Meeting Explores Sensor Technology for Remote, Interactive Aquatic Experiments

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Daly, Kendra L., "Meeting Explores Sensor Technology for Remote, Interactive Aquatic Experiments" (2000). Marine Science Faculty Publications. 841.
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obstacles to overcome. Specific problems identified by the group were 1) lack of author recognition in the scientific community by peer reviewers and editors; 2) the relatively high cost of publishing in Western scientific journals and obtaining reprints; and 3) the fact that many scientific researchers from Francophone African countries have technical difficulties writing in English, a main language for publishing in the geosciences.

To increase their recognition among scientific peers and editors in the United States, the breakout group participants agreed that it is absolutely necessary for West African atmospheric scientists to present their research at appropriate national and international meetings, such as those sponsored by the American Geophysical Union and the American Meteorological Society, even though it is very costly for them to attend. Regarding high publication costs, the participants noted that there are numerous journals in the atmospheric sciences that do not charge page fees and that provide a number of reprints free of charge. The participants also noted that there are other scientific journals that will drop or reduce page charges for camera-ready manuscripts. The group resolved to draw up a list of such journals and make it available to African atmospheric scientists on the Web site of either Howard University or Pennsylvania State University.

To assist Francophone scientists from West Africa with technical writing in English, the breakout group proposed the following:

- Establishing a network of U.S. scientists who, through the Internet and the mail, can help their African counterparts with editing and reviewing manuscripts prior to their submission.
- Ensuring that African scientists have access to graphics and other software that can be used at all stages of manuscript development. The participants noted that there are numerous "freeware" packages in these categories, and that it may be possible to work out agreements with the University Cooperation for Atmospheric Sciences (UCAR) to obtain software packages such as NCAR graphics at a reduced cost for West African universities.
- Sponsoring technical writing workshops to which Francophone African scientists could bring actual manuscripts, to improve their technical writing skills in English.

### Attendance at Conferences

The other main difficulty identified was the problem West African atmospheric scientists encounter in presenting their research at scientific conferences, especially ones held in the United States. As the participants noted, this is related largely to the high cost of international travel and costs associated with registration and lodging. The participants acknowledged that there are no simple solutions, but they also agreed that the importance of attending conferences is so great that creative, sustained efforts to help defray these costs are imperative. Partial solutions proposed included determining whether full or partial funding is available from U.S. professional societies for scientists from developing countries for attendance at individual conferences; and developing proposals for travel grants to U.S. federal agencies and/or private foundations for scientists presenting scholarly research at national meetings in the United States.

The general opinion of the breakout group was that many members of the atmospheric sciences community and in the United States specifically were unaware of the current difficulties that West African scientists face in disseminating their research to the larger community. An identified solution was for U.S. scientists to publish articles and make presentations at various scientific meetings to "publicize" the existence of these problems. Finally, the group concurred that an interdisciplinary geosciences organization similar to AGU should be formed in Africa which would host meetings similar to the biannual AGU and annual AMS meetings. These types of meetings in Africa could bring together scientists from various disciplines and continents, increasing Africa's involvement in global scientific research.

### Acknowledgments

The workshop on climate change research in West Africa was funded by the International and Atmospheric Sciences programs of the U.S. National Science Foundation. It was hosted by faculty from the Department of Meteorology of Pennsylvania State University, and from the Center for the Study of Terrestrial and Extraterrestrial Atmospheres and the graduate program in atmospheric sciences of Howard University in Washington, D.C.

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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, hydrothermal 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 reengineer 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 2000 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. Reported here are 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 limits chemical and biological observations. For example, 3000 profiling floats will be deployed as part of the internationally supported Argo Program (http://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.

### Fostering Information Exchange

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 and use required
community agreement (e.g., hardware and software compatibility issues, precision issues, calibration standards) and that other areas needed strong encouragement for continued development (e.g., O2 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.

New Types of Sensors

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 a suite of sensors that require additional development; sensors that need to be developed. Some sensors (e.g., PCO2, pH, nitrite, 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), O2, and pCO2 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 O2 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 that the success of the global ocean carbon dioxide survey was made possible by the development of easily distributed standards for total inorganic carbon. Interpreting the carbon data, however, has proven problematic, owing 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.

Problems of Mass Production

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 real time 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 a lack of 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 preprogrammed 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 and 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.

Hardware and Software Compatability

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 either to limit their sampling options to those supported by preprogrammed drivers, or to 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 and software experts.

One outcome of this workshop will be to establish a sensor network and information exchange on the ASLO Web site. 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 Web sites, and a discussion forum. We encourage anyone interested in sensor technology to watch the ASLO Web site for further developments.

Additional details on the ASLO Sensor Workshop and a listing of the participants is posted on the following Web sites: http://www.marine.rsmas.miami.edu/deos.html and http://www.soc.soton.ac.uk/ODE/GxG. We hope that this report will serve to stimulate a continuing dialogue on these topics and provide a focus for future sensor development.

Acknowledgments

This report reflects the contributions of many people. I would like to thank my co-convenors, Larry Clark, Gwyn Griffiths, and John Delaney; the working group leaders and rapporteurs, Ken Johnson, David Stahl, John Dunne, and Mary Jane Perry; and the workshop participants for their enthusiasm and thoughtful comments.

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