EMERGING TECHNOLOGIES IN BIOLOGICAL, CHEMICAL, OPTICAL, AND PHYSICAL SAMPLING OF THE OCEANS

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INTRODUCTION

Global change involves a diverse and complex set of scientific problems related to the biology and chemistry of our planet as well as its physics. Thus, interdisciplinary research directed toward global scale problems has become an exciting new scientific focus. Future global ocean monitoring and modeling programs will require comprehensive sampling of the biological, chemical, optical, and physical environment. A diverse set of sampling platforms including ships (both on station and underway), moorings, drifters, autonomous underwater vehicles, and satellites along with sophisticated models will be necessary (Figs. 1 and 2). These platforms will require sensors capable of sampling a broad suite of interdisciplinary variables which, together with models, can be utilized to provide information covering up to nine orders of magnitude in time and space scales. International programs such as the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics study (GLOBEC are addressing key issues concerning the environment and its ecology in relation to climate change. JGOFS issues involve processes that control the fate of carbon and other biologically active elements , in the ocean whereas GLOBEC questions relate to the coupling of ocean physics with population dynamics of zooplankton and fish. New technologies are being developed for these efforts. These technologies involve emerging biological, chemical, optical, acoustical, and physical sensors integrated into systems which can measure several variables concurrently. Another important aspect is the telemetry of high frequency, interdisciplinary data in near real-time. Some highlights of technological developments and sampling strategies are presented here. Importantly, these collective activities may be used to assist in the planning and implementation of interdisciplinary measurement components of the planned International Global Ocean Observing System (GOOS).

SAMPLING CONSIDERATIONS

The selection and proper sampling (in space and time) of key variables for studies of the marine ecosystem including the carbon flux problem and the recruitment of larval fish and population dynamics are daunting tasks (e.g., Dickey, 1988, 1990, 1991, 1993; Jahnke, 1990; Dickey et al., 1993a). These studies encompass interdisciplinary processes whose scales of variability span at least nine orders of magnitude (e.g., Haury et al., 1978; Dickey, 1991). There are some dominant temporal and spatial scales of variability (e.g., the diurnal and seasonal cycles, inertial oscillations, fronts, and mesoscale eddies), however, episodic phenomena represent critical events for biogeochemical fluxes as well as for individual organisms and ultimately population dynamics. There are obvious nonlinear interactions to contend with as well. High temporal resolution measurements are needed for long periods of time. Analogously, sampling of patchiness in biogeochemical and physical properties and organismal groups on a broad range of scales is necessary (e.g., Cowles et al., 1990). Clearly, a variety of specialized sampling platforms, each with its own attributes and deficiencies, must be employed. A schematic illustrating a nested experimental array of such platforms is shown in Fig. 1. Utilizing data from such arrays, numerical models can be used to synthesize the data and to enable diagnostics and predictions (Fig. 2) (e.g., see GLOBEC Special Contribution No. 2, 1996). An important link between data collection and modeling is real-time or near real-time telemetry of data. Some of the presently utilized, emerging, and needed interdisciplinary sensors and systems are described below. More detailed reviews with extensive references to specific instruments and systems are given in Dickey (1988, 1990, 1991, 1993), U.S. GLOBEC Report 3 (1991), U.S. GLOBEC Report 4 (1991), ICES Study Group (1992), special volume of Arch. Hydrobiol. Ergebn. Limnol., 36 (1992), SCOR Working Group 90 (1993), Dickey et al. (1993a,b; 1996), GLOBEC Report 3 (1993), U.S. GLOBEC Report 8 (1993), and U.S. JGOFS Planning Report 18 (1993).

SENSORS

Advances in interdisciplinary instrumentation systems have been closely linked with the development of a variety of new sensors. Instruments created for use in upper ocean current studies include mechanical, acoustical, and electromagnetic current meters, acoustical Doppler current profiling systems (e.g., ADCP's) which can be used in either vertical- or horizontal-looking attitudes, surface HF radar systems drifters, and drogues (see review by Dickey et al., 1996). Some of these instruments may be used in either moored or vertical profiling modes and can resolve time scales from minutes to several months or a few meters to a few hundred meters in the vertical depending on deployment strategy. Acoustic tomography involves the measurement of the field of sound speed fluctuations within a control volume by transmitting acoustic signals along several diverse paths. One of the attractive features of this technique is that a relatively large volume (on order of 100's of kilometers or more in the horizontal) of the ocean can be sampled synoptically. The measurement of vertical velocities has been most difficult, however measurements of vertical velocities have been done by using ADCP's and mechanical vector measuring current meters (VMCM's). Special velocity and temperature microstructure devices are capable of resolving vertical scales on order of 2 and 1 cm, respectively. These can also be used to estimate vertical diffusivity and turbulent fluxes. These special devices are expensive to operate and presently remain tools limited to a few experts. Nonetheless, their availability to the broader community is highly desirable.

