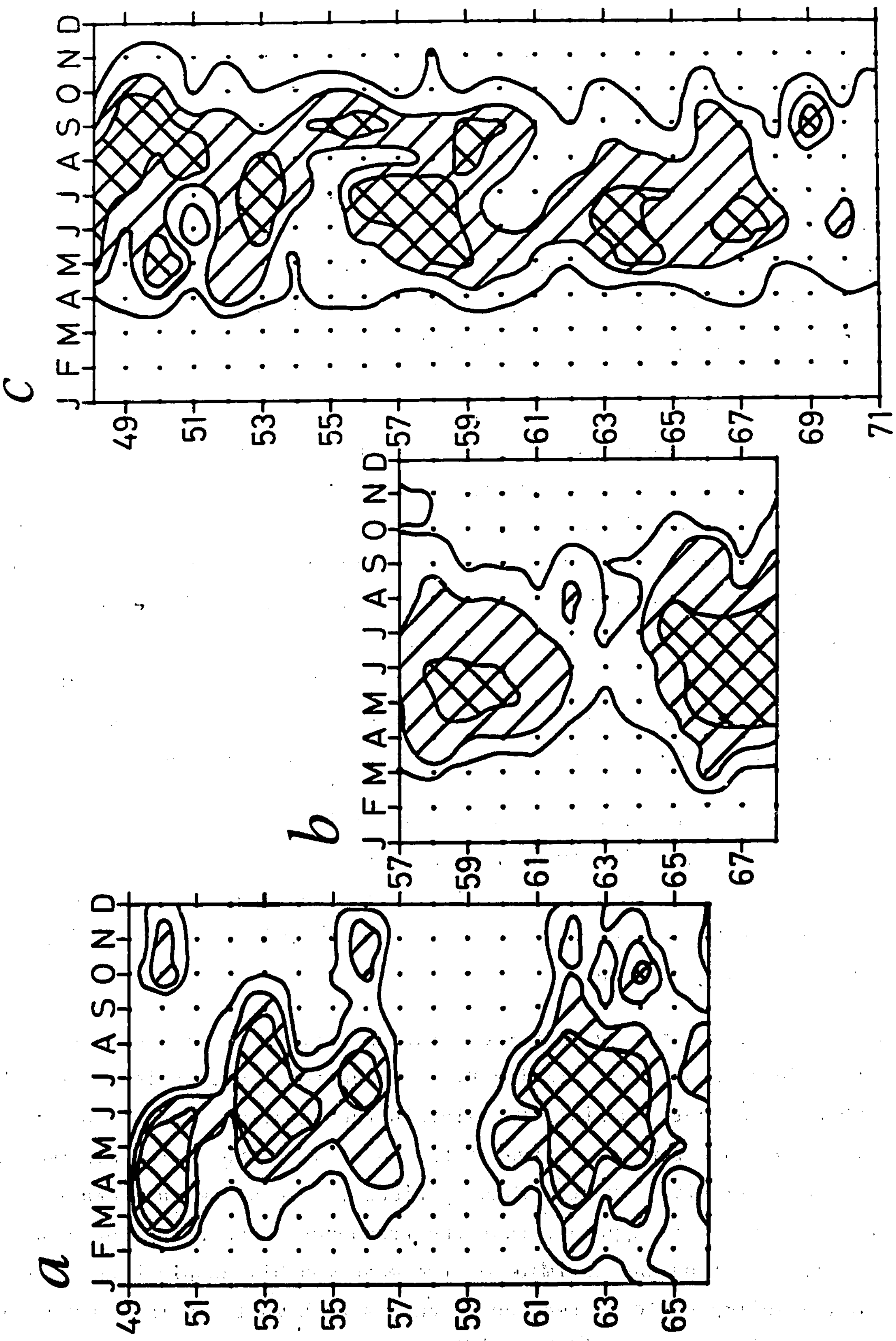

Figure 1. Annual amplitude variability in zooplankton abundance for three areas. A - southern California inshore, 31°-35°N 117°-120°W, settled volumes as mls/m^2; B - OWS "PAPA", 50°N 145°W, settled volumes as mls/m^2; C - west-central North Sea as total copepods/m^3.

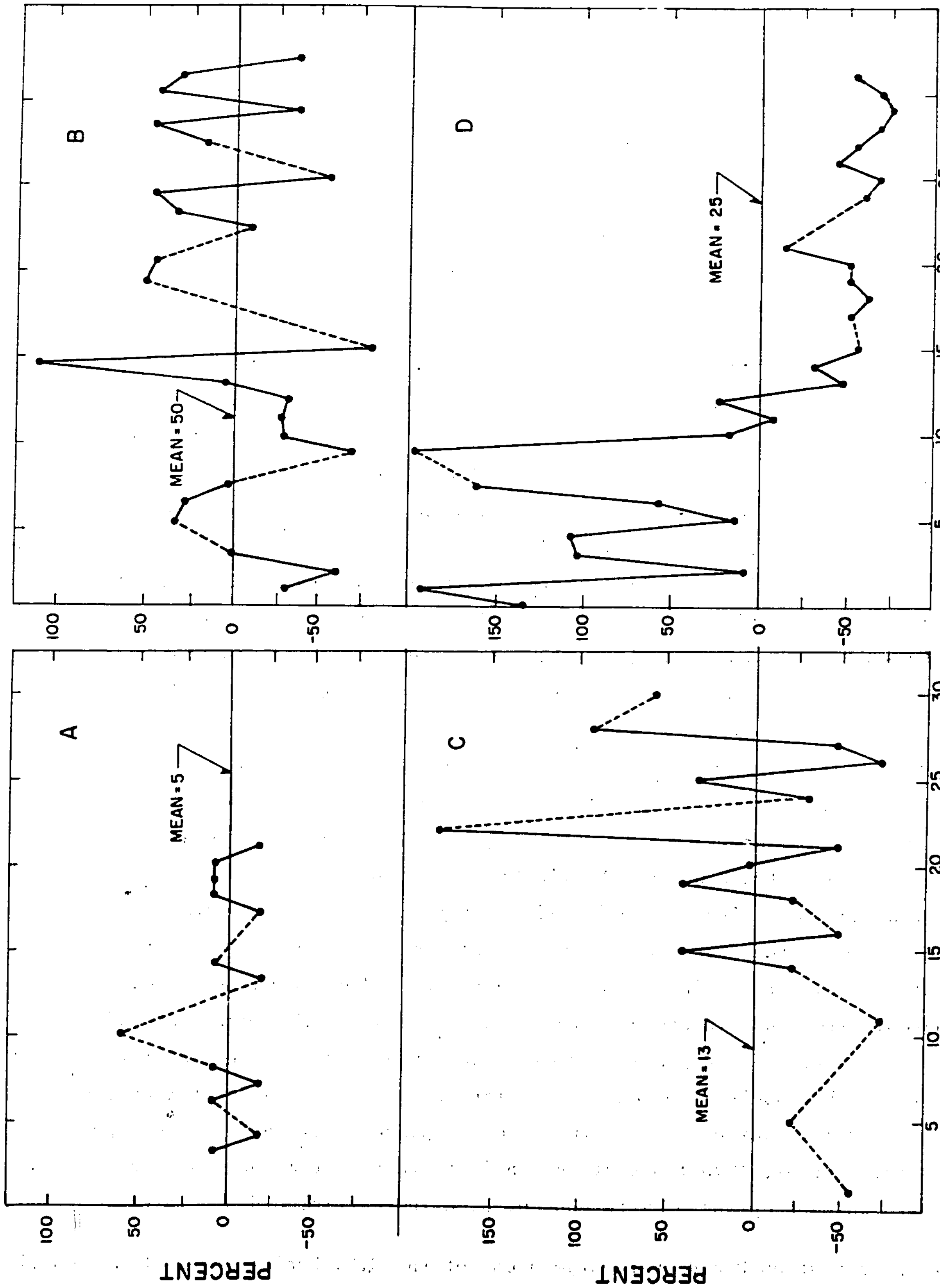

Figure 2. OWS 'PAPA', 50°N 145°W, short-term variability in biomass as indicated by net-caught zooplankton. A - winter, B - summer, C - onset, and D - collapse of bloom. (Mean = sample wet weight expressed as mg/m^3).

data could produce unsatisfactory biomass estimates, eg as in C. Also, during these periods, weekly or biweekly means would provide a better description of the change in biomass than does the monthly mean.

The physical sorting and analysis of samples is time-consuming and expensive, and the amount of effort expended in sample analysis may not be worth the amount of useful information produced. In this regard, particular attention should be directed towards the particular objectives of the study and the desired presentation of the data, when deciding how far to analyse samples.

The fact that the distribution of zooplankton organisms is non-homogeneous and non-random must influence the design of a sampling programme. Zooplankton concentrations may vary by 2 orders of magnitude in 10 metres distance, by 1 order in 10 m depth (Banse, 1969; Vinogradov, 1968) and by at least 2 orders over a 30-day period, at a single location. Such large variations in abundance create a number of sampling problems which are, in fact, minimized in continuous monitoring. At present, the only example of continuous multi-species monitoring programme through both time and space is the IMER Continuous Plankton Recorder, in which the samples are integrated over a 10-mile distance; alternate 10 mile samples are examined routinely, while coverage in time is limited by the frequency of ships' sailings. Thus, much of the variations in standing stock estimates (patchiness) are smoothed out. With such limitations, the sampling is clearly best suited for analysis of long-term trends over broad ocean areas. A rather different example of continuous monitoring may be represented by the programme utilizing American Mail Line vessels as "ships-of-opportunity" on a track between United States and Japan (discussed on p.6). In this study the most rigorous design limitation was that all observations had to be carried out with the vessel underway. This was accomplished by regular sampling of the ships' seawater cooling system for nutrients and chlorophyll-a, and for samples of phytoplankton and microzooplankton. Calibration of the equipment and extension of the observations to depth was accomplished by once-a-year transpacific crossings using research vessels. On one of the latter crossings a high frequency echo sounder (200 kHz) was used to estimate the zooplankton biomass in the euphotic zone, (Barraclough et al, 1970); one of the insights gained from the echograms was the degree to which zooplankton were concentrated in restricted depth layers.

Sampling at Station P and over large areas of the N.E. Pacific Ocean had been limited to vertical hauls (LeBrasseur, 1964). While it was apparent from the data from from these hauls that the food base (zooplankton) was not adequate to support the observed fish and whale populations in the area, it was not until the use of the echo-sounder and other sampling gear (LHPR) actually revealed large, near-surface aggregations of zooplankton that earlier intuitive relationships between secondary and tertiary producers in the area were substantiated.

7. Community Structure. One of the most important descriptions of a plankton community is its particle size distribution (Parsons 1969; Parsons and Seki, 1969). The size frequency distribution may suggest interrelationships which may warrant special attention by the identification of dominant organisms, or feeding experiments, etc. The most common method of community description, however, is to identify and count the most numerous species, grouping all rarely encountered species together, though with this technique the significance of the less common species may be overlooked. For example, an analytic programme for a series of zooplankton samples may identify only the 10 most common species, and may thus neglect the situation in which, for example, the 12th ranked species is a carnivore which because of its food preferences may have a greater effect on the community than any one of the species actually enumerated. In this example, it may have been more informative to specify the community according to the feeding habits of its members.

The most comprehensive analysis of a community requires the identification of each individual of a species to its respective stage of development, maturity and sex in order to describe the species' life cycle. However, it should be noted that exhaustive identifications per se do not automatically yield proportionately more information than judicious identifications. Other methods for examining and describing a plankton community are required, especially if they yield information on zooplankton feeding habits and relationships to other elements in the marine food web.

Other methods of chemical taxonomy which could be attractive both because of the speed of analysis and the information produced might include amino acid composition, hydrocarbon composition, carotenoid composition, antigen response and the development of a system analagous to pathogen-specific fluorescent stains (Bernhardt, pers. comm.). Blumer et al (1971) suggest that investigation of the hydrocarbons of marine organisms may be useful in examining food web relationships.

Review of fixation, handling and analytical procedures for dealing with samples is important since these may seriously limit the information which may be derived from the samples. SCOR WG 23 (Zooplankton Laboratory Methods) have made a number of recommendations in this regard. For example, freeze drying is considered to be the best method currently available for storage of materials for subsequent chemical constituent analyses. For plankton collections which are to be stored as reference material and also to provide routine information on biomass, species and numbers, WG 23 recommend minimizing or avoiding volumetric measurements, measuring separately from other planktonic forms and to minimize the delay between sample collection and fixation in formalin.

D. TERTIARY PRODUCTION

One of the primary objectives of monitoring in biological oceanography is to contribute to the development of models of fish production in the ocean. The evolution, refinements, and coupling of these models into a general production model will doubtless aid in the accomplishment of secondary objectives such as: (1) monitoring long-term changes in overall and specific fish production, (2) assessing changes in the quantity and quality of standing stock of fish, and (3) managing fishery resources.

