Technology & Related Developments For Interdisciplinary Global Studies

Sensors and Systems for Sampling/Measuring Ocean Processes Extending over Nine Orders of Magnitude

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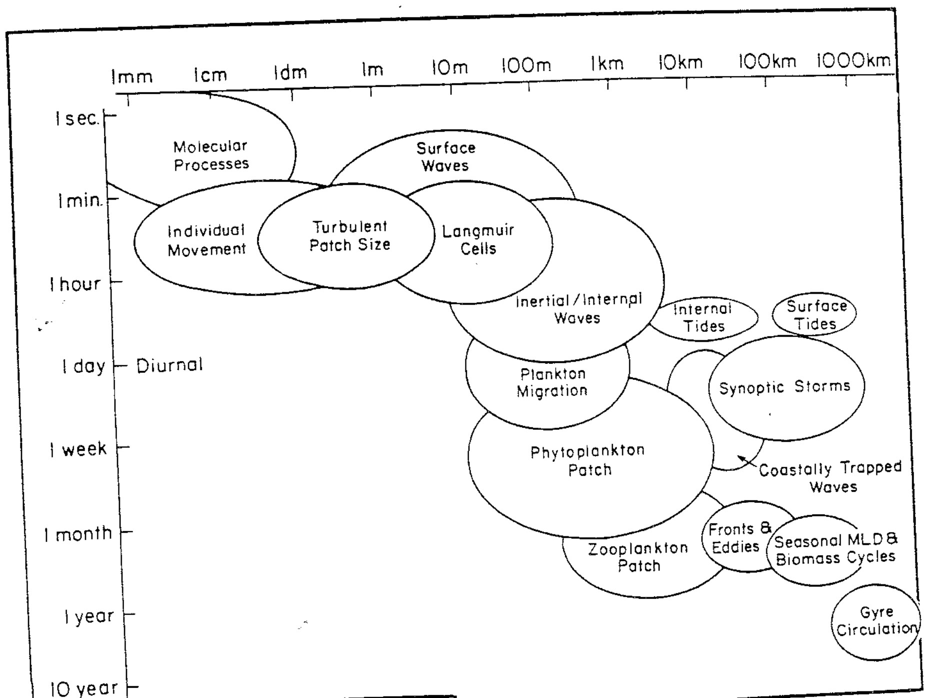
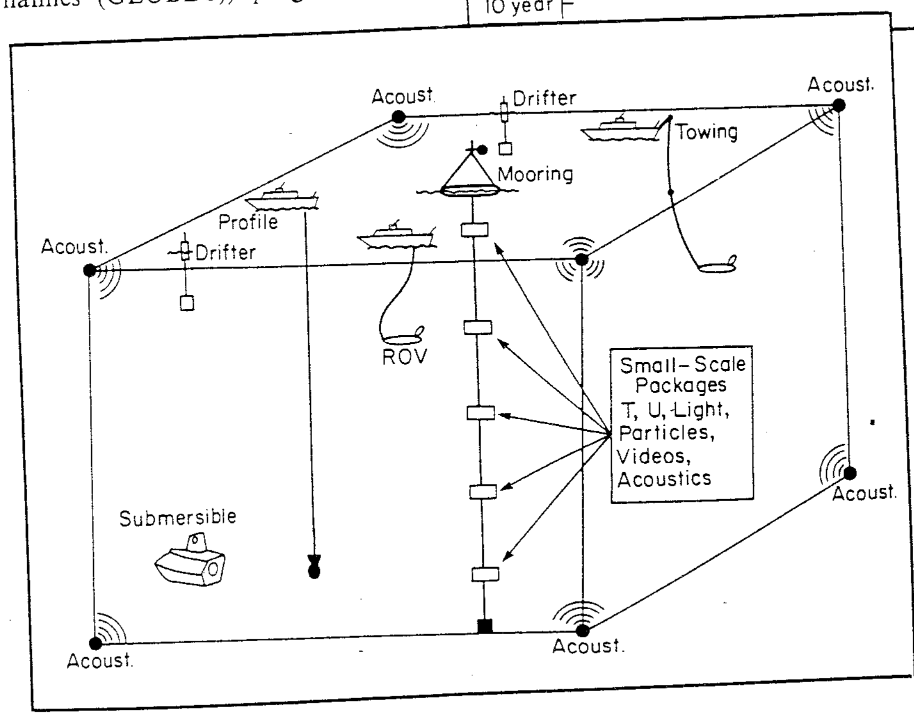
The term global change usually connotes climate change—a bias toward physical aspects. However, it involves considerably more diverse and complex set of scientific problems related to the biology and chemistry of our planet. For this reason, interdisciplinary research directed toward global scale problems has become the focus for many oceanographers recently.

