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Interdisciplinary observations from moorings and autonomous underwater vehicles: recent advances and a look toward the future

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Observations based on developments in instrumentation and supporting technologies have led to a majority of the discoveries and advances in ocean sciences (*e.g.* Dickey, 1991, 2000). A grand challenge of oceanography is to massively increase the variety and quantity of ocean measurements. Ocean measurements are expensive, but vital for effective stewardship, preservation, and utilization of the oceans and atmosphere. Many innovative technologies involving computing, robotics, communications, space exploration, and physical, chemical, biomolecular, and biomedical research are being developed at unprecedented rates for a plethora of applications. Many of these technologies will be most beneficial for oceanography. It should be emphasized that virtually all important environmental problems require interdisciplinary approaches and necessarily atmospheric, physical, chemical, biological, optical, and geological data sets. Ideally, the requisite data should be collected simultaneously (concept of synopticity) and span time and space scales to observe the relevant processes of interest. For global problems, this means that variability extending well over ten orders of magnitude in space, and much longer in time (for climate problems) is encompassed (*e.g.* Dickey, 1991, 2000). Present capabilities for obtaining needed atmospheric and physical oceanographic data are relatively well advanced in contrast to those for chemical, biological, optical, acoustical, and geological data. This is not surprising, considering the greater complexity and non-conservative nature of the chemistry and biology of the oceans. Nonetheless, remarkable advances are being made in these areas as well. In fact, several bio-optical, chemical, geological, and acoustical variables can now be made on the same time and space scales as physical variables; however many more are needed.

Detection limits, precision, and accuracy of ocean measurements are important. However, the oceans are naturally dynamic with large amplitude periodic and episodic variability, which is especially confounding for quantifying long-term trends and changes. Presently, limited numbers of variables can be directly measured in the marine environment, so it is important to carefully select those which are the most critical. Because of the paucity of data, interdisciplinary numerical models capable of synthesizing observations and predicting variability over broad time and space scales will be needed.

A MULTI-PLATFORM, INTERDISCIPLINARY APPROACH

Interdisciplinary sensor suites are critical for studying problems such as carbon cycling and variability, the role of biology in upper ocean heating, phytoplankton productivity, upper ocean ecology, population dynamics, and sediment resuspension. Many of the new sensors are relatively small and have modest power requirements. Thus, the deployment of an increasing number of these sensors from autonomous platforms is becoming practical (*e.g.* Dickey, 1991; 2000). Several major interdisciplinary oceanographic programs have adopted multi-platform approaches. These programs have utilized mooring arrays, drifters, voluntary observing ships (VOS), and satellite data. The Global Ocean Observing System (GOOS) will also follow this approach, allowing studies of El No-Southern Oscillation (ENSO) and interdecadal phenomena such as the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO), and others. Nesting of platforms can optimize utilization of these observational assets. Further, numerical modeling is central to these collective programs. Many of the societally important oceanographic problems, like their atmospheric counterparts, require forecasting and rapid information dissemination to decision-makers and the public. Thus, two important aspects are near real-time data telemetry and data assimilation modeling.

Below, brief summaries of present capabilities and future directions using two classes of platforms are presented.

MOORINGS AND BOTTOM TRIPODS

Present capabilities

Interdisciplinary moored and bottom tripod measurement systems and sensors are being used by the research community to study environmental changes in the ocean on time scales from minutes to years. An increasing number of bio-optical, chemical, geological and acoustical parameters are being measured from moorings. This work has led to discoveries of new processes such as primary production variability associated with ENSO and equatorial long waves, sediment resuspension through internal solitary waves, cloud-induced and diel fluctuations in phytoplankton biomass, phytoplankton blooms associated with incipient seasonal stratification, and frontal- and eddy-trapped inertial waves (*e.g.* Dickey *et al.*, 1998, 2000; Dickey and Falkowski, 2000). Measurements of nitrate, partial pressure of carbon dioxide (pCO2), and dissolved oxygen (DO) have enabled new insights into primary and new production and gas exchange across the air-sea interface (Tokar and Dickey, 2000). Interestingly, several diverse and often adverse oceanic regions have been studied using interdisciplinary moored systems. These range from the equatorial Pacific to high latitude areas south of Iceland and in the Southern Ocean. Moorings and bottom tripods have been used in both open ocean and coastal settings. Because of biofouling of sensors, useful data from moorings has often been limited to a few months in the open ocean and less in coastal waters; however, work is underway to mitigate this problem. Moored systems have proven their value in the research realm and need to be deployed in critical regions for studies of seasonal through decadal variability and longer term monitoring purposes.