Present day techniques of monitoring fish populations are labour intensive, and expensive in terms of cost per unit precision. While models of fish production are becoming quite theoretically satisfying, present estimates of some necessary parameters are too imprecise for use as factors, exponents and coefficients in production equations. Data processing is complex and slow so that useful estimates of a parameter may be available too late to be used for resource management purposes. Thus, it is within the scope of this section to consider ways of increasing (1) the amount of relevant data per unit cost, (2) the rate at which relevant data may be delivered, and (3) the variety of information required, by examining the potential of buoys, ships-of-opportunity, planes and satellites to furnish additional information about fishery production and environmental factors on which fish production depends.

In order to determine the priority of new needs to be satisfied by oceanic monitoring, one should work in the context of a theoretical model which should evolve by becoming more quantitative and validated. From consideration of the factors in the model one should get an even more precise estimate of the sensitivity of total fish production to other factors within the model and seek the least expensive way of estimating the most sensitive by monitoring at proper scales of distance and intervals in time. Three general properties for fish production have been selected for discussion here: growth rate, survival rate and reproductive rate.

Growth rate is determined by (inter alia) feeding efficiency (Rosenthal and Hempel, 1970). Feeding efficiency is shown by these authors to be more than a simple function of primary and intermediate production. They give reasons for measuring derived quantities such as patchiness of predators and prey, electivity of predators, perceptual feeding volume per day, and energy expended in the process of feeding per unit food capture. The potential for continuous sampling in space and time from buoys and towed bodies suggest new possibilities for monitoring these critical parameters of growth.

The electivity of fish predators is influenced by relative size and mobility, the extremes being food units so small that energy expended in feeding exceeds yield from food, to prey so large and agile that the energy expended in pursuit and the capture-failure rate exceeds the overall yield; feeding on higher trophic levels may yield more in total growth than feeding on lower trophic levels, conversion notwithstanding. Daily perceptual feeding volume, the effects of turbidity, turbulence, surface disruption by wind waves, diffusion rate, light quality, extinction coefficient, polar back scattering of light, visual contrast, all need to be studied in field conditions to measure the effects on feeding behaviour described in illuminated and placid laboratory conditions.

In a sense, survival rate of fish before reaching harvestable size is determined by the same arguments from the prey point-of-view as used in the growth rate section above as from the predator point-of-view. Survival rate of adults may be an important feature of a population in terms of sustaining reproductive capacity with infrequent recruitment. Stabilization of reproductive capacity by older fish through short term environmental fluctuations has been suggested by Murphy (1966, 1967) for the Pacific sardine. Monitoring the habits of older fish then could aid in the establishment of "preserves" in areas where older fish are likely to be found.

Reproductive rate must be influenced by the degree of aggregation each population is able to achieve. The effects of a fishery, or a subtle change in water clarity, could disperse fish or inhibit reaggregation to the degree that reproduction rate is affected. For this and other reasons the aggregation habits of fish by day and night and by time of month or season would appear to be important to be monitored.

At another scale, reproductive rate limits the ability of a population to respond to improvements in the environment. When fish populations of differing capacity inhabit the same general area the dominant species may be determined by the variability imposed by the environment. Such control of relative species-composition could be determined only by monitoring over several generations of each species and several cycles of change in stability and variability. It should be noted that the foregoing comments on rate effects for fish apply also in a general sense to all components of the biological community.

The list of seven variables discussed below as likely to be of greatest importance in tertiary production monitoring programmes has much in common with those for secondary production; this results from the fact that, although size scales are much different, there is a commonalty in the two levels of the ecosystem in that both contain a high proportion of predatory organisms.

1. Visual Environment. In consideration of the special visual capabilities and needs of fish and other high level predators, more factors may have to be measured than for secondary production and may need to be measured more precisely, and over a much greater range. For example, simple light intensity needs to be measured over a greater dynamic range than that necessary for compensation depth of phytoplankton, or migratory regulation of invertebrates. It would seem reasonable to measure from full starlight to full sunlight. Visual activities at 400-600 meters appear common in tunas, thus it would seem prudent to measure the depth-specific extinction coefficient

to that depth at least. The polar distribution of background contrast in the horizontal plane and the vertical shadow appearance may be of functional importance to fish feeding and predation on fish. The distribution and intensity of bioluminescence and its seasonality could be functional for feeding relations in some circumstances.

2. Temperature. Temperature climates are reasonably well established for the ocean as a whole. The understanding of frontal formation and meandering is likely to assist the critical study of large scale fish migrations and aggregation behaviour and is a candidate variable for monitoring programmes. A continuous description of internal waves may contribute to exploring the apparent association between fish-schools and deep sea mounts. Inasmuch as the analysis of egg and larvae surveys depend on knowledge of temperature, correlated egg and larvae collections would be very useful.

3. Primary Production. Critical measures of the degree of aggregation, dispersal rate, and species composition may have subtle effects on the feeding success of fish. In particular the species composition has obvious effects on feeding of larvae on particulate matter. One may want to be alert to vitamin factors associated with phytoplankton blooms, and similarly, bloom metabolites and anoxia may have direct deleterious effects, evidenced by gross fish kills.

4. Secondary Production. The same requirements for measuring the degree of aggregation and species composition apply to secondary as to primary production. In monitoring, the timing of the onset of secondary production response to primary production may bear on the survival rate of young fish. Specifically larval and juvenile fish may require a rapid succession of widely differing kinds of food: this succession is likely to be a function of the community composition of zooplankton (Arthur, 1956).

5. Standing Stock of Fish. The standing stock of fish is here broadened to include the depth and geographic position of the population and its size or age composition. With continuous monitoring of these features, the geographic and vertical migration rates, growth, and survival could be followed. In the planktonic stages continuous monitoring of winds and currents will assist in the measurement of critical expatriation of brood stock. Necessary standing stock estimates are not likely to be accomplished by automatic means in the foreseeable future and the ACMRR reports on (1) speedier and more direct estimates of fish abundance by acoustic and aerial survey techniques (Parrish, 1969) and (2) egg and larva surveys (Hempel, in press) should be consulted.

There is much published experience on the techniques and strategy for the assessment and monitoring of fish stocks by hydroacoustic techniques using fishery research vessels and such methods have been placed on a routine basis by several nations. However, not much thought appears to have been given to the possibility of monitoring the displacements of fish stocks by hydroacoustic methods from fixed stations, such as active sonar apparatus on ocean data buoys.

Four examples of uses of an acoustic buoy system may serve to guide thought on the utility and feasibility of this approach:

(a) Anchovy Migration - The central sub-population of the northern anchovy (Vrooman and Smith, 1972) occupies an area of 7,5000 to 100,000 square miles off the coasts of northern Baja California, Mexico, and off California. The existing acoustic data on this species, and a few other species with which it schools, indicate a mean density of schools per square mile over the whole area with most schools of fish in the 15-20 meter diameter class, while (on the other hand) most fish are in schools about 50 meters diameter. In the surveys of this area conducted to date, less than 0.25 of the area is occupied by schools at any one time and the schools are themselves aggregated in groups of 400-500 schools in areas about 50 square miles in extent.

Three levels of "buoy effort" may be useful to examine for the purpose of counting the schools, measuring their size; and obtaining their rates and directions and movement; a single buoy, a line of buoys and grid of buoys. A single buoy would adequately measure the rates and direction of migration. A line of buoys, stretching offshore-onshore spaced at 20 to 40 mile intervals to 200 miles offshore would appear adequate for counting the schools migrating past such a line; if migration is rather incomplete, ie some fish north of the buoy transect rarely migrate south of the transect, a grid of buoy transects 120 to 150 miles apart would be adequate for a complete count equal to that presently obtained from shipboard. A grid of 4 x 5 buoys would probably suffice. The sonar range in each would need to be 500 to 2000 meters.

(b) Salmon Migration - The high-seas salmon survey is currently conducted by a labour-intensive drift net sampling transect at right angles to the Aleution Islands monitoring the density and movement of salmon from the Gulf of Alaska into the stream-mouths and bays of Bristol Bay and Bering Straits. Acoustic buoys have been applied experimentally to the same task by inverted echo-sounding towards the surface (Rothschild, pers. comm.), thus counting a far greater sample of salmon than are normally caught in gill-nets, with far less direct sampling effort. The main advantage is that most of the targets can be assumed to be salmon, similar to the case in the Iceland to Norway migration of the Atlanto-Scandian herring stock monitored by shipborne acoustic surveys. The area of monitoring proposed by Rothschild for salmon is about 150 miles wide with a cheap ($1000) buoy each 30 miles, monitored by radio-link from a mother ship.

(c) Hake Migration - Pacific hake conduct an annual migration between Vancouver Island feeding grounds and Northern Baja California spawning grounds. They appear to spend two months each year migrating in each direction, three months spawning and five months feeding. Since migrations are at depth, the northward movement might be monitored by deploying echo sounders mounted on surface buoys in a transect array with ten-mile spacing extending fifty miles off the coast at the California-Oregon border; this should be done every year during March-April.

(d) Skipjack Tuna Migration - The skipjack tuna population of the eastern Pacific ranges over a 15 million square mile area, spawning in the west and migrating to the east as young fish to feed. The eastern Pacific fishery occurs in two areas, one north and the other south of the equator, but the relative amount taken in each area varies widely. It has been proposed that a gateway (or flip-flop mechanism) at ca 130°W operates to partition the population into southward and northward migrating components and that this is controlled by variations in the equatorial currents (Williams, 1972). The eastward flowing equatorial currents could be monitored for skipjack migration by putting coded acoustic tags into skipjack north and south of the equator at 150°W and by placing a line of buoys at 130°W. The numbers of tags and the density of buoys would have to be studied as a trade-off cost system but the number of passive acoustic buoys might be as few as one per degree across the equator from 3°S to 5°N and one each two degrees from 10 S to 4 S and from 5 N to 15 N. Thus 18 buoys may be adequate for monitoring the migrations of skipjack to the north and south equatorial areas, and thus for testing the hypothesis directly.

In this case it may be interesting to compare the direct monitoring of biological targets discussed here with the indirect monitoring of the same process by drawing inferences from a monitoring programme of the current structure of the area after validation of the skipjack migration model.

6. Community Composition. Automatic determination of fish community composition must in all likelihood await development of novel techniques. Obvious ones which come to mind are (1) bio-electronic sensors for determining the mixture of distinctive aromatic substances given off by fish, (2) automatic sampling of surface slicks with analysis of spectral composition of reflected transmitted light (Bullis, 1969), and (3) passive "listening" devices for distinctive sound production by fish. Sampling of commercial fish landings for species, age composition, size, maturity etc. is an established means of monitoring commercial stocks. In addition to providing information essential for fisheries management these data may also reflect environmental changes. FAO has produced a series of reports on sampling procedures and information to be gained from a fish sampling programme (Gulland, 1965, 1966; also Ricker, 1968).

7. Climate. Climate, in its various components, has profound effects on a variety of activities of fish, ranging from reproduction to aggregation, from vertical and horizontal movements to feeding behaviour. To effectively use climatic parameters such as precipitation or barometric pressure it is essential to have an understanding of the biology of the species in question and to identify that aspect of the species' biology being affected eg the reproductive success of many anadromous fish species can be correlated with the timing, duration and amount of local precipitation (Wickett, 1968).

V - FEASIBILITY OF INDIVIDUAL TECHNIQUES

In this chapter we have attempted to reverse the usual question of "which of the available techniques may be applied?" to "which of the needed techniques are available?". For those which are not available we have considered what may be needed to make them available: to improve unattended performance, to lower cost, to develop from existing laboratory techniques or to develop de novo, for example.

This chapter also contains an evaluation of three general problems which may limit the feasibility of many techniques.

A. GENERAL PROBLEMS

Data handling. There does not appear to be a serious problem in the digitization, storage, transmission, and processing of data from any foreseeable system. It is entirely feasible to handle data with presently available technology in any way that might be operationally desirable. Deployment of any satisfactory sensor that might be developed in the foreseeable future need not be delayed or prevented by a lack of communications engineering. The major problem for biologists is to exploit the available technology.

At the beginning of a biological monitoring programme, few, if any of the variables need to be transmitted in 'real-time' or at standard times for synoptic summaries. It may develop that the onset of blooms or the passage of fronts will have important biological consequences affecting, for example, fishing tactics or research surveys which would require 'real-time' data. It is anticipated that telecommunications facilities would be made adequate to such requirements in due course.

Underwater optics. Many of the systems discussed included underwater optical systems and it was recognized that there was presently no way in which optical standards could be maintained for more than very brief periods in underwater systems because of fouling of the glass/water interfaces initially by bacterial films and subsequently by other, more complex, fouling organisms. This was regarded as a problem requiring solution before several of the systems discussed below could be deployed. Several possibilities (a-f below) were discussed to prevent fouling of the water-exposed surfaces of optical systems.

