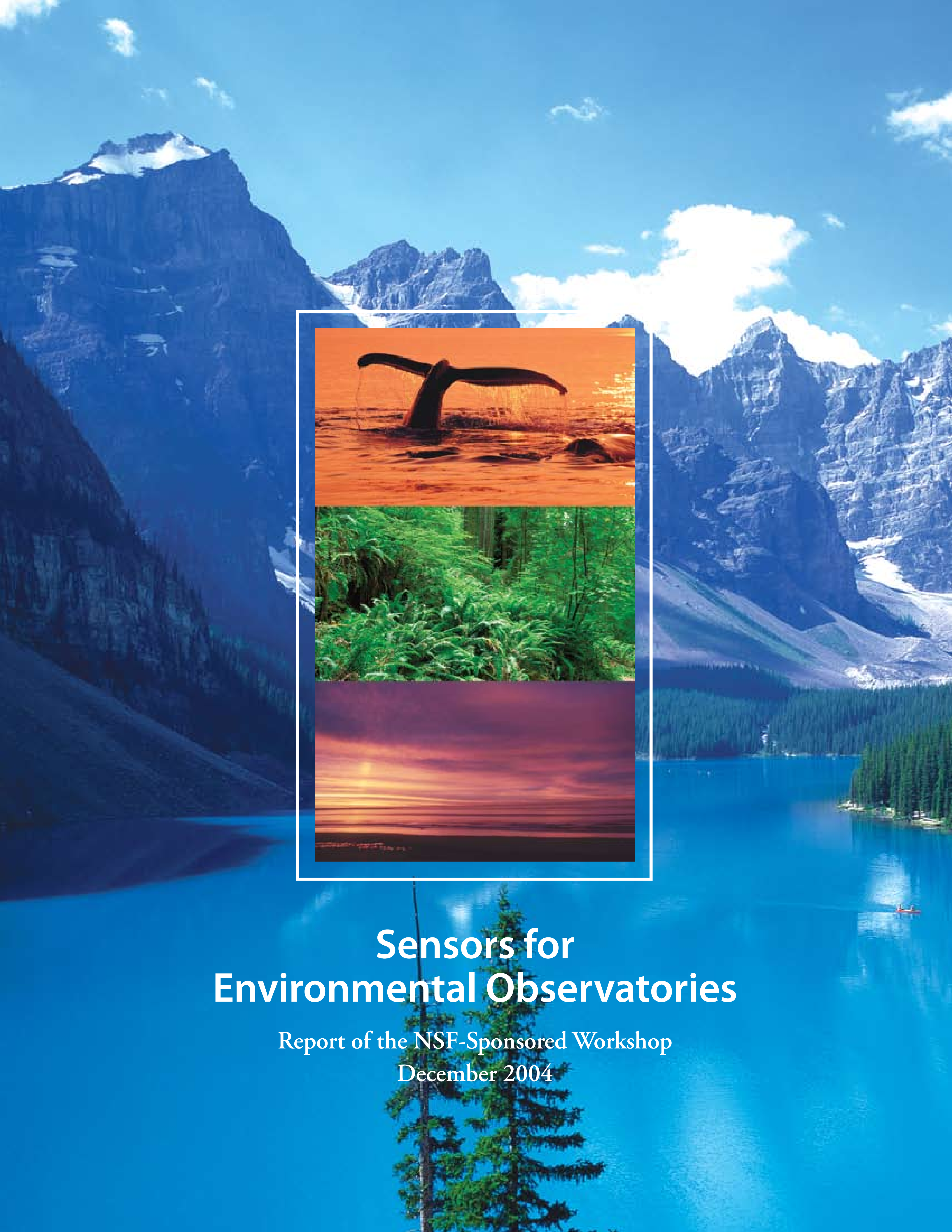

Sensors for Environmental Observatories

Report of the NSF-Sponsored Workshop
December 2004

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Abstract

In recent years, the environmental science community, with the support of the National Science Foundation (NSF) and other funding sources (e.g., National Oceanographic Partnership Program), has successfully conceived, designed, and begun implementing several new observing systems, including the Oceans Observatory Initiative (OOI), the National Ecological Observatory Network (NEON), the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER), the Hydrologic Observatory Initiative (HOI), and Earthscope. In addition, seventeen Federal agencies are currently planning an integrated, comprehensive, and sustained Earth observation system to address the nation's critical societal and economic needs. The Integrated Earth Observation System (IEOS) will integrate the data from satellites, ocean buoys, weather stations and *in-situ* Earth observing instruments into advanced science numerical models and decision support tools that will provide new data products benefiting societies and economies worldwide. These new and visionary projects will enable longer-term sensing of the environment. However, there are significant limitations to current sensor technology and the networks that collect data from them. Present work clearly demonstrates the need for:

- the development of new types of sensors and sensors with new capabilities
- the ability to link sensors to a broader network
- coordination across various environmental observatories
- capabilities for long-term autonomous deployment and maintenance

To address these needs, experts from universities, research laboratories, education and outreach activities, international activities, Federal agencies, and industry were invited to attend the workshop *Sensors for Environmental Observatories: A Framework for Progress*, from November 30 to December 2, 2004, at the University of Washington in Seattle. Attendees focused on identifying opportunities for enhancing existing sensors and sensor systems available for observing systems and on ways to fill current knowledge gaps in sensor technology.

The breadth of professional interests and expertise represented by the participants was a unique aspect of the workshop. Attendees represented a wide range of sciences (oceans, rivers and estuaries, lakes, groundwater, agriculture, terrestrial ecology, and urban pollution); many types of sensor technologies (physical, chemical, biological); and a broad base of experience with sensor deployment in a variety of environmental conditions. Although it is still too early to document specific results, researchers recognized the need for greater collaboration among different communities, discussed opportunities for such collaborations, and recommended that attendees continue to find ways to bring together professionals from across the spectrum of the sensor professions.

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Executive Summary

Sensor networks will produce a revolution in our understanding of the environment by providing observations at temporal and spatial scales that are not currently possible. Expanding observational scales will enable a deeper and broader understanding of environmental variability and change that will, in turn, improve public awareness, enabling better informed public policies and addressing the intrinsic interdependence of human society and the natural environment.

The history of integrated sensing demonstrates how its forecasting power enables scientists to understand our environment. Systematic meteorological observations, which began in the late 1800s, ultimately improved our ability to predict weather days in advance, thereby improving transportation safety while also significantly reducing the impacts of flooding and other natural hazards. Nearly continuous measurements of atmospheric CO_2 taken by Dr. Charles Keeling over forty years, starting in 1958, provided dramatic new evidence of global warming. Modern precision agriculture likewise benefits from sensors and sensor networks; the higher levels of productivity that result from more efficient application of water and fertilizers reduces the chemical runoff that adversely affects water basins and ground water.

The National Research Council (NRC, 2001) has identified eight grand environmental challenges that our nation faces today. These include understanding and managing basic environmental processes and interconnected human activities in the following areas: biological diversity and ecosystems function, invasive species, climate variability and ecological responses to climate change, hydrologic forecasting to predict changes in fresh water sources, biogeochemical cycles and their impacts on ecosystems, infectious diseases and their interactions with the environment, land-use changes as they impact ecosystems services and human welfare, and materials uses in relation to environmental impacts of their residuals. Meeting these challenges can only occur with the development of environmental sensor networks capable of collecting appropriate data at higher temporal frequencies and to a broader spatial extent than is currently done.

In recent years, the environmental science community, with the support of the National Science Foundation (NSF) and other funding sources (e.g., National Oceanographic Partnership Program), has successfully conceived, designed, and begun implementing several new observing systems, including the Oceans Observatory Initiative (OOI), the National Ecological Observatory Network (NEON), the Collaborative Large-scale Engineering Analysis Network for Environmental Research Network (CLEANER), the Hydrologic Observatory Initiative (HOI), and Earthscope. In addition, seventeen Federal agencies are currently planning an integrated, comprehensive, and sustained Earth observation system to address the nation's critical societal and economic needs. The Integrated Earth Observation System (IEOS) will integrate the data from satellites, ocean buoys, weather stations and *in-situ* Earth observing instruments into advanced science numerical models and decision support tools that will provide new data products benefiting societies and economies worldwide (NASA, ND). These new and visionary projects will enable longer-term sensing of the environment. However, there are significant limitations to current sensor technology and the networks that collect data from them. Present work clearly demonstrates the need for

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The breadth of professional interests and expertise represented by the participants was a unique aspect of the workshop. Attendees represented expertise on a wide range of environmental media (oceans, rivers and estuaries, lakes, groundwater, agriculture systems, natural landscapes, and urban areas); many types of sensor technologies (physical, chemical, biological); and a broad base of experience with sensor deployment under various environmental conditions. Although it is still too early to document specific results, researchers recognized the need for greater collaboration among different communities, discussed opportunities for such collaborations, and recommended that attendees continue to find ways to bring together professionals from across the spectrum of the sensor professions.