New optical methods may be subdivided as follows. The first involves measurement of small scale (on order of a few manometers in wavelength and tens of microns in particle size) optical properties using various light sensors (e.g., Yentsch and Yentsch, 1984; Dickey, 1991, U.S. JGOFS Report No. 18, 1993). The second involves imagery of organisms or video techniques (scales of a few microns to a meter depending on imaging optics). Two primary functions of small scale in situ bio-optical measurements are 1) to enable the determination of the intensity and wavelength of light available for photosynthesis at depth and 2) to facilitate the identification and the quantification of phytoplankton populations (including growth rates) and their products. Some of the sensors described below may be used for one or both of these purposes and provide virtually continuous sampling with vertical resolution comparable to conductivity, temperature, depth (CTD) systems (few meters or less) and temporal resolution comparable to moored current meters (few minutes or less). Photosynthetically available radiation (PAR) sensors measure scalar irradiance in the visible waveband using a spherical light collector. More sophisticated optical instruments for quantifying the oceanic photo environment include multi-wavelength spectroradiometers. In particular, high spectral resolution (-2 manometers) radiometers are now being developed. In situ fluorometers are used to obtain nearly continuous records of fluorescence in order to estimate chlorophyll-a concentration and to infer phytoplankton pigment biomass. The recently developed fast repetition rate (two-pulse) fluorometer shows great promise for measurements of basic photosynthetic parameters as well as primary production. The beam transmissometer measures an inherent optical property of seawater, the beam attenuation coefficient, which relates to the volume of suspended matter or particle concentration in the water column.

A variety of sensors are being developed to measure a more comprehensive set of optical variables so that inherent optical properties (those independent of a natural light source) and apparent optical properties (those dependent on a natural light source) may be related. Emerging instrumentation which will facilitate characterization of inherent optical properties and will be useful for detailed study of various phytoplankton groups and primary productivity are spectral absorption and scattering meters and spectral fluorometers. The use of fiber optics to bring light signals from depth to the surface for shipboard (or surface buoy or drifter) signal processing and data analysis has been shown to be a viable option for several physical and bio-optical applications. A newly developed laser/fiber optic fluorometer which is used in parallel with a physical microstructure profiling instrument can provide vertical resolution of fluorescence on the centimeter scale. Expendable probes capable of measuring biologically and chemically relevant variables are likely to be developed. Such probes could enable broad geographic coverage and are especially useful for intensive regional studies as well as global surveys. Other in situ optical instruments for determining particle size distributions are being developed as well. Camera systems have been developed to examine settling rates of large aggregates of material in conjunction with sediment traps.

Various systems have been developed for the study of zooplankton and higher trophic level organisms. Promising optical methods, which have potential application for in situ small scale predator-prey studies, include Schlieren video systems and holographic systems (e.g., Dickey, 1988, 1990). Electronic and optical particle counters have been used to determine zooplankton abundance and physical dimensions indirectly (Sprules et al., 1992). The latter systems have been deployed in tow-yo and mooring modes. Video systems using CCD arrays are being utilized quite successfully from ships and specialized optics have been applied to view organisms down to scales of a few microns (e.g., Davis et al., 1992). Automated image analysis systems are being developed to attack the difficult problem of discriminating between taxonomic groups and larval stages.

Acoustical methods are attractive because they are non-intrusive and can be used for broad spatial coverage applications (e.g., Smith et al., 1992). They are generally more effective for larger scale organisms (roughly 100 microns to a meter or more, depending on the transducer used) than optical methods. Several different acoustical approaches have been suggested. For example, individual targets differing in size have different target strengths for differing frequencies. This principle has been exploited in the development of multi-frequency (up to 21 frequencies) and dual-beam acoustic systems which have been deployed in both shipboard (profile or towed) and moored modes. Another utilizes backscatter strength fluctuations to count the number of targets in a given volume. This technique was motivated by needs for fish stock assessment. Finally one of the more promising approaches to obtaining large volumes of data over broad areal extent is simultaneous sampling of currents and scattering intensity related to organisms with some ADCP's (e.g., Smith et al., 1992) which are increasingly being deployed from research and commercial vessels.