(a) By the inherent properties of the window material. Studies are underway at the Department of Marine Microbiology, Institut für Meereskunde, Kiel, to determine the growth rate of marine bacteria on surfaces of polycarbonate materials. First results show that this material is ineffective because bacterial growth on these surfaces continues even when the number of bacteria in the water decreases due to the lack of nutrients. This phenomenon seems to be caused by the adsorption of nutrients as organic molecules on the surface.

(b) By covering the water-exposed surfaces with a film of an antifouling agent. The optical properties of the agent (eg a molecular metallic film) must remain unaltered by the sea water and be acceptable for operational purposes.

(c) By electrostatic repulsion of particles. This would require charging particles in the vicinity of the surface in the same sense as the surface itself. An α radiator incorporated into the optical material or applied to its surface may be a solution of the problem. In principle, the method appears attractive, but limitations may be imposed by the need to use fairly strong radioactive sources.

(d) By release of repellents through the optical surface. Toxic chemicals can be incorporated into glass and plastics but some marine growth may still occur on very toxic substances. However, the approach is of interest and the technique is probably practical but requires evaluation.

(e) Glass, quartz and plastics will transmit ultrasonic vibrations without mechanical failure; although a direct coupling of the ultrasonic transducer to the material is practical it has been suggested that an intermittant source should be positioned in front of the window. The process requires an energy output of between 0.3-3.0 watts/cm^2 and relies upon cavitation processes, hence is dependant upon the amount of air dissolved in the water.

(f) Finally, by far the most promising practical approach appears to be by sample mechanical cleaning of the optical surface. For instance, for the automatic <u>in situ</u> measurement of primary production is equipped with a rotary windshield wiper to keep its optical surface clean. The system is reported to have worked continuously without failure for two months (see p. 39).

<u>Towed bodies</u>. In mounting a monitoring operation from ships-of-opportunity one of the obvious possibilities is the use of a towed underwater vehicle in which may be mounted sensors and samplers for a suite of variables. Towed body design has been taken rather far for military purposes (towed underwater active hydroacoustic devices, paravanes, and so on) and though many of the problems of high speed towing have probably been solved, the military solutions are "classified" in all circumstances of which the WG are aware.

In any attempt to mount a monitoring survey based on the use of towed vehicles from ships-of-opportunity it is obviously of great importance to retain the goodwill and co-operation of the operators and crews of the ships involved. Two decades' experience with the simple Hardy Continuous Plankton Recorder (CPR) has shown that most ships' captains have been very willing to co-operate provided there is minimal interference with the ship's operations. This imposes a number of constraints on the design of such vehicles with respect to shooting and hauling procedures and the general non-operational environment.

The UK Institute for Marine Environmental Research and the US National Oceanic and Atmospheric Administration are engaged in the development of an undulating towed vehicle which, it is hoped, will replace the Hardy CPR. The vehicle is being designed as part of an integrated scheme which will include:-

(i) An 'in-water' system consisting of the vehicle in which will be mounted a plankton sampler, a set of physical sensors and a data logger.
(ii) Ship-board gear for handling the vehicle.
(iii) Laboratory, test and maintenance facilities.
(iv) Data handling facilities for the plankton and the physical data.

The specifications of the system relating to operations from ships-of-opportunity include the following targets:-

(i) Overall weight in air - 90 kg.
(ii) Length - 1.2m, height - 0.6m, wingspan - 0.75m.
(iii) Maximum towing speed - 20 knots.
(iv) Minimum towing speed - 10 knots.
(v) Winch, davit, recovery aid and transport case to be designed as an integrated launch and recovery package which can be readily dismounted and transferred from ship to ship.

The units of the system should withstand:-

(i) Vibration and shock normally encountered in road, rail and air transport and in manual handling at the dockside and on board merchant ships.
(ii) The conditions of shooting, towing and recovery at ship speeds of 10 to 20 knots in rough seas.
(iii) Exposure on the deck of ships at sea and in harbour at any latitude at temperatures from -30^{o} to $+60^{o}C$ for periods of a few months and up to $+80^{o}C$ for periods of a few hours.

It is clear that the requirements are considerably more rigorous than for a towed body operated from research ships and it seems probable that for all but the simplest of systems such vehicles must be specially designed.

Fig. 3 shows the general form of four towed bodies. The Plankton Indicator (Glover, 1953) was designed specifically for use from fishing vessels and is currently being used in surveys of the plankton of herring fishing grounds off the coast of Scotland. The Continuous Plankton Recorder (Hardy, 1939) was designed to be used from ships-of-opportunity and is being used in a survey of the plankton of the North Atlantic ocean and adjacent seas. The prototype Undulating Oceanographic Recorder is being developed as a replacement for the CPR. The Batfish (Dessureault, pers. comm.) and the Delphin are both undulating towed bodies designed primarily for use from research ships; they can be fitted with a variety of sensor packages.

B. CHLOROPHYLL SENSORS

1. Direct Methods. The chlorophyll-a molecule has properties which can be utilized to sense its presence *in situ*. It not only absorbs light in the visible portion of the spectrum (maxima at 435 and 670 nm) but when excited by blue light (430 nm) it will emit red light (670 nm). These properties have been used to measure the chlorophyll content of the water column (eg Lorenzen, 1966; 1971).

To obtain maximum sensitivity it is necessary to measure light extinction at the wave lengths at which chlorophyll absorption is at a maximum, but unfortunately, water is rather opaque at 670 nm, and many other naturally occurring materials absorb light strongly in the region of 435 nm. At the longer wavelengths one may overcome these problems by using high-energy light sources and a combination of monochromators, and/or colour or interference filters.

Fluorometric techniques depend on certain properties of photosynthetic pigments. Only porphyrins will fluoresce in the red when excited in the blue, and chlorophyll-a emits light at longer wavelengths than the other chlorophylls.

The red light which is emitted is that which is lost from the photosynthetic system and represents only a very small fraction of the energy (1-2%) which is absorbed in the blue. Observations on the use of *in vivo* fluorometric techniques suggest that fluorescence in the red (per unit of chlorophyll) is sensitive to other factors. Past history of the plant cells (eg light conditions and nutrient levels) seems to be important and is manifested in cytological changes, primarily in chloroplast configuration. Actual practice indicates that an accuracy of only ± 50% might be expected when using *in vivo* fluorometric techniques.

Detrital chlorophylls may be a system variable which could be added to the measurement scheme. It would seem possible that by restricting the band pass of a fluorometer either by the use of monochromator, or by interference filters, would improve the precision of the technique. The coupling of two instruments in series and the introduction of acid into the flow line between them may permit one to estimate both chlorophyll-a and its phaeo-pigment form.

2. Indirect Methods. Indirect methods could also be used for the estimation of chlorophyll standing crops. Phytoplankton absorb light throughout the visible range and in geographical regions where few non-living particles (silt) occur in the ocean, an empirical relationship can be established for total light extinction (eg secchi disc) and chlorophyll content; a similar relationship also can be established with turbidity (measured by α meter). Phytoplankton can of course strongly influence the colour of the water column as seen on page 37. All three of the techniques have been used in the past but, for intuitive reasons, one would favour the direct methods over the indirect methods if possible.

It is possible that under some circumstances, notably in the open ocean, it may be sufficient to monitor chlorophyll-a only at the sea surface, as this value has been shown to be correlated with total integrated water-column chlorophyll and also with integrated primary production as measured by the C-14 technique; if, however, it was desirable to monitor chlorophyll throughout the photic zone, it might be practicable to use an underwater sensor similar to those already commercially available (Inpulsphysik GMBH and Zone Research, Inc.) in the same way the vertically 'migrating' STD sensor is deployed on the Scripps lightweight ocean data buoy, the 'bumblebee' (Isaacs, pers. comm).

Instruments to sense chlorophyll from ships-of-opportunity could be similar to those discussed above and two different mounting methods are possible; the sensor could either be included in a towed fish, or water could be brought aboard and passed by the instrument. In the former case, it is envisioned that an optical system similar to the instruments mentioned above, using either absorption or fluorometric techniques, might be incorporated into a towed fish. The data could be either stored aboard the ship or in the towed fish. If it proved to be impracticable to incorporate the sensor in a fish, water could be pumped aboard either from a towed pump, or taken from a water supply through the hull. This would also be advantageous if the water collected could be used for some other purpose, ie chemical analysis, zooplankton collections, etc.

C. PRIMARY PRODUCTION MEASUREMENT

The estimation of primary production is a need common to all the production models listed above, and also to the general production model which is to emerge. What is

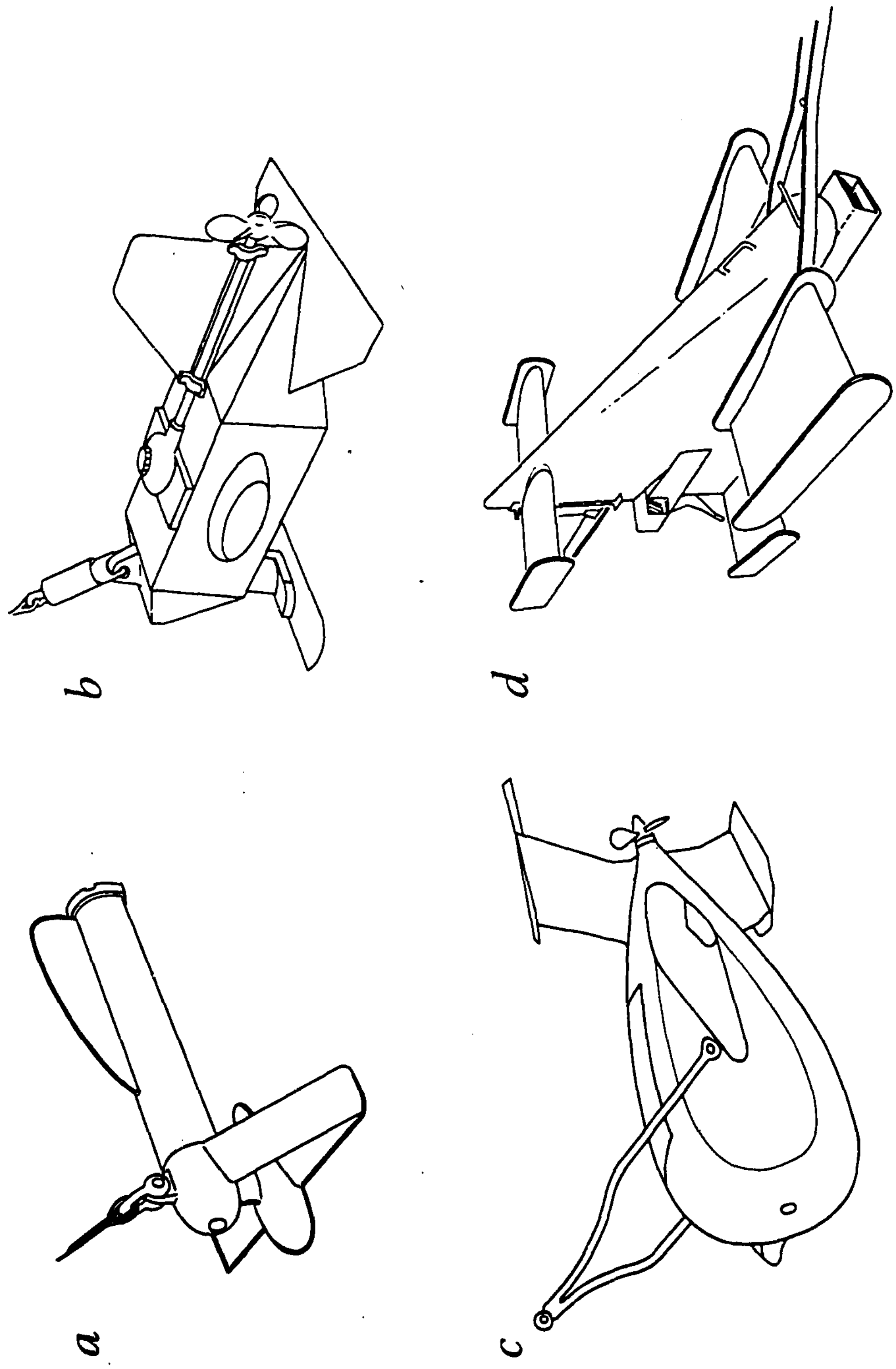

Figure 3. Towed bodies for plankton samplers. a - plankton indicator; b - continuous plankton recorder; c - undulating oceanographic recorder; d - Batfish.

not known is the degree to which primary production must be measured directly. In the following section direct and automated measurement is discussed and also the estimation of primary production indirectly from measurements of controlling oceanographic properties.

The ^{14}C technique, because of its advantages over methods based on rates of change of O_2 or CO_2, has now found almost universal acceptance in oceanic studies of primary productivity.