The workshop focused on representative scenarios that demonstrate the success of existing sensor networks while posing key questions that could not be addressed with current technology or deployment strategies. These scenarios are presented in Chapter 2. Subsequent chapters contain contextual information that cuts across the scenarios: science, community, and outreach (Chapter 3); technology development (Chapter 4); and sensor deployment (Chapter 5). Each of these sections discusses cross-cutting themes that emerged at the workshop and includes specific recommendations.

KEY OBSERVATIONS, FINDINGS, AND RECOMMENDATIONS

National Commitment to Sensor Development and R&D Coordination

Sensor networks that are adequately deployed and maintained have the potential to revolutionize science and influence major social, economic, agricultural, environmental, and health issues. These networks also will enhance educational curricula. To realize these benefits, a broad portfolio of investments and funding mechanisms will be needed to leverage inputs from other agencies and industry to develop, deploy, and maintain sensors and sensor networks. It is important that the portfolio of deployed assets, as well as the scale and duration that they are deployed, are appropriate to the environmental processes being investigated.

The development and deployment of sensors and sensor networks requires a team-based, integrative systems approach. Federal programs should reflect the inherently interdisciplinary nature of networked sensor research, development, deployment, and management. Networks should have an appropriate mix of multi-disciplinary and disciplinary approaches to environmental sensor systems. Proposed networks should consider both the potential scientific impact of the system as well as maintainability and life-cycle costs.

Community and Partners

The workshop encouraged broad, interdisciplinary participation and enabled new perspectives on sensor designs, deployment platforms, and network topologies. Participants recommended that a series of smaller and more narrowly focused workshops should be held on environmental sensors and sensor networks to encourage collaborations and reduce redundancy among efforts. Furthermore, the participants recommended that a mechanism be put in place to train researchers on new technologies, as is done in meteorology. This training should extend to the exchange of postdoctoral researchers, mid-career professionals, students, and other professionals among individual projects, and between projects and the broader community. An electronic journal may provide rapid and timely dissemination of sensor and sensor network technology. Wider dissemination is needed to engage a greater audience for sensor development activities. Editors of major journals should be encouraged to write editorials on the importance of environmental observatory efforts. A "clearinghouse" website to provide links to sensor development projects and related resources would be useful.

Long-term data from sensor networks will be valuable for educational use, and tools and development of curricula for teachers and students at all levels should be encouraged, preferably through existing organizations. Resources should be sought to enable the participation of secondary (grades 9–12) education teachers and community college faculty in multi-year projects, so that the knowledge gained from the environmental network will have a multiplying effect as it is conveyed to students. Software and education modules should be developed that will enable students, teachers, and the general public to obtain, visualize, and make use of real-time data from environmental observing systems. It was noted that educational materials based on sensor networks should be developed only when observing sensors have proven to be reliable sources of data. Once environmental sensor networks are established, it will also be important to work with local agencies to create "citizen scientists" (see Section 3.4.3).

The study of global phenomena requires engagement of the global community, and collaboration with the international community will be essential. International involvement and technology sharing should be encouraged, and collaboration in the establishment of common network infrastructure should be sought when appropriate. An open exchange of investigators and students between U.S. and international initiatives should be integrated into the early planning stages for appropriate environmental sensor networks. The NSF's Office of International Science and Engineering (OISE) could play a vital role in this coordination.

The challenges that will be faced in establishing sensor networks are beyond the experiences of individual scientists and current institutions and agencies. New partnerships need to be developed across communities involved in environmental research to engage in the development of these environmental networks. Interactions with industry must be cultivated to enable researchers to connect more easily with commercial development and to ensure that advances arising from research transition effectively to the manufacturing of sensors at sufficiently low costs that they are available for broad community use. Industry-research collaborations could be facilitated by encouraging industry involvement in the proposal phase, creating the possibility to add SBIR-like supplemental opportunities to NSF awards, and by creating additional opportunities for commercial partnerships. The National Oceanographic Partnership Program (NOPP, http://www.nopp.org) is a model to enhance partnerships through its ability to coordinate the numerous agencies and industries involved in environmental sensing. Interactions with non-governmental organizations, universities, and organizations such as museums will encourage dissemination, education and outreach, as well as technology development.

Modeling, Algorithm Development, Automation of Processes

Modeling and visualization tools are critical for environmental research and should be integral to any sensor network systems that are established. Prior to the implementation of a network, models can provide information about the appropriate placement of sensors within an environment and effectively "tune" the system to investigate particular processes. Once a network is established, sensor data support predictive models for forecasts, event detection, and process interpretation. Models also can help establish adaptive sampling strategies for sensors.

Models will improve understanding of processes and thereby reduce the uncertainty of forecasts and conclusions. Critical research topics in environmental modeling include spatial-temporal statistics, sampling techniques, and the interplay between data and models to enable informed placement of sensors and improve the predictive capabilities of existing models. The environmental science community should collaborate with the mathematical and statistical communities in pursuing these topics.

Because sensors are being deployed in greater numbers, across larger areas, and in ever more complex networks, observatory control processes must be increasingly automated. Important issues related to this topic include quality assurance/quality control processes during data collection, correction of measurement drift in sensors, and detection of unusual events. These issues have theoretical components of potential interest to computer scientists involved in the design of intelligent systems, as well as to electrical engineers engaged in signal processing. These collaborations should be actively sought out and encouraged.

Technologies to be Used in Environmental Sampling Networks

In many areas of environmental sensing researchers measure easily detectable parameters (termed proxy or surrogates) and then use simple semi-empirical correlations to infer the parameter they are really interested in. These correlations are often based on very limited data. Creating sensors to measure more directly variables of interest is critical.

Workshop participants identified many unresolved issues in sensor technology and classified them into three broad types of sensors. Environmental observatories are encouraged to formulate new "visions" to address these issues, both within sensor-based observatories and across sensing solutions.

- Physical sensor technology is the most mature of the three technologies; its key issues are better understanding of transport and fluid velocity.
- Chemical sensors are needed to measure a wide range of elements and molecules for inorganic, organic, and biochemical molecules in all environmental media (atmosphere, soils, sediments, groundwater, and fresh and marine waters). In particular, reliable means for detecting toxins and determining the presence and amount of nitrogen and phosphorus forms are critically important.
- Biological sensor technologies in general are the least mature but investments should result in tremendous scientific advances. Biological sensors can provide key information on the function and structure/composition of biologically influenced ecosystems in real time.

In addition to specific sensor requirements, there is a need to address a broad range of generic sensing-related issues, including power availability and data communication rates. Advances in power-related technologies would make a tremendous difference to a wide array of environmental observatories. Options include both longer-lasting power supplies and new or more efficient means to capture power from the environment (e.g., solar and thermal). Research to advance enabling technologies that will enhance data transfer capabilities, particularly in aqueous environments, will enable the use of a broader array of sensors in environmental networks.

Nanotechnology and associated fabrication and manufacturing techniques have provided and will continue to provide new avenues for innovative sensor design. The environmental sciences communities need to ensure that they are current on the capabilities of recent developments in nanotechnology. They also must have knowledge of nanoscale efforts to make smaller devices to be used in a variety of settings.

Several additional technological issues are of high relevance to the establishment of sensor networks. New methods must be developed that will allow sensors to exist in the environment, operate under severe conditions, and withstand attacks from the environment (e.g., biofouling). To monitor flows of animals or fish, the sensor must move with them. Therefore, methods need to be developed to allow data to be communicated while sensors are in motion. In addition, to connect sensors into networks will require efficient data interfaces that ensure the flow of data into the network and also impose minimal demands on power and size requirements of the sensor. Technologies that are useful in many other applications may need to be refined for environmental observatories. These include optical, spectroscopic, electrochemical, separation, and acoustical technologies. Enhancements of these technologies could in turn benefit many other applications.

Infrastructure and Deployment of Sensor and Sensor Network Systems

For environmental observations, sensors must be considered in the context of the network, supporting cyberinfrastructure, and environment where they are placed. Typical deployment efforts should involve multidisciplinary teams that employ a systems approach. Programs should engage researchers from the sensor networks and cyberinfrastructure communities in a dialog on future technologies to ensure end-to-end communication between researchers and their equipment.

Sensor networks are infrastructures in their own right while also being part of a developing cyberinfrastructure. Such networks will require stable long-term funding. Although Major Research Equipment and Facilities Construction (MREFC) programs can help establish a network, funding for maintenance and support will be crucial and ultimately more costly. When balancing short-term, individual-driven research with long-term investments in infrastructure (including people), the focus should be on large problems that cannot be addressed within current modes of experimentation.

When planning for the development and deployment of a sensor network, many existing technologies can be deployed to benefit science and the understanding of environmental processes. Investigators should employ a diverse set of approaches, focused on deploying existing technologies, improving technologies with short development horizons, and developing technologies for sensors that will require five or more years to mature.

