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SAMPLING AND OBSERVATIONAL SYSTEMS

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SAMPLING AND OBSERVATIONAL SYSTEMS

Report of the First Meeting of an International GLOBEC Working Group

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March 30 - April 2, 1993

PREFACE

The international program on Global Ocean Ecosystem Dynamics (GLOBEC) is sponsored by the Scientific Committee on Oceanic Research (SCOR) with the co-sponsorship of the Intergovernmental Oceanographic Commission, the International Council for the Exploration of the Sea and the North Pacific Marine Science Organization. GLOBEC is dedicated to understanding the effects of physical processes on predator-prey interactions and population dynamics of zooplankton and their relation to ocean ecosystems in the context of the global climate system and anthropogenic change.

The GLOBEC Core Program is being developed through a series of scientific working groups and regional planning efforts. This report results from the second in the series of meetings of these groups leading to the development of an international Science Plan for GLOBEC. The Working Group on Sampling and Observational Systems met at IOC, UNESCO, in Paris, France in late March, 1993.

This meeting was chaired by Dr. Tom Dickey to whom the international sponsors of GLOBEC wish to express their gratitude for his leadership and for the effort he expended in producing and editing this report.

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1. INTRODUCTION

(T. Dickey, B. Rothschild, D. Cushing, A. Robinson)

The International GLOBEC (I-GLOBEC) Sampling and Observational Systems Working Group (SOS-WG) met in Paris March 30 - April 2, 1993. The SOS-WG workshop was conducted to facilitate the exchange of ideas in the areas of sampling, technologies, and their implementation as part of the I-GLOBEC program. Participants (24) came from 8 different countries. Other I-GLOBEC topical areas include: 1) Population Dynamics and Physical Variability (workshop held in Cambridge, UK, February, 1993), 2) Numerical Modeling (workshop held in Villefranche-sur-mer, France in July, 1993), 3) Cod and Climate (workshop held in Lowestoft, United Kingdom, June 7-11, 1993), 4) Southern Ocean (workshop held in Norfolk, Virginia USA, June 15-17, 1993), and 5) Prudence (past records). The coordinated activities of these areas will be used in the development of a detailed scientific plan to be executed over the next few years. It should be noted that chairmen of the Fizzypop and Numerical Modeling Working Groups were active participants and contributors to the SOS workshop. The following workshop report presents a summary of state-of-the-art of technologies and sampling strategies which may be applied to I-GLOBEC studies in the next several years. Several participants were asked to prepare background papers and to act as discussion leaders in order to facilitate discussion, to assist in the timely production of a set of recommendations and a workshop report, and to provide a broad set of perspectives. The report roughly parallels the meeting agenda, however, there are some notable exceptions (Sections 3 and 6) which resulted from enthusiastic, spontaneous discussions and commitments by individuals to develop sections on special, important topics. The areas covered in this report include: Section 2: relevant processes and scales of variability, Section 3: observations and modeling systems, Section 4: observational tools (physical, acoustical, and optical), Section 5: sampling design and strategies, Section 6: sampling methodologies and techniques, Section 7: future technologies, and finally a summary. The meeting was lively and executed in a spirit of enthusiasm which we feel will lead to lasting international cooperation and will facilitate the planning and execution of international and national GLOBEC programs.

2. PROCESSES AND SCALES

(T. Granata, co-chair, A. Robinson, co-chair, A. Gargett, C. Marrase, P. Nival, and H. Yamazaki)

Introduction

The I-GLOBEC planning committee has specified three lines of investigation for future oceanic research:

1. Population dynamics of zooplankton;
2. Zooplankton interactions with phytoplankton and detritus;
3. Zooplankton interactions with fish stocks

All of these are within a physical setting. The physical setting is based on mean and time dependent motions and physical structures in both the atmosphere and the ocean. Time and space scales of several relevant physical and biological phenomena are summarized in Figure 1 and Tables 1 and 2. Several authors have reviewed scales (e.g., Denman and Gargett, 1983; Denman and Powell, 1984; Haury and Pieper, 1987; Dickey, 1988, 1990, 1991; Nihoul and Djenidi, 1991). Necessarily, a variety of sampling platforms and methods are required (Figures 2 and 3 and Table 3).

For biological processes, it is important to discern the spatial and temporal scales of target species, which are highly variable from species to species. Some generalizations can be made. Smaller organisms grow faster, move slower, are found closer to the surface (in or close to the mixed layer), and have smaller horizontal distributions than larger organisms (Figures 4 and 5). Vertical layering of organisms is common (Figure 6), however, when the water column is mixed, so are distributions of plankton, except for larger zooplankton which migrate. During stratified periods, plankton can be concentrated in or below the pycnocline. Conditions which entrain nutrients into the euphotic zone are generally necessary for algal blooms of 5-10 mg Chl_a m^{-3}. High concentrations of phytoplankton may be necessary for the growth of larger copepods (i.e., Calanus). Smaller copepods do not appear to be food limited and can effectively reproduce provided algal concentrations of 1-2 mg Chl_a m^{-3}. Typical abundances of organisms are $\sim 10^6$ m^{-3} for phytoplankton, 10^4-10^8 m^{-3} for ciliates, 10^3-10^4 m^{-3} for copepods, 1-50 m^{-3} for gelatinous zooplankton, and 10^2 -10^3 m^{-3} for fish larvae - however patches occur on scales of meters to kilometers (Figure 1, Table 2).

Biological as well as physical events are frequently episodic (Figure 7). Phytoplankton blooms occur in the late winter, early spring, and fall and last from days to weeks. Marine temperate fish and copepods spawn in late winter and early spring (over 2-3 months), timed to coincide with an abundance of phytoplankton biomass (Cushing, 1976), though there are late spawning species. Eggs are laid in surface layers by zooplankton and in midwater by fish and both drift with the currents. Provided food is encountered, larvae will grow quickly. Mortality is usually by predation and is high in these early stages (eggs and larvae). Species in locations where food is available do not tend to have a seasonal cycle. Metamorphosis occurs over days to months with size increases of millimeters for copepods and centimeters for fishes.

Some species have large distributions and horizontal migration distances. For example, fish populations often migrate to nursery grounds in shallow waters for two or more years before migrating to deeper water. Sea migration can range from distances of 10 Km (for small fish) to 10^3 Km (for larger fish) and fish often take advantage of currents. Swimming motions are from 10^{-2} cm s^{-1} for zooplankton larvae, to 1 cm s^{-1} for zooplankton adults, to >10 cm s^{-1} for larval fishes.

Multiple Scales

1) Global, Basin, and Sub-Basin Scales (10^3-10^4 Km)

Climate and seasonal circulation of the atmosphere will contribute to ocean gyre circulation and basin to basin flows (conveyor belt deep circulation and surface flows) through heat and water fluxes (e.g., thermohaline circulation) and by directly forcing of large current systems (wind stress). Gyres and recirculation flows within basins (sub-basin scale) are important for transporting heat, momentum and biological communities over large distances. Changes in heat fluxes on these time scales (a year to several years) can have dramatic effects on stocks of plankton and higher trophic levels. Other examples of large scale phenomenon are: annual to interannual variations from these mean flows, Southern Oscillation/El Niño events, and monsoons.

2) Regional Scale (10^2-10^3 Km)

On regional scales, episodic atmospheric events, such as storms (and other low pressure systems) and high pressure systems, will modify the "steady" ocean flows either by direct transfer of kinetic energy (through wind stress) or by sea surface height modulation associated with highs and lows over different regions Synoptic anti-cyclones and cyclones have time scales of 1-5 day. Lastly, frontal systems that separate distinct air masses (DT=5-20°C) often have associated precipitation and scales of 10^2-10^3 Km and days.

In the ocean, bottom topography, including continental shelves, slope breaks, and islands modify the flow field and the biological distributions. Large horizontal discontinuities in energy and water properties occur at convergent zones, often with accumulating biomass (e.g., shelf breaks that separate coastal from oceanic waters). It is in the onshore-offshore direction that biology often shows the greatest variability.

Upwelling fronts, set-up by wind stress and Ekman transport offshore, are biologically productive at coastal boundaries. Convergence exists at these fronts so that offshore oceanic waters are warmer; inshore, at the surface, waters are cool and nutrient rich (with subsurface component directed polarward - alongshore transport). Headlands, capes, and islands can affect alongshore flow resulting in shedding eddies. Bottom topography, such as canyons, can modify alongshore current offshore, increasing or decreasing relative vorticity of the flow. Tides can account for considerable variability in mean currents and biology (Denman and Powell, 1984), especially in coastal areas. In shallow waters, tidal fronts form where there is a pycnocline. These fronts can be permanent (e.g., estuaries) or seasonal (coastal) features.

3) Mesoscales (10-10^2 Km) and Synoptic Scales

In the atmosphere, the largest motions are often the most energetic while in the ocean the mesoscale motions are typically the most energetic. Consequently, for oceanic systems, episodic events represent important perturbations. The timing and variability of mesoscale motions may be intricately linked to seasonal heating (Strass et al., 1992) which can force biological production (Strass and Woods, 1991; Dickey et al., 1993). Coherent mesoscale flow features, such as eddies, are ubiquitous in open ocean regions and effectively transport heat, momentum, and particle mass. However, eddies can affect shore regions as well. For example, they can alter volume exchange (Bain et al., 1989) and biological characteristics (McClain et al., 1990) when they move into coastal zones. Eddies are also recognized as sites of high biomass (e.g., Wiebe 1976) and primary production (e.g., Falkowski et al., 1992). Eddies, topographic flows, and shallow coastal flows which can trap waves, may be important processes for the transport of particles and nutrients. These features can be characterized in terms of the Rossby radius, HN/f , where N is the buoyancy frequency,

$$N^2 = \frac{-g}{r_o} \frac{\partial r}{\partial z}$$

and f is the Coriolis parameter. Also, H is water depth, g is the acceleration of gravity, and r is density. Submesoscales features, such as meddies, lenses, and subsurface eddies (Richardson, 1993) may also be important for transport of distinct communities since they exist for long time periods. Other episodic features such as deep water forming chimneys, unstable rim currents, and convective regions may also be important. For example, it has been suggested that frontal jets might stimulate new production (Woods, 1988).

4) Smaller Scales (10^{-3}m-10 Km)

Scales on the order of 10^{-3} m-10 Km are pivotal to the GLOBEC program since they link community structure of organisms (regional and synoptic/mesoscales) to microscales of individual animal movement and behavior. These scales are often neglected, so there is not an extensive data base.

Atmospheric frontal systems are zones of divergence and convergence capable of affecting local upper ocean conditions via local heating and wind stress (Wells, 1986). In the ocean, internal waves represent important sources of energy for transport and mixing of particles and dissolved constituents on these scales. The frequency domain of these waves is $f < w < N$. The frequency of the wave cycle increases at higher latitudes with periods,

$$T = \frac{\rho}{2 W \sin f}$$

where W is the rotation rate of the earth and f is latitude (e.g., T = 34 h at 20°; 20 h at 34°; 17 h at 45°, and 14 h at 60°). Typical vertical scales of motions are 1-10 m in coastal regions with highs of 30 m in ocean regions. Tidal and storm surges (Denman and Powell, 1984) can also transport nutrients into the euphotic zone stimulating new production on these small scales.

On the microscale, shear flows, breaking internal gravity waves (Kelvin-Helmholtz billows), convective motions, and double diffusion are likely sources of microturbulence (Yamazaki and Osborn, 1988). It is on these microscales where most biological-biological interactions occur. For example, it has been shown that microscale turbulence has an effect on behavior, orientation, swimming, and feeding of zooplankton (Costello et al., 1990; Saiz and Alcaraz, 1992; Saiz et al., 1992) and on the level of primary production based on optimal light fields (Lewis et al., 1986).

Recommendations

1) Global scales will be coarser in time and space while local scales will be finer in time and space (on the scale of the copepods), however, the data needs are generally the same. Therefore, careful consideration should be given to resolution, duration, and extent of the sampling to ensure that a full spectrum of time and space scales are sampled (i.e., to ensure that there are no spectral gaps).

2) Pre-existing data/networks need to be utilized. These include:

- wind measurements from scatterometers and weather stations/buoys to estimate mixing and MLD;

- advective fields and regions of complex flows (e.g., jets, vorticity, etc.) from altimeter maps and currents meters, including acoustic Doppler current profiler (ADCP) data.

- heat fluxes based on data from meteorological satellites and global weather stations and buoys to determine heating trends and anomalies;

- compiled atlas data (temperature, salinity, density, oxygen, nutrients) to help in preparing the sampling design.

3) Establish global, long-term time series measurements to assess global change in the future, perhaps concentrating on north-south gradients along basin transects for phytoplankton, copepods, fish, and physical variables especially, psuedo-dissipation rates. These time scales should be sufficiently sampled to define the annual cycle. This could be coordinated with permanent stations in different basins sampling simultaneously for a century - conceptually, the biological equivalent of weather stations.

4) There is a need to do process studies before we can optimally define larger scales.

5) Some sampling systems which cover temporal and spatial domains undersampled by present systems are still needed. One example is an autonomous profiler which could resolve ~1m in the vertical and make vertical profiles every hour to a few

hours for several days or even months. This type of system could be deployed before and during process studies and for "biological weather" station measurements. Such a system could utilize standard CTD sensors, acoustic sensors for zooplankton abundance and bio-optical packages (fluorometers, natural fluorescence and PAR sensors, beam transmissometers, pump and probe fluorometers, and oxygen sensors) to measure phytoplankton abundance and production and net community production. Simultaneous deployment with an ADCP would be desirable for collecting current and backscattering data. These systems should be calibrated with physical and biological data from process studies.

3. OBSERVATIONS AND MODELING SYSTEMS

(A. Robinson, chair, J. Aiken, I. Aoki, D. Cushing, T. Dickey, J. Jaffe, B. Rothschild)

The need to optimally integrate various sensors to "feed" data to adaptive computer models linking physics, biology and chemistry is critical to moving forward in I-GLOBEC. In order to develop this technology, a transportable observational system (such as the one depicted in Figure 2) needs to be coupled to a model for data assimilation. The model is intended to generate realistic physical/biological/chemical field estimates. These estimates will be used to describe the "status" of the physics and ecology, to develop explanations of the phenomena, and to develop prognostications.

The model (or models) and assimilation schemes coupled with the sampling-theoretic observations comprise the observation and modeling system which will be designed for I-GLOBEC. The Observational and Modeling System (OMS) will therefore consist of a number of platforms and sensors and a data management and assimilation scheme, all coupled to an interdisciplinary model or models.

Recommendations

1) The system should provide quantitative field estimates and forecasts for a horizontal domain of roughly 100 to 1000 km with a resolution of the order of 5km and with high vertical resolution. Nested grids of higher resolution should be used for both observations and models.

2) The observations and field estimates should be adequate for studies of the population dynamics of zooplankton and phytoplankton, particularly in their contributions to grazing, to the dynamics of the ecosystem, to the physical forcing of the system, and to the assessment of climate change.

3) The observations should be an efficient mix of remotely sensed variables and of critical in situ variables. Platforms should be an optimal mix of satellites, aircraft, ships, moorings (both autonomous and semi-autonomous) and of free floating devices (e.g., see Figure 2). The sensors should be carefully selected as well.

4) The observations should provide a "standard" set of variables for input to models capable of providing quantitative dynamical estimates of the ecosystem. The observations must necessarily be delimited. Cost/benefit, feasibility, and scientific importance need to be considered in defining the standard variables.

5) Key variables should define physical structures (for example, temperature, salinity, velocity and pressure), species composition and size distributions of zooplankton and phytoplankton (i.e., concentrations and density fields) synoptically in terms of means, variances, and rates.

6) A combined Eulerian and Lagrangian approach should be implemented.

7) Robust and reliable data assimilation schemes, especially for the biological and chemical variables, should be developed and used.

8) Effective parameterization of sub-gridscale (small scale) physical and biological process studies (for example, mixing, grazing and predation) are essential.

9) The system should be located and maintained in regions of critical interest long enough to define critical processes in space-time variabilities (e.g., from short time scales to the seasonal and interannual) in physics and biology (e.g., from short time scales relevant to individuals to several generations).

10) Prototype criteria with alternatives, optimization, special locations and intercomparisons should be developed.

11) Validation and verification are essential and oversampling and sensor comparison are necessary at an early stage.

4. OBSERVATIONAL TOOLS

4a. Physical Measurement Systems

(A. Gargett, chair, T. Granata, C. Marrase, P. Nival, A. Robinson, and H. Yamazaki)

Rather than start out with a compendium of instruments and platforms, this discussion of physical measurement systems will be introduced by considering a very general question - if we could measure everything about the physical system in the upper layers of the ocean, is there some subset of physical fields which would maximize the information relevant to the associated planktonic system? As our measurement abilities proliferate, without equivalent increase in resources, such a question becomes interesting: at the very least, it offers a different point from which to view measurement systems.

From recently published work on the kinematics and dynamics of deep-ocean planktonic systems, it appears that physical effects of major biological concern are those associated with (i) vertical motion in a depth-varying light field, (ii) nutrient supply to the euphotic zone, (iii) physical convergence /divergence mechanisms, and (iv) shear on the scales of zooplankton-phytoplankton interactions. With this in mind, it seems that the following four physical fields, could we measure them properly, form a minimal set, in the sense of supplying enough(?) information to quantify the physical environment for the major concerns listed above.

1) Vertical velocity w: provides information on vertical movement in the light field, on nutrient supply (when associated with turbulent mixing), and on horizontal convergence/divergence (through the continuity equation or $\delta w/\delta z = -(\delta u/\delta x+\delta v/\delta y)$) where x, y are the horizontal coordinates (east and north), z is the vertical coordinate, and u,v are the eastward and northward velocity components.

2) Turbulent kinetic energy dissipation rate e: quantifies small-scale shear, with associated effects on feeding

3) Vertical density gradient $\delta r/\delta z$, or equivalently, the buoyancy frequency N: needed to characterize barriers to particle sinking

4) Light field E

What is the present state of our abilities to measure these fields?

Reliable standardized instruments exist for in situ measurement of N, with resolution dependent upon a combination of sensor and platform characteristics. On global scales we know gross upper ocean N structure, with at least the seasonal cycle outlined, from standard compilations of many years worth of CTD data (Levitus, 1982). The light field E will be discussed in section 4d, so it need not be considered in detail here.

In contrast, while in situ measurement of e using Osborn-type airfoil probes (Osborn,1974) is becoming more widespread, it is still the domain of specialists, a fact which has a number of unfortunate repercussions (Table 4). The first of these is scarcity: the number of groups able to do the work is small, while the number of field experiments desiring such support continues to expand. Then there is expense: adding measurements of e to a process-oriented field experiment presently requires a dedicated group of 5-12 (depending on whether continuous operation is required) scientists and technicians, and the associated cost puts the measurement out of reach in many situations. Finally, the small number of workers means that there is nothing approaching global spatial coverage. Most seriously, because all measurements are presently taken with ship-based (dropped or towed) systems, there is essentially no coverage under the extreme wind or buoyancy forcing conditions which may have the largest effects on the biological system.

So there are two types of problems with regard to e measurement in support of I-GLOBEC: one is to obtain measurements of e on fine time and (vertical) space scales during intensive process-oriented experiments; the other is to enable mapping of global fields of e, resolving seasonal variations as well as episodic and extreme forcing events.

No one strategy will solve both problems, but there are a couple of observational techniques whose development might contribute to both.

The first would be the use of a light-weight internally-recording CTD, measuring density in free-fall mode. Ocean Sensors makes an appropriate unit: Sea-Bird Electronics may as well. Internal recording means that users do not have to supply and maintain cables with electrical conductors; they can merely stop to upload data periodically. Use in free-fall mode allows measurement of density to finescale (~ a few cm) vertical resolution. This in turn allows accurate calculation of the Thorpe scale L_T (Thorpe, 1977) as a function of depth z.

The Thorpe scale L_T is an "overturning" length scale, calculated by re-sorting measured density profiles (solid dots in Fig. 8a) into a statically stable profile, with density increasing with depth. For each point, the raw Thorpe scale is the vertical distance, D, the point must be moved in order to achieve this. In the simple example shown, both points are moved the same distance, one up and the other down. Real density profiles are more complicated, and in practice a root mean square (rms) value of L_T is usually calculated over some vertical interval.

Dillon (see Fig. 8b above) first showed a strong correlation between L_T and another length scale, $L_o = (e/N^3)$, in oceanic measurements, suggesting that CTD-based measurement of L_T and N could provide at least a rough estimate of e. Further validation of this technique should be sought, from (perhaps existing) cruises in which specialized microscale profilers were deployed. Even if valid only under restricted conditions (defined on the basis of such comparisons), it offers enormous potential for widening our global base of dissipation estimates under all conditions, since Thorpe scale estimates could possibly also be calculated from XBT data taken by ships-of-opportunity, at least in regions where temperature dominates density.

The second technique for determining e is closely connected to the problem of measurement of w, the vertical velocity. This was the first field in the list above because it is of fundamental importance to the biological system: moreover it is possible that "proper" measurement of the w field could contain measurement of the e field, as will be seen shortly. Until very recently, oceanographers rarely even tried to measure the field of vertical velocity: w was assumed to be too small (in the deep ocean) and/or too difficult to measure in the presence of platform motion. Over the past 5 years or so, that has started to change: as new instruments and new platforms become available, we are starting to be able to measure the w field, in some places, under some conditions. An impressive example is the work of Weller et al. (1985; see Fig. 9), who modified the propeller orientation of a vector measuring current meter (VMCM) to sense w as the instrument was lowered from the stable platform FLIP, producing a detailed snapshot of the vertical velocity field associated with Langmuir circulations.

Acoustic Doppler techniques offer another means of direct measurement of the field of w, provided an acoustic beam can be maintained accurately vertical. In coastal waters, where ship motion is minimal, a specialized vertical-beam acoustic Doppler current profiler (ADCP) (Gargett, 1993) has been successfully used to measure the w-fields associated with strong tidal flows (Fig. 10).

While the conditions under which such measurements can be achieved are presently restrictive, the direction of ongoing improvements to instruments and platforms suggests rapid progress, so that measuring the field of w in the upper 200m of the ocean may be possible in the near future.

As remarked above, measurement of w may provide e as well: Fig. 11 shows a comparison between a direct (profiler) measurement of e (dashed line) and an estimate ($e2 = rw^3/L_H$, where rw is rms w and L_H is an associated horizontal length scale) obtained from the ADCP remote measurement of w (solid line). While this technique is far from proven, there remains the intriguing possibility that the dissipation field, like the velocity field, can be measured remotely, with profound implications for achieving a global spatial description, and for assessing the importance of episodic events.

While the preceding has concentrated on the deep-sea environment where time and vertical spatial dimensions are of dominant biological importance, I-GLOBEC is also concerned with coastal environments, since these dominate global biomass figures and contain most of the important fisheries. Here we will not escape the need to measure horizontal transport as well. An example is the British Columbia continental shelf off Vancouver Island, which supports the richest fisheries on the west coast of Canada. Crawford (1991) produced the nitrogen budget shown in Fig. 12: turbulent flux is estimated from direct measurements of e, wind mixing and upwelling contributions are estimated from wind fields. The budget is dominated by nutrients being advected onto the shelf in the estuarine surface layer flow out of the Strait of Juan de Fuca. Turbulence does supply these nutrients to the upper layer, but it does so in turbulent flows (such as those shown in Fig. 10) which occur in regions far from the shelf.

Such situations, in which horizontal advection dominates nutrient supply, are likely to be more the rule than the exception in coastal waters: fortunately, the tools (moored current meters, shipboard Doppler profiling) for measuring mean horizontal flows are relatively well-developed.

Recommendations

This section recommends areas for development of both instruments and techniques. Most suggestions originate in existing technologies, but require additional engineering effort and/or some scientific development in order to produce equipment needed for both the local process studies and the global aspect of I-GLOBEC.

1) Instruments

A) We recommend development of a single-beam ADCP, to allow flexible deployments, including the vertical orientation which will result in measurements of vertical velocity. The design should include adjustable dynamic range for both velocity and backscatter amplitude and incorporate most recent acoustic techniques to optimize accuracy.

B) We suggest research into an indirect method for estimating the turbulent kinetic energy dissipation rate e, using estimates of overturning scales from a free-fall CTD.

C) For intensive ship-based process experiments, direct microprofiler estimates of e are necessary: it is unclear whether this would be best achieved by a single dedicated microscale team (perhaps one of the existing groups), or by dispersing the technology throughout the biological community (Table 4).

2) Techniques

A) Stable platforms are necessary for ADCP measurements of turbulent scales in the upper ocean: some possibilities are "stiff" moorings, stable towed vehicles, autonomous vehicles, spar buoys, and SWATH vessels. Some effort should be spent on assessing the motion characteristics of existing candidate platforms.

B) Many of the new technologies proposed for use on I-GLOBEC moorings (including a turbulence via Doppler) produce large data sets; the issue of access to high rate systems for data transmission is a crucial one.

C) It is necessary to refine the empirical relationship between e and the cube of the wind speed, as it is being used to "predict" e for upper ocean biological purposes.