Major programs such as the Joint Global Ocean Flux Study (JGOFS) (*Sea Technology*, January 1993) and the Global Ocean Ecosystem Dynamics (GLOBEC)) programs are well underway. The U.S. components are primarily administered and funded by NSF with additional funds from agencies such as NOAA, NASA, ONR, DOE, and EPA. Both programs have international components and coordinating organizations critical to their success.





Above, relevant time and space scales of several physical and biological processes important for interdisciplinary global studies. At left, a conceptual illustration of "nested" bio-physical sampling platforms and sensors designed to sample processes with a broad range of temporal and spatial scales. The symbols "T" and "U" represent temperature and horizontal current sensors.

The goals of JGOFS are to determine the processes that control the movement of carbon and biologically active elements in the ocean, from the air-sea interface to the seafloor and to improve predictions of the likely response of ocean processes to changes in climate associated with man's activities. GLOBEC focuses on the coupling of ocean physics with population dynamics of zooplankton and fish, and how climate change may effect this coupling.

Both programs are highly interdisciplinary, utilize process-oriented and time series studies, entail modeling components, and require emerging technology. JGOFS places emphasis on phytoplankton and primary production whereas GLOBEC stresses organisms which are higher in the food chain, ranging from zooplankton to fish. Interestingly, JGOFS has interests in zooplankton as grazers of phytoplankton, thus zooplankton represent an intersection of two programs.

Major JGOFS field efforts have thus far taken place in the eastern North Atlantic and the equatorial Pacific as well as at the time series sites near Bermuda and Hawaii. The first GLOBEC field study is about to take place on Georges Bank. The Southern Ocean and the time-series sites near Bermuda and Hawaii will likely be common regions of study for JGOFS and GLOBEC.

Recently a dozen national/international workshops and meetings were devoted to sampling and technological needs of JGOFS, GLOBEC, and related programs.

Sampling Considerations

The selection and sampling (in space and time) of key variables for studies of the marine carbon flux problem and of the recruitment of larval fish and population dynamics is clearly a challenging task. More specifically, these studies encompass interacting physical and biological processes whose scales of variability span at least nine orders of magnitude. It is possible to identify some dominant, temporal, and spatial scales of variability (e.g., the diurnal and seasonal cycles and mesoscale eddies), however, episodic phenomena represent critical events for biogeochemical fluxes and individual organisms. There are obvious nonlinear interactions as well. Thus 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. Clearly, a variety of specialied sampling platforms must be employed.

Numerical models are needed to synthesize the data and to enable diagnostics and predictions. An important link between data collection and modeling is real-time or near real-time telemetry of data.

Sensors

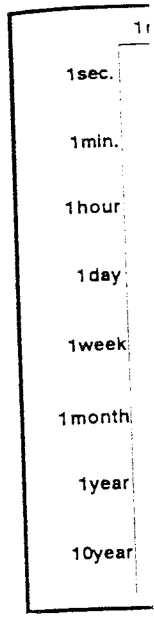
The development of interdisciplinary instrumentation systems has been highly dependent upon the availability of specific sensors. Some of the devices developed for use in measuring horizontal current are mechanical and electromagnetic vector measuring current meters (VMCMs), acoustical doppler current profiling meters (ADCPs), drifters, and drogues. 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 (and indirectly ocean temperature) 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 the order of hundreds of kilometers in the horizontal) of the ocean can be sampled synoptically. Vertical velocities have been most difficult to measure; however, measurement of vertical velocities have been done by using ADCPs and mechanical VMCMs.