SYSTEMS

Many of the sensors described above may be considered to be modules, which can be interfaced with submersible packages including data acquisition systems and microprocessors. Two of the primary goals of interdisciplinary in situ measurement systems are: 1) to sample with complementary, interdisciplinary sensors as closely in space and time as possible and 2) to sample temporal and spatial scales of the ecosystem so as to avoid aliasing and undersampling. These include specialized profilers and tow-yo or undulating packages. They are often CTD-based packages which utilize extra data channels for optical and acoustical measurements. An important tool continues to be sophisticated multiple opening and closing net systems. These are needed to directly determine speciation and abundances of zooplankton and micronekton. These systems may now include: thermistors, conductivity sensors, fluorometers, dissolved oxygen sensors, and light sensors. A few investigators have also added acoustical sensors and video systems to their net systems to enable more detailed and quantitative analyses. Continuous plankton recording (CPR) systems have been utilized on ships of opportunity by the British for North Atlantic surveys for the past few decades (e.g., Quartley and Reid, 1996). This approach has been highly productive and the planned enhancement of these systems with emerging optical and acoustical sensors will likely lead to many new insights.

Multi-variable moored systems have been used to do time series measurements of several bio-optical and physical parameters as well as dissolved oxygen in several oceanic regions within the past few years. Recently, moored measurements relevant to zooplankton have been done using optical and acoustical systems. In addition, unattended multi-variable profilers have been used for measuring the vertical distributions of bio-optical and physical parameters.

In addition, new biogeochemical sensors for measurement of chemical variables of interest (e.g., nutrients such as nitrate, the partial pressure of carbon dioxide, and several other parameters) are being developed and tested on moorings as well as bottom tripods (benthic landers). Such tripods have been used to examine chemical reactions and fluxes in the uppermost sediments as related to the fate of biogenic materials produced in the upper layers of the ocean. Finally, trace element samplers are also being used on moorings in the open ocean.

For several years, drifters, drogues, and subsurface floats have been utilized by physical oceanographers for current measurements, however integration of biological and optical sensors with these systems is relatively recent. One of the principal attractions of drifters and drogues, which are equipped with bio-optical instrumentation, is that broad geographical extents can be sampled. In addition, acoustical and optical sensors placed on Lagrangian platforms can in principle provide data on the environment as experienced by a drifting organism. Some new drifters can also profile to depth and return data via satellite while at the surface. Another interesting approach being pursued at present involves a "smart drifter" which is intended to mimic larval behavior such as vertical migration.

Data have been transmitted in near real-time from interdisciplinary profilers and moorings, primarily in coastal studies or in proximity of ships (e.g., Dickey et al., 1993a,b) as well as in the open ocean (Frye and Owens, 1991). In order for this approach to be viable for interdisciplinary applications in the open ocean, broader bandwidth capabilities for data transmission will be required. Low earth orbit (LEO) satellites with such capability are being developed.

COMPLEMENTARY SAMPLING

Most of the in situ instrumentation and systems described above are particularly well-suited for shipboard (on-station and underway sampling), mooring, and drifter data acquisition. However, they cannot provide synoptic data with fine horizontal resolution over extensive geographical regions. For this reason, satellite-borne (and to some degree airplane-borne) remote sensing systems are especially important for oceanographers. The potential geographical coverage of satellite-borne sensors is virtually global with spatial resolution dependent upon the area observed or the footprint of the sensor. The altimeter being used for the Ocean Topography Experiment (TOPEX) is capable of resolving subtle currents of the world ocean with resolvable spatial and temporal scales of about 5 kilometers and 10 days, respectively. The anticipated data to be obtained from the satellite-based ocean color sensors of SeaWiFS (Sea-viewing, Wide-Field-of view Sensor) and several other ocean color imagers will be important for many coastal and open ocean programs. Synthetic aperture radar (SAR) sensors have the advantage of imaging even in the presence of clouds with even greater spatial resolution and can provide images of features such as fronts, slicks, and surface and internal gravity waves. Scatterometers provide important wind stress data. Airplane platforms may be used for deployment of many of these sensors as well. With these platforms, cloud problems are mitigated or eliminated and improved spatial resolution is derived. Many individual nations and groups of nations are applying remote sensing technologies to the ocean and significant advances are sure to follow.

Importantly, in situ data collected from moorings, drifters, and ships, provide a critical link for satellite sensor "ground truthing" as well as providing subsurface information and continuity of data during cloudy periods. Other potential ways to deploy in situ bio-optical, acoustical, and physical instrumentation packages in the future may include submarines and autonomous underwater vehicles (AUV's).