D) The possibility of deriving turbulence characteristics from optical imaging products should be pursued, as it has the obvious advantage of producing those characteristics in the immediate neighborhood of the biological measurement.

4b. Acoustics
(T. Stanton, chair, I. Aoki, K. Foote, M. Furusawa, J. Jaffe, R. Pieper, and R. Strickler)

Introduction

Acoustical methods can be used to remotely detect and classify marine organisms such as zooplankton and nekton. They have a distinct advantage over the use of more conventional sampling devices such as nets or pumps as they can rapidly and remotely sample large areas. Data can be collected in near real-time with high resolution. In addition, acoustic sounders can be deployed for long periods of time to monitor the temporal variability of animal biomass. Under the appropriate conditions, echosounders can routinely produce the spatial and temporal distributions (abundance) of various size classes of the animals of interest.

There are inherent ambiguities in the use of acoustics such as knowing what the target animal is. There is also difficulty in discriminating between an echo from a group of several large animals and that from an aggregation of many small animals. By proper design and use of acoustic devices in conjunction with complementary sampling systems such as nets and optical imagers, ambiguities can be minimized, resulting in a powerful tool. Because of the importance of acoustics to the I-GLOBEC program, recommendations of design considerations of the systems and their deployment for use in I-GLOBEC studies are made below.

Operational Considerations

Use of an echosounder requires knowledge of the animal size with respect to acoustic wavelength, estimates of material composition of the animal (such as mass density and speed of sound), and spatial density (number per cubic meter) with respect to resolution of the sounder. The size and composition, among other parameters, determine the overall strength of the echo while the values of spatial density (number/m^3) help determine whether the animals can be resolved. Various deployment configurations of sounders include vessel-mounted transducers, towed bodies (near surface or at other depths), remotely operated vehicles, free drifting buoys, and stationary moorings. The type of deployment depends upon how high the acoustic frequency is, what resolution is required, and what type of information is required, spatial or temporal. Details related to these considerations and others can be found in U.S. U.S. GLOBEC Report 4 (1991) and will not be repeated here.

Design Challenges and Solutions

Perhaps the greatest challenges involved in the design of the sounders derive from the facts that 1) the target species assemblages are complex (wide range of size and species such as 100-mm- to 1-mm-long copepods to much larger fish) and 2) in any given echo, it is quite possible that there are contributions to the echo due to an animal not belonging to the target species (Furusawa, 1991). Hence, one must be very careful in designing an echosounding system that can allow one to routinely and automatically "sort" out the animals and produce reliable information regarding the target species only. In short, the complexity of the acoustical system should correspond to the complexity of the biological system.

Some key elements in the design of the systems involve the facts that

1) The zooplankton of interest are very small and their properties are very close to those of seawater resulting in very weak echoes; hence, the zooplankton are only detectable at very high frequencies (upper kilohertz to lower megahertz) and at short ranges,

2) The zooplankton occur at densities too high to be individually resolvable by a sounder,

3) The fish produce a very large echo and occur quite often at sufficiently small densities to be individually resolvable by a sounder, and

4) Many non-target species such as pteropods and siphonophore pneumataphores produce much larger echoes at the high frequencies than the target species zooplankton (Stanton et al., 1987; Stanton, 1990, 1991).

The resultant design should therefore have sufficient spatial resolution to discriminate between the zooplankton and fish as well as have enough frequency diversity so as to be able to discriminate between various animals when they are not resolvable. Both the hardware and echo processing software should be sophisticated enough to be able to perform the discrimination routinely and automatically so that the vast amount of data can be analyzed in a timely manner (Foote et al., 1991). Furthermore, calibration should be routinely performed.

The acoustic systems should be used in conjunction with optical and perhaps with stimulus response systems to help in the classification of the animals. The optical system will provide visual images of the animals while the stimulus response system (such as a flash of light or impulse of voltage) may cause the copepods to move, causing a Doppler shift in the signal which would allow further discrimination against other scatterers.

Recommendations

1) Overview of Recommended Echosounders and Their Deployment

Because of the wide range of spatial and temporal scales and sizes of animals involved, two types of echosounders are recommended:

A) One that is deployed at a constant depth during the surveys and involves a lower range of acoustic frequencies (10 kHz - 500 kHz). This system can insonify most or all of the water column producing images of the distribution and abundance of fish and macrozooplankton, and

B) The other involves a higher frequency range (100 kHz - 10 MHz) and must be deployed over a range of depths (such as with a "tow-yo") during surveys, since the signals at the upper frequencies are absorbed rapidly in the water. The frequency ranges of the two systems are overlapping for the purpose of intercomparison. Both systems should involve up to approximately 10 frequencies per decade of frequency resulting in a total of up to approximately 30 different frequencies (Holliday et al., 1989; Pieper et al., 1990).

Each system should be a hybrid mix of single and multiple acoustic beams. The lower cost single beam system will generally provide only volume scatter information while the multi-beam system (dual- and split-beams and imaging sonars) can track targets as well as directly provide target strength and density (number per cubic meter) of targets. Depending upon the type of echo discrimination required, the signal at each frequency should either be narrow band, resulting in a strong transmitted signal with information only at a singular frequency, or broadband resulting in a weaker signal, but producing an echo with potentially more information. The narrow band signal can provide information regarding scattering levels and possibly Doppler (and hence animal velocity) information. The broadband signal provides information over a range of frequencies possibly allowing a frequency dependence analysis of the scattering. Due to the weakness of such broadband signals, it may be required to have two transducers at certain frequencies, one broadband and the other narrowband. By using them alternately, there will be information from the narrowband system when volume scattering strengths are relatively small and data from both systems when strengths are greater.

In addition to survey deployments, systems should be deployed on platforms designed for time-series studies such as moorings (fixed and/or variable depth), free drifting buoys, and bottom mounted platforms. The fixed platforms may also be required for certain systems, such as an imager, that requires stability. The choice of frequency range on these other platforms depends on the distance between the target species and sounder system. For a bottom mounted system, a near-surface layer of zooplankton may not be seen with the high frequencies due to the severe attenuation of the signals, hence only the lower range of frequencies may be used (resulting in a reduced amount of biological information). For a platform that moves up and down throughout the entire water column (a very desirable platform), all frequencies should be used.

2) Echo Sounder Details

A) Higher frequency system: 100 kHz - 10 MHz (for 100mm-3mm zooplankton).

This system involves up to roughly 20 frequencies and covers two decades of frequency (100 kHz - 10 MHz). The design and use of this approach is modeled after the design of Holliday and Pieper's MAPS (Multifrequency Acoustic Profiling System) sounder (Holliday et al., 1989; Pieper et al., 1990). The system is characterized by very narrow acoustic beams that can resolve a small (fractions of a cubic meter) volume. Hence, the lower density fish and higher density zooplankton can be spatially discriminated. (Note that while the fish can be resolved, the zooplankton still cannot. Hence, measures of volume scattering strength of zooplankton will result, as opposed to target strength.) Scattering from the various transducers are analyzed by performing an inversion which results in estimates of the size distribution of the animals. Single beam (as opposed to dual- or split-beam) technology is recommended for most or all of the frequencies since the individual zooplankton cannot be resolved.

While it is possible to spatially discriminate between the dense zooplankton and sparse fish, other techniques are required to determine whether the echo is due to the zooplankton of interest or non-target (zooplankton) species such as pteropods or siphonophore pneumataphores that may occur in dense aggregations and produce very large echoes. Since such echoes may be much larger than the contribution from the zooplankton of interest, the data in this case could not be used to characterize the target species.

Other techniques include:

a) Echo level analysis. When levels of the echo seem unreasonably high (possibly due to animals with much larger target strengths), the echo can be labeled as possibly not being due to the zooplankton of interest. Note that pteropods and siphonophore pneumataphores have target strengths that are many tens of decibels larger than that of copepods (Stanton, 1990, 1991).

b) Frequency dependence analysis. When the volume scattering strength of a certain volume is independent of frequency (or nearly so), then the scattering is due to animals much larger than the copepods, whose scattering strength should vary dramatically from Rayleigh to geometric scattering over the 100 kHz - 10 MHz range (Holliday et al., 1989; Stanton, 1990).

c) Optics/acoustics intercomparison. An optical system (photo or video) should be mounted near the acoustic apparatus so that both acoustic and optical data concerning the same volume can be collected simultaneously in the field. Suspicious acoustic data can possibly be resolved by analysis of the optical image of the scattering volume. Analysis of the image will allow the species to be identified.

d) Stimulus response/Doppler shift analysis. When the volume scattering strength is suspicious with respect to either frequency dependence or level, a stimulus response device can possibly be used (such as a flash of light or impulse of voltage) to cause the copepods to move. The fact that copepods move and other animals such as pteropods and siphonophore pneumataphores as well as marine snow do not move allows one to further classify the echo through a Doppler analysis. The degree of shift will help determine the source of the echo. (This idea has not been sufficiently explored to predict its usefulness to date. Nonetheless, it is a concept worth exploring.)

B) Lower Frequency System: 10 kHz - 500 kHz (for fish and macrozooplankton)

This system involves up to roughly 15 frequencies over the 10 kHz- 500 kHz range. Fish are detectable over the entire range while macrozooplankton (e.g., euphausiids) are only detectable in the upper portion of the range (beginning at about 30 or 40 kHz). The copepods will only be marginally detectable at best, and only then at the highest frequencies. Since the fish and macrozooplankton typically occur at sufficiently low densities so that they can be resolved acoustically, multibeam technology (dual-beam, split-beam, imaging sonar, etc.) is recommended for use for at least a subset of the frequencies over the entire frequency range. As a result, the fish and zooplankton can be classified by target strength distribution and number density as done by Foote et al. (1986) and Greene et al. (1989). Furthermore, the target tracking information from the multi-beam systems can provide histories of inter-animal distances which are useful in predator-prey studies.

Because of the fact that the echoes are due mostly to a subset of the animals present, especially at the lower end of this frequency range, there are fewer ambiguities. However, since these larger animals are relatively sparse and mobile, the chance for intercomparison with an optical system is small which places the burden of intercomparison with nets. Since nets integrate over volume, the intercomparison is restricted to a larger volume than with the copepods.

Supporting Measurements and Studies

Interpreting data from the recommended acoustic systems cannot be performed adequately without further work in the following areas:

1) Measurement of physical properties of the animals. The density contrast and sound-speed contrast of the body material of the animals are crucial inputs into scattering models. Direct measurements of these should be performed as described in Foote (1990).

2) Development of scattering models of the animals. Relating echo level to useful biological parameters such as length and possibly orientation distribution requires understanding of the scattering properties of the animals. While use of the sphere model has shown success with copepods, the scattering characteristics of the copepods as well as the more elongated macrozooplankton and fish require a much better understanding for the routine and accurate interpretation of the data (Stanton, 1990; Foote, 1985; Holliday et al., 1989; Pieper et al., 1990).

3) Performing an intercomparison of acoustics and optical data under controlled conditions. In a laboratory, at dock-side, and/or in an area of the ocean where the population of animals is dominated by the copepods of interest, the acoustic systems and an optical system such as the VPR (Video Plankton Recorder) (Davis et al., 1992), should be used to record data from the same volume at the same time. Such a calibration will provide an empirical basis for the development and refinement of the scattering models as well as interpretation of the field data.

4) Performing controlled studies of the relationship between applied stimulus (such as voltage or light) in the water, resultant copepod reaction, and observed Doppler shift of acoustic echo. Such a study could provide invaluable information to calibrate stimulus-

reaction discrimination algorithms in field data.

Summary

Because of the wide diversity of animals and their respective size and spatial and temporal distributions, comparably complex echo sounding systems and complementary measurements and studies are recommended. The acoustics systems cover a wide range of frequencies and modes of deployment. Because of inherent ambiguities of the system, simultaneous optical measurements as well as sophisticated acoustic "sorting" or discrimination data processing algorithms are recommended. With proper use of this array of devices, it is possible to determine the spatial and temporal variability of the size classes of the copepods and fish of interest to the I-GLOBEC program.

4c. Optics: Imaging
(C. Davis, co-chair, R. Strickler, co-chair, G. Gorsky, U. Kils, and M.Lehaitre)

Background

One of the goals of I-GLOBEC is to understand the biological-physical processes controlling population dynamics of marine zooplankton in relation to global climate. Optical image sampling can provide data on the birth, death, and growth processes of these populations. With respect to these three processes, optical imaging technology can provide:

1) High resolution temporal and spatial data on the distribution and abundance of zooplankton in terms of both taxonomic and size composition.

2) Data on microscale processes including individual swimming and feeding behaviors, predator-prey interactions, spawning, and turbulent motions of seawater.

These measurements should be made in conjunction with other kinds of sampling including acoustical, non-video optical, hydrographic, and current measurements. The calibration of acoustical data is particularly important as highlighted in the previous section.

In short, the promise of optics is four-fold: 1) rapid identification of living organisms in situ, 2) quantification of organisms smaller than 1 mm, 3) observation of behavior and direct in situ rate measurements, and 4) concurrent sampling of organisms, their prey and potential predators at spatial and temporal scales at which the physical environment can be sampled as well.

Optical imaging can be used to determine rates of birth, growth and mortality of planktonic animals by accurately quantifying: 1) changes in size distribution of their populations over time, and 2) in situ rates of feeding, swimming, and spawning.

Birth Rate Estimation

Optical imaging can be used to quantify spawning behaviors of individual copepods and in some cases the distributions and abundances of egg-bearing adults and free-floating eggs or nauplii. Current imaging systems can resolve individual organisms down to 400 mm (e.g. small copepods), but accurate identification of smaller organisms has not yet been demonstrated. Higher magnification video systems are under development for quantification of these small organisms. Such systems could allow direct counting and sizing of copepod egg and naupliar abundances. High resolution time series measurements of copepod population size structure (including naupliar stages) would allow quantification of recruitment using population analysis techniques (e.g., Caswell and Twombley, 1989).

Growth Rate Estimation

The change in population size and stage structure over time can be used to estimate in situ rates of growth and development. Processes directly impacting growth and development can be studied by quantifying feeding and swimming behaviors together with physical turbulence and food concentrations. Turbulence can in principle be estimated using optical imaging systems by analyzing the 3-dimensional motions of small passive particles. Larger phytoplankton (e.g., diatom chains) are easily observed using current systems, and smaller food particles can be seen but not identified. Higher magnification systems will be able to distinguish prey type.

Death rate estimation

In addition to birth and growth estimates, changes in population structure can be used to estimate in situ mortality rates (e.g., Caswell and Twombley, 1989; Wood and Nisbet, 1991). These mortality rates can be related to predator concentrations and feeding rates. Lower magnification systems are available for quantification of larger predators such as gelatinous organisms, crustaceans, and juvenile fish. The link with acoustics is of particular importance in quantifying abundance of adult fish predators. Optical systems can provide important observations of predator and prey interactions. Such behaviors include avoidance of predators by prey and foraging strategies as a function of prey density.

Thus, optical imaging systems have the potential to provide estimates of population size structure as well as behavioral observations of vital rates at the species level. Identification of species for the smaller life stages may be difficult however, even with the high magnification systems. This difficulty may be overcome if subtle morphological differences or swimming patterns can be quantified using pattern recognition and motion analysis systems. In low diversity regions, species are more easily distinguished since the overlap in size is much reduced (e.g., Pseudocalanus and Calanus on Georges Bank). Such measurements of population size structure and behaviors together with population modeling studies will provide new insights into the mechanisms controlling recruitment in marine zooplankton. Population size structure and behavioral observations should of course be made concomitantly with measurements of hydrography, circulation, non-video optics, and food concentrations over a range of time and space scales.

Recommendations

1) Population Size Structure Estimation

The primary goal of population size structure estimation is to quantify the size structure of planktonic populations (including meroplankton, holoplankton, and ichthyoplankton) in time and space in relation to biotic and abiotic variables. The objectives are:

A) To measure the size and taxonomic composition of plankton communities in relation to their environment on space scales ranging from millimeters to tens of kilometers over time scales from days to years. The structure of plankton communities can be crudely described by size-frequency distributions (e.g., Platt and Denman, 1978; Napp et al., 1993), but understanding population and recruitment processes requires a more detailed level of analysis, preferably at the species level. In low diversity areas, species-size data may be obtained using simple pattern recognition algorithms to identify genera and species; life stages could then be separated by size. In high diversity areas, more sophisticated algorithms must be developed, together with higher resolution optical systems in order to distinguish species.

B) To relate the size-distributions of plankton populations to the physical and biological environment. The vertical and horizontal patterns in hydrography and current flow, as well as the concentrations, size structure, and pigment composition of potential food organisms must be measured concomitantly with population abundance and size structure of zooplankton species.

Quantification of zooplankton population dynamics requires rapid sampling and image processing to obtain high temporal and spatial resolution data on the size structure of target species populations. Conventional zooplankton sampling involving collection of specimens for time-consuming laboratory analysis is impractical in this regard because not enough observations can be obtained to provide the desired high temporal and spatial resolution. The recent advances in optical imaging technology can be used for population structure quantification. By deploying these systems on long-term moorings, drifters, and rapid tow bodies from ships, the required high temporal and spatial resolution data can be obtained. These detailed data on population structure can be used together with population modeling studies, and laboratory and field estimates of life history parameters to determine the causes of population fluctuations.

2) Behavioral Observations

The primary goal of behavioral observations is to measure in situ zooplankton rate processes (feeding, swimming, spawning, and predator interactions) together with fine-scale biological and physical structure and biological-physical interactions. Optical imaging technology is needed to achieve this goal since it allows for direct observation and measurement of individual plankton behavior simultaneously with their prey and predators and physical properties of the seawater (temperature, salinity, and turbulence). The objectives are to:

A) Quantify the feeding, swimming, spawning, and/or predator-prey behaviors of individual zooplankters concomitantly with 3-dimensional fine-scale (mm to cm) particle distributions and water velocities surrounding these individuals. Time series measurements of these properties are required to determine phasing with respect to tidal and diel cycles.

B) Determine how these individual scale processes are related to fine-scale (cm to m) vertical and horizontal structures in the biological (food, conspecifics, competitors, and predators) and physical (turbulence, temperature, density, light, and oxygen) fields.

C) Relate the micro- and fine-scale observations to coarser scale structure of the biological and physical properties. This includes vertical and horizontal scales of meters to kilometers.

Optical imaging technology is required to make individual level measurements of specific taxa. Again, although acoustical systems could be used to track sound-scattering particles, the identity of these particles will not be known even if parallel pump or net samples are taken for calibration. Optical systems can be mounted on remotely operated vehicles (ROV's) or moored in low velocity regions to directly obtain data on in situ behaviors of individual zooplankters as well as on surrounding biological and physical properties. The requirements for such a system would include a high resolution optical imaging system which is relatively non-invasive (i.e., long working distance coupled with a long wavelength light source). This system should be deployed on a stable platform that is capable of tracking individual particles over time scales of several seconds.

3) Sampling Systems

A) Population structure

The objectives stated above can be achieved using existing or near future (5 years) technologies and data analysis techniques. These technologies comprise various optical imaging systems. Although acoustical systems can provide synoptic or quasi-synoptic data on sound scatterers in the water column, they cannot at present differentiate between various planktonic taxa or even between living and non-living particles. Nonetheless, range-gated acoustical systems are capable of sampling the entire water column at once and can provide important quasicontinuous data on the patchiness of particulates. It is clear that a combination of optical imaging and acoustical technologies is needed to obtain high resolution data on the distribution and behaviors of zooplankton in time and space.

Several optical imaging systems have been used for taxonomic identification of planktonic organisms. These include film cameras (Ortner et al., 1981), video adapted nets (Welsch et al., 1991), the Video Plankton Recorder (VPR) (Davis et al., 1992a,b), the CritterCam (Bergeron et al., 1988), the ecoSCOPE (Kils, 1992), and the underwater video profiler (UVP; Gorsky et al., 1992).

The Plankton Camera (Ortner et al., 1981) is towed at approximately 2 knots and obtains a silhouette photograph every two seconds. The film records are quantified manually after the cruise. In addition, measurements of temperature, conductivity, depth and fluorescence are obtained every second.

The Video Adapted Gulf III Net (Welsch et al., 1991) was designed for surveys of herring recruitment in the North Sea. A videocamera images organisms as they pass into the cod end of a plankton net; the video is transmitted in real-time via conducting cable to the research vessel. The images enable the identification of organisms from 0.5-20 mm in length to major taxa (Schulze et al., 1992). This device is expected to be commercially available within one year.

The Video Plankton Recorder (VPR, Davis et al., 1992a,b) has been developed to quantify abundance of zooplankton on scales from microns to kilometers, and is now in the prototype stage. It consists of a video camera/strobe unit and an image processing system. Four video cameras are synchronized at 60 frames sec^{-1} to a red strobe light positioned 1 meter away. The field of view of each camera is adjustable from 0.5 to 10 cm, at 10 to 300 microns resolution, respectively, with corresponding depths of field of 4 to 20 cm. Imaged volumes are concentric with their centers located 0.5 m between camera and strobe. Each one microsecond strobe pulse permits highly resolved images of plankton and seston. Plankton abundance is determined by counting the number of animals per field of videotape and dividing by the field volume. The VPR has been used in towed, moored, and ROV deployments. Images from the VPR are digitized and pre-processed in real-time by an image processor and transmitted to a host computer where morphometric indices can be computed, and organisms sorted into major taxa (e.g., copepod, euphausiid, chaetognath, etc.). Software/hardware for automated sizing and taxonomic analysis is under development.

The Optical Plankton Recorder (OPR, Kils, 1981; 1989) is a compact, high-speed, underwater video microscope with optional preconcentration nets. It is designed primarily for small-scale, high resolution observations of plankton distributions. Prototype instruments have been deployed free-falling in Antarctic krill studies (Kils, 1981); towed from small vessels in mesoscale monitoring of fish schools; anchored (moored) for plankton orientation and ecotoxicology studies; and used in aquaculture for particle flow quantification (Kils et al., 1991). When towed, free falling, or hovering, each image is exposed to two short (10 ms) strobes separated by 20 ms. Three different cameras with nested magnifications allow for observation of both predators and prey simultaneously, and for taxonomic identification (Kils, 1989).

The ecoSCOPE is an optical video-endoscope that enables direct observation of predator-prey interactions between juvenile fish and zooplankton (Kils, 1992). It is a small free drifting system tracked by sonar. One endoscope projects a thin sheet of light to illuminate the prey (copepods, tintinnids, etc.), and a second endoscope records the predator-prey encounter from a distance of only 4 cm. The endoscope penetrates into the volume in which the fish would respond to large objects (30 cm sphere), but has no apparent effect on behavior. Direct readings from the ecoSCOPE are difficult to assess by eye because the optical system oscillates, the objects move, and there is microturbulence in the water. To overcome these problems, image processing software (dynIMAGE) animates sequential images by referencing a floating particle that is selected by the operator, and shifting the sequential images so that the reference particle remains stationary. As a result, when viewing the animations, the dynamics of the prey, the predator, and the remaining microturbulences are more visible. The dynIMAGE package also supports further manipulation of the images (e.g., contrast enhancement, slow-motion, reverse motion, calibration, size-, distance- , speed- and direction-quantifications).

The CritterCam (Bergeron et al., 1988; Schulze et al., 1992) is a commercially available video system developed by Rudi Strickler for imaging small-scale plankton distributions and behavior underwater. It is based on modified Schlieren optics and achieves very high resolution at sufficiently long working distances (0.15 to 0.4 m) so that organisms' behaviors are minimally affected by the instrument. It views a field of up to 6 x 4.5 cm with a resolution of 5 mm (for a 2.5 mm field) and uses shuttered camera to freeze the motion of organisms. In moored configuration, it can produce images of zooplankton sufficient in quality for the organisms to be taxonomically identified.

The Underwater Video Profiler (UVP) (Gorsky et al., 1992) is used to quantify suspended particles (>100mm) in the water column. It is also used to identify and to assess the distribution of the macrozooplankton. The system consists of a Hi8 CCD camcorder, electronic control unit, power supply, Sea-Bird CTD and two interchangeable lighting units. One unit illuminates a volume of 200 liters of water and is used for visualization of organisms. The second illuminates a precise volume and the images are digitized and processed with an image processor.

The abundance profiles of particles and their size spectra are obtained. The system has a three hour autonomy and the image processing is automatic.

The Non-Contact Measurement System (NCS2) allows engineers in addition to skilled technicians, access to stereo video, image capture and measurement options through a computer software based interface system (Turner et al., 1991). The benefit of using this system is that movement can be frozen for three-dimensional analysis. A framing rate of 25 or 30 frames/sec is possible, thus overcoming blurring problems when there is platform (diver, ROV, etc.) motion.

The 3-D Bioluminescence Mapping System (Greene et al., 1992; Widder, 1992; Widder et al., 1992) is used to identify and map bioluminescent organisms based on the spatial and temporal patterns of their stimulated bioluminescent displays. Use of species-specific bioluminescent displays enables bioluminescent organisms ranging in size from 50 mm to 1 m to be mapped simultaneously with a single video camera.