Testbeds for systems to be emplaced on the network also should be established. Such testbeds should have two primary goals: to produce data for scientific understanding and to gain experience on how new technologies work in realistic settings to improve their performance prior to longer-term and larger-scale deployments. Such testbeds should allow testing of new sensors *in situ* without having also to create other aspects of the information technology and communications infrastructure.

Several specific technological issues need to be addressed to ensure the spatial and temporal scaling of environmental sensor networks. Standards need to be developed to facilitate sensor development and to ensure the interoperability of the sensor, the network, and the data. The process of developing these standards will be difficult but important, and should involve the broad environmental science community. Finally, quality assurance and control (QA/QC) and self-calibration issues are important considerations for deployment. These issues need to be addressed to ensure the accuracy of the data and reduce the labor required to maintain a system.

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Chapter 1: Workshop Background and Overview

Environmental science is at a crossroad. Pioneering experimental sites that collect time-series data have demonstrated that a true understanding of environmental dynamics requires a sustained *in situ* presence. Technologies and platforms developed to facilitate such presence have ushered in a new era of environmental science and engineering that is increasingly reliant on *in situ* sensor networks.

In response to planning efforts within several scientific research communities, numerous sensor networks are either currently proposed within the National Science Foundation (NSF), or are already in operation through NSF funding. These networks have been established to investigate biological, hydrologic, atmospheric, and oceanic processes through programs such as the Long Term Ecological Research network (LTER), National Ecological Observatory Network (NEON), Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER), Hydrologic Observatory Initiative (HOI), and the Oceans Observatory Initiative (OOI). Each of the observing networks has unique program-specific needs in terms of scientific priorities, sensor technologies, and cyberinfrastructure. However, there are also needs that are common across many of these initiatives. One of the most significant of these is the need for sensors that can accurately characterize environments of interest for extended periods of time, and in harsh environments. The lack of sensors with this capability compromises the quality of the data collected to accurately describe the surrounding conditions. This issue is faced not only by the NSF's environmental networks research programs, but also by programs established by other agencies whose mandates include environmental monitoring.

The many factors that have contributed to this lack of capabilities to be emplaced and left unattended for long periods of time in harsh environments have already and repeatedly been noted in various community reports. Certainly, many of the factors stem from complex technical considerations. Often, *in situ* sensors must be small, reliable, and robust, with low power consumption while also being able to remain free of measure drift over the lifetime of deployment or able to self-calibrate and be resistant to deteriorating accuracy of measurements attributable to organic interaction with sensors. For unattended operation, sensors should, where possible, not be reliant on reagents or other consumables, but this has not been possible with current technology. Though proxy measurements can often provide the needed capabilities, they often come at the price of ambiguity in data interpretation.

In addition to the technical challenges, logistical issues also affect the successful funding and development of sensors and sensor systems. Because robust environmental sensors often take longer and cost more to develop than typical projects proposed, these environmental sensor development proposals often have difficulty surviving the traditional review process. The progression from conceptual design to the completion of a prototype and then to the production of an operational sensor is often time-consuming. It may take more than 10 years for a sensor to make the transition from initial concept development to routine deployment. In addition, unlike investments being made in wireless networks and mobile technologies, the small size of the market for the sensing devices (sensors) means that there is limited industrial support for environmental sensor development. Lastly, for the reasons listed above, and also because there is often no clear career path for sensor developers, the community of environmental sensor developers remains small.

Despite the need for environmental sensors, few proposals are submitted for sensors that provide data on high-priority environmental parameters within the core science programs or within broader NSF-wide announcements. To address this, various disciplinary programs at NSF and at other agencies have sponsored workshops to identify issues hindering environmental sensor development and to attempt to remedy the problem. There are striking similarities among the findings and recommendations from these workshops, despite the different disciplines from which they were developed. Common recommendations include

- longer-duration funding
- targeted funding for new technologies such as microelectromechanical systems (MEMS)
- funding the establishment of testbeds to provide platforms to test sensors in more realistic settings

Concrete progress towards restructuring funding for sensor research and development remains elusive despite the fact that it has been acknowledged that the current structure is not the most conducive to environmental sensor development, Meanwhile, the environmental community is facing a crisis, as networks are being established that cannot reach their true potential without further improvements in sensor capability.

SENSORS FOR ENVIRONMENTAL OBSERVATORIES: A FRAMEWORK FOR PROGRESS

Because the issue of sensor development crosscuts most NSF Directorates, NSF leadership decided to host a multidisciplinary workshop, *Sensors for Environmental Observatories: A Framework for Progress,* to bring together scientists who could explain the desired sensor capabilities and the engineers who could design and build sensors with those capabilities. The workshop was held from November 30 to December 2, 2004, at the University of Washington, Seattle.

The goals of the workshop were to provide a venue for members of different user communities to interact; identify common parameters that they need to measure; and inform sensor developers of these needs so that they can build the sensors with them in mind. Longer-range goals were to

- map out strategies to ensure sensor technologies are developed for long-term autonomous deployment
- build a sensor capacity for environmental observational networks for the high-priority parameters identified within research community reports
- build an interdisciplinary community of researchers who will help interested Federal agencies develop research plans that meet these needs
- provide community guidance to help shape future NSF program announcements in this area

The workshop was planned around seven "use case scenarios" focused on the science that is driving the need for new observatory systems: (1) Oceans; (2) Rivers, Estuaries, and Coastal Waters; (3) Lakes; (4) Groundwater; (5) Precision Agriculture; (6) Terrestrial Ecosystems; and (7) Meteorology and Pollution in Urban Settings. Each use case scenario was organized around a discussion of the driving science of the sensing system, its enabling technologies and the common opportunities and challenges therein and its deployment and maintenance. Participants in each use case scenario discussion were asked to consider the following common questions:

- What are the key sensor needs for use case scenario?
- How can sensor developers take advantage of new and emerging technologies for sensor design and help ensure that the needs for priority measurements are met?
- How can sensor users create strategies to ensure the long-term deployment and maintenance of sensors?
- What is the potential for applications and use of sensors in fields outside of science?
- How can the broadly conceived sensor development community take a holistic approach to address the dynamics at the interfaces between physical, chemical, biological, and human dimensions?

Participants were asked to formulate and discuss innovative ways of developing sensing capability on parameters that are essential to characterize the environments outlined in the use cases. These discussions also addressed biofouling, the dynamic nature of the environment, measurement ranges needed from the sensors, and other related systems issues. Finally, they addressed community-building and the interfaces between systems for future research and development planning.

ORGANIZATION OF THE REPORT

The foundation of this report (Chapter 2) is the use case scenarios in several areas of environmental observing, as referred to earlier. Each of these cases highlights the science that would be enabled by sensors and sensor networks, technological needs of such sensors, and issues of long-term deployment and maintenance. These scenarios are not intended to be exhaustive, but are used to illustrate needs that were discussed by the expertise present at the workshop.

Other chapters of the report highlight the common issues among the scenarios: crosscutting science issues, community development, education and outreach (Chapter 3); technology development (Chapter 4); and deployment (Chapter 5). Each of these sections discusses the themes that emerged at the workshop and makes specific recommendations to NSF.

CATEGORIES OF RECOMMENDATIONS AND OBSERVATIONS

Recommendations are given in each of the chapters addressing crosscutting issues, and key recommendations are summarized in the Executive Summary. The major categories of recommendations include NSF's Portfolio; Community and Partners; Modeling, Algorithms, and Automation of Processes; Technology; Infrastructure and Deployment; and Dissemination. Recommendations are made to NSF, in terms of concrete steps it could take to promote development and deployment of environmental sensor technology. Recommendations are also made to the broader scientific community, indicating areas of high-priority research and activities of importance to the community.

ACKNOWLEDGMENTS

We wish to acknowledge the support of the National Science Foundation in funding the participant costs under award OCE-0504087. Furthermore, we note the ongoing and continuous encouragement of several NSF program staff members, without whose support and vision this workshop would not have taken place. In particular we acknowledge the support of Sayuri Terashima for help in preparation of the report. In addition, we acknowledge the contributions of the particiants at the meeting, and of the scenario leads and presenters after the meeting, for providing input and refiements to the text. Finally, we wish to acknowledge the University of Washington for allowing us to use its facilities, and WTEC for organizing the logistics of the meeting and for editing and producing the final copy of the report. Any opinions, findings, conclusions, or recommendations expressed in this report are those of the participants, and do not necessarily represent the official views, opinions, or policy of the National Science Foundation.