There are special sensors which can measure temperature and velocity variations which occur over vertical scales of a few centimeters. Expensive to operate they remain tools limited to a few experts—increasing their availability to the broader oceanographic community is highly desirable.

Optical methods include measurement of small scale (a few nanometers in wave length and tens of microns in particle size) optical properties using various light sensors and imagery of organisms or video techniques (scales of a few microns to a meter depending on imaging optics). Principal functions of small scale *in situ* bio-optical measurements are:

- Enabling the determination of the intensity of the wave length of light available for photosynthesis at depth



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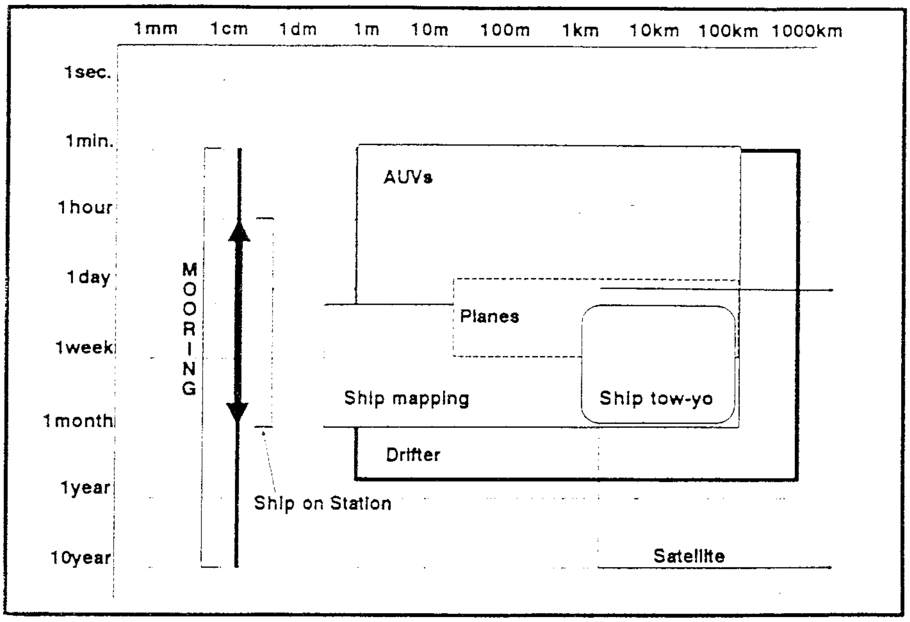

Temporal and horizontal spatial sampling coverage of several platforms.

- Facilitating the identification and and quantification of phytoplankton populations (including growth rates) and their products.

Sensors 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 photoenvironment include multi-wavelength spectroradiometers
- High spectral resolution (about 2 nanometers) devices 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
- Beam transmissometers (red wavelength) measure an inherent optical property of seawater (the beam attenuation coefficient) which relates to the volume of the suspended matter of particle concentration in the water column.

Sensor Needs, Developments

A variety of sensors are still needed to measure a more comprehensive set of optical variables so that inherent optical properties (those independent of a natural light source) and aparent optical properties (those dependent on a natural light source) may be related. Spectral (up to nine wavelengths) absorption and scattering meters are emerging devices which will facilitate characterization of inherent optical properties and will be useful for detailed study of various phytoplankton groups and primary productivity. The use of fiber optics to bring light signals from depth to the surface for shipboard (or surface buoy) 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 florescence on the centimeter scale.

Another important development is an "expendable bathyoptical (XBK)" probe (K indicates a parameter such as the spectral diffuse attenuation coefficient) which could be dropped from research ships or ships of opportunity in the same manner that the expendable bathythermographs (XBTs) are presently used for temperature profile data collection. Expendable probes such as these enable broad geographic coverage and are presently useful for intensive regional studies as well as global surveys.