B) In situ Behavior

Several optical imaging systems have been developed for quantifying zooplankton behaviors in the laboratory (Price et al., 1988; Dickey, 1988; Schulze et al., 1992). These systems range from low-resolution systems designed to measure swimming behavior (Bugwatcher, e.g., Buskey and Swift, 1983; 1985), to high-resolution systems designed to measure feeding appendage motions and particle capture (Alcaraz et al., 1980). These techniques have recently been extended to allow tracking of single individuals over time (CritterCam-2D and CritterSpy-3D), as well as examination of the behavior of groups of individuals (Bugwatcher). Extensive motion analysis software has also been developed (e.g., Motion Analysis Inc.). In addition to these laboratory systems, several of the high-resolution systems discussed above can be used to make in situ behavioral measurements. These systems can be used for measuring zooplankton swimming, feeding, and predator-prey interactions (e.g., VPR, Davis et al., 1992a,b; CritterCam, Bergeron et al., 1988; ecoSCOPE, Kils, 1992) in the ocean. These video systems can be used in two-axis mode to obtain 3-D video images of in situ behaviors of individual zooplankton as well as the surrounding particulate field.

Such in situ systems must be mounted on stable platforms in order to measure zooplankton behaviors accurately. Large ROVs such as JASON have proven to be capable of tracking individual zooplankton on small scales (20 cm window) for extended periods (minutes). Such ROVs combined with optical imaging systems should be used to quantify individual behaviors in a variety of biological and physical environments.

Future developments in optical imaging of plankton which are not yet available include in situ micro-holography, and range-gated laser imaging systems. Additionally, the prospect of using satellite or aircraft remote sensing (passive or range-gated laser imaging) to quantify zooplankton populations in the sea should be pursued in the future.

Perhaps the most important technology in need of further development is image processing/pattern recognition/motion analysis. To deal effectively with the tremendous quantity of video data collected by the systems described above, application of existing image processing systems developed for industrial or biomedical purposes should be applied to marine problems. The field of image processing is a rapidly growing one, and a huge array of hardware and software now exists that can be applied directly to the analysis of plankton images and behaviors. This area of research should be given a very high priority.

Summary of Recommendations

To determine the population structure and vital rates of target plankton species in relation to their biotic and abiotic environment, we make the following recommendations.

1) Encourage use of the existing and nearly developed instruments listed above.

2) Development of technology for deployment of these instruments on moorings (fixed depth and profiling), ROVs, and rapidly towed bodies.

3) Develop image processing, pattern recognition, and motion analysis systems using existing expertise and hardware from the field of image processing.

4d. Optics: Non-imaging
(I. Taupier-Letage, co-chair, T. Dickey, co-chair, P. Gentien, J. Jaffe, M. Lehaitre and T. Komatsu)

Overview of Non-imaging Optical Methods

The present section deals only with optical instrumentation, which is defined as that "in which the presence and size of a target organism are detected by its effect on the intensity of scattered or transmitted light as it passes through a light beam." Optical methods and techniques can be used to treat problems relevant to the upper ocean's ecosystem, particularly involving primary production and for measuring biomass of zooplankton. Several background references are available (e.g., Kirk, 1983; Gordon et al., 1984; Yentsch and Yentsch, 1984; Dickey, 1988; 1990; 1991; U.S. GLOBEC Report number 4, 1991; ICES Report, 1992; Mobley, 1992; Sprules et al., 1992; Dickey et al., 1993a; U.S. GLOBEC Report number 8, 1993). A conceptualization of bio-optical sampling platforms, systems, measurements, and the utilization of bio-optical data in models is depicted in Figure 13 (Dickey et al., 1993a). The following review is divided into two principal parts. The first emphasizes optical measurements relevant to phytoplankton and the second focuses on measurements more directly related to zooplankton and, to some degree, higher trophic levels using non-video optical methods. Video methods were addressed previously. Also, the section on scales of processes and sampling platforms is relevant to the following summary. Finally, near real-time telemetry of optical data has been accomplished in the coastal ocean and is feasible in the open ocean as well (e.g., Dickey et al., 1993a). This aspect is extremely important for several reasons (e.g., data assimilation modeling).

Optical Sensors Relevant to Phytoplankton

In situ bio-optical measurements have several important functions. Some of the principal functions are 1) to enable the determination of the intensity and quality (wavelength) of light available for photosynthesis at depth, and 2) to facilitate the identification and quantification of phytoplankton populations. Several of the sensors described below provide virtually continuous sampling capability. Thus, vertical resolutions comparable to those of CTD's (few meters or less) and temporal resolutions comparable to those of moored current meters (few minutes or less) may now be attained by sampling of several bio-optical water properties (e.g., Dickey, 1991; Dickey et al., 1993a).

Photosynthetically available radiation (PAR) sensors measure the flux of quanta or the wavelength weighted integral of spectral scalar irradiance in the visible waveband (~350-700nm) using a spherical light collector. The importance of the measurement of PAR is that it quantifies the amount of radiation (number of quanta per unit area per unit time) received at a given depth in the water column.

Another important optical instrument for quantifying the oceanic photoenvironment is the multi-wavelength spectroradiometer (e.g., Smith et al., 1984). Spectroradiometers may be used to measure downwelling and upwelling vector and scalar irradiance as well as radiance in several wavebands ranging from ~380-770nm (e.g., Smith and Baker, 1984; Siegel and Dickey, 1987b).

Fluorometers are used to obtain nearly continuous records of fluorescence in order to estimate chlorophyll-a concentration and to infer phytoplankton pigment biomass. This measurement utilizes the fact that chlorophyll-a, which is a major light sensitive pigment used in photosynthesis, is a fluorescent molecule. The fluorometer's blue light source illuminates a test volume of seawater containing the phytoplankton with their chlorophyll-a cells. The cells fluoresce red light which is detected and the signal is processed. Fluorometers are used both with water pumping systems and from in situ packages. In situ fluorometers are used in profiling and towed modes and most recently in moored mode (see review by Dickey, 1991).

Beam transmissometers measure an inherent optical property (IOP) of seawater, the beam attenuation coefficient, c. One of the more commonly used transmissometers (Bartz et al., 1978) will be described. The light source for the device is a light emitting diode and the beam of collimated light is received by a silicon photodetector. The typical wavelength used (~660nm) is chosen to minimize the absorption of light due to humic acids (yellow substance). The beam attenuation coefficient can be related to the volume of suspended matter or particle concentration in the water column and is useful for water mass analysis (Spinrad, 1986). Primary production estimates have been based on beam attenuation data as well (e.g., Siegel et al., 1989; Cullen et al., 1991; Dickey, 1991). Complicating factors (e.g., cell swelling; see Ackleson et al., 1990; Olson et al., 1990; Cullen et al., 1991) for this application have been summarized in Stramska and Dickey (1992b). The instrument can be used in most deployment modes and its vertical resolution and temporal response are comparable to those of the optical sensors described above.

The distance from which a fish can perceive its prey visually is an important parameter to know in order to understand the behavior of the organism in its physical environment. In this case, both the level and direction of ambient light and the attenuation and scattering of the beams mandate the range and resolution at which the prey can be perceived. A measurement of the directionally and depth dependent underwater ambient light field can be accomplished with a radiometer. This measurement provides the illumination level which is incident on the prey. In order to predict images which are perceived by the fish, the transformation of the light needs to be understood as it propagates after reflection by the prey. Here, the absorption (a), scattering (b) and the volume scattering function b(q) can be measured in order to predict both the amount of light and the light spreading via Monte Carlo modeling or some similar procedure. Alternatively, a small angle scattering meter, or Modulation Transfer Function meter (MTF) can be used to measure the degradation in image quality (via small angle scattering) which takes place.

The measurement of the evolutions of size distributions of both phytoplankton and zooplankton is important for achieving several of the I-GLOBEC goals. Acoustics are more appropriate for the zooplankton while optical methods are more appropriate for phytoplankton. A new system, SLAPS (Size and Load Analysis of Particles in the Sea), was developed for measuring both the total load of suspended particles (up to 30mg/liter dry weight) and their size distribution (Lehaitre et al., 1990). SLAPS was developed to avoid some of the problems associated with acoustical measurements (high sensitivity to small changes in water density, difficulties in grain-size discrimination, etc.). It is an optical system which uses a laser beam. Analysis is based on a diffraction pattern created in situ by particles. It allows measurement of the volume contribution of 32 size classes. The upper limits of the size classes are: 400, 320, 260, 210, 165, 135, 110, 90, 70, 56, 45, 36, 30, 23, 18, 15, 12, 10, 8, 6, 5, 4, 3, 2, 1.7, 1.4, 1.2, 1, 0.9, 0.8, 0.7mm. SLAPS does not allow discrimination between dead and living particles. However, the system can be used to obtain a good estimation of the total available potential food (algae, detritus, aggregates, etc.) and its distribution in microstructures. The discrimination in size, especially in the small ranges, can potentially be used for real-time in situ estimation of phytoplankton assemblages and patchiness, provided an accurate sampling can be implemented. Data are acquired and displayed in real-time every second. Maximum operating depth is 300m, and the instrument is designed to work on short period moorings or with a profiling system. Industrialization of the SLAPS should be underway shortly.

A new instrument has been designed for in situ discrimination of phytoplankton populations, combining optical fiber technology and multi-wavelength excitation for pigment identification using the fluorescence technique (Lehaitre et al., 1993). Initially, the light is injected (presently a burst of 4 pulses at 300Hz every sec) into an optical fiber (200mm diameter), and output fibers from a multiplexer deliver 4 equivalent light sources centered on wavelengths of 450, 490, 530 and 580nm. The fluorescence is then detected at about 30° of the excitation axis for best efficiency by a bundle of fibers. The fluorescent light is then spectrally analyzed with a specific multichannel and multifiber spectrometer coupled to an ICCD video camera (50 frames/sec). The wavelength range is scaled between 400 and 800nm with 1nm resolution. Up to 50 spectra can be separately and simultaneously visualized or stored in real-time, and processing can be done on a personal computer. Lab tests have been performed on monospecific cultures, showing the capability for fiber optics (immersed in the sample) to detect low light level signals and to yield significantly different spectral signatures. More work is now needed to define the most pertinent criteria for automatic identification of the spectra, and to deal with the induced secondary effects (problem of organic matter) on measurements The spectrometer has fine wavelength resolution and its size is convenient. Thus, it can be easily used for other underwater applications in conjunction (or not) with algae discrimination such as up- and downwelling irradiance as well as chemical parameters provided by specific optical fiber sensors. Cowles et al. (personal communication) are also developing a spectral fluorescence system.

Development of autonomous sensors and systems requires special consideration of constraints such as sampling rate, power consumption, data storage, and biofouling. These constraints are common to both moored (fixed depth or profiling systems) and drifting modes; thus, the same sensors can usually be used for these applications without major modification.

Although much progress has been made in our capability to sample the marine ecosystem, there remain several obvious high temporal resolution measurements which need to be included in future systems. For example, further advancement of bio-optical measurements will require a variety of sensors which measure a more comprehensive set of optical variables so that inherent and apparent optical properties may be related. Devices which are presently being developed include spectral absorption, transmission, and scattering meters (e.g., Carder et al., 1988; Zaneveld and Bricaud, personal communication). The pump and probe fluorometer of Falkowski et al. (1991) shows promise for primary productivity measurements. Finally, the use of fiber optics to bring light signals from depth to the surface for signal processing and data analysis appears to be a viable option for several physical and bio-optical applications (e.g., Cowles et al., 1990). Presently, work is underway to develop in situ radiometers to be able to measure with higher spectral resolution (~2 nanometers) across the visible (and into the ultraviolet region) in order to link in situ data with advanced satellite (and aircraft) observations (multiplicity of wavelengths) and for spectral bio-optical models of primary production and species identification (e.g., Bidigare et al., 1987; Morel, 1991; Bidigare et al., 1992).

Non-video Optical Sensors Relevant to Zooplankton

Early optical instruments for the study of zooplankton include: the opto-electronic plankton sizer (Cooke et al., 1970), the Hiac Particle Size Analyzer (Pugh 1978; Tungate and Reynolds, 1980; Horwood, 1981) and a silhouette photography system (Ortner et al., 1979, 1981)

The optical plankton counter (OPC, Herman and Dauphinee, 1980; Herman 1988, 1992; Focal Technologies 1990, Herman et al. 1991) is one of the most advanced optical systems in routine use for zooplankton biomass and size structure assessment. It is intended for large-scale continuous sampling of zooplankton size and density. Versions of the system are designed to count and size organisms in the size range from 120 or 250mm to 30 or 200 mm ESD (Equivalent Spherical Diameter). Flow speed in the OPC is at minimum 0.5m/s and at maximum 4m/s. The maximum count rate is 200 particles/s. Using a constant horizontal towing speed of 2.6m/s, the best resolution is 1.3m.

The principle of operation for the OPC follows. A collimated light beam 4x20mm travels 22cm across the sampling tunnel from a bank of 640nm wavelength LED's to a photodiode receiver. When an animal passes through the beam, the blocked light triggers a negative pulse at the receiver. The pulse height is a measure of animal size. The effects of turbidity are partially compensated by a feedback circuit which maintains constant average light intensity on the photodiode array, and the associated fluctuations in LED output are monitored as a measure of light attenuance. A deck unit displays light attenuance (relative values), number of counts, and size-frequency histograms. Organism sizes are then converted to ESD by an empirical relationship. Several applications of the OPC, in conjunction with other systems (e.g., BIONESS, Batfish, acoustical devices), have shown that the OPC meets the goals for which it was designed, and can be a valuable tool for zooplankton studies.

The OPC does not require nets for concentration, nor prefiltration, nor pumping; data processing is relatively easy and quickly accomplished (compared to video data sets, if pattern recognition is a consideration). One can in principle acquire large volumes of data and process them in near real-time. The OPC can be used with other instruments and packages, allowing concurrent measurements of phytoplankton and zooplankton and CTD parameters. The developers of the OPC suggest that there should be other complementary measurements, namely net collections, otherwise there will be no detailed descriptive information on the zooplankton (e.g., distinct size classes corresponding to different copepods/zooplankton types or larval stages). Moreover, such ancillary data would allow further and more detailed interpretation of OPC data. It should be noted that the OPC is useful for identifying the dominant copepods in boreal environments where relatively few species dominate much of the planktonic biomass. The OPC was originally designed to represent a trade-off, given typical coastal marine zooplankton densities, between increased coincidence associated with a larger tunnel and poor sampling associated with a smaller tunnel. Integration of a flowmeter and combination with an imaging system are being considered.

The OPC has been deployed from ships and moorings; however, it can also be used in conjunction with net sampling and remotely operated vehicles. It should be possible to deploy OPC'S from autonomous profilers as well. The OPC is one of the more mature optical systems for assessing zooplankton biomass and distribution, is commercially available, is relatively easy to use, and is modestly priced compared with video systems. However, in its commercial mode, it cannot be used for imaging individual zooplankton and is limited in its capability to determine taxonomic structure of zooplankton assemblages. The recorded size is affected by the orientation of the animal as it passes through the light beam, which can lead to underestimates of the volume by a factor of two. Coincidence occurs when multiple particles pass through the light beam simultaneously so that large organisms mask smaller ones or abundant small organisms are counted as a single large one. This can lead to density estimates as low as 37% of true abundance when copepod concentrations are high. However, errors in biomass caused by coincidence may be less than errors in abundance.

There are excellent prospects for collecting large amounts of data on zooplankton size and abundance over a wide variety of spatial and temporal scales. This is very relevant to the current emphasis on size-based models and analyses in aquatic ecology. When such data sets are available, advances also must be made in statistical and analytical techniques (GIS, spatial patterns).

Complementary Remote Sensing

The two primary methods which will be available to ocean scientists for studying the upper ocean's ecosystem within the foreseeable future are in situ sampling using sensors placed in the ocean as described above and remote sensing from satellites and aircraft (e.g., Hoge and Swift, 1981; Hovis et al., 1985). These are complementary, with satellites and aircraft providing near surface data over great expanses of the oceans and in situ systems providing subsurface and high temporal information for long periods of time.

The use of satellite altimetry using TOPEX/Poseidon to determine basin scale surface general circulation (e.g., Fu et al., 1988) began in 1992 also. Similar data obtained from the oceanographic satellites Seasat and Geosat have been used to observe features such as the Gulf Stream and its rings. Satellite derived currents can provide important contextual information which greatly enhances our ability to ascertain advective versus local processes measured with in situ physical and bio-optical instrumentation (e.g., Dickey et al., 1993b).

Ocean color data were collected from the Coastal Zone Color Scanner (CZCS), which orbited on the Nimbus 7 satellite, from late 1978 through mid-1986. These data have been used to estimate phytoplankton biomass over particular regions and recently the world oceans (Feldman et al., 1989). Excellent examples of the utilization of these data are presented by McClain et al. (1990) who have examined the coupling of physical and biological processes in the North Atlantic Ocean in both open ocean and shelf regions and by Lewis et al. (1990) who have focused on the equatorial Pacific. Remote sensing of ocean color and the derivation of upper ocean pigment biomass and primary productivity on regional and global scales will begin in 1994 with SeaWiFS (e.g., Yoder et al., 1988; Esaias et al., 1992; Hooker and Esaias, 1992). However, the requisite algorithms rely on in situ observations of bio-optical variables (e.g., Evans, 1992; Hooker and Esaias, 1992; Mueller and Austin, 1992). These observations need to be done in such a way that inconsistencies between satellite and in situ sensors and in temporal and spatial sampling scales can be interpreted and corrected. Additionally, satellite-based ocean color and temperature measurements are often obviated because of cloud or water vapor conditions. Intensive and extensive shipboard sampling at mooring sites and elsewhere over the world ocean will be important.

Fisheries researchers have been utilizing satellite data since the mid-1970's. The direct observation of fish schools remains beyond the resolution capability of present satellite sensing systems, thus indirect observations must be used. Many of the fisheries studies have utilized ocean temperature and color data to locate fronts and wind stress maps to estimate transport. These data have been correlated with ground truth observations from research and fishing vessels. Excellent reviews of satellite data utilization for both research and fishing operations have been provided by Laurs and Brucks (1985) and Simpson (1992).

5. SAMPLING DESIGN AND STRATEGIES

5a. Local process studies

(U. Kils, chair, C. Davis, M. Furusawa, P. Gentien, J. Jaffe, T. Komatsu, R. Pieper, and H. Yamazaki)

Background

The local process group focused on scales less than 1 m. Many of the major hypotheses for the recruitment success of fish (microlayer, retention area, microturbulence), need more data on processes at microscales in space - and even more important - in time. The time spent by a juvenile 25 mm herring for locating, pursuit, attack, capture and handling of one copepod is less than 300 ms. Hence, our strategy, to learn more about one of the most important foodchain transitions in the world, requires that we sample these processes with adequate temporal and spatial resolution. Actions taking place within these few milliseconds determine the patterns that will be found in the next distribution survey. Therefore, sampling strategies are needed to obtain more detailed knowledge of predator-behavior as well as feeding and prey escape. One of the objectives of I-GLOBEC is to obtain an improved understanding of how important processes at the level of individual organisms control population abundance (i.e., the "Concentration on First Principles"). Thus, special emphasis needs to be given to assessing the little-studied roles of ocean physics in feeding success, growth rates, reproductive output, and mortality rates including losses to predators. Clearly, extensions of both physical and biological sampling from the mesoscale into the fine- and microscale environments are needed.

The context and importance of small scale sampling is highlighted in the following quotations from GLOBEC (1989): "From long term fishery catch statistics and other records, we know that decadal changes of orders of magnitude have occurred in the major fish stocks of the ocean which cannot be explained merely by fishing pressure. It has been hypothesized that large year classes are uncommon events driven by a combination of favorable interactions of ocean physics and chemistry on the early life history of species, which occasionally magnify the normal, very low survival rates that occur during the recruitment process and vastly increase adult biomass. Exploring these patterns is a major challenge for marine ecology that has acquired a sense of urgency in connection with Global Change. ... information on feeding and predation rates is crucial to modelling population growth and mortality, ... the prey is picked out of the water with a complex behavioral mechanism. The processes of detection and capture depend entirely upon the local physics. The physics of grazing is a difficult but essential problem that requires much more sophisticated investigation. Sampling technology for the size range of 5 mm to 5 cm should be set as a goal, ... within this size range most grazing and most acts of predation would occur, ...

It was recognized that no single technological device was likely to be capable of dealing with the entire range but that possibly a combination of acoustic and optical technologies might provide the solution."

Scales

After much discussion it was agreed that two sections should be considered:

1) Scales between 1 m and 10 km. Relevant features and processes on these scales include: frontal zones, Langmuir circulation, local upwelling, and stratification. However, because these scales are more related to the methods and topics considered by the Regional WG, they are addressed there (see following section 5b).

2) Scales below 1m in space and less than 1 minute in time. Processes occurring on these scales can be studied in situ, semi-in situ, and in the laboratory with concentration on individual predator/prey interactions, their microdistributions, and details of particle-motion. The knowledge obtained from process-orientated laboratory work, numerical simulations, and enclosures will be most helpful in "ground truthing" the observations, data, and concepts derived from the field at comparable scales.

Special attention is needed for particular regions. For example, the coastal zone and small scale processes developing between the shore-line and the 15-m isobath need more study. In this zone, there are nursery grounds and transition areas of many important fish species. Further, it is the location of direct interface to humans. In addition, because "episodic events" seem to play major roles in marine ecosystems, one of the most evident episodes, the passing of a school, should receive more focus.

Finally, it should be stressed that more information on behavior, especially of schooling animals, like tilt-angle- or polarization-changes with respect to physics and environment, is crucial for biomass-quantification based on acoustics.

Topics requiring more investigation

There are several important topics which require further investigation. These include:

1. Predator prey interactions on the level of the individual behavior

1) Foraging
2) Reactions to microgradients of physics
3) Reactions to microgradients of chemicals
4) Reactions to microgradients of prey-concentration

2. Detection

1) Optics of the ocean
2) Optics of the organisms
3) Reduction of contrast and acuity due to phytoplankton blooms
4) Brightness contrast of predator and prey
5) Data on camouflage: transparency, countershading, silvery sides
6) Turbulence field of the individual's direct surroundings (within ~3 cm)

7) Dynamics of particle diffusion and particle aggregation
8) Sensory systems of the organisms

3. Capture/escape

1) Reaction time of prey to opticalstimulus
2) Reaction time of prey to shear
3) Time resolution of crustacean- and fish-eye
4) The role of motion for detection
5) Attack and escape speeds
6) How often can a copepod jump?
7) How long is the time before retriggering is possible?
8) Escape direction
9) Flight length
10) Angle in space
11) Energy budgets in turbulent fields
12) Effects of starvation, reduced oxygen, ammonia, toxic blooms
13) Changes during transitions (e.g., flatfish-larvae from pelagic to benthic)

4. Schooling of fish

1) Age, time, and length of first school formation
2) Functions of schooling
   a) Reduction/increase in predation risk
   b) Orientation in environmental gradients
   c) Inter-individual communication about environmental changes
   d) Responses and advantages under reduced visibility conditions (blooms, eutrophication)
3) Synergistic effects
   a) Flow field and turbulence caused by the propulsion of aggregated organisms
   b) Synchronizedpredation strategies
   c) Behavioral changes correlated with physics

5. Schooling and aggregation of zooplankton

1) Organism motion and flow field of bioconvection in extremely heavy blooms
2) Modelling of bioconvection
3) Influence of bioconvection on the upper millimeter of the sea surface (remote sensing)
4) Behavior of krill, especially sea-ice/organism interactions

6. Effects of microaggregations and schooling on target strength

1) Swimming angle distribution with respect to environmental parameters
2) Swimming angle changes with respect to feeding
3) Internal reflections/interference of sound in schools

7. Dynamics of particles and bubbles

1) Direct measurements of sinking particles, interactions with water andorganismsand formation/d isintegration of aggregates (marine snow)
2) Formation of aggregates by the feeding process of filter feeding animals (barnacles and krill)
3) Direct measurements of rising bubbles and their interactions with water and organisms (waves)
4) Physiology of fish larvae with respect to bubbles and gas oversaturation
5) Direct measurements of rising ice tals and their interactions with water and organisms, scavenging of

organisms/particles by rising ice crystals (frazil-ice formation)

8. Documentation of reoccupation of formerpolluted/ overfished areas

1) Details of egg and larvae developments
2) Tracking and imaging of schools of juvenile herring in the Baltic and Norway fjords
3) Tracking the migration of recovering Atlanto-Scandian herring along the Norway coast
4) Details of the mass-overwintering of Atlanto-Scandian herring in Norway fjords

9. Work on avoidance and its implication on gear construction

1) Security distance to different sizes of objects
2) Escape speed and direction
3) The role of sound, shear, and vision
4) The limitations of the sensory system
5) Possibilities of physical interference and distortion

Instrumentation

High resolution acoustics and optics have high potentials for meeting the objectives of this WG. These methods are summarized elsewhere in this report (see sections 4b and c). Excellent overviews on acoustic techniques for in situ observations of zooplankton can be found in Smith et al. (1992) and on video systems for in situ studies of zooplankton in Schulze et. al. (1992).

