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MEETING EXPLORES SENSOR TECHNOLOGY for REMOTE, INTERACTIVE AQUATIC EXPERIMENTS

Oceans, lakes, rivers, and groundwater are complex, dynamic environments in which physical, chemical, and biological processes occur over varying temporal and spatial scales (e.g., eddies, nutrient fluxes, patchiness of organisms, benthic processes, and pollution). In addition, deep, remote, or hostile systems, such as hydrothermal vents and polar regions, traditionally are poorly sampled, but are important to understanding global biogeochemical and hydrological cycles. In the coming decades moored, cabled, and autonomous observatories will be used to investigate a spectrum of basic processes in aquatic environments. In anticipation of the need to develop or re-engineer sensors to measure physical, chemical, biological, and geological processes *in situ*, a one-day workshop and special session on sensor technology was held during the June meeting of the American Society of Limnology and Oceanography (ASLO) in Copenhagen, Denmark. The goal of the workshop was to exchange ideas on new experimental approaches and methodology, to define strategic themes, and to formulate specific recommendations related to sensor development. The 25 participants from North America and Europe represented academic and industry sensor developers and users, as well as a broad spectrum of scientific interests. Here I report the recommendations resulting from that meeting in hope that they will be useful as a catalyst for further development of sensor systems.

There was consensus among the workshop participants that development and validation of chemical and biological sensors were urgently needed. Lack of inexpensive and reliable sensors generally limit chemical and biological observations. For example, 3,000 profiling floats will be deployed as part of the internationally supported Argo Program (www.argo.ucsd.edu) to monitor global changes in ocean temperature and salinity as part of a climate observing system. The inability of biogeochemists to utilize these floats was perceived as a tremendous missed opportunity to link physical, chemical, and biological processes to climate variability.

Our community needs to ensure that development and use of sensors will progress more efficiently. The primary recommendation was that workshops involving scientists, engineers, and technologists were essential to foster information exchange and to provide advice on community priorities for sensor development. More than one workshop would be warranted because of the specialized needs of different habitats and the varying research focus of different scientific programs. A coordinating committee could be beneficial for tracking the common themes among these groups and finalizing cross-cutting recommendations in a document for funding agencies, sensor developers, and user groups. There also was a consensus that some areas of sensor development/use required community agreement (e.g., hardware/software compatibility issues, precision issues, calibration standards) and that other areas needed strong encouragement for continued development (e.g., O_2 sensors, profiling moorings). Additional suggestions to enable information exchange included establishing a network for sensor developers and users, holding a Gordon Conference on cross-technology issues, and establishing training grants for users and technologists.

The first working group recommended the following criteria to prioritize the chemical and biological sensors needed to address fundamental science questions during the next decade.

- Sensors that are now operational, but could be better utilized.
- Individual sensors or suite of sensors that require additional development.
- Sensors that need to be developed.

Some sensors, for example pCO_2, pH, nitrate, fluorometers, and spectral radiometers, are currently operational on moorings, but long deployments may be limited by biofouling. Biofouling came up repeatedly as a problem that must be resolved. A combination of optical (i.e., absorption, transmissometers, and fluorometers), O_2, and pCO_2 sensors was given as an example of a suite of sensors that would be useful to address a broad array of questions related to aquatic productivity and biogeochemical cycles. However, instrumental drift of O_2 sensors in marine systems was a concern. The wish list for new sensors was as long as the number of participants. Examples of chemical sensors that must be developed included particulate and dissolved organic carbon, nitrogen, and phosphorus, phosphate and acetate, and sensors for speciation of elements. The need for robust, stable sensors at extreme temperatures was discussed. The development of sensors for microbial activity also was strongly endorsed. Our understanding of microbial ecology is far behind all other biota. Recent developments in microfabrication provide the foundation for developing high-density arrays of biologically-based detection elements (e.g., nucleic acid, enzymatic, or immunochemical). For example, DNA microarrays could be used to monitor both abundance and activity level variations among natural microbial populations.