Benthic processes may be studied and monitored using instrumentation deployed on bottom tripods. Bottom tripods and their instrumentation may be placed in virtually the same environments as moorings and essentially the same suite of sensors and samplers deployable from moorings can be used on bottom tripods. The chemical species and geological parameters of interest will vary depending on the type of environment (*e.g.* harbor, coastal, or open ocean).

Offshore platforms, including dedicated and oil production platforms, provide unique opportunities for conducting oceanic and meteorological research and monitoring. These often large and very stable platforms typically have space and facilities for manned research laboratories and are equipped with adequate power and other needed services making them ideal for oceanographic observations. They offer several advantages over shipboard platforms, including absolute stability in high sea states, suitability for time series measurements, and capability for housing personnel. It should be possible to launch autonomous underwater vehicles (AUVs) and other mobile sampling devices from these platforms for spatial sampling as well. Active platforms would not be preferable for all types of measurements because of possible chemical contamination and non-representative biology that may result from drilling operations.

Looking forward

Time series observations in the coastal ocean and at selected sites of expected high environmental consequence (*e.g.* equatorial Pacific, high latitude sites of water formation and/or CO2 and Atlantic Oceans, the Arctic region, the Southern Ocean, and near Antarctica) will require the aforementioned platforms (*e.g.* see Griffiths *et al.*, 1999). Optimal selection of locations will be essential because of costs and return of investment. Increased multi-use of platforms for interdisciplinary sensors and systems is imperative. For example, a mooring designed for a tsunami warning system has been used in the Pacific for measuring upper ocean parameters relevant to global climate change. There is also a need for essentially expendable moorings, which can be deployed in remote areas, which require excessive shiptime for recovery, and for special observational programs (*e.g.* in paths and wakes of hurricanes and typhoons and in harmful algal blooms).

Novel uses of the platforms will evolve (*e.g.* Griffiths *et al.*, 1999; Dickey, 2000)). For example, moored profilers – *e.g.* buoyancy or mechanically (*e.g.* traction-drive) driven for the open ocean; wave-driven in the coastal zone – have been and can be used to good advantage for situations requiring high vertical as well as temporal resolution data (*e.g.* including temperature, salinity, current, and bio-optical variables). This mode of sampling can be preferable to gliders used in "virtual mooring" mode (described in detail below) for high current regimes and where surfacing (*e.g.* under ice) is not possible. In addition, moored profilers have the advantage of measuring absolute velocity whereas virtual mooring gliders require additional position data to reference their relative velocity measurements. A variant of moored profilers is the "pop-up" system, which could be deployed as an expendable system with a telemetry module.

AUTONOMOUS VEHICLES

Present capabilities

New technologies have enabled the development of AUVs and three related types of unmanned oceanographic vehicles: untethered underwater vehicles (UUVs), autonomous surface vehicles (ASVs), and gliders (*e.g.* Griffiths *et al.*, 1999; Dickey, 2000). These can be roughly described as robotic platforms designed to execute functions normally performed by ships, submarines, and divers. AUVs and UUVs are designed for a diverse set of activities in coastal or open ocean waters and can carry sensor payloads for specific applications. They generally vary in size from about a meter in length to over 10 m and utilize battery or fuel cell propulsion. AUVs are pre-programmed to perform sampling along specified track lines, to dock for downloading of data and recharging of batteries or fuel cells, and to key on specific oceanic cues (*e.g.* adaptive sampling based on temperature and chemical gradients). ASVs operate similarly to AUVs, but are restricted to surface operations.

Novel autonomous sampling platforms called gliders are the newest class of platforms being tested. Gliders have design elements and attributes of both profiling floats and AUVs. Gliders use buoyancy control to move vertically through the water columns, but utilize wings and hydrodynamic shape to produce horizontal motion. They are intended to perform with two sampling options: 1) performing long transects (*e.g.* up to 10,000 km) in sawtooth pattern (down to 2000m) and 2) as "virtual moorings" executing vertical profiles at fixed location. In both cases, sampling strategies could be modified (adaptive sampling) and the gliders could be remotely commanded to sample new sections or selected sites.

Looking forward

At present, several specialized groups are developing and using autonomous vehicles and the numbers are expected to grow as mission length capabilities increase, costs decline, reliability improves, operation becomes more routine, and more sensors become available for various sampling needs. It is likely that major breakthroughs in fuel cell technologies (allowing longer missions in space and time), improved navigation and telemetry (via acoustic and satellite links) capabilities, and miniaturization of sensors will facilitate and accelerate widespread use of these platforms. It is anticipated that creative uses of the vehicles will involve networking and informational feedback loops to guide sampling programs (in some areas involving predictive models) and responses to extreme natural and anthropogenic driven events.