Additional instrumentation is needed for high resolution quantification of the optical properties of the ocean to determine the visibility of prey and detectability of predators (e.g., see section 4d). If some parameters can be calculated from the available sensors the algorithms should be installed and tested.

Sampling Procedures

In situ scanning devices should be used in a stand-by or flush-through mode under normal conditions. Instrumentation packages should use acoustics to locate areas of interest (e.g., micropatches, feeding schools, or aggregates) to estimate the rough dimensions of the phenomena or episodics, and to alert the operator - or better the system itself - to switch to the highest possible sampling rate.

Below are a set of relevant sampling problems:

Biological problems

1) Security distance similar as blurring distance
2) Avoidance, attraction
3) Extremely fast motion of many of the small organisms
4) Camouflage, transparency, countershading, silvery sides

Technical problems

1) Small optical attenuation lengths, especially in productive waters
2) System motion due to vibrations, swaying, and microturbulences
3) Small field of vision at the high optical magnifications

Possible solutions

1) Use available light with image intensifier, IR light
2) Increase attenuation length with Schlieren optics (Crittercam), range-gated-laser or IR
3) Reduce contrast of instruments by countershading, mirrors
4) Separate sensorhead and main-instrument (bulky parts on platform)
5) Long-range-find with acoustics
6) Minimize noise (be quiet): use sails, drifter, glider
7) Approach and view from below
8) Approach free-drifting or slowly sinking/rising
9) Keep instruments as small as possible
10) Sneak into security sphere with endoscopes (EcoSCOPE)
11) Compensate system swaying with gyros or software (dynIMAGE)

Quantification

1) A direct 3-dimensional evaluation capability of the instrumentations is desirable
2) Thin field of sharpness
3) Light sheet
4) Optics in two dimensions plus acoustics for third dimension
5) Holography

A key technology for many acoustic and for all optic systems is data compression. DSP (digital signal processing) chips now allow for on-line compression of 16 bit 2 channel sound-sources at 45 kHz with on-line FFT evaluations plus live display (<$8,000), and JPEG or MPEG hardware now allow for video compression at full resolution with direct-to-disk recording (<$25,000).

For the problems addressed by the present WG, images are of predominant importance, and a standardization for easy image display and exchange is desirable. The KODAK Photo CD-I in conjunction with some additional software developments including motion could serve as a future image base.

The evolution of CYBERSPACE and virtual reality technologies should be highly useful

a) for increasing the performances of submersible or ROV control by utilizing the unparalleled 3-dimensional skills of our eyes, brain, and head-coordination-apparatus ,

b) for fast quantifications of xyz coordinates and motion with overlay 3-dimensional crosshairs

c) for visualization of the results - not only for the scientific community but also for school children, precollegiate education programs, and for fundraising (agencies and industries). The traditional sampling methods (nets, pump samples, bottles) and evaluation methods (mortality estimations based on length/frequency distributions), should still be carried out synchronously to validate the new technologies.

Platforms

A variety of platforms can be employed to study small scale processes. These include:

1) Submersibles
2) ROVs
3) AOVs
4) Manned and automatic buoys
5) R/P FLIP
6) LEO 15
7) ATOLL
8) Sailboats
9) Remote controlled model sailboats

It is important to note that smaller scales will be more affected by platform interference and disturbance. Thus, motion decoupling and/or compensation is critical.

Recommendations

1) More work should be conducted with and in natural assemblages of organisms.
2) Markers for grazing quantification should be identified.
3) Laboratory and field workers should meet and work together more often.
4) More research should be conducted in coastal ecosystems.
5) More research should be focused on the 1m stratum directly below the sea-surface/ice.
6) Platforms for long term observations should be deployed.
7) Lagrangian tracking of organisms should be done.
8) Acoustics, optics, and traditional methods should be nested (Fig. 2).
9) More work on avoidance with respect to gear construction should be conducted
10) Interchangeable image- and animation-formats should be standardized.
11) Motion-display and -analysis capabilities of instruments and software should be enhanced.
12) Dynamics like swimming speed,particle displacement and micro-flow should be studied.
13) Easy to use, reliable visualization techniques should be developed.

5b. Regional studies

(J. Aiken, chair, A. Gargett, C. Marrase, B. Rothschild, I. Taupier-Letage)

Regional Studies: Small to Sub-basin Scales

This section focuses on regional studies and considers sampling on spatial scales ranging from 1m, the upper limit of the local process scales considered in the previous section, to sub-basin scales on order of 1000 km. This includes the mesoscale, considered here to cover the range from 10-1000 km. To understand mesoscale to sub-basin ecosystems, requires the study of processes in the vertical with a resolution of *ca* 1m. Appropriately, this minimum dimension links with process studies such as copepod grazing, physical turbulence, etc., which are important processes in the vertical dimension and are the focus of the local process section.

There are a number of regions which may serve as models for the conceptual definition of procedures and methods which should be adopted for regional studies. Examples include: The North Sea, the Mediterranean Sea, The Baltic, The Sea of Japan, the Bering Sea, Korean Sea, Arabian Sea, and Benguela. These are largely discrete ecosystems (the Mediterranean contains several ecosystems) which can be studied as complete entities and serve as models for experimental development and testing of I-GLOBEC hypotheses and models. These examples also encompass the continental shelf; shelf areas are suggested to be responsible for about 30% of the productivity of the world's oceans, and important areas for I-GLOBEC studies. Non-shelf systems will serve as significant models for regional studies also. Examples include: current systems, eddies (warm core rings), upwelling zones, and convergence and divergence zones.

To quantify the spatial dimensions of processes which are significant at regional scales, we can make use of statistical analysis and spectral analysis of existing data sets. For example, Yoder et al., (1987) analyzed satellite imagery (Coastal Zone Color Scanner, CZCS, resolution 1km) and Yoder et al., (1993) analyzed laser induced chlorophyll fluorescence (LICF) and temperature (T) measurements from the Airborne Oceanographic Lidar (AOL, resolution 0.1 km) during the North Atlantic Bloom Experiment 52° to 60°N, 20°W, May 1989. They concluded: "Spatial statistics (structure functions) showed that the dominant scales of LICF and T were significantly correlated in the range 10-290 km. Spectral analysis of the results of long flight lines showed spectral slopes averaging -2 for both LICF and T for spatial scales in the range 1.2 - 50 km. As for previous investigations of this type, we interpret the correlation between LICF and T as evidence that physical processes such as upwelling and mixing are dominant processes affecting spatial variations in Chl *a* distributions in the North Atlantic during the period of our sampling. The minimum dominant T and LICF spatial scales (*ca* 10 km) we determined from structure functions are similar to minimum scales predicted from models (Woods, 1988) of upwelling induced by vortex contraction on the anticyclonic side of mesoscale jets". This result suggests that spatial variability in phytoplankton less than 10 km may not be generally significant (i.e., the amplitude of variation is small compared to amplitude of variations at scales > 10 km); however, there will still be the need for "oversampling" down to 1 km or smaller, to ensure that significant variability is not missed. Clearly there are smaller scale fluctuations and processes such as zooplankton patches, juvenile fish schools operating at dimensions considerably less than 1 km. Important questions include: 1) Are these processes significant at the mesoscale (which is the important dimension in regional studies) and 2) Can we parameterize these sufficiently well to accurately model and understand the dynamics of discrete ecosystems as defined above? It seems that the answer is unknown at present, so some studies and sampling down to a scale of 1-10m may be necessary but should be conducted within the context of sampling processes at smaller scales.

The Significance of Regional Studies

The significance of regional studies has been introduced above. These studies often consider discrete ecosystems, many of which have been the subject of study for considerable periods already, and, as such, will serve as prototype experimental systems for I-GLOBEC studies. I-GLOBEC will benefit and make rapid progress if existing long-term study sites are developed.

Regional studies are not just intermediate in scale between small scale and basin scale studies, they are pivotal scientifically, as the link between the small scale process studies (zooplankton grazing, phytoplankton production) and the global scale problems which are the core objectives of GLOBEC. Regional studies must deliver the parameterizations of processes which are deemed to be important at the mesoscale to allow the creation of realistic, accurate global scale models which will operate efficiently and produce accurate simulations. Experiments at the regional scale must determine the significance of physical-biological interactions as well as their parameterizations, and provide preliminary prototype models for the larger basin-scale studies.

Conceptual Model for the Design of GLOBEC Experimental Sampling

To provide a direction and focus for the design of sampling strategies, there is a need to have a conceptual model in place so that the key parameters can be sampled with the necessary temporal and spatial resolutions. At the outset, there needs to be some cost benefit analysis to optimize the key sensors and sampling strategies for data acquisition. No program can sample everything, everywhere, at all times; the data acquired would not be optimized or appropriate to basic I-GLOBEC models. Statistics, variance, and sampling theories need to be explored to produce a refined sub-set of key variables, rates and extent of data sets (spatial coverage, temporal resolution and duration; see section 6). There are a wide range of sub-models already available, but no consensus model has yet been produced; this aspect is in the domain of the I-GLOBEC Numerical Modeling WG.

In the absence of a consensus model, we have used the following I-GLOBEC goal to provide a preliminary definition of the key processes and variables etc. This is: "To understand the effects of physical processes on the predator-prey interactions and population dynamics of zooplankton and their relation to ocean ecosystems in the context of global climate change and anthropogenic change".

The global-scale focus of I-GLOBEC requires that a top-down approach to modeling and sampling should be adopted as a central core element of sampling strategy. Basin scale and regional scale modeling and sampling need a top-down approach. The bottom-up approach should be adopted for small scale process studies and modeling, with the objective of describing the parameterization of these processes which are required in the larger scale models.

Components of the conceptual regional-scale model for I-GLOBEC include:

1. Physical processes
2. Phytoplankton production/biomass
3. Zooplankton grazing
4. Predation of zooplankton

Some of the key parameters and processes which need to be measured include:

1. Physical structure, T, S, s_t (vertically and seasonally)
2. Phytoplankton biomass (chlorophyll concentration, seasonal production species composition, seasonal succession)
3. Zooplankton biomass, stocks (species composition, geographical distribution seasonal successions)

Sampling Strategies and Methods

The top-down approach to modeling and sampling means that methods which provide large-area coverage, seasonal, year-long coverage or long-time series, must form the core elements of sampling strategy. Sampling strategies should comprise an appropriate mix of the nested sampling method described by Dickey, 1988, 1989; Dickey et al. 1992a,b;1993 (see Figs. 1-3), but there must be an emphasis on methods which can cover spatial scales of 100 to 1000 km quasi-synoptically, i.e. in a period of 1 day or so. These are: towed methods, expendable sensor deployments and surface-water monitoring systems for standard parameters which can be installed on-board research ships or ships-of-opportunity. The synergistic combination of satellite remote sensing and *in situ* sampling methods, especially towed sensor systems, must be exploited to meet the goals of I-GLOBEC. Methods will include:

1) Moorings (instruments in fixed and profiling mode);
2) Drifters (instruments in fixed and profiling mode);
3) Research ships (standard sensor studies and model methods);
4) Ship-of-Opportunity(self-contained, autologging instrumentation packages, on merchant vessels and military vessels);
5) Towed instruments (research ships and ships-of-opportunity towing fixed depth and semi-autonomous undulating sensor packages);
6) Expendable sensors (deployed by research ships and ships-of-opportunity, logged or consummated via satellite to shore);
7) Autonomous vehicles (profilers, working from mother ships or shore bases and communicating to shore via satellite);
8) Satellite and airborne remote sensing (for biological properties, physical structure, sea surface temperature, wave height, roughness, etc.).

Sampling strategies must include time series to give answers to specific problems:

1) Seasonal cycles and seasonal variability
2) Interannual variability and long-term trends
3) Higher frequency cycles (e.g., surface, internal and inertial waves, diel) and effects of episodic events

Time series from moorings provide measurements from a fixed point over seasonal and annual time scales (some with sampling rates ~ 1/minute), and drifters give time series of data for a specific water mass followed in Lagrangian terms. There have been time series of standard stations and standard sections operated from research ships by research laboratories, some over several decades: e.g. MBA stations in the Western English Channel and standard sections in the Mediterranean, Barcelona to Mallorca (Estrada et al., 1993) and Nice to Calvi (Boucher et al., 1987). The Continuous Plankton Recorder (CPR) is an established time series survey now operated by the SAHFOS, Plymouth, UK.

PRUDENCE should have cognizance of these existing surveys, some of which may form the foundations of specific I-GLOBEC studies.

Synergism Between Satellite Remote Sensing and *in situ* Methods

Satellite remote sensing (SRA) of oceanic biology, physical structures like sea surface temperature (SST) and conventional *in situ* methodologies for biological oceanography can and should be made to operate synergistically. Together, they give an integrated and virtually complete suite of sampling strategies covering the full spectrum of time and space scales from seconds to years and mm to 1000 km up to quasi-synoptic global coverage. This synergetic partnership is particularly pertinent to the I-GLOBEC regional studies addressing the goals of "understanding the effects of physical processes on predator-prey interactions, etc.".

Airborne and satellite remote sensing technology and methodologies provide quasi-synoptic, large area observations unobtainable from boats or moorings, repeated regularly with long term missions. The overview from these methods provides the broad-brush framework into which the nested *in situ* detailed sampling can be fitted (e.g., Dickey, 1991).

Actual in water measurements of oceanographic properties, medium to long term moorings, daily sampling on station from research vessels and towed measurements from research vessels or merchant vessels on passage, give higher precision, extra resolution in depth and time and a wider range of measurements of biological properties unobtainable by remote methods. These provide the complementary link to the remote measurements; they join together and fill in the gaps in the remote observations.

In the context of I-GLOBEC, the basic premise is: observations of ocean color from space provide a measure (superficial, to one optical depth) of the areas of enhanced biological production and plant biomass which can accumulate at shelf-sea fronts, topographic features (banks and ridges), shelf edge, and other upwelling zones, and at physical structures (current systems, eddies, spurts, jets, etc.) where zooplankton and fish populations are known to accumulate for feeding, spawning and early life development. Remotely sensed measurements of sea surface temperature provide an additional measure of these physical structures where biological processes are enhanced through AVHRR measurement (skin temperature only) and need careful interpretation (e.g. diel solar heating of the surface layer can reduce the utility of sea surface temperature imagery).

Thus, imagery of ocean color provides both an estimation of the primary production and biomass at the base of the food chain and the location of the areas where the higher tropic levels will thrive; by contrast there are oceanic features, such as long-lived anticyclonic eddies which act as sinks for primary production, drawing down plants to the deep ocean.

The role of SRS to fisheries research and zooplankton population dynamics in the context of intra-annual variability provides an illustration of its utility to the problems at the core of I-GLOBEC regional studies.

Historically, fisheries research has been focused on the inter-annual variability of measurements of recruitment and year-class strengths of fish eggs, larvae and juveniles in response to physical and biological forcing. Generally, this approach has been unsuccessful in explaining the observed changes year-to-year, with no success towards the development of predictive tools (models). The failures of this approach are largely a result of intra-annual (seasonal) variability in the forcing functions, e.g. timing and interactions. Thus, to understand the fundamental year-to-year variability it will be necessary to study the seasonal processes (and perhaps even higher frequency phenomena), such as the duration and spatial extent of episodic events (upwellings etc.) which may be vital to the survival fish eggs and larvae. Ship-board methods cannot adequately measure the extent of variability of physical and biological processes either temporally or spatially and satellite remote sensing of water color will be vital in this context to fisheries research, and related I-GLOBEC goals.

All the *in situ* methodologies can contribute measurements of finer resolution in space and time to provide a broad brush framework of remotely sensed measurements: moorings, ships on station, drifters and towed sensor systems (see Fig. 13).

As described in detail in previous sections, there are a large number of sensors developed or in advanced prototype form ready for operational deployment, which can be used in moored ways; drifters, profiling systems (from research vessels), in underwater towed vehicles, semi-autonomous and autonomous vehicles. They cover the complete spectrum of oceanographic variables which are of interest:

1) Physical: C, T, D, SAL;
2) Biological: Chlorophyll fluorescence, DO, pH, DOC, phytosynthetic parameters, P_{max} (by P+P, FFF);
3) Bio-optical: beam attenuation, radiance, radiance, PAR;
4) Optical: OPC;
5) Acoustical: Plankton biomass and size;
6) Chemical: Nutrients, NO_2, NO_3, PO_4, etc.

Conventional deployments of most of these sensors from research ships and moorings have become routine, giving measurements of many of the parameters relevant to I-GLOBEC. This type of measurement will certainly have a role to play in regional studies, despite the limitation of spatial coverage to a few stations per day or a single point mooring, albeit providing many measurements at high temporal resolution.

Towed Sampling Systems and Sensors

Regional studies require methods which give greater spatial coverage and necessitate the deployment of towed, semi-autonomous and autonomous systems, using both research vessels and especially ships-of-opportunity. In this respect, towed sensor systems give quasi-synoptic measurements which can be related to concurrent or quasi-contemporary satellite observations.

Table 5 lists the measurements which can be used in towed and autonomous applications, or require some development which is achievable in foreseeable time scales.

The main instrument systems focused upon in this section are:

1) The Continuous Plankton Recorder (CPR);
2) The CPR with Oceanographic sensors;
3) The Undulating Oceanographic Recorder (UOR);
4) The Advanced UOR (AUOR);
5) SeaSoar;
6) Stretched SeaSoar;
7) Autosub (Dolphin, etc.);
8) Semi-Autonomous Ship-Board Instrument Packages.

The CPR samples plankton in the surface mixed layer at *ca* 10 m depth, over large areas 100 to 1000 km, with relatively coarse resolution (typically 10 km) using high-speed (up to 20 knots, 10 m s^{-1}) merchant ships on passage (ships-of-opportunity); the survey operated in the UK by the Sir Hardy Foundation (located at PML, Plymouth, UK) has been operational since 1932, covering the N. Sea and N.E. Atlantic Ocean. Data are analyzed manually (observational microscopy). Other surveys include:

1) USA (NMFS, Narragansett RI, U.S. East Coast, Gulf of Maine)
2) Australia: (CSIRO, Tasmania)
3) Projects: Gulf of Guinea (LME), Yellow Sea.

The CPR can carry an electronic sensor package and data logger for measurement of physical (CTD), biological (Chlorophyll fluorescence, DO, pH), and bio-optical (irradiance beam attenuation) parameters. There is consideration currently of a new CPR to provide a plankton sample suitable for automatic data analysis.

The UOR (Aiken, 1985; Aiken and Bellan, 1986, 1990) is a multi-sensor oceanographic sampler which profiles automatically from near surface to *ca* 100 m (optimum range) when towed on unfaired steel cable at speeds in the range 4-6 m s^{-1} (8-12 knots) covering distances up to 500 km per day; the maximum depth is restricted to *ca* 40 m at the higher merchant ship speeds of 9-10 m s^{-1} (up to 900 km per day). The undulation pitch length is typically 1.6 km (adjustable from 0.8-4.0 km). The UOR carries sensors for physical properties (temperature and conductivity) and bio-optical properties chlorophyll fluorescence, particulate scattering and water transmission, dissolved oxygen (DO, pH, DOC, and it has a suite of light sensors to measure downwelling and upwelling irradiance in several wavebands and provide the means to interpret satellite, remotely-sensed images of ocean color.

Data can be logged *in situ* (merchant ships or research ships) with endurance's of several days, depending on sensor complement and data rates or communicated via conductor-cored towing cable to a ship-board computer or data logger.

The UOR, like the CPR is an established instrument, having been developed for over 20 years and deployed widely in research cruises in the western English Channel, Celtic Sea, Irish Sea, North Sea, N.E. Atlantic, Greenland, Iceland, Norwegian and Barents Seas, Mediterranean Sea, mid-Atlantic Bight, Gulf of Maine, Indian Ocean, Antarctica, and the Equatorial Pacific; it has been used from high speed merchant vessels in the western English Channel (Plymouth to Roscoff), the North Sea (Hull to Aberdeen to Denmark) and the North East Atlantic Ocean (Iceland to Portugal). Consideration has been given to the development of an advanced UOR to carry a pump and probe fluorometer (to measure phytoplankton photosynthesis characteristics) an optical plankton counter (OPC), acoustic biomass counters and nutrient sensors.

SeaSoar is an undulating towed vehicle capable of reaching 500 m depth when towed on a faired-conductor-cored cable at speed in the range 4-5 m s^{-1}; data are logged by computer on board the research vessel. Sensor complement is similar to the UOR and a stretched SeaSoar is planned to include, OPC and acoustic biomass sensor.

Ship-of-Opportunity Methods

The ship-of-opportunity philosophy should not be restricted to towed sensor systems such as the CPR and UOR. Sensors for PCO_2, C, T, Chlorophyll and nutrients with integral logging systems have been installed as semi-autonomous packages on merchant ships, plumbed into sea water systems. These measurement systems should be expanded, developed and then exploited to a greater extent.

It is conceivable that plankton samplers, video systems, particle counters and imaging systems, developed into an integral package could be used on the deck of a merchant ship, plumbed into the fire hydrant system and operated semi-autonomously. Acoustic biomass sensors could be added to the measurement suite and use of ADCP's for zooplankton biomass estimations should be given consideration.

Data from any of these sensors could be relayed to a shore laboratory by a satellite or cellular phone link (e.g., see Dickey et al., 1993); data from XBTs deployed from merchant ship are already relayed to shore using METEOSAT & ARGOS satellites. Finally, in the post cold-war world, the world's navies are under employed and often looking for jobs to to justify their existence.

Expendable Methods

Expendable probes can be deployed by ships on passage and offer a relatively low-cost, low-tech solution to the problems of large area coverage. Used in configuration with surface-water monitoring instrumentation they provide the additional measurement of depth structure at selected positions though for only a few parameters (typically only XBT for temperature are deployed widely). Data can be logged by ship-board computer and communication of data directly to shore laboratories by satellite links (METOSAT and ARGOS) is well established and fairly routine. Additional expendable probes have been developed for:

1) XBCT: conductivity and temperature
2) XBSVT: sound velocity, T;
3) AXBT: airborne XBT;

New expendable probes under development include:

1) XBK: diffuse attenuation coefficient (development well advanced)
2) XBF: fluorescence of chlorophyll)

I-GLOBEC should endorse the development of these probes and their use in ship-of-opportunity modes to provide regional scale and basin scale coverage of these parameters.

Relationship to Existing International Programs and PRUDENCE

I-GLOBEC should have cognizance of existing research programs (both international and national) with comparable and compatible goals. Many of the measurements planned for these programs will be of interest to I-GLOBEC modelers and these data should be integrated into I-GLOBEC data bases.

International programs include:

1) JGOFS: Global biological sampling
2) WOCE: Global circulation, physical structure

3) LOICZ: Land ocean interactions on the coastal zone

PRUDENCE should be activated to compile and review existing data sets from both current international programs and historical long time series data, e.g. CPR Survey and data sections from other regions of interest to I-GLOBEC.

5c. Basin scale
(P. Nival, chair, D. Cushing, G. Gorsky, T. Granata, and R. Strickler)

Background

As populations of plankton species can be dispersed and transported over wide areas and their growth rate can depend on the overall behavior of the pelagic environment, it is necessary to develop studies at the ocean basin scale. These studies are intended to give information on spatial as well as temporal trends in population dynamics of different populations of a targeted species. Motivations for such studies include:

1) Information on basin scales are necessary to set the boundaries for regional and mesoscales studies. Large scale patterns define the extent of area where the main processes governing population dynamics of marine species have a similar behavior.

2) Large scale pattern change may set the stage of timing of small scale processes (e.g., changes in molting of copepods, spawning of reef corals, etc.). Change in latitude of a large scale pattern like the cold boundary of a large current system (Gulf Stream, Kuroshio, etc.), in response to an overall change at the basin scale, can affect the local timing of a plankton bloom.

3) Rapid changes of a large scale structure can induce significant trends at the mesoscale.

4) Ocean-atmosphere connections occurring at the large/basin scale can trigger mesoscale to small scale changes and strongly effect population dynamics and community structure.

5) Large scale patterns depend on different processes and especially on basin bottom or coastal topography. It is also evident that important large scale gradients are north-south.

6) Large scale patterns of deep circulation could affect population dynamics of a species through transport of overwintering stages.

The Sampling Problem

Sampling at the basin scale is perhaps the most challenging observational problem because of the vastness of the scale. As illustrated in Figures 1, 2, and 3, no single platform can satisfy the need of synoptic sampling on the basin scale. Satellites can in principle sample the basin scale; however, there is not yet a satellite sensor or set of satellite sensors which provides direct information on trophic levels higher than phytoplankton and even phytoplankton distributions can be estimated only for the very near surface waters. Further, ships are too slow and few in number to provide synoptic data and moorings provide excellent temporal coverage, but at single points. The various sensors, systems and platforms described in previous sections along with numerical models (e.g., for interpolation, data assimilation, etc.) will need to be utilized with careful planning and well-developed sampling strategies to enable meaningful studies at the basin scale.

Recommendations

It is necessary to:

1) Plan simultaneous studies in different basins. In order to make mesoscale comparisons in different ocean basins, we need to have measurements in different distant locations, simultaneously. The use of moorings will be necessary to provide continuous data.

2) Encourage large scale mapping of mesoscale structures by remote sensing or other appropriate methods. As a consequence methods minimizing time or space averages are needed.