Unfortunately, the measurement of ^{14}C uptake by plankton algae is plagued by operator-induced variability. In addition, there appears to be no accepted consensus on the proper method of exposing the water sample to light conditions, duration of the experiment, and indeed the interpretation of the resulting count. These apparent difficulties with the technique lead to the conclusion that the method, if it is to be useful, must be standardized. In addition, to be used on a buoy it must also be automated (which in itself may also standardize the method). It may not be necessary to obtain "absolute" estimates since relative numbers may be satisfactory for monitoring purposes.

An engineering test model of an in situ automatic primary productivity instrument (APPI) has been designed and tested (Levin & Lindgren, pers. comm.).

The objective of APPI is to function unattended for several months; the test instrument (Figure 4) is contained in a pressure case (33 cms x 81 cms). The top of this case is a transparent plate which contains the incubation chamber. The case contains all supplies, reagents, recepta les, mechanisms, electronics, logic system, and a programmer. The assay consists of acquisition of the water sample through a protected inlet, addition of a metered quantity of sterile $NaH^{14}CO_3$ solution to the sample, delivery of 100 ml of the labelled sample into the photosynthesis chamber, retention of a duplicate 100 ml in a dark chamber, conducting of a two-hour incubation period, the sequential filtration of the samples through respective 47 mm diameter areas of a membrane filter tape, advance of the tape through a heating chamber to dry the filtered areas, and then advance of the filtered areas to a Geiger tube chamber for the counting of their activity. The data may be recovered by telemetry in real-time on a shore or a boat-based display. The filtering tape is retained in the instrument for future examination of the photosynthetic organisms or verification of the activity counts. Automated housekeeping operations include: pre-assay wiping of the optical window of the incubation chamber to prevent fouling or the accumulation of sediment, post-assay rinsing of the entire plumbing system to prevent fouling, onboard storing of all waste streams, chemical scrubbing of $^{14}CO_2$ released (primarily in the drying step) within the hull to suppress noise, and verifying each completed function.

A difficult problem was that of preventing fouling of the photosynthesis chamber window and other sensitive portions of the instrument. Results from a variety of tests proved a wind-shield wiper to be the best practical solution. After two months of continuous operation, the glass surface remained completely free of any undesirable material buildup and without physical degradation or scratches.

Internal fouling of the various chambers, including the photosynthesis chamber, was similarly prevented through the wiping action created by an O-ring sealing a floating piston to the inner wall of the chamber. The internal plumbing and surfaces of the remainder of the instrument were maintained free from fouling by the application of repeated aliquots of a wash solution between test cycles.

Test results from the APPI are given in Table 3. It is notable that the values obtained by the APPI generally exceed those of the manual method.

Such automated ^{14}C uptake measuring devices may find use not only in a buoy programme, but also on ships-of-opportunity or other platforms.

D. PARTICLE SIZING AND COUNTING

Because the formation, distribution and fate of particulate matter form the basis of exchange and transformation of energy through trophic levels in the ocean it is important for ocean monitoring programmes to be able to identify, count and meas re the various particles.

1. Turbidity. Turbidity is a good index of the total amount of particulate material suspended in water, and such an index can provide an instantaneous estimate of the abundance of particles without the need to collect and filter samples. This could be particularly useful in areas where industrial and domestic wastes are discharged. The disadvantage of measuring turbidity is that it provides no information as to the size or kind of particles causing a loss in light transmission, and for this reason other parameters should also be measured. A beam-attenuation meter system is perhaps the most generally suitable type of instrument.

Such a system requires a minimum of sophistication in instrumentation and gives a measure of the attenuation coefficient of light passing through the water, and this value has a good correlation with the total load of suspended solid if an appropriate range of wavelength of light is used. A double-beam system with a compact monochrometer is preferable for obtaining long-term stability of operation and also versatility in obtaining information other than the overall load of particles, such as their size spectrum and absorption coefficient. The main use of this sort of instrument, however, is in continuously monitoring the variation in the overall amount of particulate material. Concurrent monitoring of particle size and number with the measurement of chlorophyll and (were it practicable) particulate organic carbon would also be desirable.

TABLE 3.

Summary of primary productivity data from comparative trials of APPI and manual techniques (Levin and Lindgren, pers. comm.)

Trial No.	pH	Inorganic C (mg/m^3)	Primary Productivity $mgC/m^3/hr$ APPI	Manual
	Occoquan Reservoir, Virginia			
1	6.6	17,000	96	110
2	6.8	13,400	226	224
3	6.8	12,800	118	113
4	7.0	10,200	505	388
	Lake Lanier, Georgia			
5	6.6	5,420	77	33
6	6.8	6,080	354	154
7	7.1	4,200	16	2.6
8	7.1	3,640	9.1	2.9
9	7.4	5,400	374	186
10	9.6	3,960	708	323
11	8.2	3,600	7.2	1.1
12	7.0	3,830	2.4	1.0
13	7.0	5,220	2.0	0.8

2. Visual Counting. Generally, additional information regarding the kind and abundance of particles is obtained only through visual enumeration. The drawback to the visual counting and identification of particles is the high degree of specialised training required. Many inaccuracies may occur as a result of non-random distribution, counting and handling errors as well as from subjective interpretation. Among the smaller sized particles (< 100μ) identification may be further hampered through the lack of adequate taxonomic descriptions. Furthermore, many of the small particles are fragile and may disintegrate through sampling and handling procedures. Nevertheless, there is a substantial literature which offers a wide range of techniques for identifying and counting particles; these range from traditional microscopy to computer-aided semi-automated recognition systems (Parsons & Seki, 1969).

The number and volume (or equivalent volume) of individual particles in a particular range of size categories may be recorded to produce a continuous size spectrum of biomass in which the principal components of a sample of water are identified by the height and position of a peak in the spectrum. The value of this method is that it is possible to express community structure in quantitative terms using a single technique. The more conventional techniques (biomass measurements, production estimates and taxonomic studies) have tended to view a community at a particular production or trophic level with the subsequent difficulty of attempting to associate one group of organisms with another. In practice, the use of particle size spectra and conventional identification and counting techniques may be carried out concurrently to describe an aquatic community. Parsons (1969) discusses the relevance of particle size spectra to plankton community structure and gives examples of its application to studies of nannoplankton and microplankton. In another report, Parsons and Anderson (1970) demonstrate the use of the particle size spectra concept in a community which ranges in size from primary producers through to juvenile fish. In the latter example, however, several techniques were used to measure size.

Ideally, instrumentation is required which would provide in situ measurements of all particulate material ranging in size from bacteria to adult fish. With suitable engineering the existing instrumentation could probably be adapted to provide continuous size spectra for material ranging in size from 2μ to 20,000μ, ie from bacteria to adult euphausiids. The size spectrum could give equal spacing to various plankton groups, from ultra nano- to megaplankton, following Dussart's (1965) size classification.

The least expensive (in terms of equipment) system for counting and sizing is a microscope and a measuring grid or micrometer. This method is both tedious and slow and is limited to relatively small samples of filtered and settled material and, because of these limitations, it is subject to large counting errors. Systems involving semi-automated techniques have the advantage of working with whole samples or several

TABLE 4

REVIEW OF SEMI-AUTOMATED EQUIPMENT FOR SIZING AND COUNTING PARTICLES IN SEA-WATER

System	Size Range (µm)	Usage	Status	Area	Reference
Optical transmitted light	100 - 1000	Eggs and larvae	Operational	Lab/field	(Mitson, 1963)
	500 - 20,000 in 7 size classes	Temperate zooplankton	Operational	Lab	(Cook et al, 1970) (Fulton, 1972)
	100	Inorganic particles Uniform particles	Commercial	Lab	(Zeiss) (Millipore) (Wild)
Reflected light	2 - 100	Suspended particles	Developmental		(Grasshof, pers. comm.)
	2 - ?	Suspended particles	Developmental		
Electrical	* 10 - 1000 requires several cells; output in size classes	Nano-microplankton	Commercial	Lab	(Coulter Counter)
	20 - 3500	Micro - mega	Operational	Lab/field	(Boyd & Johnson, 1969)
	?	Micro - mega	Developmental	Lab/field	(NRC)
	? - 20,000	Micro - mega	Developmental		
Acoustical		Micro - mega	Developmental		(Grasshof, pers. comm.)
		Micro - mega	Operational	Field	(McNaught, 1968)
		Fish	Operational	Field	(Braithwaite, 1971)

* All require several cells to cover total size range - most accurate for particles with a diameter of 15 to 65% of orifice diameter.

subsamples or making repeated counts quickly. However, they require separate treatment for identification of the organisms. The most common of the mechanical systems for counting are based upon optical, electrical, or acoustical apparatus either separately or in some combination of the foregoing systems. Currently, the least expensive system is one which counts a series of uniform particles in the range of 500 - 1500u (eg fish eggs) using transmitted light and a photocell. Variations, using lenses to focus the light and more sensitive photocells may extend the range of particles counted. A variety of such instruments have been described, (eg Mitson, 1963), which are obviously of use in only very specialized situations. In temperate and high latitudes, where the plankton may consist of large numbers of relatively few species it is possible to identify species on the basis of their size alone. The apparatus reported by Fulton (1972) measures and counts particles in seven size ranges (the ranges may be selected to suit the local situation) through the use of an array of photocells. One sample, diluted to 8000 organisms/l, is counted every 10 minutes. During this time, the most numerous species in the next sample are being identified, and every 5th or 10th sample is treated separately in that all species and stages are counted and identified. This method is satisfactory only where there is a high degree of homogeneity between samples, and where there is a relatively wide range in the lengths between individual zooplankton species.

Semi-automatic measurement (length and/or area) and counting of some categories of small particles in the range 1 - 100μ may be accomplished using a microscope, television monitor and interfacing equipment such as sold by Zeiss or Millipore. In practice, this equipment is not satisfactory for plankton because these are generally complex and frequently overlap in size and form with the result that the microscope-computer assembly is unable to "sort" the shapes as would a human. This apparatus is particularly useful for examining inorganic materials such as sands or muds which consist of relatively uniform shapes and sizes, and perhaps some categories of small hard shelled plankton (forams, radiolarians).

The use of reflected light (the apparatus measuring the amount of light scattering by particles against a known standard) is still in the developmental stage and it is significant that equipment which was commercially available earlier has now been withdrawn. At the Institute for Applied Physics of the Kiel University a system for particle-size spectrometry is under development; a probe has been constructed and successfully tested which measures light-damping in the red part of the spectrum. The resolution is $0.001 m^{-1}$, the maximum operating depth 6000m. A corresponding light scattering meter is presently being constructed.

3. Electrical Sizing. Electrical sizing techniques make use of changes in conductivity or capacitance as particles pass through a theoretically uniform electrical field (Sheldon and Parsons, 1967; Kindlemans et al, 1968). In general, the particle size

must be small in relation to the area of the field it is being passed through (particle diameters should range from 15 to 65% of the field diameter) and its resistivity relative to that of the electrolyte solution must be large. These conditions imply certain practical limitations: for example, flow rate must be controlled since some systems may be rate-sensitive. Several instruments have been developed which, collectively, sample most of the range from 1 to 3500u. For example, the use of the Coulter Counter has been well documented by Sheldon and Parsons (op. cit.) in their manual outlining its use in culture and field experiments with phytoplankton, and in grazing experiments with zooplankton for particles ranging from 1 to 500μ. Boyd and Johnson (1969, and personal communication) report the development of a towed <u>in situ</u> particle-counter for particles ranging in size from 20u to 3500u. In both the above examples it is necessary to use several electrode apertures before covering the full range of sizes. With the Boyd apparatus access to a computer is essential for analysis of the signals. A more versatile instrument which is capable of a faster counting rate and with the possibility of fewer electrodes may be developed by National Research Council, Canada. In this, as with other instrumentation under development, the main constraints appear to be time and financial support. However, data have been published which suggest caution in the use of electronic particle counters; Leslie et al (1972) have shown serious discrepancies between optical counts of plant cells and numbers from two different electronic particle counters. In their abstract they present the following table of comparisons which suggests that for the present, electronic particle counters should be restricted to applications to which they are best suited and most efficient, eg the counting and sizing of unicelled phytoplankton and pure cultures.