Another important optical technique, presently restricted to shipboard use, is flow cytometry. Using this methodology, several optical properties of particles ranging in size from about 1 to 150 microns may be measured quite rapidly. Some of the properties include: particle index of refraction, forward scattering for particle sizing, and spectral fluorescence for determination of physiological states and particle type. *In situ* optical devices for determining particle sizing distribution are also being developed. The estimation of particle flukes at several depths is of major interest for JGOFS. Camera systems have been developed to examine settling of large aggregates of material in conjunction with sediment traps. Sediment traps have now been developed to obtain time series of these fluxes by using computer-based sampling controls.

Various systems for the study of zooplankton and higher tropic level organisms have been developed relatively recently. Promising optical methods, which have potential application for *in situ* small scale predator-prey studies, include Schieren video systems and holographic systems. Electronic and optical particle counters have been used to determine zooplankton abundance and size indirectly. Shipboard towing and mooring deployed video systems using CCD arrays and specialized optics can view organisms down to scales of a few microns. Automated image analysis systems are being developed to solve the problem of discriminating between taxonomic groups.

Acoustic Methodology

Acoustic methods sample marine organisms non-intrusively and can provide broad spatial coverage that is otherwise difficult to obtain. They are generally more effective for larger scale organisms (about 100 microns to a meter or more, depending on the transducer used) than optical methods. Several different acoustical approaches have been suggested:

- The first is based upon variation of target strength. 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.

• The second method utilizes backscatter strength fluctuations to count the number of targets in a given volume. This technique was motivated by fish stock assessment.

• The third method utilizes phase statistics. This technique involves successive transmissions which are processed coherently. In order to resolve multiple size classes of organisms, several frequencies must be sampled.

• The fourth method uses a coherent doppler measurement with processing of backscattered signals from several pulses. This principle has been used for remote current profiling measurements, and thus shear data relevant to organism distributions is a natural product. This technique has the potential of estimating contact rates of zooplankton and phytoplankton.

• The fifth method entails the acquisition of acoustic images based upon target strength distributions in coherent flow structures. This techniques could be used to determine physical structures and possibly to investigate plankton behaviors.

• Finally, multiple sonar and receiver arrays are being developed to obtain real-time data on spatial distributions of organisms.

Many sensors can be interfaced with submersible packages including data acquisition systems and microprocessors.

Systems

Two primary goals of interdisciplinary *in situ* measurement systems are:

• To sample with complementary, interdisciplinary sensors as closely in space and time as possible

• To sample temporal and spatial scales of the ecosystem so as to avoid aliasing and undersampling.

Some of these systems include specialized profilers and towing or undulating packages (sometimes called "tow-yos" as they are "yo-yo"ed up and down while being towed). These are often CTD-based packages which utilize extra data channels for optical and acoustical measurements.

An important tool for GLOBEC continues to be sophisticated multiple opening and closing net systems. Net collections are needed to determine species composition and abundances of zooplankton and micronekton and to provide organisms for physiological and genetic studies. These systems 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 systems have been on ships of opportunity by the British for North Atlantic surveys for the past few decades. This approach has been highly productive and the enhancement of these systems with emerging optical and acoustical sensors is highly desirable.

Unattended multi-variable profilers have been used for measuring the vertical distributions of bio-optical and physical parameters. Multi-variable moored systems have been used to do time-series measurements of several bio-optical and physical parameters as well as dissolved oxygen, and moored measurements relevant to zooplankton have been done using optical and acoutical systems recently.

In addition, new biochemical sensors for measurement of chemical variables (e.g., nutrients, the partial pressure of carbon dioxide, and others) are being developed and tested on moorings as well as benthic landers (*Sea Technology*, January 1993). The tripods or landers have been used during JGOFS 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. JGOFS investigatora have also used advanced chemical analytical techniques to estimate new primary production using radiochemical methods and dissolved organic carbon concentrations with new high temperature methods.