3) Encourage future (and use of available) technologies (sensors) that would (could) exploit satellite platforms in order to estimate zooplankton biomass globally.

4) Study the large scale patterns of deep circulation at the depth of the overwintering stages of a targeted species.

5) Couple large scale models with remote sensing and continuous vertical sampling (data assimilation). The usefulness of data assimilation for population dynamics modeling should be evaluated.

6) Develop various sampling strategies and also interpolation methods (e.g. krieging techniques) (see next section).

7) Encourage basin scale surveys using ships of opportunity and autonomous vehicles (e.g., towing or carrying specific instruments, using expendables, etc.) with the aim of estimating zooplankton biomass, life stages of selected species, etc. Systems could include: arrays of optical particle counters, Continuous Plankton Recorders, and other platforms and sensors described in previous sections).

8) Test the ability of biotechnologies to provide new methods for the identification of different populations of a targeted species and make comparisons at the large/basin scale.

9) Cooperate with WOCE, and general meteorological community as well JGOFS to provide complementary physical and biological models and data on basin scale forcing.

10) Develop studies on the sea surface elevation from altimetric data and sea surface pigments (for phytoplankton) to investigate the patterns of dynamic structures at large scale (Topex-Poseidon and SeaWiFS).

6. SAMPLING METHODOLOGIES/ TECHNIQUES

(K. G. Foote, chair, I. Aoki, M. Lehaitre, T. K. Stanton)

Background

Sampling of spatial and temporal phenomena, such as those characterizing plankton distributions (e.g., Haury et al., 1978, Haury and Pieper, 1988; Dickey, 1988, 1990, 1991), as due, for example, to upwelling (Woods, 1988), involves statistical considerations by its nature. Appropriate techniques may be divided into two classes: time series analysis (Brillinger, 1981) and geostatistics (Matheron, 1971; Cressie, 1991), otherwise known as spatial statistics. Examples of application areas are 1) monitoring of oceanographic parameters near hydrothermal vents by event-triggered double-rate sampling with fixed-position sensors (Chevaldonne, et al. 1991), 2) abundance surveying of herring by echo integration (Foote and Rivoirard, 1992), 3) abundance surveying of shrimp by trawl sampling (Simard et al., 1992), and 4) integration of temperature fields over distinct sea areas, such as the North Sea (Svendson and Magnusson, 1992).

In geostatistics, knowledge about a spatial distribution, which is acquired by sampling, is used to characterize the structure and, by means of a model based on the discerned structure, to infer properties about the distribution. In particular, geostatistics may be used for the following purposes:

1) Characterization of spatial distribution by a structure function, which is typically the variogram,

2) Estimation of spatial variables at points and, by extension, over local areas, as well as extended or global areas, hence mapping too, and

3) Determination of a realistic variance estimate that includes effects of placement of samples, observed distributional properties, and extent of the survey region.

Geostatistics is based on samples collected at finite stations or along transects without requirement of a particular sampling scheme or survey design, although the estimation process may be improved substantially through the design. Auxiliary variables may be incorporated in the analysis. Anisotropy may also be incorporated, through the variogram. Weaknesses of the method are associated principally with assumption of stationarity and specification of the variogram model. Remedies are available, but require a higher order of knowledge about the phenomenon being studied.

Time series analysis, for example, Kalman filtering (Cooper, 1986), may be used for estimation of time-varying processes. Analogues of time-domain and spatial-domain techniques are strong, if frequently unrecognized because of the historically separate development of the two.

Recommendations

1) Planning

Design of a survey should be based on the objective of the measurement, including desired scale size, spatial and temporal properties of the phenomenon being studied, of the Nyquist theorem, and availability or affordability of sampling resources. Use should be made of prior information, as through auxiliary variables, as available. In the absence of prior information (i.e., in a state of ignorance), sampling in space should be done as uniformly as possible. For phenomena characterized by patches, multi-tiered, adaptive, or directed surveying should be considered. For phenomena characterized by events, adaptive observation at different rates should be considered.

2) Data analysis

Geostatistics, or spatial statistical techniques, should be adopted for analysis of data. Development of geostatistics to address time-varying phenomena is to be encouraged.

7. EMERGING AND FUTURE TECHNOLOGIES FOR I-GLOBEC

(Jaffe)

As part of the I-GLOBEC meeting, a session was held on the possibilities for new technologies and how they might be used to answer the scientific problems that I-GLOBEC is aimed at addressing. This session was naturally speculative, however, a view toward the future was considered to be a valuable exercise in planning. The goal of this section is to summarize some of the discussion/presentation that ensued.

In looking at what new types of technological progress are being made and how they may facilitate the goals of the I-GLOBEC effort, there are several areas which are clearly applicable. In particular, since much of the I-GLOBEC effort is based on in-situ sensing of animal distributions and behavior, the ability to collect, store and recall information is extremely important. In addition, there are several areas such as data processing, optical system evolution, and also biotechnology, which may have an interesting effect on the future of technology based sampling.

A great deal of our discussion concerned the utilization of both optically and acoustically based sensing techniques. Since these techniques are largely complementary, it is likely that a combination of both acoustics and optics will offer the optimal mix for the evolution of I-GLOBEC technology. How will emerging advances in technological advancement affect the development of new I-GLOBEC instruments?

Considering first, the evolution of optical imaging methods, there is a great deal of research that is being done by the commercial sector with respect to real-time storage of video data. In this regard, it is likely that recent advances in our capability to obtain quality video information about underwater organisms will be combined with real- time digital storage and processing systems. The advantages of digital storage over analog methods for video are in increased dynamic range and signal fidelity. Since zooplankton are inherently low contrast objects, both signal-to-noise and dynamic range, or ability to distinguish small changes in grey level, are important.

Perhaps, more importantly, in the realm of imaging, will be the capability to perform automated pattern recognition on the input data stream so that human observer identification will either be unnecessary or, at the worst, an assisted mode will be necessary. Although a great deal of discussion about this has occurred over the last several years, achieving the long range goal of automated identification of live video images is certainly imaginable. Moreover, one can easily imagine a set of intermediate goals which, although, short of this full goal, are nevertheless informing. For example, as described earlier, the OPC or Optical Particle Counter, developed by Alex Herman and colleagues is an analog optical device which produces a stream of data values which indicate the cross-sectional area of the particles which are flowing through it. Certainly, between this and a full fledged image identification system, there are a number of sub-goals which could be achieved. For instance, digital processing of particle aspect ratio, degree of scattering, multi-spectral attenuation are just a few enhancements which can be imagined. Also, in the view of this author, what is required of a digital automated imaging system is not 100% accuracy, but rather unbiased estimates. Put another way, the system does not need to judge each and every organism that comes through it correctly, but rather, a fraction of them in an unbiased way.

Digital video acquisition, on the other hand, has problems associated with the limited volume of interrogation of these systems which, to some extent are a result of the attenuation of light. This will limit the instantaneous volumes which can be surveyed.

In recent years, sonar techniques for surveying distributions of organisms have become more and more recognized. How will the evolution of emerging technologies affect these methods? As with the optical imaging techniques, the enhanced storage and processing capability of modern computers will allow commensurate advancements in this field. Since, in the case of sonar, limited success has been achieved with the use of sonar lenses, unlike optical imaging, sonar imaging systems need to rely on digital image formation. In this regard, one can envision a set of systems evolving whose complexity is only hinged on the capability of performing digital beamforming. Thus, three-dimensional sonar imaging systems operating in the near field with resolution of fractions of a degree in azimuth and bearing are eminent.

In addition, most if not all sonar systems that are in use today rely simply on the estimation of the fraction of backscattered sound, or target strength to estimate individual size. It is certainly conceivable that this type of estimation will be superseded by more sophisticated techniques. For example, although frequency/size dependence has been used for volumetric estimation of particle densities, wide band reflections from individuals would allow more accurate echo counting statistics/size relationships to be estimated. These methods are critically dependent upon the sonar systems ability to discriminate individual organisms in moderate to high densities, which in turn, hinges upon the resolution of the system. Higher resolution thus adds capability to analyze echo data in a more sophisticated fashion.

An additional degree of freedom over simply looking at frequency dependent echo statistics also exists. Assuming that the ultimate goal of a sonar imaging program would be to characterize the exact organism that is being ensonified, a number of possibilities for advanced echo processing exist. As one example, it may be possible to look in a more detailed way at the reflected signal to see how say the movement and orientation of the organism has effected the reflected sound. Temporal coherence is one parameter that has been underexploited in addressing this issue.

On the other hand, as with optical techniques, the limitations inherent in the attenuation and scattering of sound at high frequencies prescribe a physical arena which will be impossible to circumvent. The end result of this fact, coupled with the limited reflectivities of the species under examination, will mandate limitations in both the range and resolution of sonar systems.

In examining the technological possibilities for enhanced sensing and processing of I-GLOBEC data, the general field of optical components, storage, and processing comes to mind. Over the past several decades, the general area of optical technology has been rapidly advancing. Some of the advances have already been discussed, for example, the newest generation of cooled, scientific grade CCD sensors are capable of detecting on the order of 10's of photons in the visible wavelength band with very low noise and high dynamic range. In addition, optical signal processing techniques will likely emerge in a very practical way in the 21st century. Optical storage methods have extreme promise when looking at the diffraction limitations of even visible light. For example at storage densities of 1 micron, a 10 cm cube can store 10^{15} bits of information. Therefore, very likely, the future of computer storage technology will depend upon optical techniques. For I-GLOBEC, optical technology, such as laser diodes, solid-state scanning devices in combination with different types of more exotic imaging geometries, may provide an interesting set of technological opportunities. For example, one can imagine an underwater lidar type system which uses direct backscatter of laser induced fluorescence to measure the distribution and abundance of phytoplankton. Systems like this could probably operate over distances of at least 10's of meter.

Optical communication systems using fiber optic technologies are currently being used in many underwater applications. What are the potential implications that these types of systems have for I-GLOBEC? One advantage of fiber optics, in this regard, is the relative size/weight of the cables attached to underwater devices when compared with electrical connectors. One of the areas that stimulated much discussion was the evolution of drifting instrument packages. Perhaps these drifting packages could be connected to fiber optic cables to provide real-time information and allow control of the package. In addition, if the drag provided by these cables was too much, perhaps free ocean propagation of modulated light (over short distances) could provide the link.

Optical techniques may present another advantage when combined with in-situ sensors. For example, the biomedical industry is rapidly advancing the capability of using light for medical diagnosis. In some situations, a molecule with optical properties that is also sensitive to some parameter that one is interested in measuring can be used as a photochromic sensor. Using fiber optic cables in conjunction with such compounds may have very interesting advantages. For example, the outside of a fiber optic cable could be coated with such a compound, and the backscatter from a short light pulse which was propagated down the fiber could be used as a continuous monitor of the depth dependent concentration. One advantage of this technology is that extremely specific and sensitive types of probes, at least in principle, can be envisioned.

Another area which warranted some discussion was the potential availability of extremely inexpensive in-situ samplers. For example, in the case of acoustics, deployable, potentially expendable Doppler based sensors would be valuable for conducting experiments where high density spatial surveys would be desirable. In addition, the procurement of expendable optical sensors such as transmissometers (multiwavelength) or fluorescence spectrometers would be extremely valuable. It is very likely that as the cost of electronics continues to decrease, these devices will start to become available.

In examining the primary goals of the I-GLOBEC program, it is clear that the program could be advanced with the advent of new and different engineering research and development. In particular, although the skills of individual investigators in these areas are quite advanced and have become, out of necessity, honed in the development of in situ sampling and analysis systems, it is acknowledged that an advance in engineering technology would greatly augment the quality of the science. This is because a great deal of phenomena that are of interest are currently unobservable.

Most of the present engineering advances in this field have come from the cross-fertilization of consumer technology goods into the scientific arena. Clearly, this strategy is very different from that of say, the space technology arena, where the technology has usually developed out of scientific necessity as opposed to commercial opportunism. We should not expect the commercial marketplace to solve our problems as in many cases, the financial incentives for funding some of the large development costs do not exist.

In order to remedy this situation, it is proposed that an international collaboration of engineers be established. There exists a great diversity of ocean engineering areas which could lead to great advances in the I-GLOBEC effort. Both bioacoustics and data processing should take advantage of these so that all participants can both capitalize on their skills as well as accommodate any financial constraints that the programs may possess.

One fact that makes this collaboration straightforward is that the standards of the computer industry have recently been coalescing and there are relatively few options when it comes to instrumentation integration. In addition, ready access to electronic mail and fax machines permits researchers in different countries to be able to pursue projects on an almost continuous 24 hour bases. This is especially helpful for meeting cruise deadlines on challenging projects.

8. SUMMARY AND RECOMMENDATIONS

Highlight points are summarized here as a general synopsis of the SOS-WG's deliberations.

1) A Testbed for an I-GLOBEC Observations and Modeling System

The problem of prioritizing or even defining measurements of key variables and their sampling (in time and space) remains a daunting problem for I-GLOBEC. The level of detail needed for satisfying I-GLOBEC objectives must be considered by virtually all I-GLOBEC scientists. Sampling of all species and their various lifestages at time and space scales spanning several orders of magnitude is clearly impossible. Section 2 of the report synthesizes a great body of information concerning this issue. Importantly, a subgroup of participants led by Allan Robinson have developed a conceptual framework (Section 3) which defines some of the critical elements for an Observation and Modeling System (OMS) which would link observational systems and models with a key objective of bridging scale gaps through data assimilation schemes. The classical problem of subgrid scale parameterization dictates that nested sampling arrays and control volumes be used in conjunction with nested numerical models (e.g., top down: basin scale model results used for input to regional models, etc.; bottom up: small scale/organismal model results used for mesoscale, etc.). Clearly, physical and biological measurements need to be taken concurrently from a broad suite of instrumented platforms capitalizing on their positive attributes. Model results should be used to design sampling to the greatest degree possible. In order to make progress in achieving the objectives of I-GLOBEC, it is suggested here that sampling systems be located and maintained in several regions of critical interest long enough to define critical processes in space and time. "Oversampling" and sensor comparison are necessary at an early stage. Nested arrays of sensors are needed to establish subgrid scale parameterizations and robust, reliable data assimilation schemes should be developed and applied for the sampling region. This effort should greatly facilitate the definition of critical variables and sampling domains. As indicated in the previous section, an international commitment to technology and engineering development is highly desirable and should be particularly attractive for the testbed approach where new instruments and platforms (e.g., "stiff" moorings, stable platforms, SWATH vessels, etc.) may be tested.

2) Behavioral Observations

Unlike other global studies such as WOCE and JGOFS, the behavior of individual organisms is deemed important to answering critical questions. Clearly optical/video techniques will be necessary for individuals, however group behaviors of larger organisms may be studied with acoustical methods.

3) Predator-Prey Observations

Observations of predators and their prey require small scale measurements. Concurrent velocity fields on the scale and in the vicinity of the organisms are needed. New, non intrusive methods for deriving these data are needed. Questions concerning perception, detectability, schooling strategies, etc. need to be examined with new techniques.

4) Rate Measurements

The production and losses of organisms requires rate measurements. It is important to determine mortality rates, however this is a difficult task as it is virtually impossible to follow individual organisms for adequate time intervals. The length of time spent in specific larval stages is also difficult to determine. Methods for making estimates of these important rate processes need to be established. These may require methods other than those addressed in then present report.

5) Size Distributional Data

A recurring need expressed at I-GLOBEC planning workshops is size distributional data for phytoplankton, zooplankton, larval development, and population dynamics. For the larger scale organisms, multi-frequency acoustical methods are applicable whereas video and optical methods are needed for the smaller scale organisms.

6) Gaps in Sampling Scales

A classic problem which confronts oceanographers is the dilemma of sampling of scales over several orders of magnitude. Interestingly, the research interests of many of the participants of the present workshop, as well as previous relevant workshops, focus on scales of less than a few meters while several others have interests in problems on scales in excess of several kilometers. Thus, there may be a gap in interest in scales from a few meters to a few kilometers. This may not be the case, however sampling in this intermediate range should not be overlooked. Further, the linking of data collected from a multiplicity of platforms must be considered as an integral sampling and modeling problem. For acoustical methods, consideration needs to be given to measurements with overlapping frequency ranges as well as single versus multiple sounding beams.

7) Linkage of Variable Types and Undersampling

As indicated earlier, platforms ranging from satellites to individual moorings and drifters will be needed to provide requisite data. The diversity of data variables as well as their optimal sampling domains presents a great data synthesis problem. Nested sampling implies that some data will be collected at specific sites with high temporal resolution while other data will be collected over great expanses of the ocean via ships non-synoptically, leading to questions of advection for the local measurements and temporal aliasing for the shipboard survey sampling. Data management and modeling will be needed to translate disparate data sets into coherent scientific information.

8) Data Calibration, Interpretation, Visualization, Integration, and Utilization

In order to improve data quantity and to broaden sampling domains, several of the newly developed systems involve indirect determinations of key variables. Hence, calibration and interpretation of signals (e.g., acoustical and optical) needs to be given a high priority. The "testbed" concept described in the first point above provides an obvious starting point. Clearly, continued direct observations of organisms will be useful and pursuit of overlapping measurements of organisms optically and acoustically will be necessary (both in the lab and the field). The development of visualization methods is advancing rapidly and need to be applied to I-GLOBEC data sets. Taxonomic information is important for I-GLOBEC and video (image identification) data processing. Improved acoustic models of organisms are needed also. The utilization of I-GLOBEC data by investigators in near real-time is important for both sampling via ships and other platforms and for data assimilation modeling as discussed in point 1 above. Telemetry methods are advancing rapidly and should be utilized. Finally, integration of data sets (cross-sensor, cross-station, etc.) is essential in providing as complete a database as possible. Selection of a common data format to allow integration is a great challenge to the program.

9) Sampling Theory

As meteorological and physical oceanographic observational systems have matured, optimal sampling schemes (field of "geostatistics") have been developed. For example, sampling with XBT's in the Pacific along shipping routes has enabled studies of sampling requirements. I-GLOBEC will need to consider how to optimize its sampling, especially because of limited resources and the great number of key variables. Use of historical data is important and falls in the purview' of "Prudence."

10) Availability and Application of Current Technology

There is currently a large number of specific sensors and systems which can be applied to I-GLOBEC problems. These include physical (turbulence probes), acoustical (e.g., ADCP's), optical (e.g., various light sensors), and video (e.g., based on CCD arrays) devices. In addition, integration of new sensors with appropriate platforms such as moorings and drifters is reasonably well developed. One exception is an autonomous profiler platform capable of measuring with high vertical resolution for several months or longer. There remains a great need for expendable optical and acoustical sensors which can be deployed from ships and airplanes on regional and basin scales. As impressive as our collection of specific systems is, most are one-of-a-kind. While it is important to continue to develop new systems, the execution of major I-GLOBEC sampling programs will require community access to key observing systems. One way to accomplish this is through commercialization of selected systems.. Careful cost-benefit analyses need to be done for new sensors and systems. It is important to learn how to better utilize data sets collected in a routine mode. Examples include acoustic Doppler current profilers (ADCP's) and advanced continuous plankton recorders. An interesting approach to derive turbulence and vertical velocity information using ADCP data has been described in the present report and the use of backscatter signals from ADCP's for zooplankton quantification is well underway. Utilization of optical data for flow, turbulence, and organismal characterization may be possible as well.

Figure Captions

1. A schematic diagram illustrating the relevant time and space scales of several physical and biological processes of importance to I-GLOBEC (after Dickey, 1991).

2. A conceptual illustration of a nested physical-biological sampling configuration designed to sample several of the processes indicated in Figure 1 (after Dickey, 1991).

3. Temporal and horizontal sampling coverage of several platforms (based on Dickey, 1991; after Bidigare et al., 1992).

4. Sizes versus swimming speeds of various organisms (after Granata and Dickey, 1991).

5. Organismal sizes and growth rates along with rates of advection and dispersal (modified after Steele, 1975).

6. Top: Vertical profiles (0-80m) of (left to right) temperature, chlorophyll fluorescence, vertical shear of horizontal velocity, and 10cm estimates of turbulent kinetic energy dissipation rates, e, during an interval of low wind speed (< 3 m/s). Center: same as top but with expanded view of the 30-60m segment; thin layers are indicated by circles. Bottom: same as upper panels, but expanded view of segment from 57-59m. Note the association of fluorescence layer with temperature step at 57.95m and the diminished e at the same depth.

7. Time series of chlorophyll fluorescence and the northward component of velocity based on data collected from a multi-variable moored system deployed in the surface layer of the Sargasso Sea in 1987 (see Dickey et al., 1993). a. 4 hour segment b. 4 day segment c. 1 month segment d. 9 month segment.

8a. Left: Simple example of resorting of a density profile (solid dots) into a statically stable profile (open circles). Right: Thorpe scale is vertical distance, D, point must be displaced to achieve static stability.

8b. Correlation between Thorpe scale, L_T, and length scale L_0 (from Dillon(1982).

9. Vertical velocity measurements made from R/P FLIP using a horizontally oriented VMCM indicating Langmuir circulations (from Weller et al., 1985).

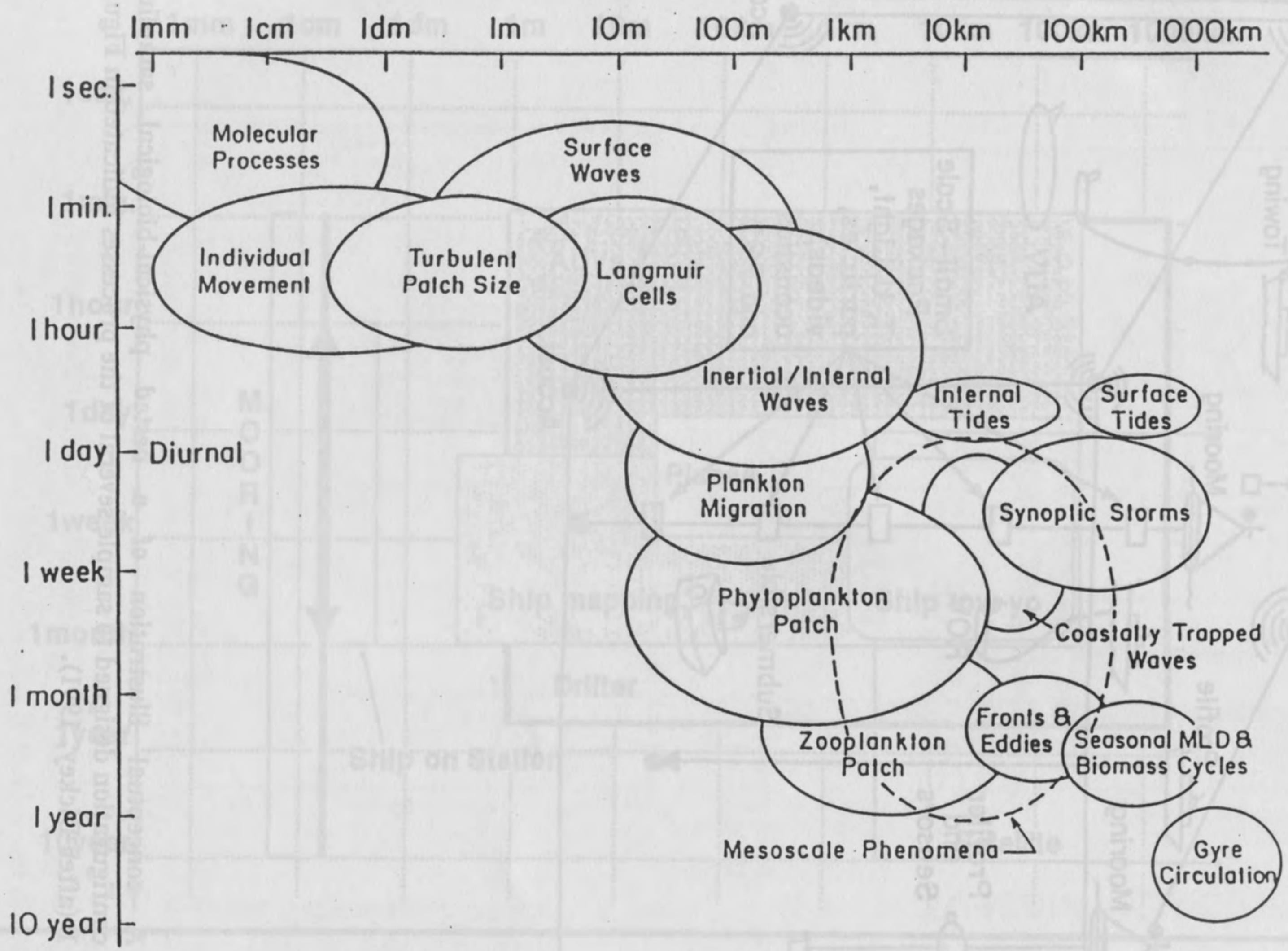
10. Vertical velocity measurements made in coastal waters from a ship-mounted ADCP. Strong vertical velocities associated with tidal flows are apparent (from Gargett, 1993).