Count/Volume Comparisons	r
1. Microscope (cell/ml.) vs. Millipore™ MC (cells/ml)	+0.03
2. Microscope (total cell vol.) vs. chlorophyll <u>a</u> (μg/L)	+0.11
3. Millipore™ MC (cell/ml.) vs. Coulter Counter (cells/ml)	+0.17
4. Microscope (cell vol.) vs. Coulter Counter (cell vol.)	+0.33
5. Microscope (cell/ml.) vs. Coulter Counter (cells/ml.)	+0.42
6. Coulter Counter (cell vol.) vs. Chlorophyll <u>a</u> (μg/L)	+0.49
7. Microscope (plastic spheres, pollen) counts vs. Coulter Counter (plastic spheres, pollen) counts	+0.99
8. Microscope (plastic spheres, pollen) counts vs. Millipore ™MC (plastic spheres, pollen) counts	+0.94

4. <u>Acoustic Sizing.</u> In theory, acoustics would appear to offer the greatest potential for sizing and counting small particles in the sea. However, the only operational acoustic system at present provides no more than a record that particles are present. Thus, McNaught (1968), reports on the use of a 200kHz transducer which was successfully deployed to measure, <u>in situ</u>, concentrations of organisms

ranging in size from 400u to 10000u. This technique is limited by the distance of the particle from the sound source and the relative density of the particle compared to that of the surrounding water. The University of Kiel is working with the use of a continuum of sound waves between 1 and 10 mHz. The sensor using the 10 mHz sound source will detect the integral scattering induced by particles ranging upwards in size from approximately 10u to 1000u. The scattering volume is several cubic centimeters in a distance of approximately 17 cm from the sound generator, the angles of scattering extend 60^o and 150^o. A prototype model is currently being tested under laboratory and field conditions.

5. Laser Holography. The use of holography for particle sizing and identification is being studied at a number of laboratories, for instance by the Food Chain Research Group at Scripps Institution of Oceanography (Beers et al, 1970). Here, the apparatus (by TRW Systems Inc) is intended to obtain an estimate of the total biomass in a water column and to study the in situ feeding behaviour of organisms such as copepods. In practice, the apparatus has not so far yielded the desired information. At present, it seems likely that this research will be continued at only a low level of effort (Beers, personal communication).

6. Acoustic Holography. Acoustic holography may offer another means for particle detection and identification. This suggestion is based upon the supposition that whales and porpoises using a coherent sound background as a reference are thereby able to discriminate amplitude and phase of ultrasound waves. Metherell et al, (1967), report some success in producing recognizable visual images from acoustic holograms. The current status of this technique and its applicability to particle sizing has not been determined.

It should be noted that the foregoing systems whether locally developed or commercially produced are all expensive. There is an obvious requirement for stable electric power and, in addition, reliable servicing. Less obvious, perhaps, is the need for skilled operators and access to relatively sophisticated systems of data processing, ie computers and associated technology.

E. REMOTE SENSORS

This section is concerned with two modes of remotely sensing state variables in the ocean; firstly, from aircraft and from near-space satellites and secondly, from sea-floor mounted capsules in general.

1. Remote Sensing from the Air and from Satellites. This is clearly in its infancy and its probable cost-effectiveness is presently difficult or impossible to assess in regard to any particular case, both in view of the paucity of real experience in operations and of the probably optimistic claims for performance levels of equipment on the part of the agencies deploying them.

In some cases, it is easy to use simple logic to see through the "hard sell": consider, for instance, the case of stated fine-resolution of an infra-red sea-surface temperature sensor aboard a near-space satellite in polar orbit which is arranged to give progressive global coverage. Sensor resolutions may be stated in terms of a "window" on the sea-surface of, say, 4 miles square below the space-craft. This may give rise to an enthusiastic response on the part of an uncritical fisheries oceanographer who requires real-time sea-surface temperature charts with a spatial resolution of this order.

However, in operation it becomes clear (1) that this resolution is available only along a narrow band directly beneath the orbit and separated by a wide zone of much less resolution (because of the viewing angle) from the next high resolution band below the next orbit and (2) that because of interference problems due to water vapour and aerosols in the atmosphere and to imprecisions due to sea-state the data-bits over much wider areas than 4 x 4 miles must be processed to give area means - which may perhaps not be much finer in final resolution than the operational charts received in real-time currently from ship reports.

However, this caution is not to be interpreted that there is no future in remote sensing: indeed, the opposite is the case. The present technological and interpretational problems will gradually be overcome, providing orderly progress can be made and that deflated hopes of immediately operational sensors and spuriously high cost-benefit ratios (which may not be verified) do not politically impede programmes of development.

Remote-sensing equipment, in aircraft or near-space satellite modes, offers novel monitoring possibilities as yet almost totally unrealised; in defining these possibilities and in planning to realise them, it is important that one departs from a proper understanding both of the general nature of what is offered and of the general nature of the constraints.

The general nature of the possibilities offered are, of course, well known and lie in two main areas:

- (i) synoptic data acquisition over large areas, of ocean-basin scale, and
- (ii) detailed data acquisition from smaller areas, in regions otherwise difficult of access.

The general nature of the constraints are not so widely admitted, and perhaps less well understood; they mostly derive from two attributes of the ocean:

- (i) that the superficial layers observable by remote sensors represent only a very small fraction of the total living-space of the oceans, and

(ii) that active lateral transport in the surface layers of the oceans may render fallacious the construction of detailed mosaics of properties by sequential, overlapping passes of a sensor platform.

The resolving power of satellite-borne remote sensors is increasingly fine and presently planned instruments will resolve in the HRIR and visible fields to less than 250m; the utility in terrestrial resource surveys of this resolution by mosaicing from sequential passes is not to be questioned, but this technique seems likely to be less useful at sea where active lateral displacement of surface observables between one pass and the next may render mosaicing impossible or fallacious.

It seems likely that relatively small ocean areas (c.50 x 50 miles) may be scanned in great detail at intervals of several tens of days but it is unlikely that larger regions, especially approaching the scale of ocean-basins, can be detailed significantly finer than the HRIR resolution already obtained from the NIMBUS series of satellites (eg Szekielda, 1970, for the Somali coast), in which the finest observables were features of the order of 10-50 miles across.

The same set of arguments also apply to observations of animals by remote sensors over the seas: fish-schools, whales, fish oil, and bioluminescence may be resolvable by satellite or aircraft sensors but only in transect-format linearly below the flying or orbiting platform. This reduces the utility of the technique to the same order of data acquisition as a survey vessel on the surface, except for faster transit speeds.

Biological observables in the ocean are meagre compared with what can be seen, and quantified, from remote sensors over the continents principally because marine plant life is predominantly microscopic and may be observed only by the alteration in the quality of upwelling radiation by the presence of biochromes, principally the chlorophylls, distributed (as if in solution) in the upper, lighted part of the ocean. The manifestations of distinct plant communities, frequently having well-defined ecotones, on the continents that are well shown in photographic imagery from even relatively distant platforms, thus have no counterpart in the oceans; nor can the effects of disease, agriculture and season on terrestrial plant communities have their counterpart in observables from the ocean,with the limited exception that in certain mid-ocean regions, principally the Sargasso Sea and along the shorelines there are macrophytic plants which are possible candidates for direct observation with remote sensors, and it is only here that MSS techniques might be applied in a manner directly comparable with that for terrestrial vegetation.

Animal life in the ocean is very poorly observable by air or spacecraft sensors: only marine mammals, marine reptiles and some of the schooling fish are regularly and directly observable at the surface; most oceanic animal life, and all of that which is at the base of the food chain, comprises relatively small particulate matter contributing probably only slightly to the overall spectral quality of the upwelling radiation from surface waters.

Since the biological processes in the ocean are so meagrely observable by remote sensors as presently conceived, the most important questions facing us are not the technological difficulties involved but rather the identification of real problems for the solution of which equipment may be devised, once the problems themselves are properly defined. In such exercises it is important to examine the possibility of cheap, indirect solutions as well as examing direct solutions which may be no more effective, and much more expensive.

The most frequently listed candidate observables are probably the following:

(i) chlorophyll content of surface water, by upwelling radiation at around 0.5um.

(ii) surface occurrences of large organisms (whales, porpoises, seals, turtles, schools of tuna) mostly identified by the nature of their surface disturbance patterns.

(iii) sub-surface occurrences of large schools of small, tightly-packed fish, mostly clupeids and trachurids, identifiable by the spectral quality of light reflected from their dorsal surfaces.

(iv) occurrence of ephemeral molecular surface films of fish-oil emanating mostly from schooling clupeid fish) by the alteration of the spectral quality of upwelling light (see p. 50).

(v) occurrence of similar films of oil in areas of high biological production compared with nearby areas of low production, said to be observable by modification of the quality of the sun-glint pattern (Bowley *et al*, 1969).

(vi) sub-surface occurrence of bioluminescence at night (Bullis, 1967).

This is a very slight list compared with the wide spectrum of variables of marine biota that are measured in the course of general research and monitoring in the ocean; it is facile (but regrettably frequently done) to propose that such observations as are listed above may be used to monitor cycles and location-shifts of primary productivity in the ocean, both as an aid in understanding the process and (at its most naive) 'to direct fishing fleets to areas of high production'. It is at this stage, the 'justification' stage, that the literature of remote sensing in general is probably weakest. There appears to have been relatively little operational analysis by biologists on behalf of engineers in the marine application of remote sensing equipment to monitoring, and the analyses by engineers tend, with reason, to identify justifications which may not stand up to critical analysis.

Chlorophyll is, for many reasons, widely accepted as the prime candidate biological observable for systems remote sensor deployed over the ocean, and it has been widely proposed that such systems could monitor, either over wide ocean areas or in special (usually upwelling) situations, the processes of primary production. The work presently being organised by a consortium of US scientists and the FAO-CINECA Project to study the upwelling process off N.W. Africa with ERTS-A MSS sensors, and using FAO vessels for ground truth is certainly likely to add to our understanding of the upwelling process by providing rather detailed maps of surface temperature and chlorophyll, so that the evolution of an upwelled bolus of water can be followed after it has reached the surface and moves away from the upwelling site, while its chlorophyll content increases as a bloom of phytoplankton develops within it.

Furthermore, it may be possible to specify the nature of the dominant groups of organisms involved in phytoplankton blooms monitored by remote sensors; it has been demonstrated that the reflectance spectra of blue-green algae (Cyanophycae) and green algae (Chlorophycae) may be distinguished by a peak absorption at 0.650u in the latter group, absent in the former. This might be extended to differences between natural communities succeeding or replacing each other in the open sea.

At the present time, research (see Clarke et al, 1970a, 1970b) is progressing along a number of different avenues in search of a satisfactory sensor. All of the proposed techniques would utilize the quantity and quality of the backscattered light as a measure of the quantity of chlorophyll-a present in the surface and near-surface waters. Basically the colour one observes from above the surface is light that is backscattered from the water and modified by suspended and dissolved substances and by the quality of backscattered air light from the atmosphere (Curran, 1972; Tyler & Smith 1967, 1970). In the open ocean, and in areas unaffected by land run-off and tidal mixing the signal received above the surface is a reasonable estimate of the surface chlorophyll content. One should expect interference if the sediment load is heavy, as near the mouths of large rivers, and where shoals of fish (eg menhaden) stir up bottom sediments; the possibility that the signal may be interfered with by contaminants must not be ignored.

Promising techniques for remote chlorophyll sensing under development at the present time include: (1) multi-spectral scanners, either television, or film packs incorporated with light filters, and (2) photomultipliers coupled with prisms or diffraction gratings by which a complete scan is received of the backscattered light, and (3) laser fluorometry. Multispectral scanning works at reasonably low altitudes, that is from 15,000 feet down, and some experiments have carried the technique to

45,000 feet, so it appears that they should also work at satellite heights. At the present time, these remote sensing techniques are being employed only in a development mode. Laser fluorometry or 'Lidar' (Collis, 1972; Kim, 1972) has been tested successfully at heights of <100m from helicopters for rapid in vivo survey of surface chlorophyll. The lidar comprises a xenon/dye (Rhodamine 6G) laser 15 cm telescope receiver; the laser has an output of 250 mJ in 500ug pulses and peak transmittance at 680 nm. Efficiency of fluorescence for chlorophyll-a at 5µg/cm^3 in situ was 7.0 x 10^{-8}W per incident watt of the 590 nm light.

Lidar is an example of an active rather than a passive remote sensing system; another such may be the forward and side-scanning radar which is present in many commercial aircraft for the purpose of measuring ground speed and lateral drift. The frequency of these radar signals is sensitive to the sea surface film so that it is possible to distinguish smooth from rippled surfaces by the return signal. Guinard (1971) and Katz (1965) have used this technique to show areas of slicks. It might be possible through the use of "aircraft-of-opportunity" to extend this technique for the routine monitoring of areas of upwelling and convergences.

2. Remote Sensing from Sea-floor Mounted Capsules. In recent years there has been a considerable development of automatic and semi-automatic 'water-quality monitoring stations' for deployment in rivers and estuaries, and in sewage and industrial effluents to monitor the level of various contaminants either directly or indirectly. Very little of this technology has passed across to biological oceanography, even to enterprises in inshore waters, though much of it seems to be applicable.

These water quality stations are mostly modular and are deployed in several ways - on buoys in harbours and estuaries, on the banks of rivers and estuaries with a submerged intake and a pipeline to the analysis module, and beside sewage and industrial effluents with the module indoors in an analytical laboratory; finally, in a few cases, the modules are designed to be laid on the beds of rivers or estuaries and to work unattended in depths up to about 50m for periods of 3-4 weeks.