CONCLUSIONS

The global problems addressed by programs such as JGOFS and GLOBEC at present and by GOOS in the future require the consideration of biological, chemical, optical, and physical processes which can span scales up to nine orders of magnitude. Sampling remains a central issue in regard to the selection of key measurements as well as resolution and range. There has been a remarkable growth in the number of bio-optical, acoustical, and chemical sensors and systems which can be applied. Methods and instruments to obtain size distributions and taxonomic identification of phytoplankton and zooplankton (as well as their larval stages) are still needed. Techniques to observe organismal behavior and predator-prey interactions are important as well. Instrument standardization and calibration and interpretation of signals in a biological context remain as important issues. It is evident that intensive field testing and "ground truthing" of in situ sensors must be done periodically with standard shipboard sampling at representative oceanic sites. Simultaneous video and acoustical observations are likely to be quite effective. These efforts, which are somewhat analogous to the "ground truthing" of satellite-borne sensors, will be important for building our confidence in systems which will expand our interdisciplinary databases by several orders of magnitude. Further, selection of sensors and systems which are economical, as well as effective, is critical as large numbers must be deployed for global coverage of our presently undersampled environment.

Strides have been taken in interdisciplinary observational technology within the past decade. A most challenging aspect of emerging technologies is calibration, management, and optimal utilization of large volumes of optical and acoustical data (Dickey et al., 1993a). Careful consideration of time and space scales associated with the more energetic processes can be used to optimize both sampling and modeling. Yet the task of understanding processes whose scales lie between those scales which can more easily measured and modeled remains formidable. An important step for modelers and observationalists is to be able to accurately parameterize the smaller scale processes such as turbulence, particle motion, and animal feeding activities. It is imperative that modelers and technologists work together on these problems. Data assimilation modeling will be a vital aspect of GOOS (e.g., LMR-GOOS Planning Workshop, 1996).

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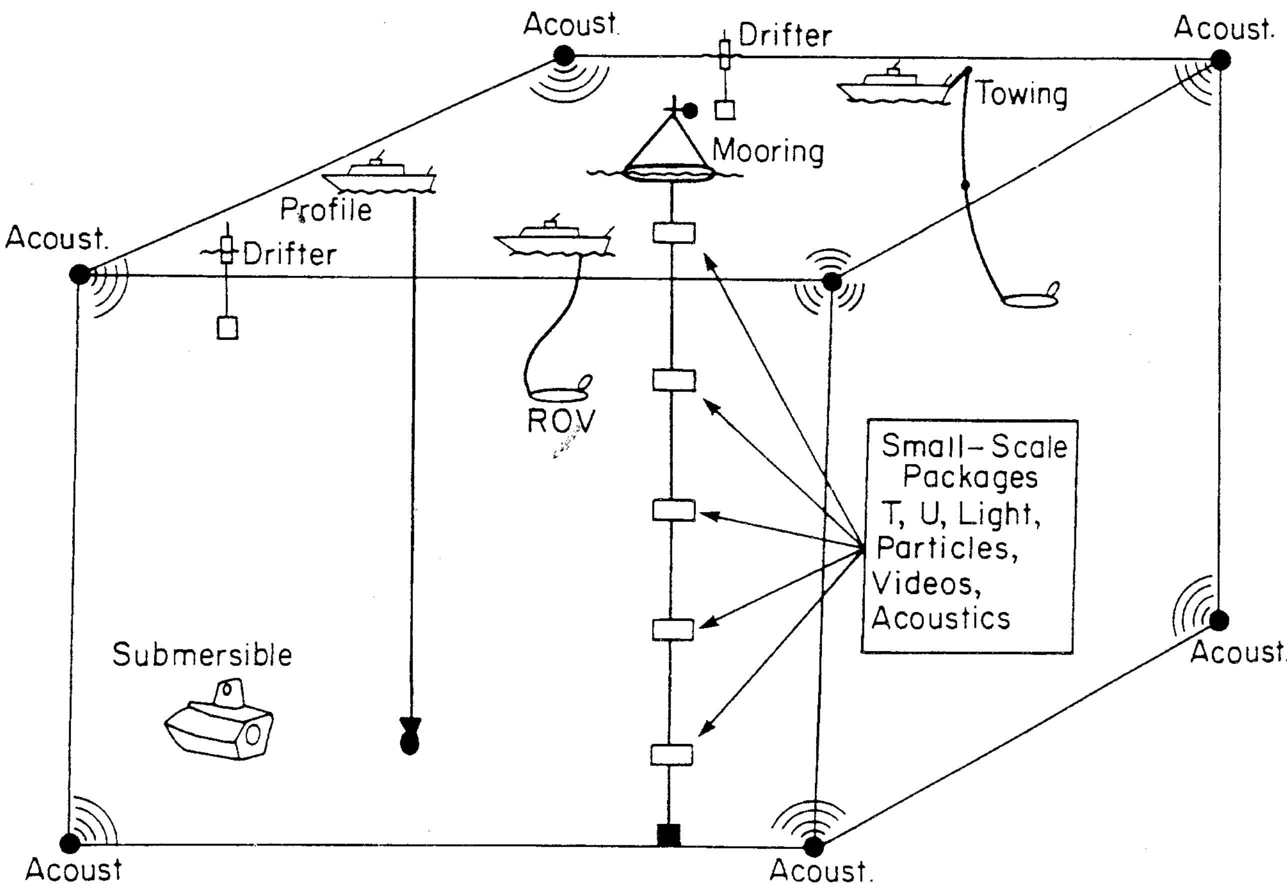