11. Vertical profiles of the logarithm of dissipation rate, e, (dashed curve) (James Moum, Oregon State University) and estimates of lorithm of dissipation rate, e2, based on remote measurement of vertical

velocity, w, obtained from DCP (solid curve) (Gargett).

12. Depiction a nutrient budget turbulent fluxes produced by wind mixing, upwelling and transport on the continental shelf off Vancouver Island (from Crawford, 1991).

13. Schematic illustrating a methodology for determining variability of bio-optical properties in space and time. Applications could include determinations of the subsurface light field and primary production (after Dickey et al., 1993)



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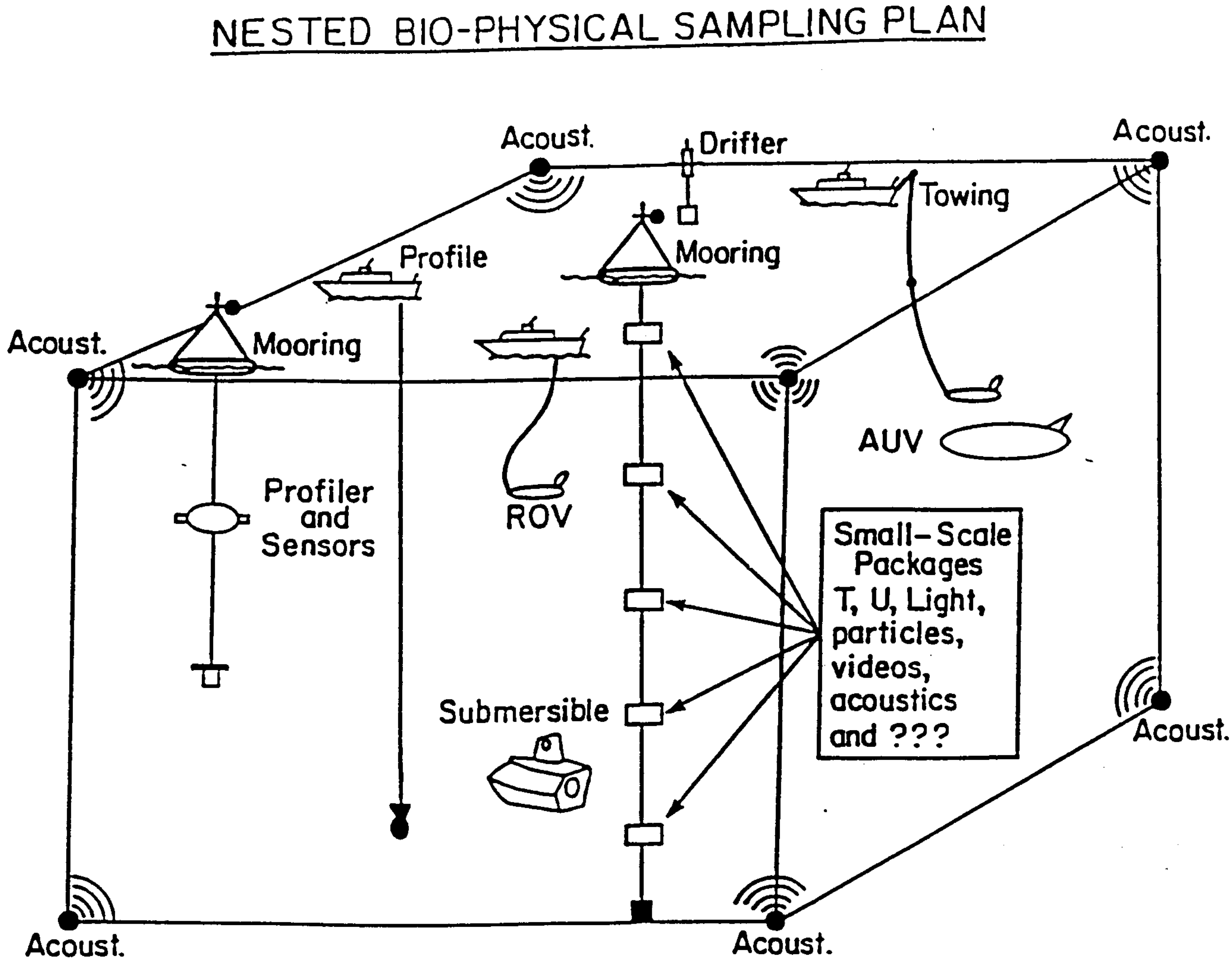

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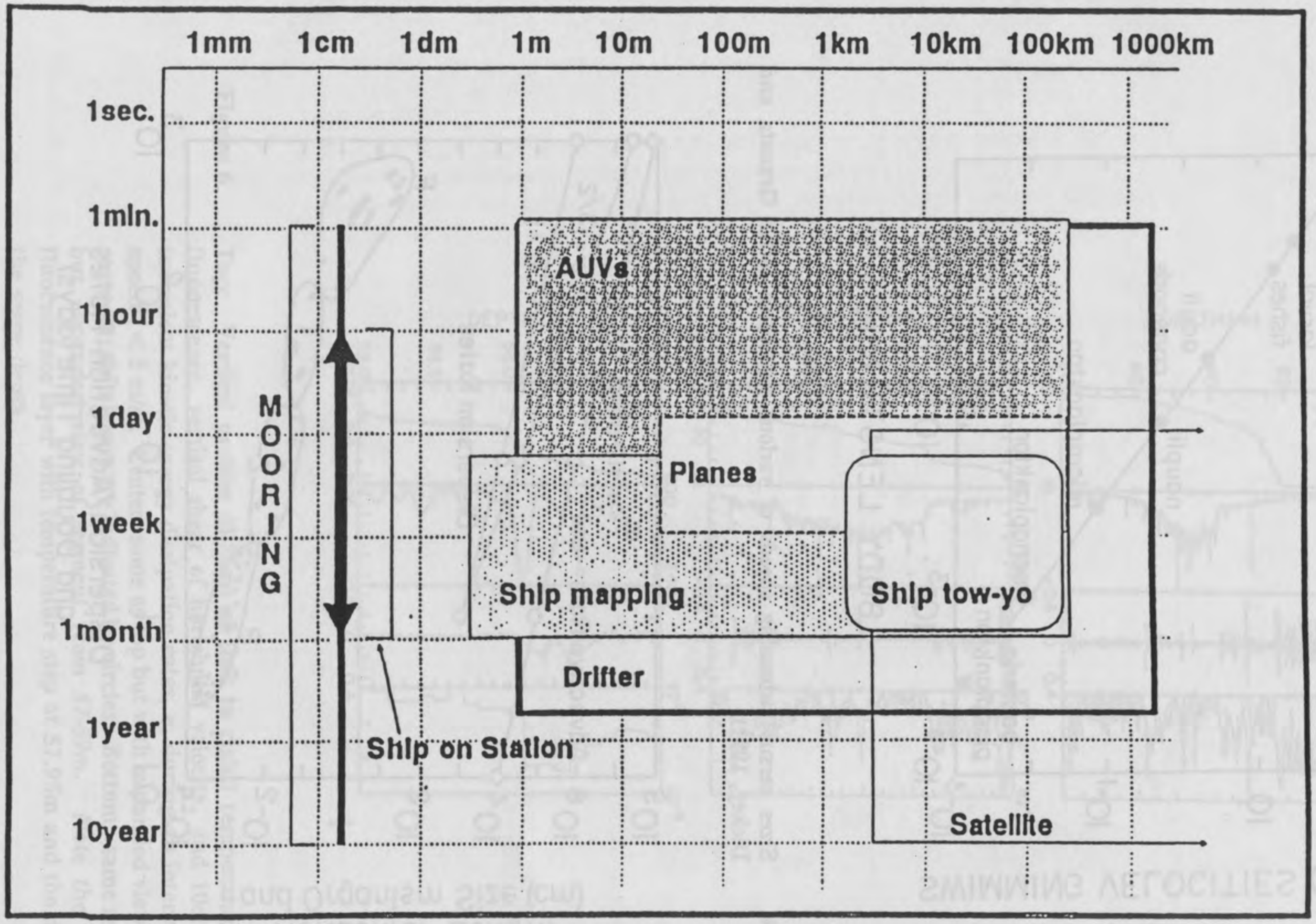

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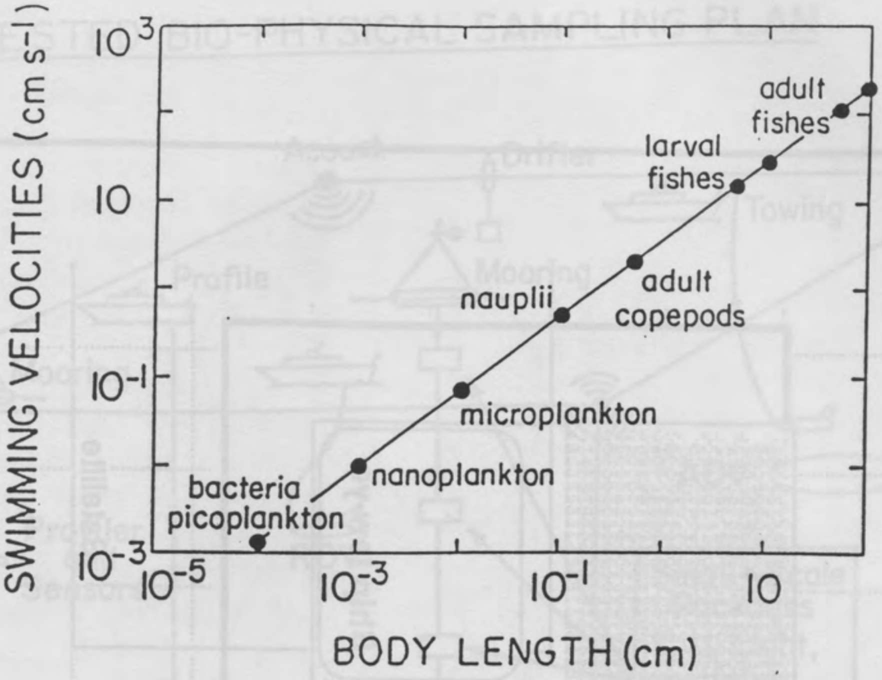

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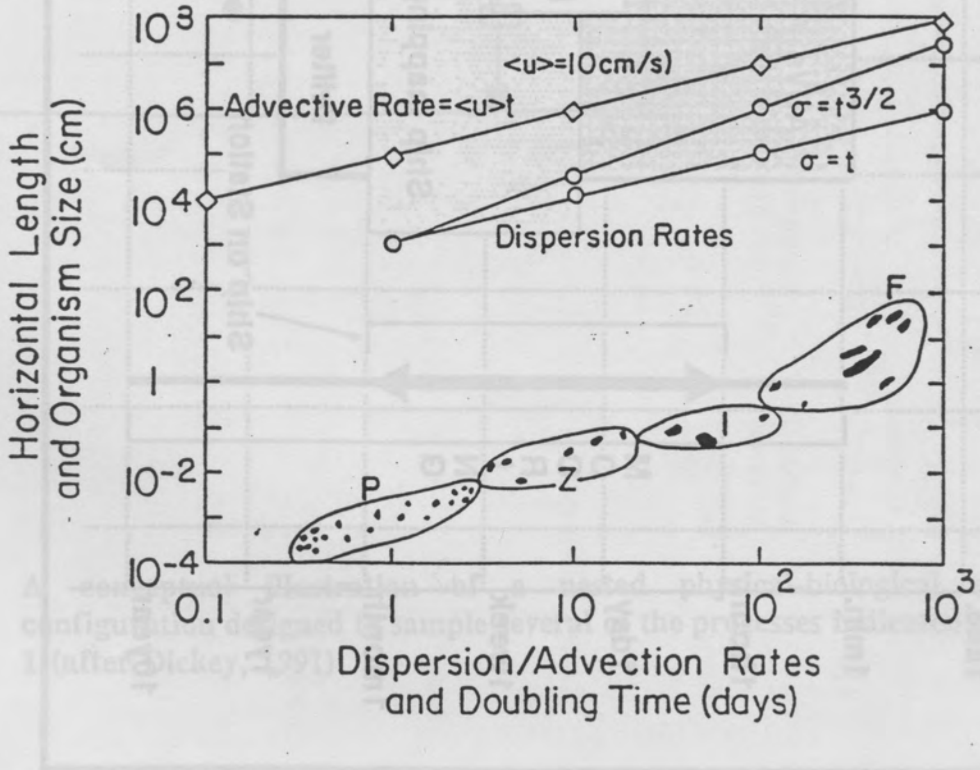

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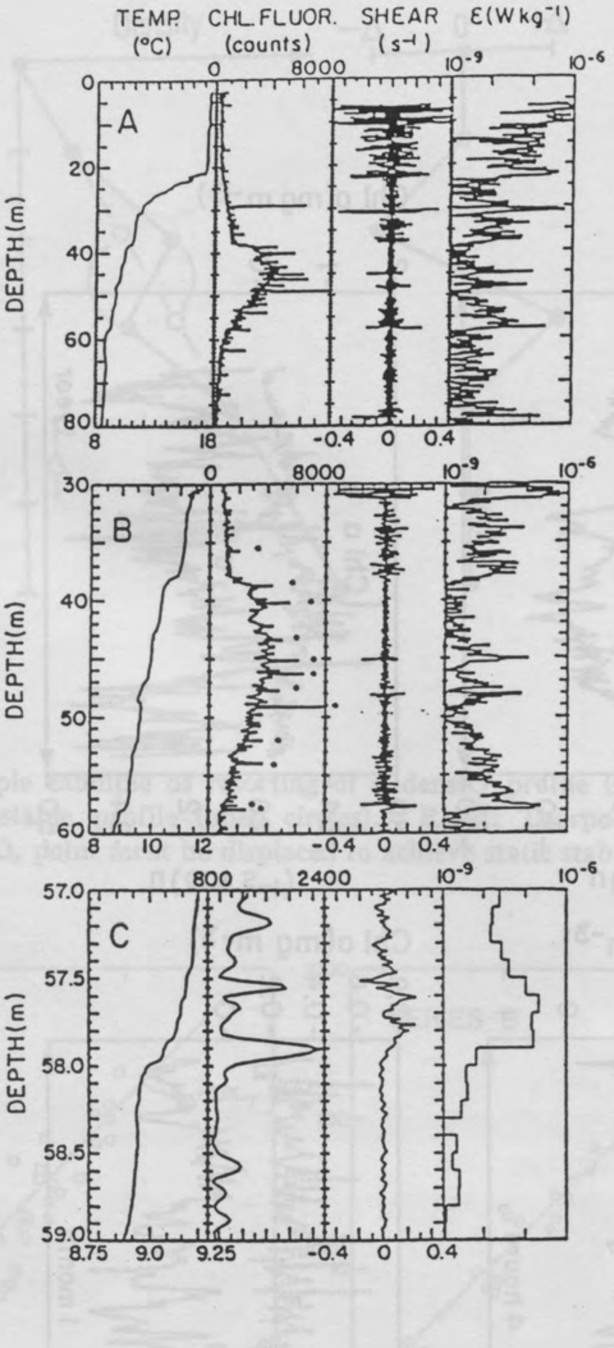

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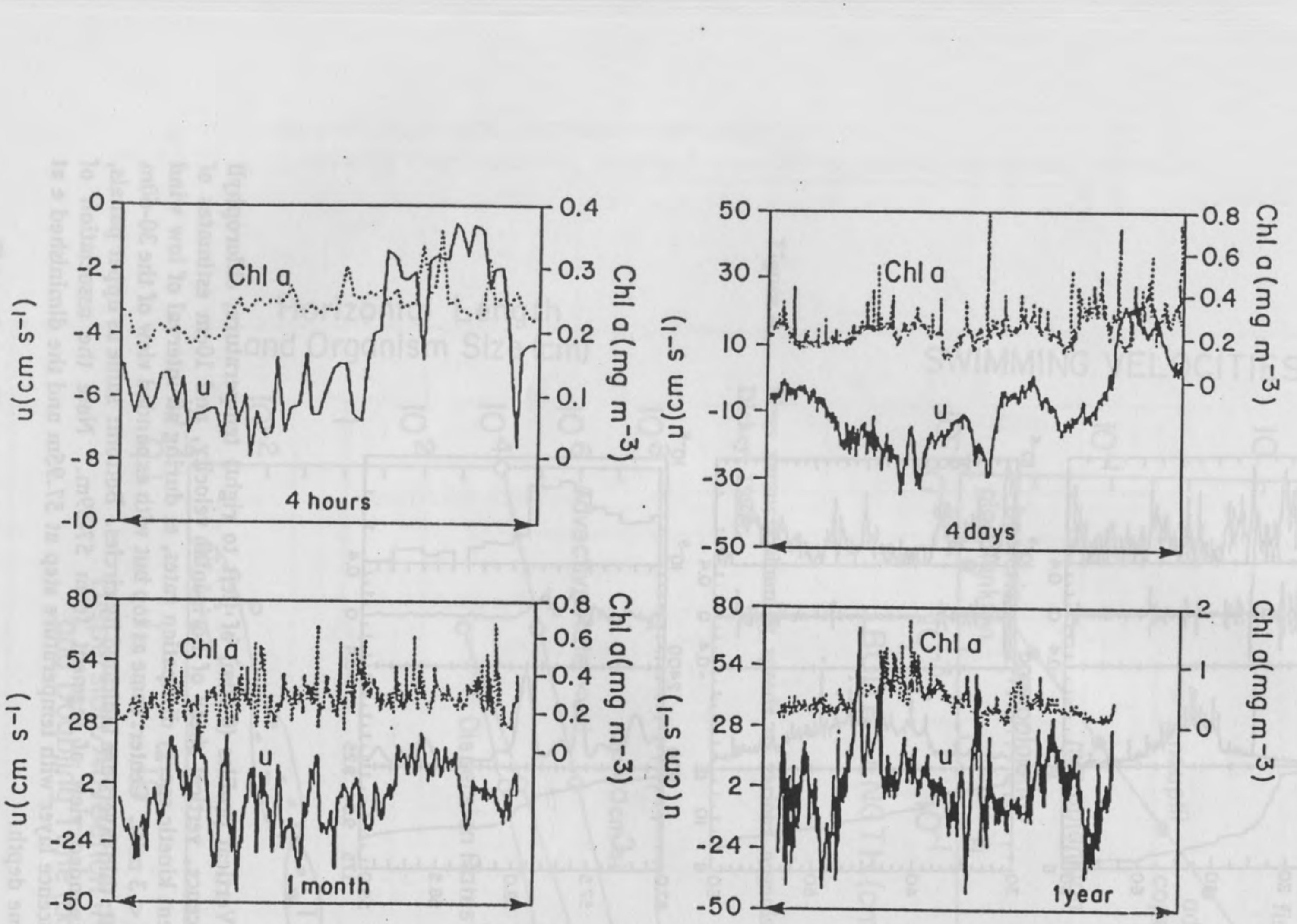

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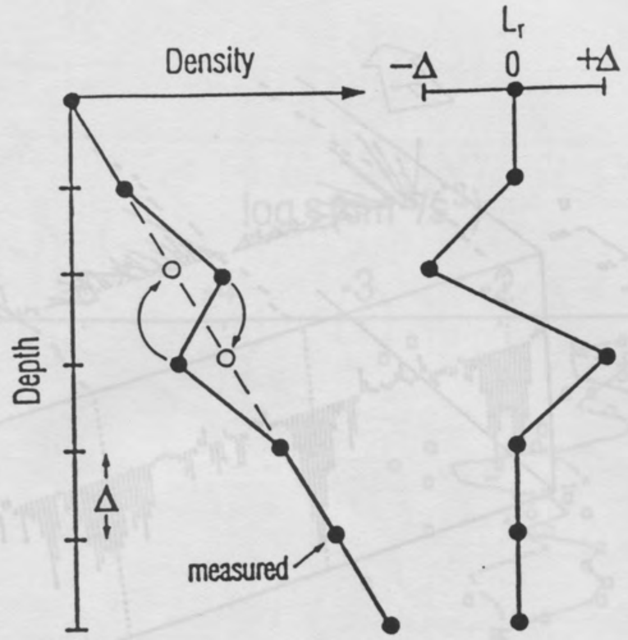

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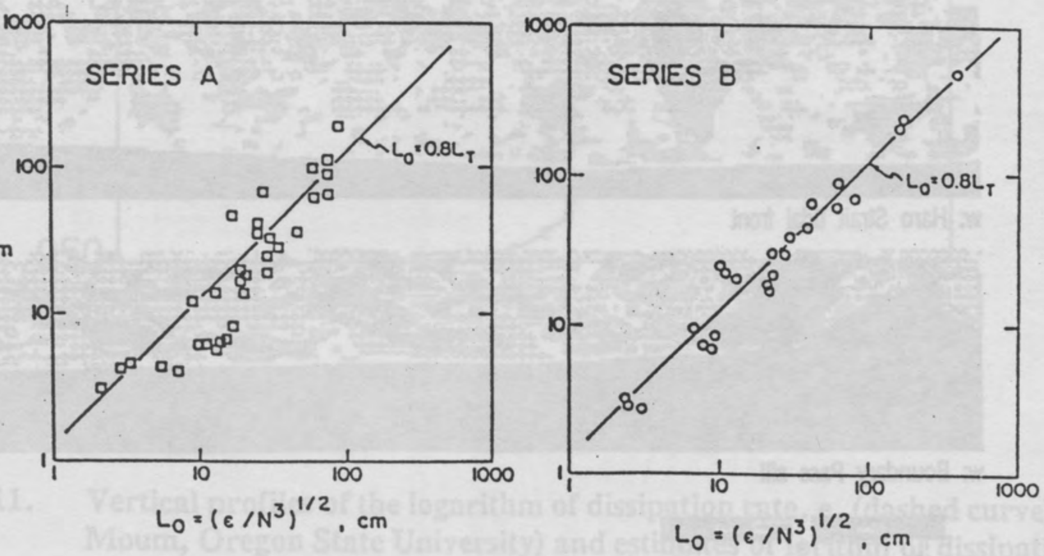

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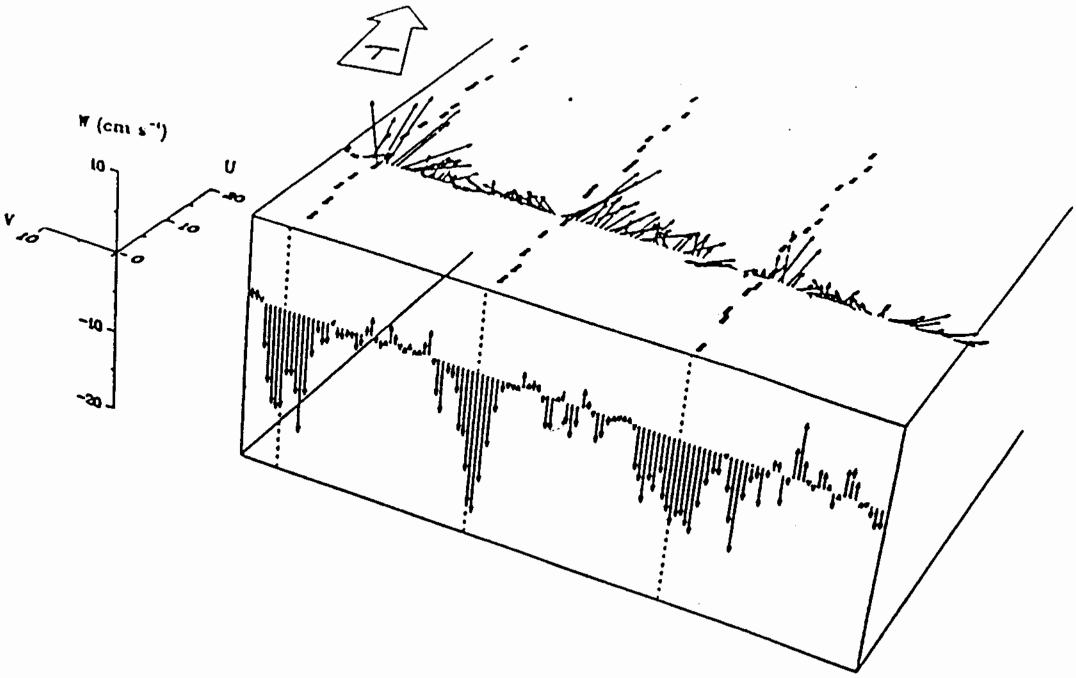