Chapter 2: Application Scenarios

2.1 INTRODUCTION

The cornerstone of the workshop *Sensors for Environmental Observatories: A Framework for Progress* was the presentation of the set of seven concrete scenarios related to the following concerns:

1. Oceans
2. Rivers, Estuaries, and Coastal Waters
3. Lakes
4. Groundwater and Secure Earth
5. Precision Agriculture
6. Terrestrial Ecosystems
7. Meteorology and Urban Pollution

This chapter features a detailed summary of each scenario, divided into several broad topics, namely (1) Science, (2) Technology, (3) Deployment and Maintenance, and (4) Future Issues and Recommendations. The Science section identifies the important parameters to measure, as well as some key scientific goals that require data from sensors. The Technology section details the performance requirements of envisioned sensors and describes weaknesses of currently available sensor technology. The Deployment and Maintenance section notes any special considerations in deploying sensors in the environment considered, and discusses the costs and issues related with long-term maintenance of each sensor. The Future Issues and Recommendations section highlights the major challenges and suggestions for overcoming these challenges. Each summary provides examples of sensor and sensor network applications, outlines the potential impact of further development and deployment of such networks, and identifies impediments to progress. While the scenarios discussed at the workshop are not intended to be comprehensive, they do include components of key observatory projects supported by the National Science Foundation (NSF), and generally reflect the opportunities and challenges researchers face in different environments. It is significant that this is the first workshop of its kind to bring together such a diverse group of researchers from various disciplines working on sensors for environmental observatories. Having concrete scenarios focused the discussions and allowed participants to identify similarities of needs in each field. This in turn created opportunities for these researchers to synergize in the future by collaborating with each other.

2.2 OCEANS SCENARIO

Members of the Oceans Scenario Committee: Jules S. Jaffe (chair), Scott Gallager, Tim Cowles, Mary Jane Perry, Kendra Daly

Speakers at the Oceans Scenario Plenary Session: Tim Cowles (Science), Jules S. Jaffe (Enabling Technology), Scott Gallagher (Long-term Deployment)

2.2.1 Science

In the ocean a multitude of processes occur on a variety of spatial and temporal scales. As a result, new and planned ocean observatory deployment initiatives present both a host of opportunities and significant challenges for the study of the Earth's oceans. The oceanographic community can point to a number of past programs that have resulted in scientific discoveries that could not have been made without the prior commitment to a long-term sampling regime; the new ocean observatories will not only permit such extended sampling to continue, but they will also offer several advantages over ship-based programs.

The results of the ship-based observations of the California Cooperative Oceanic Fisheries Investigations (CalCOFI; http://www.mlrg.ucsd.edu/calcofi.html) are an example of the benefits that can be obtained from a long-term sampling regime. Instituted as the result of the crash of California's sardine industry, the observations led to a greater understanding of how El Niño creates fluctuations in the sardine and anchovy populations. Similar advantages for the observation of long-term variations in sea temperature, populations of zooplankton, and the potential shift in paradigms through food webs are possible. An important ecological motivation is the need to sort out the differences between longer-term climate change and the shorter-term regime shifts that accompany phenomena on the scale of decadal oscillations.

Fixed observatories can offer substantial advantages over mobile ones, in terms of longer sampling periods and higher sampling frequencies. Examples of successful fixed platforms that have permitted long-term studies include the Incorporated Research Institutes for Seismology's Global Seismological Network (GSN; http://www.iris.edu/about/GSN/), which is used for recording seismic data and monitoring seismic activity, and the declassified U.S. Navy Sound Surveillance System (SOSUS; http://www.pmel.noaa.gov/vents/acoustics/sosus.html) array, which has been used to track blue whales over ocean basins. Fixed platform observatories offer exciting possibilities for gaining a greater understanding of both mean trends and shorter-term fluctuations. As one example of a fixed underwater observatory under development, the oceans sidebar (page 7) illustrates the basic elements of the new Monterey Bay Aquarium Research Institute's MARS array (http://www.mbari.org/mars/).

Field programs that use mobile platforms as autonomous sensing systems are proliferating. Global networks of surface drifters such as the Global Drifter Program (GDP; http://www.aoml.noaa.gov/phod/dac/gdp.html; formerly the Surface Velocity Program) and profiling floats such as the international Argo program (http://www.argo.ucsd.edu/) are critical components of programs studying the ocean's effect on and responses to climate change. These arrays operate on a global scale, reporting their location and ocean conditions via satellite telemetry. Recently, gliders, which are more controllable than drifters, have been deployed in coastal and remote locations. Gliders are capable of operating for weeks to months at a time and can change mission parameters from remote command. Programs that use gliders include the Autonomous Ocean Sampling Network (AOSN; http://www.mbari.org/aosn/) and the Rutgers University Coastal Ocean Observation Laboratory's COOLroom project (http://www.thecoolroom.org/). See also the sidebar in Chapter 3 on this subject.

Since the ocean is composed of fluid that is turbulent over a range of spatial scales, sampling in this dynamic environment is a major challenge. The combination of fixed moorings with the more adaptive mobile systems has great potential for addressing adequate sampling at many of these scales that have heretofore been unobtainable. Moreover, optimal sensors for these autonomous packages share many features with the moored versions, although the power constraints for the latter are often greater than for the former. Many of the issues considered here therefore concern deployment of these sensors on a multitude of platforms.

Although fixed and mobile observatories promise to have a wide-ranging impact on many scientific disciplines, two representative examples are considered here: air-sea interactions and assessment of primary and secondary productivity.

Air-Sea Interactions

As the Earth becomes warmer, scientific interest has turned to the capability of the oceans to act as carbon sinks. Understanding and measuring CO_2 and O_2 flux across the air-sea interface is therefore critical. Although the "eddy correlation technique" is a promising method to accomplish this task, sensors and platforms necessary to perform this are not currently available. For ocean science, the capabilities needed could be provided by horizontally separated sensor packages that oscillate from 0.5 m above the sea surface to 40 – 50 m below the sea surface. Both pCO_2 and O_2 sensors are necessary that can take a new measurement of gas at rates as fast as 1Hz. Current sensors do not provide these sensitivities or speeds.

Primary and Secondary Productivity

From the earliest days of oceanography, among the most important and fundamental quantities to measure have been the abundance and productivity of primary and secondary producers. These data enable researchers to answer a host of questions about the transport of mass and energy via the oceans, such as What are the dominant organisms and the dominant energy pathways? How many steps are involved in energy transfer? When does the microbial loop dominate? and How does change in community composition affect material and energy transfer? In collecting data to answer these questions, attention must be placed on community structure, including organism identification, abundance as a function of species, and particle size distributions.

Oceanographers envision the use of *in situ* optical imaging sensors to collect data on organisms from the micron scale (prokaryotes) to the meter scale (fish and cetaceans). For organisms larger than 1mm, acoustic methods have the potential to survey large volumes and can be valuable in the presence of "ground truth." *In situ* flow cytometry and molecular methods should be considered for classifying small particles. The dynamic processes in the upper ocean—that is, the energy cycles—can be determined by measuring dynamic fluorescence, light, nutrients, pH, pCO_2, and O_2 using these in *in situ* optical imaging sensors.

2.2.2 Technology

An important aspect of sensor development is keeping costs and therefore price at a reasonable level. Furthermore, because these sensors will often be placed on platforms with low power capability, sensors should consume as little power as possible. These issues have been discussed at length, but continue to be a concern. One issue rarely considered by sensor manufacturers is the integration of sensor information into a data "stream." More often than not, the data from each sensor are logged independently (as a function of time) and the data are combined afterwards. Since the concentrations of oceanic constituents can vary greatly over small scales, the temporal registration necessary to combine these disparate data streams makes this task challenging.

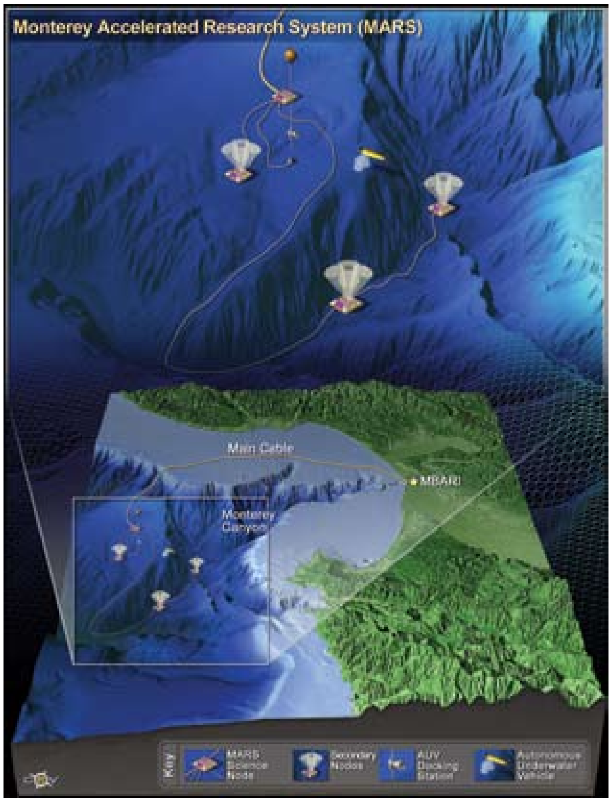
Oceans: Monterey Accelerated Research System (MARS)

The Monterey Accelerated Research System (MARS) is a cable-based observatory system, incorporating a benthic instrument node, remotely operated vehicles (ROVs), and various benthic and moored instrumentation. The MARS infrastructure will provide the capability to place and power instruments in areas of scientific interest in various geographical sites.