Participants noted that the accuracy, precision, and interpretation of sensor data must be improved. They recommended that calibration protocols be developed for all sensors, especially *in situ* calibrations, that standards for calibrations of sensors and analyzers be developed and maintained, and that training workshops should be encouraged to provide instruction on the proper use of equipment. Workshop participants noted the success of the global ocean carbon dioxide survey was enabled by the development of easily distributed standards for total inorganic carbon. Interpreting the carbon data, however, has proven problematic due to the lack of similar standards for nutrients. Biological sensors have suffered from a lack of rigorous field validation and must be accorded sufficient funding to complete this essential development phase. Too often biosensor validation has been done in an *ad hoc* fashion during field research, resulting in a lack of confidence in data interpretation.

The second working group discussed the problem of moving from prototype sensors to mass production. The example of the TAO/Triton mooring array across the Tropical Pacific Ocean was used as a focus for the discussion. About 70 ATLAS and TRITON moorings, with physical sensors at 11 depths, telemeter oceanographic and meteorological data to shore in realtime via the Argos satellite system. The chemical and biological oceanography communities must develop strategies to deploy a comparable number of sensors in order to achieve a similar synoptic coverage. In addition to conceptual hurdles, sensor development and mass production was viewed as being limited by funding, lack of a trained workforce (users and repair), poor long-term stability and reliability of sensors, and inadequate follow-up on calibration and data quality control. It was clear that community acceptance of a sensor technique was necessary before mass production could occur.

Several directions for broadening the application and use of sensors were considered. Sensor designs could be simplified so that non-experts can use them. Sacrificing precision should be evaluated in terms of the process being measured and whether it increases instrument reliability or reduces the level of expertise needed to maintain the instrument. Alternatively, sensor designs could be made more complex, whereby an intelligent sensor would perform the function of the expert technician. Smart sensors also could be designed to detect natural scales of variability and respond in some pre-programmed way to collect data more intensively during or near the phenomenon of interest. Smart sensors would be easier to transport to different environments that operate on different scales of variability (e.g., hydrothermal vents, freshwater, and sediments). Dedicated scientific/engineering centers were suggested for intensive development of certain sensors and to facilitate the broad use, validation, and mass production of sensors. Cooperation between scientists and industrial partners should be encouraged for the final development. Finally, there must be a broad effort to inform and train users to interpret results. Support groups should be set up to provide advice to all users.

The second working group also discussed problems associated with hardware and software compatibility, the so-called "Plug-N-Play" issue. Everyone agreed that this problem continued to be a tremendous time- and money-consuming challenge. The most flexible instrument drivers utilize low-level C programming language. Investigators wishing to combine observations from multiple instruments are forced to either limit their sampling options to those supported by pre-programmed drivers or invest significant time and resources into electronic and software programming themselves. Mutual compatibility is an increasingly difficult problem as serial instruments are each programmed and interrogated separately. This is a community problem that could benefit from standardization of power and communication, while recognizing that power requirements and data output rates vary among sensors. One solution suggested was the use of Master-Slave processors, which would have the capability of distinguishing three modes of sensor operation; autonomously driving itself, autonomously driving other sensors, and being fully driven by another processor. Another option would be to develop an identification reference system allowing the "smart" central processor to talk with individual sensors. Currently these systems are custom-designed and maintained by only a few hardware/software experts.

One outcome of this workshop will be to establish a sensor network and information exchange on the ASLO website. The exchange will include an interactive, searchable directory where individuals and industry representatives will be able to submit or update statements about their research activities, interests, and basic contact information. Other features will include links to sensor-related websites, and a discussion forum. We encourage anyone interested in sensor technology to watch the ASLO website for further developments early this fall. We hope that this report will serve to stimulate a continuing dialogue on these topics and provide a focus for future sensor development.

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