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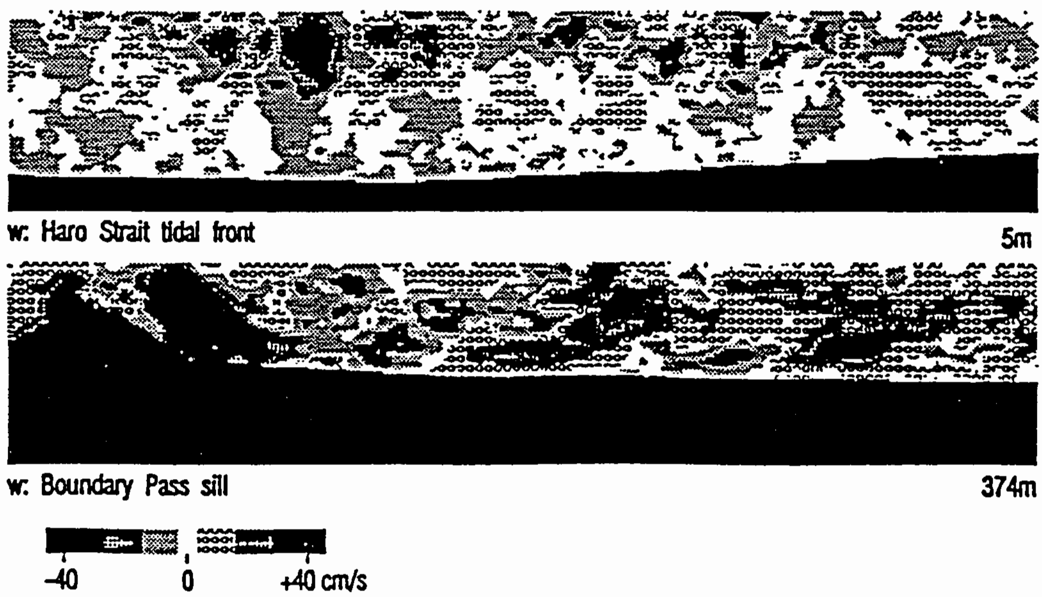

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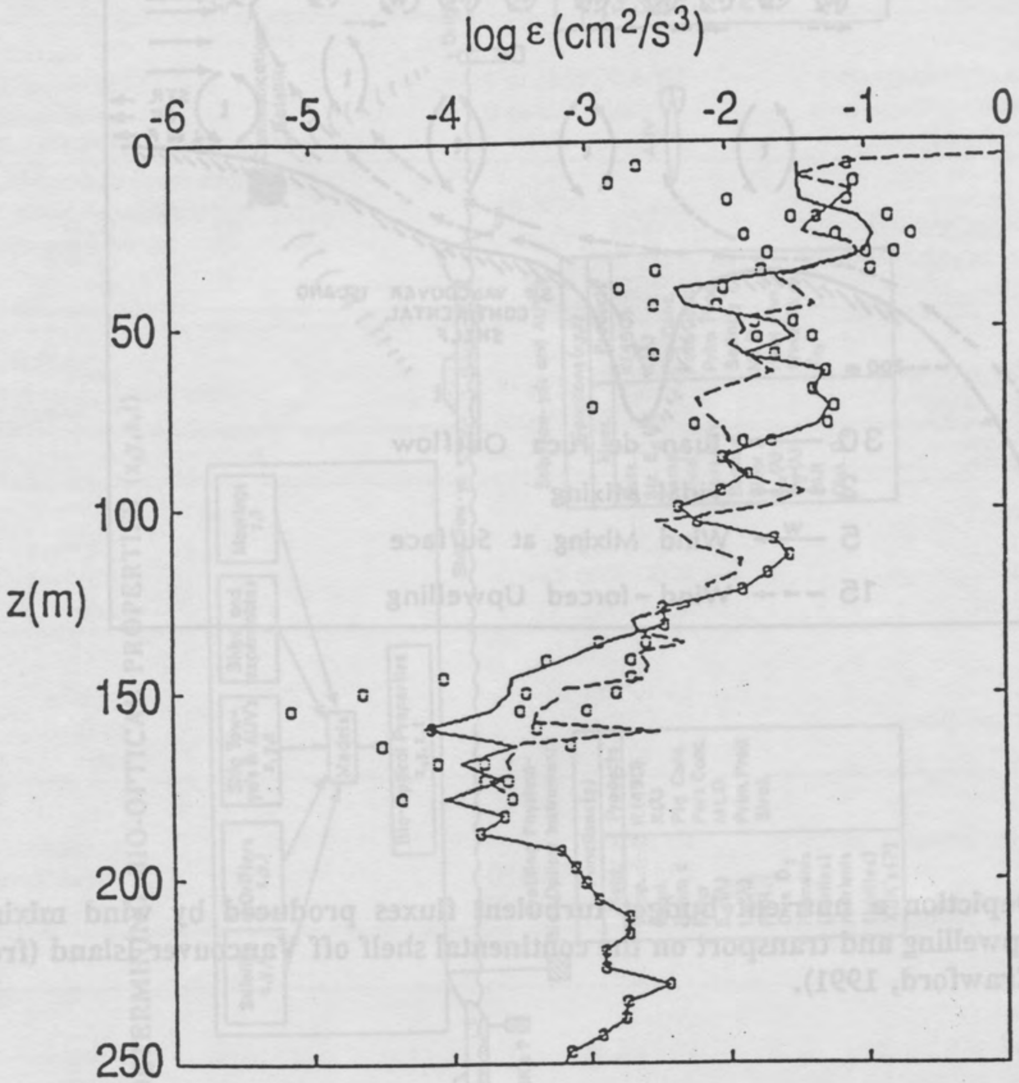

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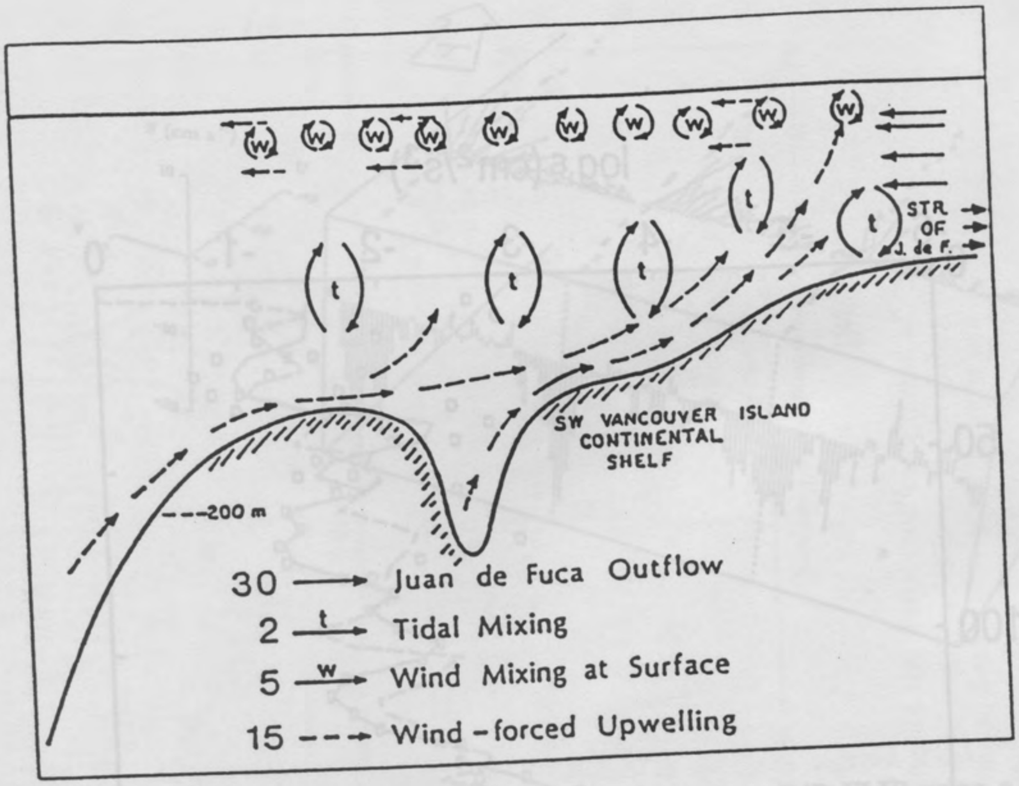

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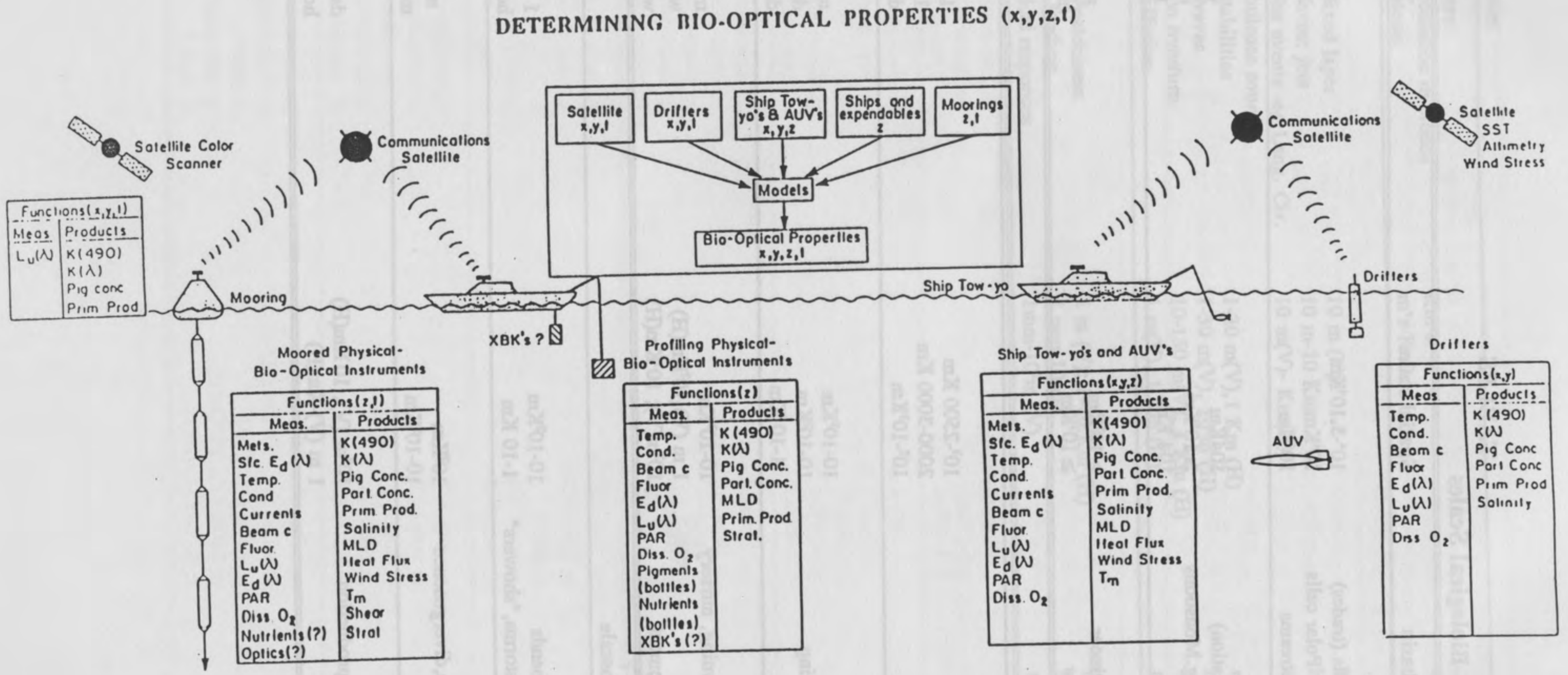

Figure 13. Schematic illustrating a methodology for determining variability of bio-optical properties in space and time. Applications could include determinations of the subsurface light field and primary production (after Dickey et al., 1993)

TABLES

Table 1. Physical-Biological Scales

1. Global-Basin-Subbasin	Spatial scales	Temporal scales
1a. Atmosphere		
i. Hadley-Walker Cells (trades)	10^4-5.10^4Km	years
ii. Farrel (westerlies), Polar cells	10^4Km	years
iii. Rossby waves/ jet streams	10^4Km	months
1b. Ocean		
i. Gyres (mean circulation)	104Km	years
ii. Wind-current var.eg.Monsoons	$\geq 10^3$Km	months
iii. Conveyor belt	104 Km	10^3 year
1c. Biology		
i. Biogeographic provinces	$\geq 10^3$Km	years
ii. Migration of species	$\geq 10^3$Km	months-year
2. Regional scales		
2a. Atmosphere		
i. Cyclones:	10^3-2500 Km	1-5 days
ii. Anticyclones	2000-3000 Km	1-5 days
iii. Frontal systems	10^2-10^3Km	days
2b. Ocean		
i. Shelf fronts	10-10^3Km	months
ii. Wind driven upwelling	10-10^2Km	days
iii. Tidal fronts	1-10 Km	days
2c. Biology		
i. Migrations -eg.spawning, nursery	10-10^3Km	months
ii. Spawning	1 m (V),10^2Km(H)	weeks-months
ii. Larval drift/Development	10^2m(V), 10^3Km(H)	weeks-years
3. Mesoscale -submesoscale		
3a. Atmosphere		
i. Squal line and rain bands	10-10^2Km	1 day
ii. Sea breezes,thunderstorms,"showers"	1-10 Km	hours
3b. Ocean		
i. Eddies, convergence,divergence	10^2Km	months-years
ii. Lenses/ Meddies	10-10^2Km	months-years
3c. Biology		
i. Eddy pumping/new production	10^2m (V), 10 Km(H)	days?-years
ii. Patchiness, transport	1 m (V)-Km(H)	hours-months

4. Smaller Scales

4a. Atmosphere		
i. Eddies, circulation in clouds	Km's	minutes
ii. Frontal systems	m's-Km's	minutes
4b. Ocean		
i. Diurnal mixed layer	10 m (V)	hours
ii.. Internal waves; jets	10 m-10 Km	hours-days
iii. Wind driven events -eg Lang. Cir.	10 m(V)- Km(H)	days
iv. Microturbulence sources		
-shear instabilities	1-30 m(V),1 Km (H)	minutes-days
-internal waves	1-30 m(V), 10^2m (H)	minutes-hour
-convection overturn	10-150 m(V), 1 Km (H)	hours-1 day
-double diffusion	1 m(V), 1 Km (H)	seconds-minutes(?)
4c. Biology		
i. swimming/patchiness	1 m (V); 1-10^3Km (H)	hours-months
ii. predation/ feeding	1 mm-10 cm	seconds-minutes
iii. physiological responses	1mm-10^2m (V)	mseconds-hours

Table 2. Nominal scales of various biological processes for m: microplankton; c: copepods; e: euphasids; g: gelatinous zooplankton; and f: fishes.

1. Abundances/Size	number m^{-3}	cm
	m: $>10^6$ (10^4-10^8 ciliates) c: 10^3-10^4 e: 10^3-10^4 g: 1-50 f: 10^2-10^3	p: 10^{-4}-10^{-2} c: $5*10^{-2}$-10^{-1} e: 10^{-1}-$5*10^{-1}$ g: 1-10^3 f: 10^{-1}-10^3
Biological Processes	**Spatial Scales**	**Temporal Scales**
2. Exchanges of Individuals a. Vertical excursions mixing/swimming swimming	m: 1-50m c: 1-300m e: 1m-bottom? g:1-10^2m f: 1-10^3 m	p: hours-days c: hours-months e: hours-months g: hours-months f: hours-seasons
b. Horizontal excursions	m: <10 Km c: 10-10^2 Km e: 1Km-? g:1-10^2Km f: 1-10^3 Km	p: days-months c: days-months e: ? g: days-months f: days-months
c. Swarming/Patches	m: 10^2m-1Km c: 10^2m -10 Km e: 1Km g: 10m-1 Km f: 1 Km	p: days-months c: hours-weeks e: hours-seasons(?) g: hours-weeks f: hours-years
2. Losses of Individuals a. Mortality natural	m: mm-10^3Km c: mm-10^3Km e: mm-? g: cm-1 Km f: mm-10^3Km	p: days c: weeks e: ? g: days-months f: years
b . Mortality predation	m: mm-10^3Km c: mm-10^3Km e: mm-? g: cm-1 Km f: mm-10^3Km	p: seconds-days c: seconds-months e: seconds-months g: minutes-months f: seconds-months
c. Sedimentation	p: 10^3 m (V), 10^3 Km (H) c: 10^3 m (V), 10^2 Km (H) e: 10^3 m (V), (H?) g: 10^3 m (V), 10^2Km(H) f: 10^3 m (V), (H?)	p: days-year c: days-months e: days-? g: days-months f: days-?

3. Additions of Individuals a. Life cycle	m: 10^2Km c: 10^2-10^3Km e: 10^3Km (?) g: 1-10^2Km f: 10-10^3Km	p: hours-days c: months-years e: years (?-5) g: days-months f: years (5-20;max.40)
i. Reproduction	m: mm-Km c: mm-Km e: mm-? g: cm-Km f: mm-Km	p: hours-days c: hours-months e: hours-? g: hours-weeks f: hours-months

Table 3 : Sensors and Systems (from U.S. GLOBEC Report 6, 1992)

Sensor System	Measurements Made by Sensing System	Sampling Mode	Time Scale Min:Max	Resolution Vert:Horiz
CTDs	Temperature Conductivity Pressure Dissolved O2 pH	Profiled Moored/yo-yo tow-yo Towed	1 hr:1 mon 1 min:1yr 1 sec:1 day	0.5m:1 km 10m:10 km 0.5m:1 m
Current Meter	Water Velocity, Speed, & Direction	Moored	1 min:1 yr	10m:10 km
Water Bottles	Water for Shipboard or Laboratory Analysis	Profiled	1 hr:1 mon	10m:1 km
Bio-Opitcal	Beam Attenuation Stimulated Fluorescence PAR Upwelling Radiance Downwelling Irradiance Optical Plankton Counter	Profiled Moored Towed	1 hr:1 mon 1 min:1 yr 1 sec:1 day	1 m:1 km 10m:10 km 1 m:1 m
In situ chemical analyzer	Inorganic nutrient: O2	Profiled Moored Towed	Continuous; 2 hr:2-3 mon	2m:100 km
In situ microbial rates (SID)	Primary production; tracer uptake	Moored Surface drifter	3-9 hr:1-3 mon (100 samples max)	10m:100 km
Optical Imaging	Video Images of Number, Size, Taxa and Biomass	Moored Towed	<1sec:3 mon	1 pm:10 km 1 m:10 km
Nets	Species, Number & Size	Towed	1 hr:1 day	1 m:100 m
ADCP (300kHz)	Current Profiles Acoustical Backscattering	Moored Towed	1 min:1 yr 1 min:1 mon	1 m:10 km 1 m:10 m
MET	Wind Speed and Direction Atmospheric Temperature Atmospheric Pressure Relative Humidity Precipitation Long & Short Radiation Sea Surface Temperature Wave height and direction	Moored Shipboard	10 min:1 yr 10 min:1 yr	1 pt:50 km 1 pt:100 m

SODAR	Wind Velocity Profiles	Moored Shipboard	10 min:1 yr 10 min:1 yr	10 m:100 m
Lagrangian Drifters	GPS Position CTD & Bio-Optical	Drifting	1 hr:6 mon	10 m:100 m
Acoustical Imaging	Acoustical Backscattrering Numbers & Target STrength	Profiled Moored Towed	1 hr:1 mon 1 min: 1 yr 10 sec:1 day	1 m:1 km 1 m:10 km 1 m:30 m

Table 4. Technical challenges, consequences, and solutions associated with the development of oceanic turbulence measurements. Many of the problems have been surmounted during the past 15 years (prepared by H. Yamazaki).

Item	Technical Difficulty	Symptom/Consequence	Resolution by Researchers
i	Vibration and excessive tilting of the profiler.	Contaminates and may completely obscure the oceanic velocity signal.	Hydrodynamically smooth profilers, rigid mounting of all hardware, motion monitoring with accelerometers, and large righting moment.
ii	Construction, calibration and stability of the shear probe velocity sensors.	Poor sensitivity to velocity, excessive sensitivity to temperature and pressure.	Construction of calibrator. Careful selection of piezoceramics, water proofing to 1011 ohms.
iii	Variations in decent rate of the profiler.	Variations in amplitude of velocity signal -- shear probe sensitivity is proportional to fall rate.	Profiler weight in water bigger than 50 Nt, fall rates larger than $0.5\ m\ s^{-1}$
iv	Deployment and recovery of the profiler.	Shear probes are delicate and easily damaged. High wind conditions are most interesting scientifically.	Profiler weight less than 400 Nt, deployed from boom pointed into wind.
v	Collision between shear probe and plankton creates short large-amplitude transients.	Contaminates velocity signal, variance unrealistically large by many orders of magnitude.	Assessment of data quality and the editing of spurious signals has been automated on mini-computers
vi	Processing and rendering of a large volumes of raw data into a small base suitable for scientific interpretation.	Long delay between data gathering and scientific interpretation.	Adaptive processing routines that can handle a wide (10°) range in signal variance implemented on mini-computer.

Table 5: Available/Required Sensors and Samplers for Regional Studies

Sensors / Sampling Devices	Measured Parameters	Status
Platforms		
SeaSoar	Conductivity, depth, temperature, oxygen, chlorophyll, productivity, light, nutrients	Basic model exists, develop enhanced systems
Undulating Oceanographic Recorder	As for SeaSoar	Exists
Autosub	As for SeaSoar, plus new sensors	Develop
Nets		
RMT Trawls	Zooplankton specific composition biomass	Exists
LHPR	" "	Exists
CPR		Exists and being developed
Acoustic Sensors		
ADCP	Biomass, migration rates, current velocity	Exists
Multi Frequency Acoustic	Biomass, size class distribution	Exists
Optical Sensors		
Discrete band irradiance sensors	Diffuse attenuation, Chlorophyll biomass	Exists
Transmissometer (single wavelength)	Particle concentration (beam attenuation)	Exists
Fluorometer	Phytoplankton biomass	Exists
Nephelometer	Particle concentration/size distribution	Exists
	Photosynthetic rates	Exists
Pump and probe fluorometer	Particle type/taxa	Exists
3 band transmission	Biomass, pigments/taxa	Develop
3 band fluorimeter	Biomass, particle size, taxa, spectral diffuse attenuation and reflection	Develop (SIDAL)
Continuous band transmission, scatterance and irradiance system	Phytoplankton growth, nutrient limitation	Exists
Fluorometry/Molecular Probes	Marine Snow Distribution, characteristics	Exists, needs development
Marine Snow Scanner		
Video Imaging /Bioluminescence	Plankton distribution, behavior	Exists, needs development
Plankton Counter	Plankton numbers, size distribution	Exists

Chemical sensors		
Polargraphic electrode	Oxygen concentration	exists but needs development
		exists but needs development
Nutrients (mm levels)	NO_3, NO_2, SiO_2, PO_4^{3-}	exists but needs development
(colorimetric)		
Nutrients nm levels	NO_3, NO_2, NH_4	exists but needs development
electrochemical		
Trace metals		requires development
pH	NI CU FE CR	requires development
alkalinity		requires development
PCO_2		requires development
TCO_2	H^+	requires development
DOC	alkalinity	requires development
Biogenic gases	CO_2 partial pressure	
	Total inorganic carbon	
	Dissolved Organic Carbon	
	N_2O, CH_4 DMS	

REFERENCES

Ackleson, S. G., J. J. Cullen, J. Brown and M. P. Lesser (1990) "Some changes in the optical properties of marine phytoplankton in response to high light intensity" SPIE, Ocean Optics X:238-249.

Aiken, J. (1985) "The Undulating Oceanographic Recorder Mark 2, a multirole oceanographic sampler for mapping and modelling the biophysical marine environment" in Mapping Strategies in Chemical Oceanography (ed.) A. Zirino, American Chemical Society, 209:315-332.

Aiken, J. and I. Bellan (1986) "Synoptic optical oceanography with the undulating oceanographic recorder" SPIE, Ocean Optics VIII: 221-230.

Aiken, J. and I. Bellan (1990) "Optical oceanography: an assessment of a towed method" in Light and Life in the Sea (eds. P.J. Herring, A.K. Campbell, M. Whitfield, and O. Maddock) Cambridge University Press, 39-57.

Alcaraz, M., G.-A. Paffenhofer and J.R. Strickler (1980) "Catching the algae: a first account of visual observations on filter feeding calanoids" pp. 241-248 in W.C. Kerfoot, (ed.) Evolution and Ecology of Zooplankton Communities, University Press of New England, Dartmouth, New Hampshire.

Bane, J., L. O'Keefe and N. Mooers (1989) "Mesoscale eddies and submesoscale, coherent vortices" in Mesoscale/Synoptic Coherent Structures in Geophysical Turbulence (eds. Nihoul, J. and B. Jumart) Elsevier Ocean., Series, 50:501-18.

Bartz, R., J. R. V. Zaneveld and Ḥ. Pak (1978) "A transmissometer for profiling and moored observations" in Water, Proc. of the Soc. for Photo-Opt. Instr. Eng., Ocean Optics V, SPIE:102-108.

Bergeron, E., A. D. Bowe, W. J. Hersey, W. N. Lange, J. R. Strickler (1988) "Reaching the ultimate goal: observing live zooplankton in situ" EOS, 69:1087.

Bidigare, R. R., R. C. Smith, K. S. Baker and J. Marra (1987) "Oceanic primary production estimates from measurements of spectral irradiance and pigment concentrations" Global Biogeochemical Cycles 1:171-186.

Bidigare, R. R., B. B. Prezelin and R. C. Smith (1992) "Bio-optical models and the problems of scaling" in Primary Productivity and Biogeochemical Cycles in the Sea (eds.) P.G. Falkowski and A.D. Woodhead, 175-212.