The variables most commonly monitored at present are: O_2, pH, conductivity, $CaCO_3$ hardness, suspended solids, NO_3, NH_3, Cl. Drake (1972) usefully reviewed this field, tabulating a range of 19 presently available instruments. He also suggested the areas in which R. & D. was likely to move the capability forward, and listed needed developments. Clearly, this is a technological field which should be familiar to oceanographers planning to monitor the marine environment, especially in coastal and estuarine regions.

F. BIOLOGICAL ASSAY AND SENSORS

Animals, parts of animals and plants may be used to monitor environmental conditions, either natural or the results of technology on the oceans. There appear to be three main approaches to this technique of monitoring:

1. Biossay - the performance of sensitive test organisms, often in vitro, as in pharmaceutical testing.
2. Bio-accummulators - the use of natural or deployed organisms, in whose tissues contaminant levels reflect those in their environment.
3. Bio-electronics - the use of the neurological responses of sensor organs and organelles, in vivo or in vitro, to determine levels of environmental variables, including contaminants.

1. Biossay. Classical bioassay tests, to determine the concentrations of contaminants or the effects on biota of various concentrations of a contaminant, can be used as a monitoring technique by repetition in time. Most of the tests currently in use are based upon the death-response (LD 50, or the time taken for 50% of the test organisms to die at specified levels of eg contamination, but this may not be entirely satisfactory in instances where extrapolation from bioassay tests used in monitoring programmes is required in order to estimate effects in natural populations because:

(i) The effects of a pollutant upon organisms at sublethal concentrations may be as significant for the survival of the population in the long-term as a lethal concentration.

(ii) Toxicity tests, run for short periods, may have little relevance to what happens to organisms continually immersed in even lower concentrations. Toxicity tests appear suitable for ranking the pollutants according to their relative toxicities and actual concentrations, but not for making predictions on what their effect may be on what their effect may be on biota.

For such reasons, increasing attention is now given to sub-lethal responses indicated by physiological or behavioural indices of stress. In this context "stress" may be defined as a disturbed physiological steady-state condition. The disturbance may be temporary or permanent, but it is measurable. A permanent change in a physiological steady-state condition may render the animal or the population more sensitive to further environmental change. Laboratory studies are necessary to determine the ultimate effects of the altered physiological condition. Some examples of tests presently under development are: yeast respiration rate, phytoplankton division rate, growth rates of *Fucus* and *Ulva*, development of invertebrate larvae, growth rates and settlement of oyster larvae.

The choice of organism for this type of work is critical and it is worth listing some of the features that are desirable:

(i) Sessile organisms that are easy to cultivate in the field or laboratory.

(ii) Organisms that are sensitive to, but tolerant of, a wide range of variables with easily measured features reflecting their sensitivity.

(iii) Organisms which may be cultured as clones to exclude genetic variation.

2. Bio-accumulators. The deployment of organisms to indicate contamination levels in the environment by their own levels of contamination has been usefully reviewed recently by Butler (1970). Bivalve molluscs have proved particularly useful in monitoring programmes not only because of their capacity to accumulate both metals and chlorinated hydrocarbons (DDT, for instance, to x 70,000 over ambient), but also because of their ability to flush these compounds from their tissues when the water becomes less contaminated.

An estuarine monitoring programme in the USA (Butler, 1969) has utilised these properties over the past decade or so both to determine trends in levels of hydrocarbons in the environment by assaying bivalve tissue from 170 permanent stations but also in identifying specific sources of pollution in areas receiving industrial effluents.

This type of monitoring provides information on the build-up of pollutants in the tissues of food species. Monitoring in order to prevent biological damage requires both laboratory studies to determine short and long-term effects, and the study of animals receiving discharges in the field.

3. Bio-electronics. This is an almost undeveloped area of R. & D., in which it is sought to harness the potentials of the sensitive receptor organs and organelles of marine organisms. Snodgrass (1972) has recently reviewed this topic. To quote from his text -

> "........... the feasibility of utilizing living bio-sensor mechanisms as part of our sensor package. Many marine organisms possess chemo-receptor mechanisms that respond to extremely low levels of chemicals, some of which are pollutants. It is suggested that we might well be able to extirpate suitable chemo-receptor mechanisms complete with their afferent nerve to which we can attach microcircuit amplifiers and signal conditioners even with the power supply. The whole could be mounted in a suitable package with semi-permeable membranes to

permit passage of the measurand but to prevent the passage of undesirable bacteria and viruses. Suitable nutrient solution would need to be utilized properly buffered. It is proposed that cold-blooded systems be employed since their metabolic demands are minimal and further, and very significantly, the rate of accumulation of metabolites is extremely low and manageable. The complete package would in a sense be a bio-electronic sensor system".

The application of techniques such as those outlined here to monitoring programmes, would clearly be very great, if feasibility could be achieved.

G. PLANKTON SAMPLERS FOR TOWED BODIES

Two plankton sampling systems have been used in monitoring surveys involving ships-of-opportunity; they are the Plankton Indicator and the Continuous Plankton Recorder.

The Plankton Indicator (Glover, 1953) is a very small (c. 30 cm) tubular, high speed sampler used primarily from fishing vessels. A survey of the herring fishing grounds in the north-western North Sea (Bainbridge and Forsyth, 1972) has been maintained yearly since 1947 and an average 1000 samples have been collected in each year. This survey is an example of how to mount an effective long-term monitoring survey using unsophisticated methods which could readily be adapted to other areas.

In this sampler the plankton is collected on a simple silk gauze disc mounted in a holder across the exit aperture of the tube; it would be possible to adjust the mesh size of the gauze so that particles in a selected size-range were captured. After deployment, the gauzes are removed from the holder and preserved.

The Continuous Plankton Recorder (Hardy, 1939) has been used in a long-term survey of the plankton of the North Atlantic and the North Sea. Plankton Recorders are towed at monthly intervals by merchant ships and Ocean Weather ships along a number of standard routes; in recent years the survey has produced, in each year, over 250 records and well over 1000,000 miles of continuous sampling. More than thirty vessels of seven countries have taken part in the survey.

The Plankton Recorders are towed at a fixed depth of about ten metres and sample the water through an aperture of ½ in. square. The plankton is filtered through a slowly moving bank of bolting silk which has an aperture of 300μm. The plankton is held in place by a second band of silk and the double band is wound onto a storage spool in a tank containing formalin; about 10 cm of silk is wound through the machine for every ten miles of tow during which about 3 cubic metres of water are filtered. When each Recorder is returned to the laboratory the roll of silk is unwound and divided into sections each of which represents 10 miles of tow. For most routes, the plankton are counted for alternate 10 mile sections of silk.

In recent years, several organisations have considered extending the CPR survey from its present relatively high-latitude coverage (areas where plankton may generally be relatively large and abundant) to lower latitudes where the tropical plankton is smaller and frequently less abundant; but it has not been clear whether the CPR would sample adequately in such areas. To test this three sets of tows were taken in warm water areas. The cruises investigated were:-

(i) METEOR : four tows in the Mediterranean in May 1965.
(ii) OCEANOGRAPHER : five tows in the warm water of the North Atlantic drift system in April 1967.
(iii) OCEANOGRAPHER : six short tows in the Indian Ocean in July and August 1967.

A comparison of the numbers of organisms in the samples taken in these tows with those taken in the North Atlantic indicates that the samples are probably large enough to make meaningful studies of the fluctuations in abundance and the distribution of the plankton in these warm water areas.

The principle of the CPR sampling mechanism has been further developed in the Longhurst-Hardy Plankton Recorder (LHPR) so that both gauze strips filter plankton, and the gauze is stepped by an AC motor programmed by a recorder control unit which also monitors temperature, salinity and flow (Longhurst et al, 1966; Benthos Inc.); though deployed so far only in a vehicle unsuitable as a towed body for monitoring programmes this development could readily be modified for such use.

The same principle, of stepped discrete samples rather than a continuously advancing gauze, is presently being used in the development of the second-generation plankton sampler for the IMER/NOAA Undulating Oceanographic Recorder (UOR); the first-generation sampler is a 'stretched' 1500-mile version of the CPR sampler. This second-generation sampler will probably be based upon a series of separate opening-closing packets which will include a filtering area and will be sequentially exposed across the water tunnel somewhat after the fashion of a 35 mm slide projector. The UOR itself is under development in response to a need to develop a method of sampling behind ships-of-opportunity that would integrate plankton collections over most of the mixed layer rather than sampling only at the 10 meter level, as does the CPR.

H. PLANKTON RECORDERS FOR DATA BUOYS

The deployment of ocean data buoys for other purposes naturally has raised the question of whether or not it might be practicable to utilise them for direct sampling of plankton and automatic storage of the samples.

An ingenious start towards solving some of the problems of sampling from a buoy has been made (Isaacs, pers. comm.). By employing the vertical motion of the buoy in response to wave action it is possible to pump water through an LHPR-type filter mechanism. One can visualize this system developing into a satisfactory buoy-mounted plankton sampler.

If, indeed, the pumping problems can be solved, the filtration and storage of reasonable numbers of samples should present no serious difficulty. The CPR or LHPR filters could be used for the zooplankton, membrane filters for the phytoplankton and, if the fixation problem can be solved, small volume water samples could be used for the micro-zooplankton and nannoplankton.

One application of a pumping buoy would be to supplement or replace oblique plankton tow samples for a fish egg census. An egg census, to be effective must define (1) the geographic boundaries, (2) the vertical distribution profile, (3) the seasonality of spawning, and (4) the fine-scale pattern of eggs. The fine-scale distribution of many fish eggs is complex owing to their deposition by schooled adults and their subsequent diffusion by various scales of turbulence through the mixed layer of the ocean. To appreciate this complexity and be able to distinguish between unimportant and important differences in the number of eggs, one must have many positive samples of eggs at all seasons, in all regions, at a representative set of development temperatures, and at all states of dispersion. Intuitively one would expect a buoy, with a capacity for obtaining continuous and contiguous samples over an entire season, to enable improved estimates relative to the point sample oblique net tows. Also, if the intake of the pump were continuously moved from 140 m to the surface and the temperature were simultaneously recorded, the resulting improvement would permit a better estimate of the development rate and residence time of the egg than is presently possible from integrated oblique net tows.

Perhaps the greatest barrier to the use of buoys for egg census work would be the requirement to define the perimeter of spawning. The area to be sampled is probably defined initially by the physiological limits and behavioral preferences of the spawning stock, and these limits are probably filled proportionately to the size of the spawning stock. One may expect from the patchy nature of the eggs, that the perimeter of the spawning area may well be quite uneven. For example, an organism occupying a 75,000 square mile area for spawning, would require perimeter definition for 1 to 2 thousand miles for simple circular or elliptical spawning area shapes. Complications caused by, for example, currents would further lengthen the perimeter. Perimeter definition by buoys would appear to require unreasonable densities of implacement.

Another practical problem would be to determine the probability of obtaining eggs in each unit sample, and how many eggs per unit sample there might be. This markedly affects the costs of sorting since the precautions one must take in the sorting of rare objects are somewhat more demanding than those needed for common objects. For example, we have chosen a series of anchovy egg counts from the Los Angeles Bight where the anchovy is extremely common. To convert data from oblique net tows, which use the unit number per 10 m^2, to data applicable to a pump, expressed as numbers per m^3, one must make some assumptions about the vertical distribution of eggs. For the purpose of this report, we have chosen to assume that all eggs are in the upper 40 meters. In the following frequency distribution table, are listed the results from a 102-sample series of net hauls taken in February, 1971:

eggs per 10 m^2 (net)	eggs per m^3 ($\therefore$ pump)	station frequency
<1024	<3	17
1024 - 4095	3 - 10	55
4096 - 16,383	10 - 41	29
$>16,384$	>41	1
		Total: 102 (stations)

A third practical problem would be to get representative regional numbers of eggs per unit area. From examination of the anchovy spawning area of 75,000 mi^2, over the past 20 years, one would judge that representative data could be taken by one buoy per 5000 to 20,000 square miles, or 4 to 15 buoys/ in three lines 250 miles apart, normal to the coast, the outermost buoys being about 50 miles from the coast.

In consideration of the superior definition of spatial pattern, vertical distribution, and definition of temperature-specific development rates and the resultant residence times necessary for quantitative sampling, which pumping buoys might offer, one might overcome the perimeter definition problem by use of the buoy tender to perform the delimitation of spawning areas. In any case, the temporary deployment of pumping buoys would serve to evaluate the spatial and temporal errors inherent in the net tow survey: the trial deployment would also allow one to evaluate the relative costs of surveys conducted by either technique or some combination.

I. HYDROACOUSTIC TECHNIQUES

The applications of hydroacoustic techniques to monitoring discussed earlier would demand some advances in current technology (eg see Thorne & Lahore, 1969); since power requirements, signal-to-noise ratios and installation costs vary widely from platform to platform, the hydroacoustic systems for ships and buoys will be discussed separately.