Recently biological and optical sensors have been integrated into drifters, drogues, and subsurface floats used for years by oceanographers for current measurements:

- A principal attraction of drifters and drogues equipped with bio-optical instrumentation is that broad geographical extent can be sampled.
- Optical and acoustic sensors placed on Lagrangian platforms can in principle provide data on the environment as experienced by a drifting organism.
- A "smart drifter" which is intended to minic larval vertical migration behavior is being pursued.

Data have been transmitted in near real time from interdisciplinary profilers, drifters, and moorings primarily in coastal studies or in proximity to ships. For viable general usage, more satellite communication bandwidth and/or fiber optic telemetry of data transmission of interdisciplinary variable fields will be required.

Complementary Sampling

Most *in situ* instrumentation, well suited for shipboard, mooring, and drifter data acquisition, cannot provide synoptic data with fine grain horizontal resolution over extensive geographical regions for long periods of time. For this reason satellite- and airplane-borne remote sensing systems are especially important. The potential geographic coverage of satellite-borne sensors is virtually global with spatial resolution dependent upon the area observed or the footprint of the sensors.

- The altimeter being used for the Ocean Topography Experiment (TOPEX) is capable of resolving subtle currents of the world's oceans with resolvable spatial and temporal scales of about 5 kilometers and 10 days, respectively
- Data from the satellite-based ocean color sensors of SeaWiFS (Seaviewing, Wide-field-of-view Sensor) will be important for JGOFS and GLOBEC programs
- NASA's Earth Observing System (EOS) could provide additional useful satellite-based data—the moderate-resolution imaging spectrometer (MODIS) and the high-resolution imaging spectroradiometer (HIRIS) could collect optical data with spectral resolution of a few nanometers and horizontal spatial resolution of a few hundred meters
- Synthetic aperture radar (SAR) sensors have the advantage of imaging even in the presence of clouds with even greater spatial resolution.

Airplane platforms may be used for deployment of some of these sensors as well, mitigating cloud problems and improving spatial resolution.

In situ data collected from ships, moorings, and drifters will provide satellite sensor "groundtruthing," subsurface information, and continuity of data during cloudy periods. Other potential ways may include sub-

Conclusion

With the processes addressed by the global programs spanning scales up to nine orders of magnitude, sampling remains a central issue in regard to selection of key measurements as well as resolution and range.

There has been a remarkable growth in the number of bio-optical and acoustical sensors and systems for JGOFS and GLOBEC programs. Many of these are being used by JGOFS and GLOBEC investigators. However, methods and instruments to obtrain 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 for GLOBEC objectives as well. Instrument standardization and calibration and interpretation of signals in a biological context remain issues.

It is evident that intensive field testing and "groundtruthing" of *in situ* sensors must be done periodically with standard shipboard sampling at a few representative sites. Simultaneous video and acoustical observations are likely to be quite effective. These intercalibration efforts, which are somewhat analogous to "groundtruthing" 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.

The future role of small businesses, which have developed and eventually marketed emerging sensors and systems cannot be underestimated.

Significant strides have been taken in interdisciplinary observational technology and computer modeling within the past decade. Furthermore, 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 be measured and modelled remains formidable. An important step for modelers and observationalists is to accurately parameterize small scale processes such as turbulence, particle motion, and animal feeding activities so that they may be included in models of larger scales. It is imperative that modelers and technologists work together on these problems.

Oceanographers have traditionally benefitted from technologies developed in other sectors of the scientific community. In fact, the clever application of these technologies has led to exciting interdisciplinary discoveries in recent years. Optics and acoustics have been emphasized here, but developments in diverse fields such as genetics, artificial intelligence, and computer animation either have been or may be utilized. /st/

Dr. Tommy D. Dickey, professor of oceanography in the department of geological sciences at the University of Southern California in Los Angeles, received his Ph.D. from Princeton University in geophysical fluid dynamics. He currently serves as chairman of the technology committees for the U.S. JGOFS, U.S. GLOBEC, and International GLOBEC programs. Annually he teaches oceanography to 600 undergraduates. Graduate students and postdoctoral fellows in his group pursue diverse research topics including coastal ocean pollution, modeling of light in a turbulent fluid, time series of primary productivity in regions ranging from the equator to 60° N.