This project will design and install an advanced cabled observatory in Monterey Bay that will serve as the test bed for a state-of-the-art regional ocean observatory, currently one component of the NSF Ocean Observatories Initiative (OOI). The MARS cabled observatory represents the next step toward harnessing the promise of new power and communication technologies to provide a remote, continuous, long-term, high-power, large-bandwidth infrastructure for multidisciplinary, *in situ* exploration, observation, and experimentation in the deep sea. MARS will be located in Monterey Bay offshore the Monterey Bay Aquarium Research Institute (MBARI).

It will include one science node on 51 km of submarine cable with expansion capability for more nodes in the future (see graphic below). The science node will provide eight science ports and each port will have a 100-Mbit-per-second bidirectional telemetry channel. The node will have the ability to deliver a total of 10 kW of power to the eight ports. Extension cables will provide power and communications up to 4 km away from the original node using the most cost-effective deployment vehicle from several options, including MBARI's ROVs, ships of opportunity, or other vessels. The system will make use of tools, techniques, and products developed over the last several decades for high-reliability submarine telecommunication and military systems to ensure that it can operate over a 30-year lifetime with minimum life-cycle cost. MARS will serve as the engineering test bed for future regional (plate-scale) cabled observatories.

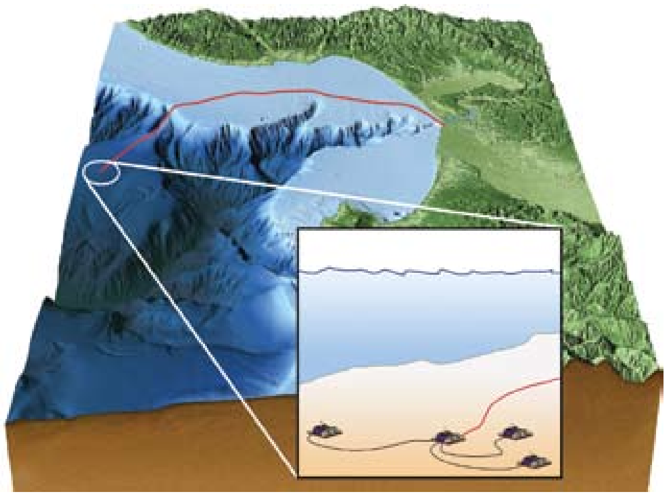
The broader implication of installing MARS is that the oceanographic community will be a major step closer to providing real-time, continuous access to unprecedented power and communications capability underwater on a regional scale. This type of ocean observatory will revolutionize the way researchers study the ocean and the sea floor beneath. Benefits will include more cost-effective collection of much larger amounts of integrated, multidisciplinary data relevant to important scientific and societal issues, such as natural hazards, the climate system, the carbon cycle, and other biologically-mediated processes in the ocean. In addition, researchers will use such facilities to explore new classes of problems currently unapproachable with existing assets. (Source: http://www.mbari.org/mars/new/overview.html)



Conceptual drawings of a planned and funded underwater observatory system in the Monterey Bay area that will provide infrastructure for the deployment of ocean sensors.

Image above is the proposed configuration for MARS. (Image courtesy of the NEPTUNE Project and the University of Washington Center for Environmental Visualization)

Image below is a conceptual drawing for the MARS cable configuration. (Kim Fulton-Bennett © 2003 MBARI)



The problem can be ameliorated by putting all of the sensors into a single “package” with exact temporal synchronization. Moreover, some savings might result because not every sensor will need its own microprocessor. Various solutions to this problem—for example, the use of a serial communications protocol—have appeared recently; nevertheless, more work is needed. In addition, since the costs of deployment (and perhaps maintenance) can often be more than the sensor systems themselves, longevity is an important consideration for ocean sensors.

2.2.3 Deployment & Maintenance

Experiences with several existing near-shore coastal observatories, such as the Woods Hole Oceanographic Institution/Rutgers Institute of Marine and Coastal Sciences LEO-15 system (http://marine.rutgers.edu/cool/LEO/LEO15.html) and the Martha’s Vineyard Coastal Observatory (MVCO; http://mvcodata.whoi.edu/cgi-bin/mvco/mvco.cgi), provide a wealth of knowledge that should be incorporated when preparing to deploy the next generation of ocean observatories. Based on the remoteness of the newer oceanic stations, the issues and costs related to both deployment and maintenance must be seriously considered. Since the ocean is an extreme and hazardous environment for sensor operations, special considerations are necessary. In addition, because the costs of deployment and maintenance are often greater than those of the sensor systems themselves, longevity is an important consideration for ocean sensors.

Corrosion of the sensors is another significant problem, especially in the top 100 meters of the ocean where biological productivity is high. There are various schemes employed to keep sensors free of fouling, but they only last for periods of several weeks. Preventing biofouling for months or even years is currently unattainable. Efforts to develop such techniques date back to work on keeping ship hulls clean; today the problem is complicated by the need to use “environmentally friendly” methods. The development of new non-toxic surface modifiers, the use of UV light, and/or the local generation of ozone, particularly for applications where optical clarity is essential, could be important breakthroughs in controlling biofouling. The detrimental effects of corrosion can be mitigated by carefully choosing materials similar in galvanic voltage. Completely inert materials such as plastics like Delrin®, nylon, and PVC (polyvinyl chloride) should be used when and where possible.

Another significant problem is the “drift” that can accompany sensor output over long periods of time. The next generation of ocean sensors should be capable of auto-calibrating. This in the long run will be able to provide much better accuracy than manual calibration and also will reduce maintenance costs. Auto-calibration is especially appealing in consideration of the high deployment costs.

2.2.4 Future Issues and Recommendations

Although many of the issues related to sensor deployment in the ocean—for example, cost and longevity—are similar to those of sensors deployed in other environments, the remoteness and turbidity of the ocean environment make the problems particularly challenging. In addition, because the commercial marketplace for oceanic sensors is quite limited, companies are generally unwilling to invest large amounts of money to develop the next generation of ocean sensors. Opportunities for commercial development might be found in the biomedical technology industry. Many newer biomedical sensors are designed to work in a saline environment for extended periods. In addition, many of the variables that such systems are designed to measure—e.g. CO_2, O_2, pH, and nutrients—are similar to those that interest oceanographers.

2.3 RIVERS, ESTUARIES, AND COASTAL WATERS SCENARIO

Members of the Rivers, Estuaries, and Coastal Waters Scenario Committee: Ken Reckhow, Hans W. Paerl, William Showers

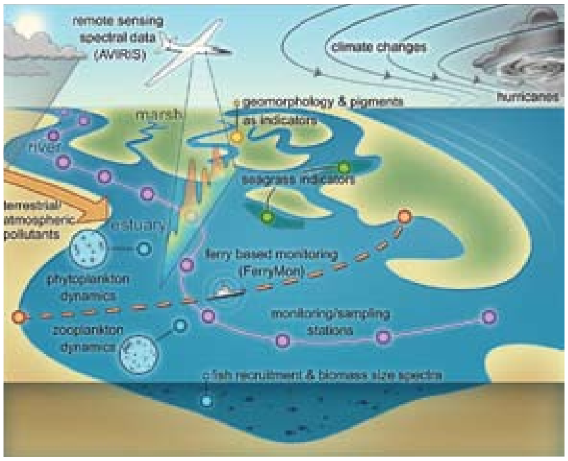
Speakers at the Rivers, Estuaries, and Coastal Waters Scenario Plenary Session: Ken Reckhow (Science), Hans W. Paerl (Enabling Technology), William Showers (Deployment Strategies)

2.3.1 Science

Water quality monitoring and modeling programs in the Neuse River/Estuary/watershed and Pamlico Sound (both in North Carolina) provide a good case study of the current opportunities and challenges facing environmental sensor observatories. An interdisciplinary (physical-chemical-biotic) array of water quality and habitat condition indicators is being developed for deployment on unattended monitoring platforms in inland and coastal waters. These indicators can function either independently or complementarily, depending on specific water quality, or on habitat or ecosystem evaluation criteria needs such as total maximum daily loads (TMDLs), harmful algal blooms, or ecological thresholds, as part of the Atlantic Coastal Environmental Indicators Consortium project (http://www.aceinc.org). Coupled with remote sensing, these indicators can be used to ground truth and calibrate data sources. UNC/Duke/NC DENR/DOT’s ferry-based water quality program, FerryMon (http://www.ferrymon.org), currently operates in the nation’s

Rivers: Environmental Indicators in the Estuarine Environment

With support from the EPA-STAR Estuarine and Great Lakes Environmental Indicators Program (EaGLe), broadly applicable, integrative indicators of ecological condition, integrity, and sustainability are being developed and tested across four distinct and representative estuarine systems on the Atlantic Coast of the United States. These include the Nation's two largest estuarine complexes, Chesapeake Bay and Albemarle-Pamlico Sound, a small estuary--the Parker River, in the Plum Island NSF Long-Term Ecosystem Research (LTER) site in Massachusetts, and a tide-dominated estuary in the southeast Atlantic Bight, the North Inlet, SC. These sites are representative of three primary producer bases: intertidal marsh, plankton-dominated, and seagrass-dominated systems. They also have ongoing, long-term water quality/habitat monitoring programs in place, producing databases for indicator development and testing. These systems contain both pristine and anthropogenically-impacted waters.