Figure 1: A conceptual illustration of a "nested" *in situ* biogeochemical-bio-optical-physical sampling configuration designed to sample processes with a broad range of temporal and spatial scales. (after Dickey, 1991)

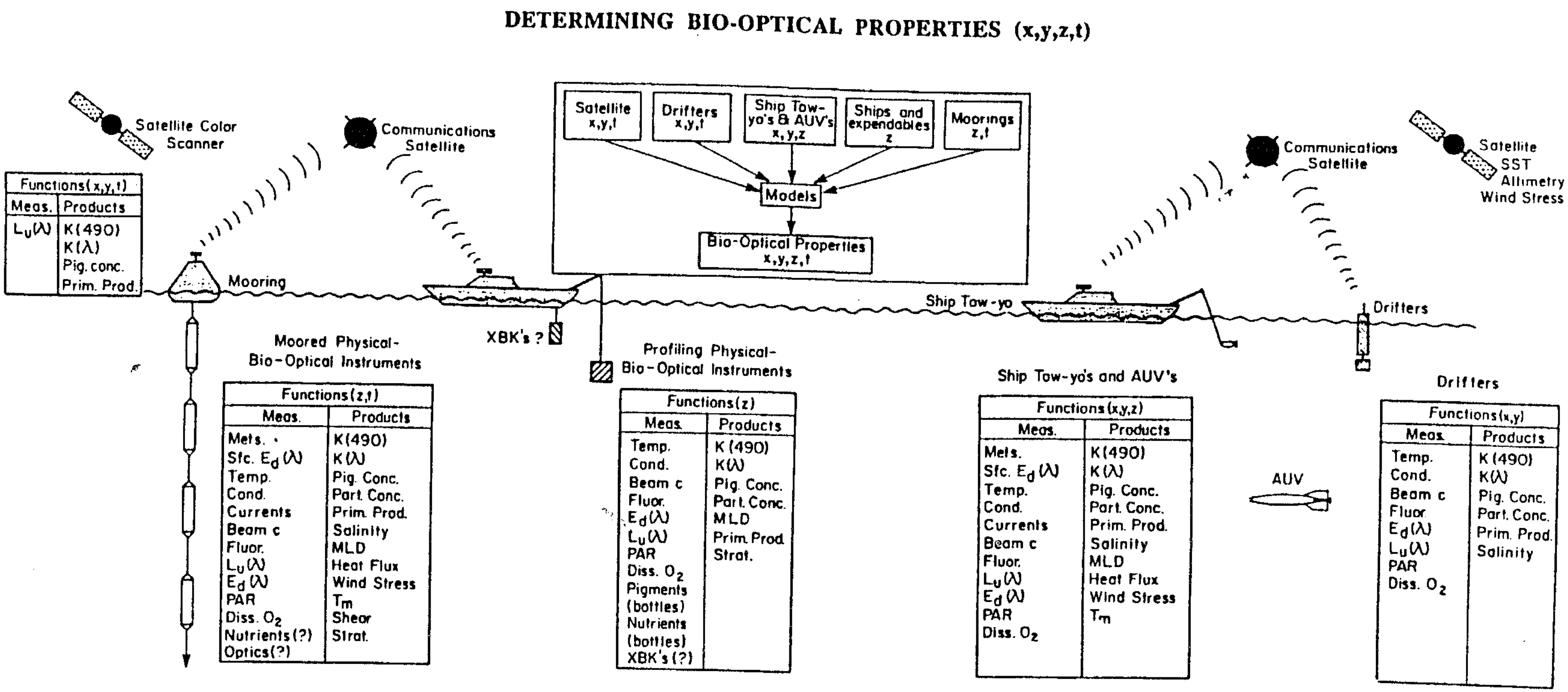

Figure 2: A schematic illustrating a methodology for determining the variability of the interdisciplinary variables (e.g., bio-optical properties as indicated here) in space and time on a global basis using satellite as well as *in situ* data sets along with appropriate models (after Dickey, 1991).