Boucher, M., F. Ibanez and L. Prieur (1987) "Daily and seasonal variations in the spatial distribution of zooplankton populations in relation to the physical structure in the Ligurian Sea Front" J. Mar. Res. 45:133-173.

Brillinger, D. R. (1981) "Time-series: Data analysis and theory" (Holden-Day, San Francisco, 1981).

Brutzman, D. P. and M. A. Compton (1991) "AUV research at the Naval Postgraduate School" Sea Tech. 32:35-40.

Buskey, E. J. and E. Swift (1983) "Behavioral response of the coastal copepod Acartia hudsonica to stimulated dinoflagellate bioluminescence" J. Exp. Mar. Biol. Ecol. 72:43-58.

Buskey, E. J. and E. Swift (1985) "Behavioral responses of oceanic zooplankton to simulated bioluminescence" Biol. Bull. 168:263-275.

Carder, K. L., R. G. Steward and T. G. Peacock (1988) "Spectral transmissometer and radiometer: design and initial results" SPIE, Ocean Optics IX:189-195.

Caswell, H. and S. Twombly (1989) "Estimation of stage-specific demographic parameters for zooplankton population: methods based on stage-classified matrix projection models" In Estimation and Analysis of Insect Populations, L. McDonald, B. Manly, J. Lockwood, and J. Logan (eds.) Springer-Verlag, New York, 93-107.

Chevaldonne, P., D. Desbruyeres and M. Le Haitre (1991) "Time-series of temperature from three deep-sea hydrothermal vent sites" Deep-Sea Res. 38:1417-1430.

Cooke, R. A., L. D. B. Terhune, J. S. Ford and W. H. Bell (1970) "An opto-electronic plankton sizer" Fish. Res. Bd. Canada Tech, Rep. No. 172, 40pp.

Cooper, W. S. (1986) "Use of optimal estimation theory, in particular the Kalman filter, in data analysis and signal processing" Rev. Sci. Instrum. 57:2862-2869.

Costello, J. et al. (1990) "Grazing in a turbulent environment: Behavior response of the calanoid copepod, Centrofages hamatus" Proc. of the Natl' Acad., Sci., U.S.A. 87:1648-52.

Cowles, T. J., R. A. Desiderio, J. N. Moum, M. L. Myrick and S. M. Angel (1990) "Fluorescence microstructure using a laser/fiber optic profiler" Proc. SPIE-Int. Soc. Opt. Eng., 1302:336-345.

Crawford, W. R. (1991) "Tidal mixing and nutrient flux in the waters of southwest British Columbia" Tidal Hydrodynamics (ed.) Bruce B. Parker, J. Wiley and Sons, Inc. 855-869.

Cressie, N. (1991) "Statistics for Spatial Data" (Wiley, New York, 1991).

Cullen, J. J., M. R. Lewis, C. O. Davis and R. T. Barber (1991) "Photosynthetic characteristics and estimated growth rates of phytoplankton in the equatorial Pacific" J. Geophys. Res. 97:639-655.

Cushing, D.H., (1976) "The Ecology of the Seas" Alden Press, Oxford.

Davis, C. S., G. R. Flierl, P. H. Wiebe and P. J. S. Franks (1991) "Micropatches, turbulence, and recruitment in plankton" J. Mar. Res. 49:109-151.

Davis, C. S., S. M. Gallager, M. S. Berman, L. R. Haury and J. R. Strickler (1992a) "The video plankton recorder (VPR): design and initial results" Arch. Hydrobiol. Beih. Ergebn. Limnol. 36:67-81.

Davis, C. S., S. M. Gallager and A. R. Solow (1992b) "Microaggregations of oceanic plankton observed by towed video microscopy" Science 257:230-232.

Denman, K. L. and A. E. Gargett (1983) "Time and space scales of vertical mixing and advection of phytoplankton in the upper ocean" Limnol. and Oceanogr., 28:801-815.

Denman, K. and T. Powell (1984) "Effects of physical processes on planktonic ecosystems in the coastal ocean" Oceanogr. Mar. Biol. Ann. Rev. 22:125-168.

Dickey, T. D. (1988) "Recent advances and future directions in multi-disciplinary in situ oceanographic measurement systems" in Toward a Theory on Biological and Physical Interactions in the World Ocean, B. Rothschild (ed.), Kluwer Academic, Dordrecht, The Netherlands, 555-598.

Dickey, T. D. (1990) "Physical-optical-biological scales relevant to recruitment in large marine ecosystems" in Large Marine Ecosystems: Patterns, Processes, and Yields, K. Sherman, L.M. Alexander, and B. D. Gold (eds.), AAAS 82-98.

Dickey, T. (1991) "The emergence of concurrent high-resolution physical and bio-optical measurements in the upper ocean" Rev. of Geophys. 29:383-413.

Dickey, T., J. Marra, T. Granata, C. Langdon, M. Hamilton, J. Wiggert, D. Siegel and A. Bratkovich (1991) "Concurrent high resolution bio-optical and physical time series observations in the Sargasso Sea during the spring of 1987" Journal of Geophysical Research, 96: 8643-8663.

Dickey, T. D., T. C. Granata and I. Taupier-Letage (1993a) "Automated in situ observations of upper ocean biogeochemistry, bio-optics, and physics and their potential use for global studies" Ocean Climate Data Workshop, Goddard Space Flight Center, Greenbelt, MD, Feb. 18-21, 1993, 317-353.

Dickey, T., T. Granata, J. Marra, C. Langdon, J. Wiggert, Z. Chai, M. Hamilton, J. Vazquez, M. Stramska, R. Bidigare and D. Siegel (1993b) "Seasonal variability of bio-optical and physical properties in the Sargasso Sea" Journal of Geophysical Research 98:865-898.

Dillon, T. M. (1982) "Vertical overturns: A comparison of Thorpe and Ozmidov length scales" J. Geophys. Res. 87:9601-9613.

Esaias, W. E., S. B. Hooker, C. R. McClain, G. C. Feldman and W. W. Gregg (1992) "SeaStar/SeaWiFS: ocean color data for the 1990s (abs.), Autonomous Bio-optical Ocean Observing Systems" (ABOOS) Scientific Symposium Abstracts, Monterey, CA, April 6-10, 1992.

Estrada, M., C. Marrase, M. Latasa, E. Berdalet, M. Delgado and T. Riera (1993) "Variability of deep chlorophyll maximum characteristics in the Northwestern Mediterranean, Mar. Ecol. Prog. Series 92:289-300.

Evans, R. H. (1992) "Implementation of a satellite in situ observation match-up database- a prerequisite for development and validation of satellite algorithms" (abs.), Autonomous Bio-optical Ocean Observing Systems (ABOOS) Scientific Symposium Abstracts, Monterey, CA, April 6-10, 1992.

Falkowski, P. G. Ziemann, Z. Kolber and P. K. Bienfang (1991) "Role of eddy pumping in enhancing primary production" Nature 352:55-58.

Feldman, G. C., N. Kuring, C. Ng, W. Esaias, C. McClain, J. Elrod, N. Maynard, D. Endres, R. Evans, J. Brown, S. Walsh, M. Carle and G. Podesta (1989) "Ocean color: availability of the global data set" EOS 70:634-641.

Focal Technologies (1990) "Optical plankton counter user's guide" Focal Technologies Inc., 40 Thornhill Dr., Unit 7, Dartmouth, Nova Scotia.

Foote, K. G. (1985) "Rather-high-frequency sound scattering by swimbladdered fish" J. Acoust. Soc. Am. 78:688-700.

Foote, K. G. (1990) "Speed of sound in *Euphausia superba*" J. Acoust. Soc. Am. 87:1405-1408.

Foote, K. G., and J. Rivoirard (1992) "Geostatistical analysis of acoustic survey data on 0-group herring in a fjord" ICES C.M. 1992/D:10.

Foote, K. G., A. Aglen and O. Nakken (1986) "Measurement of fish target strength with a split-beam echo sounder" J. Acoust. Soc. Am. 80:612-621.

Foote, K. G., H. P. Knudsen, R. J. Korneliussen, P. E. Nordbo and K. Roang (1991) "Postprocessing system for echo sounder data" J. Acoust. Soc. Am. 90:37-47.

Furusawa, M. (1991) "Designing quantitative echo sounders" J. Acoust. Soc. Am. 90:26-36.

Gargett, A. E. (1993) "Measurement and analysis of the energy-containing eddies of turbulent flows in the coastal ocean" Proceedings of the Ah'a Hulikoa Hawaiian Winter Workshop 1993 (ed. P. Muller) SOEST, U. of Hawaii at Manoa, 100 Pope Road, Honolulu, HI 96822.

GLOBEC, Global Ecosystems Dynamics (1989) EOS 70, 6:82-85.

Gordon, H. R., R. C. Smith and J. R. V. Zaneveld (1984) "Introduction to ocean optics" SPIE, 489, Ocean Optics VII:2-41.

Gorsky, G. C. Aldorf, M. Kage, M. Picheral, Y. Garcia and J. Favole (1992) "Vertical distribution of suspended aggregates determined by a new video profiler" Ann. Inst. Oceanogr., Paris, 2.

Granata, T. and T. Dickey (1991) "The fluid mechanics of copepod feeding in a turbulent flow: A theoretical approach" Prog. Oceanog., 26:243-61.

Greene, C. H., P. H. Wiebe and J. Burczynski (1989) "Analyzing zooplankton size distributions using high-frequency sound" Limnol. Oceanogr. 34:129-139.

Gregg, M. (1983) "Diapycnal mixing in the thermocline: a review" J. Geophys. Res., 92:5249-86. 1987.

Gregg, M. and Briscoe (1979) "Internal waves, finestructure, microstructure, and mixing in the ocean" Rev. Geophy. Space Phy., 17: 1524-48.

Harris, G. P. (1986) "Phytoplankton Ecology" Chapman and Hall, London, 384pp.

Haury, L. R. and R. E. Pieper (1987) "Zooplankton: scales of biological and physical events, in Marine Organisms as Indicators" (eds.) D.F. Soule and G.S. Kleppel, Springer-Verlag, New York, 35-72.

Haury, L. R., J. A. McGowan and P. H. Wiebe (1978) "Patterns and processes in the time-space scales of plankton distributions" In J. H. Steele (ed.) "Spatial pattern in plankton communities" (Plenum, New York, 1978), pp. 277-328.

Herman, A. W. (1985) "Biological profiling in the upper oceanic layers with a Batfish vehicle: a review of applications, In Mapping Strategies in Chemical Oceanography" A. Zirino (ed.), American Chemical Society, Washington, D.C., 293-314.

Herman, A. W. (1988) "Simultaneous measurement of zooplankton and light attenuance with a new optical plankton counter" Cont. Shelf Res. 8:205-221.

Herman, A. W. and T. M. Dauphinee (1980) "Continuous and rapid profiling of zooplankton with an electronic counter mounted on a "Batfish" vehicle" Deep-Sea Res. 27A:79-86.

Herman, A. W., D. D. Sameoto, C. Shunnian, C. Mitchell, M. R. Petrie and N. Cochrane (1991) "Sources of zooplankton on the Nova Scotia Shelf and their aggregations within deep-shelf basins" Cont. Shelf Res., 11:211-238.

Holliday, D. V., R. E. Pieper and G. . Kleppel (1989) "Determination of zooplankton size and distribution with multi-frequency acoustic technology" J. Cons. Int. Explor. Mer. 41:226-238.

Hooker, S. B. and W. . Esaias (1992) "An overview of the SeaWiFS project, NASA Technical Memorandum, SeaWiFS Technical Report Series" S.B. Hooker ed., preprint.

Horwood, J. (1981) "Variations of fluorescence, particle-size groups, and environmental parameters in the southern North Sea" J. Cons. int. Explor. Mer., 39:261-270.

ICES Study Group on Zooplankton Production, Bergen, Norway, March 23-26, 1992.

Kils, U. (1981) "Swimming behaviour, swimming performance and energy balance of Antarctic krill, Euphausia superba" BIOMASS Sci Ser, 3:1-122.

Kils, U. (1989) "On the micro-structure of micro-layers: results of an in situ plankton counter" ICES C.M. 1989/L 15:1-4.

Kils, U. (1992) "The ecoScope and dynIMAGE: microscale tools for in situ studies of predator prey interactions" Arch. Hydrobiol. Beih. Ergebn. Limnol., 36:83-96.

Kils, U., K. Ruohonen and T. Makinen (1991) "Daily food intake estimates for rainbow trout evaluated with sonar and x-ray techniques at commercial net cage farms" Coun. Meet. Int. Coun. Explor. Sea./F, 3:1-8.

Kirk, J. T. O. (1986) "Light and Photosynthesis in Aquatic Ecosystems" Cambridge Univ. Press, Cambridge, U.K., 401pp.

Lasker, R. (1975) "Field criteria for survival of anchovy larvae: The relation between inshore chlorophyll maximum layers and successful first feeding" Fish. Bull. 73:453462.

Laurs, R. M. and Brucks, J. T. (1985) "Living marine resources applications" In Satellite Oceanic Remote Sensing (ed.) B. Saltzman, Academic Press, Orlando: 419-452.

Lehaitre, M., P. Gentien, M. Lunven, Ph. Bassoullet, Y. Guern, A. Bideau-Mehu (1990) "The IFREMER in situ particle analyzer: technical aspects, Marine Instrumentation '90" Marine Technology Society, San Diego, CA.

Lehaitre, M., D. Birot, P. Feron, O. Hureau, J. Lain and P. Charrier (1993) "Optical fiber spectrofluorimetry for in situ algae discriminations" "underwater light measurements" SPIE, Troms, June 1993.

Levitus, S. (1982) "Climatological Atlas of the World Ocean" NOAA pp-13, Envir. Res. Lab., Geophys. Fluid Dynamics Lab., Princeton, N.J., 173 pp.

Lewis, M., et al. (1986) "Vertical nitrate fluxes in the oligotrophic ocean" Science 234:870-73.

Lewis, M. R., M.-E. Carr, G. Feldman, W. Esaias and C. McClain (1990) "Influence of penetrating solar radiation on the heat budget of the equatorial Pacific Ocean" Nature, 347:543-545.

Marine Zooplankton Colloquium 1. (1989) "Future marine zooplankton research - a perspective" Mar. Ecol. Prog. Ser., 55:192-206.

Matheron, G. (1971) "The theory of regionalized variables and its applications" Les Cahiers du Centre de Morphologie Mathematique de Fontainebleau, Fasc. 5, Ecole Nat. Sup. des Mines de Paris.

McClain C., J. Ishizaka and E. Hofmann (1990a) "Estimation of processes controlling variability in phytoplankton distributions on the southeastern U.S. continental shelf" J. Geophys. Res. 95:20213-35.

McClain, C. R., W. E. Esaias, G. C. Feldman, J. Elrod, D. Endres, J. Firestone, M. Darzi, R. Evans and J. Brown (1990b) "Physical and biological processes in the North Atlantic during the first GARP Global Experiment" J. Geophys. Res. 95:18,027-18,048.

Mobley, C. D. (1992) "The optical properties of water" In Handbook of Optics M. Bass (ed.), Second edition, McGraw-Hill, New York, in press.

Mueller, J. L. and R. W. Austin (1992) "Ocean Optics Protocols for SeaWiFS Validation" NASA TM 104566 (Vol 5), SeaWiFS Technical Report Series, Vol. 5 (Hooker, S.B. and E.R. Firestone, Eds). NASA GSFC, Greenbelt, MD. 46p.

Napp, J. M., P. B. Ortner, R. E. Pieper and D. V. Holliday (1993) "Biovolume-size spectra of epipelagic zooplankton using a Multi-Frequency Acoustic Profiling System (MAPS)" Deep-Sea Res. 40:445-459.

Nihoul, J. C. J. and S. Djenidi (1991) "Hierarchy and scales in marine ecohydrodynamics" Earth-Science Rev., 31:255-277.

Olson, R., S. W. Chisholm, E. R. Zettler and E. V. Armbrust (1990) "Pigments, size, and distributions of Synechoccus in the North Atlantic and Pacific Oceans" Limnol. and Oceanogr. 35:45-58.

Ortner, P. B., S. R. Cummings, R. P. Aftring and H. E. Edgerton (1979) "Silhouette photography of oceanic zooplankton" Nature 277:50-51.

Ortner, P. B., L. C. Hill and H. E. Edgerton (1981) "In-situ silhouette photography of oceanic zooplankton" Deep-Sea Res. 28A:1569-1576.

Osborn, T. R. (1974) "Vertical profiling of velocity microstructure" J. Phys. Oceanogr., 4, 109-115.

Pieper, R. E., D. V. Holliday and G. S. Kleppel (1990) "Quantitative zooplankton distributions from multifrequency acoustics" J. Plankton Res. 12:433-441.

Platt, T. and K. Denman (1978) "The structure of pelagic marine communities" Rapp. P.-v. Reun. Cons. int. Explor. Mer. 173:60-65.

Price, H. J., G.-A. Paffenhofer, C. M. Boyd, T. . Cowles, P. L. Donaghay, W. M. Hammer, W. Lampett, L. B. Quetin, R. N. L Ross, J. R. Strickler and M. J. Youngbluth (1988) "Future studies of zooplankton behavior questions and Technological Developments" Bull. Mar. Sci., 43:853-872.

Smith, R. C., C. R. Booth and J. L. Star (1984) "Oceanographic bio-optical profiling system" Appl. Opt. 23:2791-2797.

Smith, S., Pieper, R., Moore, M., Rudstam, L., Green, C., Flagg, C., Williamson, C., Zamon, J. (1992) "Acoustic techniques for the *in situ* observation of zooplankton" Arch. Hydrobiol. Beih. 36:23-43.

Sprules, W. G., B. Bergstrom, H. Cyr, B. R. Hargraves, S. S. Kilham, H. J. MacIsaac, K. Matsushita, R. S. Stemberger and R. Williams (1992) "Non-video optical instruments for studying zooplankton distribution and abundance" Arch. Hydrobiol. Beih. 36:45-58.

Stanton, T. K. (1990) "Sound scattering by zooplankton" Rapp. P.-v. Reun. Cons. int. Explor. Mer. 189:353-362.

Stanton, T. K. (1991) "Sound scattering by spherical and elongated shelled bodies" J. Acoust. Soc. Am. 88:1619-1633.

Stanton, T. K., R. D. M. Nash, R. L. Eastwood and R. W. Nero (1987) "A field examination of acoustical scattering from marine organisms at 70kHz" IEEE J. Ocean. Eng. 12:339-348.

Stramska M. and T. D. Dickey (1992) "Variability of bio-optical properties of the upper ocean associated with diel cycles in phytoplankton populations" J. Geophys. Res. 97:17,873-17,887.

Strass, V. H. and J. Woods (1991) "New production in the summer revealed by the meridional slope of the deep cholorophyll maximum" Deep-Sea Res. 38(1):35-56.

Strass, V. H., H. Leach and J. Woods (1992) "On the seasonal development of mesoscale variability: the influence of the seasonal pycnocline formation" Deep-Sea Res. 39(9):1627-1639.

Svendsen, E. and A. K. Magnusson (1992) "Climatic variability in the North Sea" ICES mar. Sci. Symp. 195:144-158.

Thorpe, S. A. (1977) "Turbulence and mixing in a Scottish loch" Phil. Trans. Roy. Soc. A., 286:125-181.

Tungate, D. and E. Reynolds (1980) "The Lowestoft on-line particle counting system" Fish. Res. Tech. Rep., MAFF Direct. Fish. Res. Lowestoft 58, 11pp.

Turner, J., D. J. Yule and J. Zanre (1991) "Real-time photogrammetry - a technique for today or tomorrow?" J. of the Soc. for Underwater Tech. 17:17-23.

U.S. GLOBEC Report Number 4 (1991) U.S. GLOBEC Workshop on Acoustical Technology and the Integration of Acoustical and Optical Sampling Methods, Woods Hole, Massachusetts, April 2-4, 1991.

U. S. GLOBEC Report 6, June (1992) Northwest Atlantic Implementation Plan, SSC Coordinating Office, Division of Environmental Studies, University of California, Davis, CA, 69pp.

U. S. GLOBEC Report (1993) U.S. GLOBEC Workshop on Optics Technology, Savannah, Georgia, February 20-22, 1993.

Weller, R. A., J. P. Dean, J. Marra, J. F. Price, E. A. Francis and D. C. Boardman (1985) "Three-dimensional flow in the upper ocean" Science 227:1552-1556.

Wells, N. (1986) "The Atmosphere and Ocean. A Physical Introduction" Taylor and Francis Publishing.

Welsch, W., K.-G. Barthel, R. Froese, B. Hermann, J. Lenz, S. Mees, D. Schnack, U. Waler (1991) "A high-speed video recording system for in-situ studies on small scale distribution of zooplankton and ichthyoplankton: preliminary results on the distribution of plankton in the Born-Holm Basin (Central Baltic)" ICES, C.M. 1991/L, 82, 1-12.

Widder, E. A. (1992) "Mixed light imaging system for recording bioluminescence behaviors" J. Mar. Biol. Assoc. U.K. 72:131-138.

Widder, E. A., C. H. Greene and M. J. Youngbluth (1992) "Bioluminescence of sound-scattering layers in the Gulf of Maine" J. Plankton Res. 14.

Wiebe, P., et al. (1976) "Gulf Stream cold core rings: large-scale interaction sites for open ocean plankton communities" Deep-Sea Res. 23:695-710.

Willebrand, J. and D. Anderson (1985) "Large Scale Transport Processes in Oceans and Atmosphere" NATO ASI Series, D. Reidel Publ.

Wood, S. N. and R. M. Nisbet (1991) "Estimation of mortality rates in stage-structured populations" Lecture Notes in Biomathematics, Springer-Verlag.

Woods, J. (1988) "Scale upwelling and primary production" in B.J. Rothschild (ed.) Toward a Theory on Biological-Physical Interactions in the World Ocean (Kluwer, Dordrecht, 1988), pp. 7-38.

Yamazaki, H. and T. Osborn (1988) "Review of oceanic turbulence: Implications for biodynamics" in Toward a Theory on Biological-Physical Interactions in the World Ocean. (Ed. B. Rothschild) NATO ASI Series, Kluwer Acad., 215-234.

Yentsch, C. M. and C. S. Yentsch (1984) "Emergence of optical instrumentation for measuring biological properties" Oceanogr. Mar. Biol. Ann. Rev. 22:55-98.

Yoder, J. A., J. Aiken, R. N. Swift, F. E. Hoge and P. M. Stegman (1993) "Spatial variability in near-surface chlorophyll a fluorescence measured by the Airborne Oceanographic Lidar (AOL)" Deep-Sea Res. II:40, 37-53.

Yoder, J. A., W. E. Esaias, G. Feldman and C. R. McClain (1988) "Satellite ocean color - status report" Oceanography, 1:18-20.

Yoder, J., J. A., C. . McClain, J. O. Blanton and L.-Y. Oey (1987) "Spatial scales in CZCS-chlorophyll imagery of the southeastern U.S. continental shelf" Limnol. and Oceanogr. 32:929-941.

APPENDICES
Appendix I. Agenda

International GLOBEC SOS-WG Meeting Agenda
Paris March 30- April 2, 1993

Day 1, March 30

900 Welcome, introductions, local information: Dickey
915 Purpose of meeting/discussion of agenda: Dickey
930 Background on International GLOBEC: Rothschild
945 Summary & recommendations of Fizzy Pop meeting: Cushing
1005 Plans for Modeling WG meeting: Robinson
1015 Break
1045 Processes and scales: Granata/Robinson
1115 Discussion and subgroup selection: All
1145 Lunch
1300 Physical measurement systems: All scales: Gargett
1330 Discussion and subgroup selection (SG-P): All
1400 Acoustics: Inversions of data/system design: Stanton
1430 Discussion and subgroup selection (SG-APT): All
1500 Break
1530 Acoustic: System deployment methods: Jaffe
1600 Discussion and subgroup selection (SG-AM): All
1630 Optics/imaging: Davis/Strickler
1700 Discussion and subgroup selection (SG-OI): All

Day 2, March 31

900 Plan for day: Dickey
915 Optics/non-imaging: Taupier-Letage/Dickey
945 Discussion and subgroup selection (SG-ONI): All
1015 Subgroup discussions of background papers and drafting of report sections
1200 Lunch
1300 Drafting of report sections
1400 Break
1415 Sampling strategies for local process studies (SG-LP): Kils
1445 Discussion/Subgroup selection: All
1515 Sampling strategies for regional studies (SG-R): Aiken
1545 Discussion: All
1615 Sampling strategies for basin scale (SG-B): Nival
1645 Discussion/Subgroup selection: All
1715 Review: Dickey

Day 3 April 1

0900 Plan for Day 3: Dickey
0915 Subgroup discussions of background papers and drafting of report sections
1200 Lunch
1300 Future technologies for GLOBEC/Link to Modeling: All
1330 Discussion/subgroup selection
1430 Break
1500 Subgroup discussions/writing
1700 Review of progress/plan for Day 4

Day 4 April 2

0900 Plan for Day 4: Dickey
0915 Discuss set of recommendations: Dickey
0915 Review of document/synthesize report: All
1200 Lunch
1300 Continue
1700 End

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