(Figure Source: Atlantic Coast Environmental Indicators Consortium/Paerl presentation)

Primary objectives include the following:

- Enhance the archive of existing data for these systems with remotely sensed and time-series information on key variables.
- Exploit detailed knowledge of ecosystem structure and function to synthesize this archive and develop candidate indicators.
- Test the ability of these indicators to gauge ecosystem health and unambiguously detect trends resulting from both natural variability and anthropogenic stresses in multiple estuaries.

Research plan includes the development of

- indicators of microalgal and macrophyte functional groups controlling much of estuarine and coastal primary production
- indicators capable of determining plankton and fish community structure (organization) and function, specifically indices that relate to trophic transfer and sustainable higher trophic levels
- coupling these biological indicators to physical-chemical and remote sensing assessments of ecosystem function, trophic state and change
- developing and applying indicators and assessments within a national coastal indicator framework (EPA-EaGLe Program)

These indicators form the backbone of ecosystem, regional, and national water quality; habitat assessment; and living resources monitoring and modeling efforts. These indicators will serve to calibrate and ground truth aircraft and satellite remote sensing of estuarine and coastal resources, including plant community structure, function, and ecological health. These phytoplankton, marsh, and seagrass proxies will be linked with metrics of trophic structure to provide indicators of living resources status.

The present lack of established regional and national bio-indicators, despite extensive monitoring at thousands of sites nationwide and specific community efforts to develop bio-indicators, is testimony to the magnitude and complexity of the task ahead. Prior efforts toward this ambitious goal have shown that the most promising avenue to success must link theoretical constructs and empirical relationships. (Source: Atlantic Coast Environmental Indicators Consortium, http://www.aceinc.org/more.htm)

second largest estuarine complex, the Pamlico Sound in North Carolina. The program features multiple applications of pigment-based indicators of phytoplankton community structure and function coupled to physical-chemical controls quantified in real time.

In the Neuse watershed, human activities have more than doubled the inputs of biologically active nitrogen into the ecosystem. This has resulted in the doubling of N flux in rivers and the eutrophication of estuaries and coastal waters. However, there are gaps in researchers' knowledge of the quantification of the N flux out of watersheds. While it is known that riverine export of N commonly equals about 25% of N inputs into a watershed, atmospheric deposition is a poorly understood component of N flux. The RiverNet program (http://rivernet.ncsu.edu/) has deployed *in situ* water quality stations and developed innovative stable isotope techniques to measure nitrate flux in the Neuse River Basin. To date, the important results of the RiverNet Program are as follows:

- Significant riverine nitrate flux variations are associated with large point sources. Agricultural watersheds without point sources do not exhibit these concentration variations. Errors associated with calculating N flux with these nitrate concentration variations cause the flux of N from watersheds to be underestimated by 10 to 30%.
- Atmospheric N is transported into rivers associated with hydrologic events. During most of the hydrograph, ^{17}O (triple oxygen isotope) is low in rivers, indicating that the flux of atmospheric nitrate is not important. During falling hydrographs, ^{17}O rapidly increases and decreases over a period of hours; at peak concentration, it can be ~100% of river flux, a cycle that would be missed by conventional nutrient monitoring networks.
- Nitrate loss in the Neuse River occurs episodically and is associated with hydric soils and bank infiltration and not in-stream processes. Watershed nutrient mapping indicates where NP inputs and nitrate losses occur.

2.3.2 Technology and Deployment

Using an array of YSI sensors placed in a flow-through module, the FerryMon "ships of opportunity" use modems and cell phones to transmit spatially- and temporally-intensive data streams of temperature, levels of dissolved oxygen, pH, salinity, turbidity, chlorophyll *a*, and other diagnostic (of phytoplankton taxonomic groups) pigments. GPS locations are time-stamped during transits across Pamlico Sound and the Neuse River Estuary. The data from the ferry-based sensors complement samples of nutrients, dissolved and particulate organic matter, and pathogen-HAB that are automatically collected for laboratory analysis via ISCO refrigerated automated sampler.

In the RiverNet program, sondes (YSI; http://www.ysi.com) and chemical nitrate analyzers (YSI and WS Envirotech; http://www.n-virotech.com) or UV nitrate analyzers (Satlantic, http://www.satlantic.com) are attached to bridges to measure water quality and nitrate concentrations. Nitrate flux is calculated from discharge by USGS gage stations or recording pressure transducers (http://www.in-situ.com); stage/discharge relationships are developed using SONTEK River Surveyor ADP systems (http://www.sontek.com). Atmospheric contribution is calculated from ^{17}O composition of nitrate and the quantity and isotopic composition of rainfall. Nonpoint source inputs can be located with watershed mapping techniques using GPS (http://www.trimble.com) and UV nitrate analyzers. Though *in situ* dissolved phosphate and ammonium analyzers are commercially available, they are difficult to deploy and maintain in a river system because of complicated chemistries. *In situ* analyzers for organic N and particulate P do not yet exist.

The Neuse and Pamlico studies are good examples of current applications, but they also demonstrate the long-term, short-term, and real-time needs for sensor development and deployment:

- *Long-term:* Can sensors be used to assess compliance with the Total Maximum Daily Load (TMDL) for nitrogen and with the water quality criterion for chlorophyll?
- *Short-term:* Can flow and pollutant concentration be monitored during extreme floods and hurricane stormflows?
- *Real-time:* Can sensors provide an effective "alarm" system associated with wastewater spills, lagoon breaches, and hypoxia events?

2.3.3 Future Issues and Recommendations

Future instrumentation plans include acoustic Doppler current profilers and real-time inorganic nutrient sensors to complement modeling efforts. Ferry-based automated monitoring is a cost-effective method, capable of integrating with upstream estuarine and automated or conventional coastal monitoring networks. Furthermore, ferry-based monitoring can address a wide range of temporal scales, including diel, synoptic, seasonal, and multi-annual, for assessing ecological change in estuarine and coastal waters. The goals of the FerryMon program are to

- assess and predict the relationships between human nutrient and pollutant inputs, climatic forcings such as hurricanes, algal blooms, water quality changes, and ecosystem response
- enable access via the FerryMon website (http://www.ferrymon.org) to information that is critical for long-term water quality and fishery modeling and management
- develop FerryMon as a national model for real-time coastal water quality assessment

Over the long term, surface water quality is assessed for physical, chemical, and biological variables by water quality monitoring programs that are regulated by each state's ambient standards. When a standard is violated, the state is required to determine the TMDL required to return to compliance. Following implementation of the TMDL, compliance is assessed through water quality monitoring; however, limited data collection programs and uncertain model forecasts impede the compliance assessments. Bayesian updating (or data assimilation) should be used to integrate pre-implementation modeling with post-implementation monitoring data. Sensitivity analyses obtained from the model would be used to guide monitoring design, and sensors provide needed flexibility in data collection. For this to be effective in the Neuse Estuary, sensors need to be designed for total nitrogen assessment. In more general terms, reliable sensors are needed for all of the major water quality criteria that are regulated in state ambient standards.

In the short term, the Neuse River Basin and coastal North Carolina are periodically impacted by hurricanes and flooding. Monitoring is difficult to maintain under such extreme conditions; however, these storms may significantly impact pollutant loads and water quality in the affected areas. Researchers seek to answer the following questions:

- What fraction of annual pollutant load occurs during a hurricane?
- Do hurricanes “cleanse” the system?
- Can a sensor-based monitoring program be designed and maintained to assess hurricane impacts? Here, too, total nitrogen and total phosphorus are critical.

In real time, both the growth of the human population and the tremendous increase in confined animal feedlots have increased the risk of large pollutant spills and significant accidental discharges. Such events can have profound effects on water quality unless they can be quickly contained or treated. Workshop participants believe that spill alarm systems that incorporate sensors can be designed and deployed. Again, sensors that detect total nutrient concentrations (as opposed to those designed to detect only inorganic concentrations) would be most useful here.