The major alternatives in mounting acoustic gear on ships-of-opportunity are (1) hull mounted, (2) pylon mounted and (3) towed transducers, the relative cost of installation rising as signal-to-noise ratio is improved. Considering the speed and resultant noise of commercial ships the power probably needed will be at least 2 kw. Flush through-the-hull mounted transducers can only be used in the sounder mode and would be noise-limited at frequencies less than 30 kH, and performance will vary with sea state. Pylon mounts, projecting away from the ships hull, could be entirely external and sampled for noise at specific frequencies of interest. Sounder performance would be markedly improved but sonar from the pylon would still vary with sea state. Towed transducers would allow good sonar and sounder performance at all sea states but would require major expenditures for launch and recovery of a towed body, permanent cable fairing, winch and block specialization for storing and handling the faired cable; occasional loss of equipment would be expected. Since no deployable system presently exists, development time and costs would be substantial.

The information to be collected by the sounder would be depths and target strengths of individual fish, schools of fish and invertebrates, and layers of fish and invertebrates. The sonar would be used to collect data on the horizontal size and density of fish schools in the upper mixed layer.

Existing acoustic equipment could be mounted on buoys if the heavy power requirements could be met. In a buoy with little self-noise the pulse power of the sounders and sonars could be low, in the 500 to 1000 W range. Lower frequencies also could be used. Passive hydroacoustic receivers could be employed to monitor and record marine mammal and fish noises, and the passage of fish-mounted acoustic tags for migration studies. The best strategy for power conservation for the sounder would be infrequent pinging; for example, all the interesting features of scattering layer migrations could be described from one 10 m sec. pulse each 15 minutes, though this would be useful only on buoys moored deeper than 500 m. The sonar could be programmed to pulse 1 m sec. each second for a minute each hour or 2 hours. There would be performance gains from mounting the sonar transducer at 10 - 50m depth.

Acoustic monitoring of volume reverberation may serve as an index of particulate matter including zooplankton. This parameter shows changes with time space and with frequency of emission. (Anderson, pers. comm.).

VI - RECOMMENDATIONS

A. That the section of this report concerning the feasibility of various individual techniques and methods be considered as a series of recommendations both for positive courses of action and for cautions as to low probabilities of success of individual techniques.

B. That working groups be set up to perform critical reviews, more detailed than was possible for this report, and to recommend courses of action in three particularly critical fields of R. & D.

1. Towed body systems, including underwater vehicles, towing systems and deck modules for deployment from ships-of-opportunity; consideration should be given to a study of likely future trends in maritime transportation relevant to this problem: deck design, speed, scheduling strategy, and routing of candidate classes of ship.

2. Automation of plankton sorting, counting and identification of taxa, for both phyto- and zooplankton.

3. Design strategy for sampling and analytical procedures in monitoring as opposed to survey programmes.

C. That reviews of the status of the techniques of monitoring in biological oceanography should be repeated at intervals of from two to five years, in recognition of the rapid evolution within the field.

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In addition to the above three recommendations pertaining strictly to their terms of reference WG 29 wished to extend their list with the following two recommendations concerning the data resulting from monitoring programmes in biological oceanography:

D. That the sponsoring bodies should, in implementing the various resolutions of the Stockholm conference (nos. 87, 90, 91 in particular) concerning the monitoring of marine pollution, also take note of the importance of the monitoring of natural variability by the methodologies reviewed in this report, for without a proper understanding of the ranges and causes of natural variability, it is not possible to interpret the results of pollution monitoring programmes.

E. That the sponsoring bodies should give every practicable encouragement to individuals and to agencies, world-wide, in assembling, processing, indexing and (most importantly) assessing time-series data from the ocean in order to further our understanding of the actual processes of variability and to estimate how well our ongoing programmes have served to monitor these processes.

VII - ORGANIZATION OF ACTIVITIES

This Working Group was established in 1968 on the initiative of SCOR which invited the ACMRR of FAO to be co-sponsors. Together with IBP/PM and UNESCO, these organizations nominated the ticicipants who are listed below who met from 25-29 May, 1970 at the NMFS Southwet t Fisheries Center, La Jolla, California and from 6-17 March, and 5-8 December, 1972 at the NERC Institute for Marine Environmental Research, Plymouth, England. Drs Beklemishev and Clarke participated by correspondence.

Dr C W Beklemishev	Institute of Oceanology, Moscow.	SCOR
Dr J M Colebrook	Oceanographic Laboratory, Edinburgh, Scotland.	IBP/PM
Dr G L Clarke	Biological Laboratories, Harvard University, USA.	SCOR
Dr K Grasshof	Institut für Meereskunde, Kiel, Federal Republic of Germany.	ACMRR
Dr R J LeBrasseur	Fisheries Research Board of Canada, Nanaimo, British Columbia.	SCOR
Dr A R Longhurst (Chairman)	Institute for Marine Environmental Research, Plymouth, England.	SCOR
Dr C J Lorenzen	Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.	UNESCO
Dr S Nishizawa	Laboratory of Oceanography, Tohoku University, Sendai, Japan.	SCOR

In addition, the following consultants participated in the second meeting:

Dr M Ehrhardt	Institut für Meereskunde, Kiel Federal Republic of Germany.	ACMRR
Dr E Fagetti	FAO, Rome.	ACMRR
Dr E I Hamilton	Institute for Marine Environmental Research, Plymouth, England.	NERC
Dr P E Smith	NMFS Southwest Fishery Center, La Jolla, California.	SCOR

At the third meeting Drs Colebrook, Longhurst and Smith met to complete the task of drafting this report; Drs Stebbing and Bayne (IMER, Plymouth) and Mr J Snodgrass (SIO, La Jolla) acted as consultants at this stage.

The Terms of Reference included in the following extract from SCOR Proceedings (vol. 4, 1968) were proposed by SCOR and accepted by ACMRR, IBP/PM and UNESCO:

"Biological Variability

"It was noted that the IOC Group of Experts on Ocean Variability (now known as IRES) recently constituted by the IOC Bureau and Consultative Council because of its responsibility towards the Integrated Global Ocean Station System (IGOSS), consisted primarily of physical scientists. At the same time, it was recognized that variability in biological systems had considerable scientific and practical importance and that there existed opportunities to include biological measurements in observational systems designed primarily to monitor physical changes in the ocean. Accordingly it was decided to establish a new working group (WG 29), on Continuous Monitoring in Biological Oceanography, with the following terms of reference:

"Using the outcome of various relevant working groups of SCOR and other organizations, to review critically the present status of devices for (a) continuous observation of parameters such as pigments, particles, transparency, submarine irradiance, primary production, nutrients, and (b) continuous or intermittent sampling of organisms, and to list suitable techniques and instruments for such measurements. The WG would work, where relevant, with the Chairman or rapporteurs of other SCOR WGs."

It was the intent of the sponsoring organizations that the report of WG 29 should be useful to IGOSS, and to planners of other ocean monitoring systems, although such an intent was only expressed in the preamble to the terms of reference and not in the terms of reference themselves.

The Chairman therefore, proposed that the WG should structure its discussions along two lines:

(1) What parameters of the oceanic biota are required by biological oceanographers and why might they be recommended to planners for inclusion in proposed systems of ocean monitoring.

(2) What is the feasibility of continuously measuring these parameters?

From such discussions, the WG hoped that it could recommend a series of actions to ensure that suitable observational systems are ready when needed.

Preliminary correspondence showed the need for agreement on the meaning of "continuous monitoring"; the following agreed usages were accepted by all participants:

Continuous - A series of observations or samples in space or time with intervals between them which are small compared with the smallest significant scale of variability of the parameter being measured. Thus, this term may be used either for analog or digital outputs, and may be applied to continuous underway observations from research vessels or ships-of-opportunity, to continuous vertical profiling observations, to relatively short continuous horizontal transects, to relatively short period continuous in situ observations and similar situations.

Monitoring - A time-series of observations designed to provide information about major patterns of fluctuation extending over long periods of years, in most cases. In particular, to be applied to observations of the results of climatic changes or technological stress on marine biota. Might be applied to observational series based on in situ apparatus mounted on data buoys, piers, sea-bottom capsules, and so on, as well as to the regular and routine occupation of ocean stations, and to regular daily (or more frequent) measurements of biological parameters from satellites in near-earth space.

In view of these considerations, it was agreed to eliminate the word "continuous" from the title of the WG.

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Input from other Working Groups

Other SCOR Working Groups have made recommendations (or have in preparation reports and manuals) which are of direct interest to biological monitoring studies. In most instances, the final reports are not generally available though interim or preliminary draft copies may perhaps be obtained through correspondence with the chairman of the appropriate Working Group. In addition, a number of IBP handbooks and FAO training manuals are available for consultation.

	Title	Status
WG 13	Zooplankton Sampling Methods.	Published
WG 15	Photosynthetic Radiant Energy in the Sea.	Experiments underway
WG 23	Zooplankton Laboratory Methods.	Report in preparation

	Title	Status
WG 24	Estimation of Primary Production under Special Conditions.	In press
WG 28	Air Sea Interaction.	Interim report available
WG 33	Phytoplankton Methods.	Report in preparation

References

ANDERSON, G.C. and R.E. MUNSON. 1972. Primary productivity studies using merchant vessels in the North Pacific Ocean. Plankton Soc. Japan: Motoda Commemorative Volume.

ANDERSON, G.C., T.R. PARSONS and K. STEPHENS. 1969. Nitrate distribution in the sub-arctic Northeast Pacific Ocean. Deep-Sea Res. 16: 329-334.

ARTHUR, DG. (M.S.) 1956. The particulate food and food resources of the larvae of three pelagic fishes, especially the Pacific sardine, Sardinops caerulea (Girard). Univ. California, Scripps Institution of Oceanography. PhD Thesis, 231 pp.

BAINBRIDGE, V. and D.C.T. FORSYTH. 1972. An Ecological Survey of a Scottish herring fishery. Part V: the plankton of the north-western North Sea in relation to the physical environment and the distribution of herring. Bull. mar. Ecol. 8: 21-52.

BANSE, K. 1964. On the vertical distribution of zooplankton in the sea. M. Sears (ed.), Pergamon Press, London. Progress in Oceanography. 2: 53-125.

BARRACLOUGH, W.E., R.J. LEBRASSEUR and O.D. KENNEDY. 1969. Shallow scattering layer in the sub-arctic Pacific Ocean. Detection by high-frequency echo sounder. Science 166: 611-613.

BEERS, J.R., C. KNOX and J.D.H. STRICKLAND. 1970. A permanent record of plankton samples using holography. Limnol. Oceanogr. 15(5): 967-970.

BERNER, L.D. and J.L. REID, Jr. 1961. On the response to changing temperature of the temperature-limited plankton Doliolum deuticulatum Quoy and Gaimard, 1835. Limnol. Oceanogr. 6(2): 205-215.

BLACKBURN, M. 1965. Oceanography and the ecology of tunas. Oceanogr. and Mar. Biol. Ann. Rev. 3: 299-322.

BLUMER, M., R.R.L. GUILLARD and T. CHASE. 1971. Hydrocarbons of marine phytoplankton. Mar. Biol. 8(3): 183-189.

BOYD, C.M. and G.W. JOHNSON. 1969. Studying zooplankton populations with an electronic zooplankton counting device and the LINC-8 computor. In Trans. of the applications of sea-going computors symposium. Ed. J.D. Mudie and C.B. Jackson. Marine Technology Soc.: 83-90.

BRAITHWAITE, H. 1971. A sonar fish counter. J. Fish Biol. 3: 73-82

BULLIS, H. 1970. World fishery technology. Calif. Coop. Fish Invest. Rep. 14: 57-66.

BUTLER, P.A. 1969. Proc. Roy. Soc. B. 177 (1048): 321-329.

BUTLER, P.A. 1970. Monitoring organisms. In Report, Seminar on methods of detection of the measurement, and monitoring of pollutants in the marine environment. FAO Fish Rpts. (99) Supp. 1: 101-112.

CLARKE, G.L., G.C. EWING and C.J. LORENZEN. 1970a. Spectra of backscattered light from the sea obtained from aircraft as a measurement of chlorophyll concentration. Science 167: 1119-1121.

CLARKE, G.L., G.C. EWING and C.J. LORENZEN. 1970b. Remote measurement of ocean colour as an index of biological productivity. Proc. Sixth Int. Symp. Remote Sensing of the Environment, Oct. 13-16, 1969, Univ. Mich. Press, Ann Arbor. 2: 991-1001.

COLLIS, R.T.H. 1966. LIDAR: a new atmospheric probe. Quart. J. Roy. Meteo. Soc. 92: 220-230.

COOK, R.A., L.D.B. TERHUNE, J.S. FORD and W.H. BELL. 1970. An opto-electronic plankton sizer. Fish Res. Bd. Canada, Tech. Rpt. 172: 40 pp.

CURRAN, R.J. 1972. Ocean colour determination through a scattering atmosphere. Preprint X-651-72-58. Goddard Space Flight Center, Greenbelt, Md. USA.