2.4 LAKES SCENARIO

Members of the Lakes Scenario Committee: Rich Axler, Dan Cooper, Harry Hemond, Tim Kratz, George Luther, Sally MacIntyre, Paige Novak, John Vande Castle

Speakers at the Lakes Scenario Plenary Session: Tim Kratz (Science and Needs), Sally MacIntyre (Science and Needs), Rich Axler (Deployment and Education)

2.4.1 Science

Aquatic ecologists and limnologists are addressing a number of large, challenging, and important science issues that require the development and deployment of appropriate sensor technology. The broad issues that need better understanding and better sensor technology can be grouped into three categories. These categories are meant to be exemplary rather than exhaustive:

- *Couplings among pelagic, littoral, and profundal zones within lakes, between lakes and the atmosphere, and between lakes and their watersheds.* Understanding the movement of water, solutes, and particulates across the boundaries of lakes or within different regions of a lake is a key to understanding the role that lakes play in elemental cycling and hydrology at a landscape level. Quantification of the fluxes and storage of solutes and particulates such as carbon, phosphorus, nitrogen, oxygen, and mercury is essential for addressing questions of climate change and the effects of eutrophication and introduced species on the disruption of nutrient cycles and food web structure. By understanding physical and biological coupling and the coupling of turbulent mechanisms between lakes and the atmosphere, researchers will be able to further quantify fluxes at interfaces.
- *Factors controlling the dynamics of biotic community structure in lakes.* Improved knowledge of community structure and its relationship to ecosystem function is especially important for researchers to understand microbial communities and the effects of invasive species in lakes.
- *The role of episodic events in influencing the physics, chemistry, and biology of lakes.* Hurricanes or typhoons, windstorms, and rainstorms produce high rates of runoff and cause high loading of nutrients, suspended sediments, and dissolved and particulate organic carbon and other solutes and pollutants. These events can also reset biotic communities. The frequency and intensity of such events are predicted to increase as the climate continues to change. The transient nature of episodic events all but requires the use of automated sensor systems to obtain the needed data.

Already, *in situ* sensors have helped increase scientists’ understanding of lake dynamics. For example, a study of lake metabolism being carried out in lakes in Wisconsin and Taiwan is among the first to use not only moored meteorological instruments and thermistor chains, but also oxygen sensors. The additional data have enabled scientists to calculate gross primary production, respiration, and net ecosystem production. *In situ* sensors also showed the response of Yuan Yang Lake in Taiwan to the effects of several typhoons, and the data provided helped scientists to interpret the apparent resetting of the microbial community's composition as a result of the mixing and increased runoff from the typhoons. *In situ* sensors sample at a higher spatial and temporal frequency than is possible to achieve manually and also provide data during important events when access to a site is limited.

Recent oceanographic measurements using high-resolution optical and acoustical sensors; conductivity, temperature and depth profilers; and moored instrumentation have revealed that organisms accumulate at subtle density discontinuities. Patchiness of organism distribution is linked to physical structure, with changes in physical structure leading to new organization. Limnological studies require similar instrumentation. The response time for conductivity, temperature, and depth sensors on these instruments is sufficient; when chemical and biological sensors are able to sample at similar rates, scientists will make tremendous progress in understanding the factors that mediate organism growth and species composition.

2.4.2 Technology

Although several types of sensors are commercially available for lake studies, existing sensors need to be improved and new sensors must be developed. Workshop participants agreed that sensors in the following two classes were of especially high importance:

- *Sensors able to detect biotic structure.* Microbial communities can shift rapidly in response to changes in their environment. They are also known to be spatially variable. Therefore, the development of *in situ* sensors that are capable of quantifying various microbial populations and delineating microbial community structures is a high priority. In addition, sensors that are able to detect particular waterborne pathogens are needed. In many lakes, invasive species are causing shifts in the composition of the biotic community. There is a critical need for sensors that are capable of detecting selected invasive species such as zebra mussels, Eurasian water milfoil, and spiny water flea.
- *Next-generation chemical sensors.* The source, movement, and fate of carbon, phosphorus, oxygen, and nitrogen are of particular importance for an understanding of healthy aquatic systems. Sensors are sorely needed that are capable of measuring dissolved CO_2 at micromolar levels, measuring flux across the air/water and sediment/water interfaces, and characterizing the types and amounts of dissolved organic carbon present in surface waters. Measurement of Total N and Total P, either directly or through the measurement of inorganic and organic forms, is critical for understanding nutrient cycling and loading to lakes. Furthermore, while inorganic fractions of N and, to a certain extent P, can be measured with existing sensors in eutrophic water bodies, sensors are inadequately sensitive for oligo- and mesotrophic water bodies. Mercury contamination in lakes is of increasing concern to scientists, and sensors are needed that are capable of measuring elemental or methyl mercury at picomolar levels. Rapid response times are particularly important for flux studies. At this time, only a few oxygen sensors have response times that are adequate to support eddy correlation flux measurements. The response time of N, P, and S sensors needs to be significantly shortened. For long-term studies, sensors with minimal drift are also essential.

2.4.3 Deployment and Maintenance

Workshop participants identified and discussed a number of sensor deployment issues. Sensors are needed that are capable of making measurements across steep gradients occurring at small spatial scales, such as at the sediment/water and water/atmosphere interfaces and within the metalimnia of stratified lakes.

High temporal and spatial resolution lidars that are capable of mapping scalars and fluxes are required before scientists can fully understand the scaling properties of the physical and biological systems that are inherently coupled in lake-atmosphere systems. Turbulent intermittency occurs in the water and atmospheric environments across a broad range of temporal and spatial scales that are not well measured or documented at present. Turbulent mixing in lakes profoundly affects the fluxes that evolve into the atmosphere; the ability to measure this mix awaits the availability of sensors capable of measuring the physical and chemical properties of turbulent mixing at high temporal and spatial resolutions.

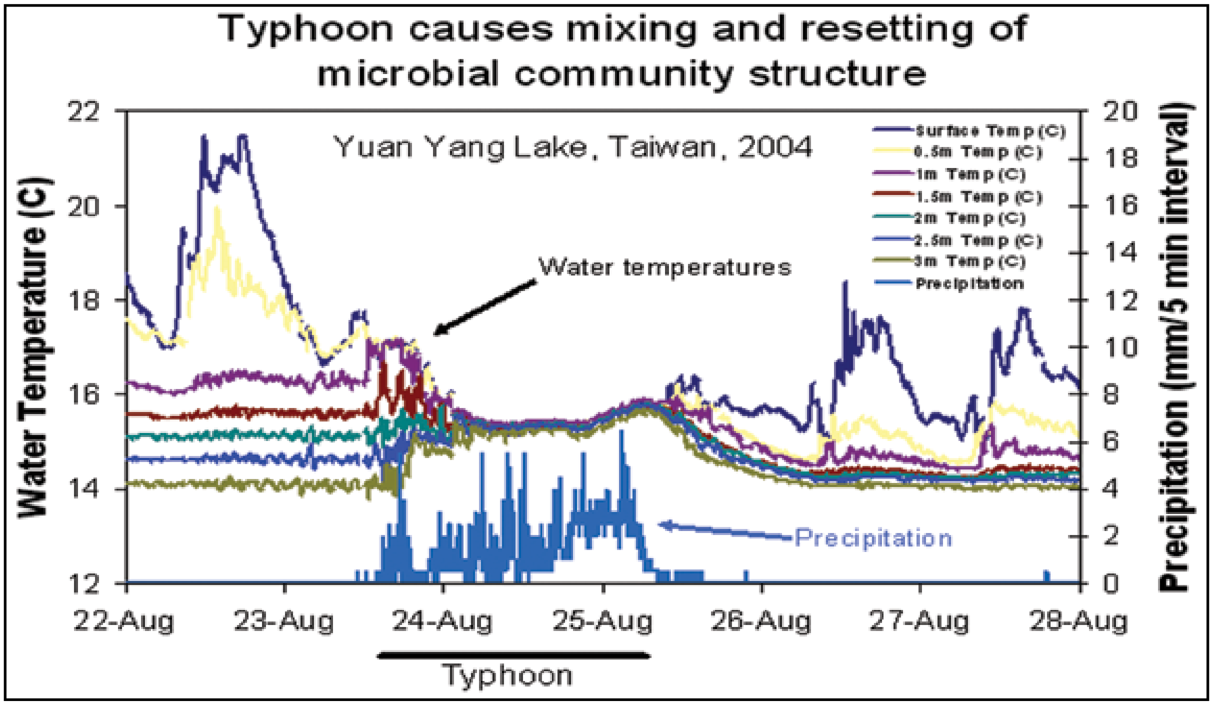
Commercially available sensors tend to be too large, expensive, and power-hungry for widespread use; the size, cost, and power requirements of existing devices must therefore also be reduced. For example, most commercially available conductivity, temperature, and depth sensors (CTDs) are too expensive for routine limnological use, especially because of the costs of housings and components that are designed for deep ocean work. An emphasis on profilers with research-quality sensors in a lighter smaller body would have a high payoff. These units should allow for attachment of additional sensors. The costs of combined conductivity and temperature sensors are currently prohibitive for most studies, yet they are essential for tracking changes in water masses when storm events occur. It is necessary to bring down the expense of purchase and

Lakes: Episodic Events and Threshold Dynamics

Typhoons can be important disturbance events that "reset" the physical, chemical, and biological characteristics of a lake. In October 2004, a typhoon caused Yuan Yang Lake in Taiwan to mix completely for 1 to 2 days before regaining thermal stratification. A network of automated, instrumented buoys in the lake transmitted the effects of the typhoon on the lake's thermal structure and dissolved oxygen concentration in real time. Had the sensors not been in place, the effects of the typhoon on the lake system would never have been known.