DAVIS, C.C. 1964. Evidence for the eutrophication of Lake Erie from phytoplankton records. Limnol. Oceanogr. 9(3): 275-283.

DRAKE, J.F. 1972. The present and future role of instrumentation in water pollution control. Effluent & Water Treatment Journal (April, 1972): 181-193.

DUSSART, B.H. 1965. Les différentes catégories de plancton. Hydrobiologia 26 (1-2): 72-74.

FISH, C.J. 1936. The biology of Calanus findmarchicus in the Gulf of Maine and Bay of Fundy. Biol. Bull. Woods Hole. 70: 118-141.

FORBES, S.T. and O. NAKKEN. 1972. Manual of methods for fisheries resource survey and appraisal. Part 2. The use of acoustic instruments for fish detection and abundance estimation. FAO Manuals in Fisheries Science.

FULTON, J. 1972. Trials with an automated plankton counter. J. Fish Res. Bd. Canada 29: 1075-1078.

GLOVER, R.S. 1953. The Hardy plankton indicator and sampler : a description of the various models in use. Bull. mar. Ecol. 4: 7-20.

GLOVER, R.S. 1967. The continuous plankton recorder surveys of the North Atlantic. In Aspects of marine zoology. Symp. Zool. Soc. Lond.,(19):189-212.

GRAINGER, E.H. 1959. The annual oceanographic cycle at Igloolik in the Canadian Artic. 1. The zooplankton and physical and chemical observations. J. Fish. Res. Bd. 16(4): 454-501.

GUINARD, N.W. 1971. Radar monitoring of oil slicks. 7th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, May 1971.

GULLAND, J.A. 1965. Manual of methods for fish stock assessment. Part 1. Fish population analysis. FAO Fish. Biol. tech. Pap. 40 (Rev. 1) 68 pp.

GULLAND, J.A. 1966. Manual of sampling and statistical methods for fishery biology. Part 1. Sampling methods. FAO Manuals in Fisheries Science (3) 87 pp.

HARDY, A.C. 1939. Ecological investigations with the continuous plankton recorder: object, plan and methods. Hull Bull. mar. Ecol., 1: 1-57.

HEINRICH, A.K. 1962. The life histories of plankton animals and seasonal cycles of plankton communities in the oceans. J. Cons.perm.int.Explor. Mer 27: 15-25.

HELA, I. and T. LAEVASTU. 1970. Fisheries Oceanography. Fishing News (Books) Ltd., London. pp. xv + 238.

HEMPEL, G. (in press). FAO manual on egg and larval surveys.

ISAACS, J.D., A. FLEMINGER and J.K. MILLER. 1969. Distributional atlas of zooplakton biomass in the California current region : Spring and Fall 1955-1959. CalCOFI Atlas (10): i-xxv + plates.

ISAACS, J.D., A. FLEMINGER and J.K. MILLER. 1971. Distributional atlas of zooplankton biomass in the California current region : Winter 1955-59. CalCOFI Atlas (17): i-ix + plates.

JERLOV, N.G. 1957. Optical studies of ocean waters. Rep. Sweden Deep Sea Exped. 3: 1-59.

KATZ, I. 1965. Radar backscattering from the sea. In G.C. Ewing (Ed.) Oceanography from space., Woods Hole Oceanographic Inst. Ref. 65-10. 367-376.

KIM, H.A. 1972. Airborne laser system for monitoring phytoplankton in the ocean. (Abstr.) Spring meeting of Optical Soc. America, 1932.

KINDLEMANS, P.J., P.B. APPLEWHITE and H.J. MOROWITZ. 1968. Capacitive detection of very small aquatic animals. Rev. scient. Instrum. 39(1): 121-122.

LeBRASSEUR, R.J. 1964. Biomass atlas of net zooplankton in the northeastern Pacific Ocean, 1956-1964. Fish. Res. Bd. Canada., Man. Rpt. Series (201): 315 pp.

LeBRASSEUR, R.J. 1965. Seasonal and annual variations of net zooplankton at Ocean Station P, 1956-1964. Fish. Res. Bd. Canada, Man. Rpt. Series (202): 163 pp.

LESLIE, J., L. DEVEY, A. NAUWERCK, M. MUNAWAR and E. PICKETT. 1972. Comparison of electronic and microscopic counting methods of phytoplankton. Abstracts, Third Canadian Oceanographic Symposium 2-4 May, 1972, Burlington, Ontario.

LONGHURST, A.R., A.D. REITH, R.E. BOWER and D.L.R. SEIBERT. 1966. A new system for the collection of multiple serial plankton samples. Deep-Sea Res. 13 (2): 213-222.

LORENZEN, C.J. 1966. A method for the continuous measurement of in vivo chlorophyll concentration. Deep-Sea Res. 13(2): 223-227.

LORENZEN, C.J. 1971. Continuity in the distribution of surface chlorophyll. J. Cons. int. Explor. Mer 34(1): 18-23.

LOVE, C.M. 1972. Eastropac Atlas I. US National Marine Fisheries Service Circular (330): 1-12 + plates.

McALLISTER, C.D. 1969. Aspects of estimating zooplankton production from phytoplankton. J. Fish. Res. Bd. Canada, 26: 199-220.

McALLISTER, C.D. 1971. Some aspects of nocturnal and continuous grazing by planktonic herbivores in relation to production studies. Fish. Res. Bd. Canada., Tech. Rpt. (248): 281 pp.

McNAUGHT, D.C. 1968. Acoustical determination of zooplankton distributions. Proc. 11th Conf. Great Lakes Res. Int. Assoc. of Great Lakes Res. 1968: 76-84.

MARSHALL, S.M. and A.P. ORR. 1955. The biology of a marine copepod. Oliver & Boyd, Edin. & Lond. 1955.

METHERELL, A.F., H.M.A. EL-SUM, J.J. DREHER and L. LARMORE. 1967. Introduction to acoustical holography. J. accoust. Soc. Am. 42(4): 733-742.

MILNE, A. 1959. The centric-systematic-area sample treated as a random sample. Biometrics, 15(2): 270-297.

MITSON, R.B. 1963. Marine fish culture in Britain V : An electronic device for counting the nauplii of Artemia salina L. J. Cons. perm. int. Explor. Mer, 28: 262-69.

MULLIN, M. and E. BROOKS. 1967. Laboratory culture, growth rate and feeding behaviour of a planktonic marine copepod. Limnol. Oceanogr. 12:657-666.

MURPHY, G.I. 1966. Population biology of the Pacific sardine (Sardinops caerulea). Calif. Acad. Sci. Proc. 34(1): 1-84.

MURPHY, G.I. 1967. Vital statistics of the Pacific sardine (Sardinops caerulea) and the population consequences. Ecology 48: 731-736.

NAKAJIMA, J. and S. NISHIZAWA. 1968. Seasonal cycles of chlorophyll and seston in the surface water of the Tsugara Strait area. Rec. Oceanogr. Works Japan (2): 219-246.

PARRISH, B.B. 1969. Manual of methods for fish stock assessment V : The use of acoustic instruments in fish detection and fish abundance estimation. FAO Fish. Tech. Paper (83) 71pp.

PARSONS, T.R., L.F. GIOVANDO, and R.J. LeBRASSEUR. 1966. The advent of the spring bloom in the eastern subarctic Pacific Ocean. Fish. Res. Bd. Canada 23(4): 539-546.

PARSONS, T.R. 1969. The use of particle size spectra in determining the structure of a plankton community. J. Oceanogr. Soc. Japan 25(4): 172-187.

PARSONS, T.R. and H. SEKI. 1969. A short review of some automated techniques for the detection and characterization of particles in sea water. Bull. Jap. Soc. Fish. Oceanogr. (Spec. No.) 173-177.

PARSONS, T.R. and G.C. ANDERSON. 1970. Large scale studies of primary production in the North Pacific Ocean. Deep Sea Res. 17: 765-776.

RICKER, W.E. 1968. (Ed.) Methods for assessment of fish production in fresh waters. In IBP Handbook (3). Blackwell Scientific Publ., Oxford, 313 pp.

ROBINSON, G.A. 1970. Continuous plankton records : variation in the seasonal cycle of phytoplankton in the North Atlantic. Bull. mar. Ecol. 6: 333-345.

RODEWALD, M. 1960a. Bestandsschwankungen des Rotbarsches vor Südlabrador und die atmosphärische Zirkulation im Nordwest-Atlantik. Hansa 97 (6/7):

b. Die jüngsten Wassertemperatur und Fishpendelungen in der Barentsee als Folge von Schwankungen der Luft-Zirkulation. Hansa 97 (8/9): 481-482.

c. Die extreme 1958 and 1950 des nordatlantischen Rotbarsh-Jahrgangs: atmosphärisch ausgelöst? Hansa 97 (18): 933-934.

d. Seelack-Wanderungen unter dem Gesichtspunkt der Anderung des Gross-wetterlage. Hansa 97 (19-20): 1017-1018.

ROSENTHAL, H. and G. HEMPEL. 1970. Experimental studies in feeding and food requirements of herring larvae (Clupea harengus L.). In J.H. Steel (Ed) Marine Food Chains., Oliver and Boyd, Edinburgh. 344-364.

RUSSELL, F.S., A.J. SOUTHWARD, G.T.B. BOALCH and E.I. BUTLER. 1971. Changes in biological conditions in the English Channel off Plymouth during the last half century. Nature, Lond. 234: 468-470.

SHELDON, R.W. and T.R. PARSONS. 1967. A practical manual on the use of the Coulter Counter in marine science. Publ. Coulter Electronics Sales Co., Ontario, Canada, 66 pp.

SMITH, P.E. 1971. Distributional atlas of zooplankton volume in the California current region, 1951 through 1966. CalCOFI Atlas (13): i-xvi + plates.

SNODGRASS, J.M. 1972. Pollution monitoring, an engineering challenge. J. Hydronautics 6(2): 115-116.

STEELE, J.H. and D.W. MENZEL. Conditions for maximum primary production in the mixed layer. Deep Sea Res. 9: 39-49.

STEPHENS, K. MS 1970. Data Record. Primary production data from the northeast Pacific Ocean, January 1967 to December 1969. Fish. Res. Bd. Canada. MS No. 1123, 16 pp.

STRICKLAND, J.D.H. 1958. Solar radiation penetrating the ocean. A review of requirements, data, and methods of measurement, with particular reference to photosynthetic productivity. J. Fish. Res. Bd. Canada. 15(3): 453-493.

STRICKLAND, J.D.H. 1960. Measuring the production of marine phytoplankton. Fish. Res. Bd. Canada Bull. 122, 172 pp.

STEPHENS, R. 1970. Automated measurement of dissolved nutrients. Deep Sea Res. 17: 393-396.

SUZUKI, T. and J. ITO. 1967. On the DSL in the NW area of the North Pacific Ocean I : Relationship between vertical migration of DSL, submarine illumination and plankton biomass. Bull. Jap. Soc. Sci. Fish. 33(4): 325-337.

SVERDRUP, H.V. 1952. Some aspects of the primary productivity of the sea. FAO Fish. Bull. 5(6): 215-223.

SZEKIELDA, K.-H. 1970. The development of upwelling along the Somali Coast as detected with the Nimbus 2 and Nimbus 3 satellites. Goddard Space Flight Center Preprint X-651-70-416.

THORNE, R.E. and H.W. LAHORE. 1969. Acoustic techniques of fish population estimation with special reference to echo integration. Fish Res. Inst. U. Wash. Circular (69-10).

THORSON, G. 1961. Length of pelagic larval life in marine bottom invertebrates as related to larval transport by ocean currents. AAAS Oceanography: 455-474.

TYLER, J.E. and R.C. SMITH. 1967. Spectroradiometric characteristics of natural light under water. J. opt. Soc. Am. 57(5): 595-601.

TYLER, J.E. and R.C. SMITH. 1970. Measurements of spectral irradiance under water. Gordon and Breach, Science Publishers, N.Y.

UNESCO. 1968. Zooplankton sampling. Monographs Oceanogr. Methodology II, 174 pp.

VINOGRADOV, M.E. 1968. Vertical distribution of the oceanic zooplankton. Izdatel'stuo "Nauka", Moscow. (Translation: Israel Programme for Scientific Translations, 339 pp.)

VROOMAN, A.M. and P.E. SMITH. 1972. Biomass of the sub-populations of the northern anchovy Engraulis morda Girard., Calif. Coop. Oceanic Fish. Invest. Rep. 15: 49-51.

WICKETT, W.P. 1956. Review of certain environmental factors affecting the production of pink and chum salmon. J. Fish. Res. Bd. Canada 15 (5): 1103-1126.

WILLIAMS, F. 1972. Consideration of three proposed models of the migration of young skipjack (Katsuwonus pelamis) into the eastern Pacific Ocean. Fish. Bull. 70(3): 741-762.