Because access to field sites can be difficult or impossible during important disturbance events, automated sensing that incorporates wireless transmission of field data to web sites is critical for researchers to be able to study ecosystem response to such events. However, such devices pose information management challenges, including: sensor maintenance and calibration; quality control and quality assurance of data; production and updating of machine-readable metadata when sensor configurations are changed; and the availability of data on publicly accessible web sites.

Currently, many of these tasks are performed manually. This limits the number of observing buoys that can be deployed and maintained. Furthermore, it currently is infeasible to install sufficient instruments to allow researchers to make regional or continental inferences on the direction and pace of change in the ecological characteristics of lakes. A grassroots, international consortium of lake research groups—http://lakemetabolism.org—has been formed to discuss ways to address this situation.



The graph above shows the effects of a typhoon on thermal structure of Yuan Yang Lake in Taiwan. The graph, covering six days in August, tracks water temperatures at different lake depths. Before the typhoon, the lake waters were well stratified by temperature. The typhoon "mixed" the waters, nutrients, and plankton communities. A day-and-a-half later, the waters were stratified again. Had autonomous sensors (inset) not been in place, this turnover would never have been known.

(Chart: from data collected by the lakemetabolism.org research group. Buoy: Alan Lui) deployment of sensors. Efforts to reduce physical, chemical and biological fouling and increase sensor stability must continue.

2.4.4 Future Issues and Recommendations

Improvements are needed for sensors mounted on unmanned aerial vehicles (UAVs) and small piloted aircraft. Inland aquatic systems, including small lakes, rivers, streams, and wetlands, require sensors with narrow bandwidths and sufficient sensitivity to permit spatial resolution on the order of meters. Such sensors should have sufficiently broad wavelengths to calibrate for atmospheric corrections when flown at high altitude.

Sensor-underwater robot combinations have great scientific potential. Small size and low power consumption are particularly important for sensors deployed on robotic vehicles. Communication protocols are needed to allow real-time data acquisition. Here, the development of acoustic modems will be valuable. With respect to sensor deployment in observatories, researchers require hydrodynamic models for planning the number and locations of sensors. Data from *in situ* sensors have the potential to be excellent educational and outreach tools, with real-time data and simple visualizations being of particular importance. Excellent examples of time-relevant data being made available for education and outreach can be found at Water on the Web (http://waterontheweb.org/).

2.5 GROUNDWATER SCENARIO

Members of the Groundwater Scenario Committee: Russ Hertzog, Ned Clayton, Ian Papautsky, Paul Bishop, Judy Erb, Paul Bergstrom, Clare Welty, Sayuri Terashima

Speakers at the Groundwater Scenario Plenary Session: Russ Hertzog (SECUREarth and Groundwater), John Barich (Science and Social Issues), Ned Clayton (Technology), Rick Johnson (Deployment and Maintenance)

2.5.1 Science

Groundwater supplies worldwide are becoming degraded and people use these resources ever more intensively. The effects of mining, industrial and domestic waste, and agricultural activity are threatening already stressed drinking water supplies. It is clear that people must find ways to manage and remediate water resources more efficiently, cost-effectively, and sustainably. To accomplish this, scientists and researchers require a better and more complete understanding of groundwater conditions and processes. This understanding requires better, more pervasive, and cost-effective measurements. *In situ* sensor observatories are the best sources for such measurements.

Overall, the greatest needs for groundwater sensor observatories are

- better spatial and temporal resolution of sensor networks, which would require more closely spaced and more frequent discrete horizontal and vertical measurements
- better understanding of *in situ* microscale processes, requiring microscale sensor measurements
- more and better quality *in situ* chemical and biological sensor measurements to understand biochemical reactions and to identify potentially harmful levels for humans and other biota

Spatially and temporally high-resolution monitoring observatory sensor networks in groundwater environments will provide insights into complex and coupled bio-geochemical processes that affect the quality of drinking water resources. The basin-wide instrumented groundwater-monitoring network in California is an excellent example of this approach (see sidebar on page 15). The two basic questions that scientists are trying to answer with this approach are as follows:

1. What flow, biological, and geochemical reactions occur in groundwater at the exact site of process activity?
2. How do we satisfy the need for non-invasive measurements that do not alter chemical and biological conditions at the observation site? Current methods are too invasive and, for example, change redox potentials in a way that fouls the data.

Realistic conceptual models of the processes that affect contaminants in groundwater require sensors that are capable of conducting measurements at the microscopic scale. These sensors must be able to detect, monitor, and understand the impact of biofilms and bio-geochemical reactions. In addition, new sensor technologies are needed to study and understand the fate and transport of pathogens, pharmaceuticals, pesticides, and other toxic contaminants in urban and agricultural systems.

2.5.2 Technology

In situ sensors are needed for basic measurements of specific chemicals and pathogens such as *E-coli.* Emerging technologies such as nanotechnology, microscale measurements, and sensors that employ polymer-sensing films are promising. However, they require further development before they can provide the long-term reliability, wide dynamic range, and sensitivity to a broad spectrum of

Groundwater: Basin Wide Instrumented Ground Water Monitoring Well Network in California

Groundwater meets 75% of the water demand for approximately two million residents in the 900 km^2 service area of the Orange County Water District (OCWD) in Southern California (Figure 1). OCWD uses approximately 200 monitoring wells. Approximately 60 of the wells are discrete-depth multilevel monitoring wells (Figure 2) that provide a total of approximately 550 monitoring zones, with each zone being a data point. Transducers are used to measure pressure and temperature in each zone, and samples are routinely extracted from the zones and analyzed for water chemistry. These data, combined with information from other "traditional" monitoring wells, have vastly improved the monitoring and modeling of the groundwater basin. Improved modeling allows better management decisions regarding the future use of the basin. Understanding the distribution of water quality has also changed the design of new production wells, for example by allowing drillers to avoid zones of poor water quality.

OCWD has realized a number of benefits from improved characterization and monitoring of the basin. However, the major benefit is that the District believes that it can increase annual groundwater production from the present 440,000,000 m^3 to over 600,000,000 m^3 (>35% increase). The ability to increase the sustainable yield of the basin will help Orange County meet the needs of residents, even as the population continues to grow.

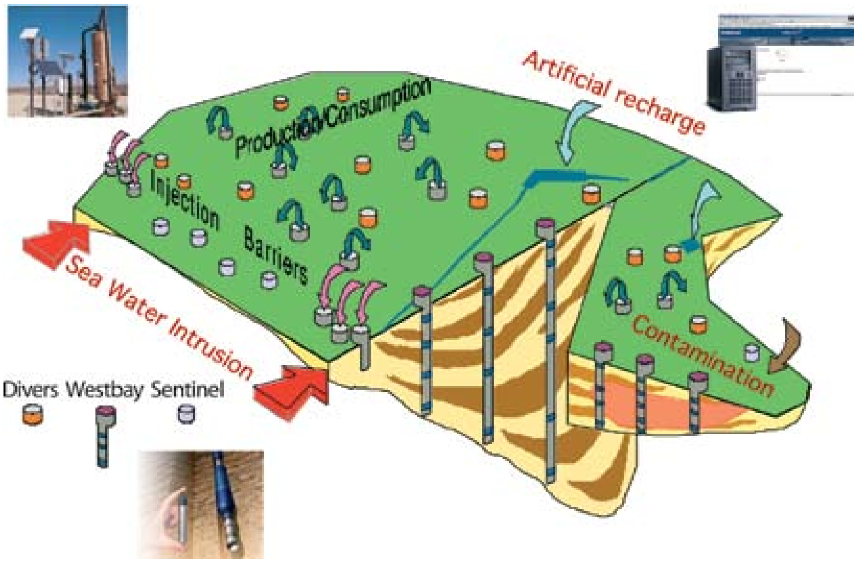


Figure 1. Schematic of the groundwater basin encompassed by OCWD. Groundwater production occurs throughout the basin. Artificial recharge is accomplished using percolation basins along the Santa Ana River. Water injection occurs in two areas near the coast where seawater intrusion can be a problem. Chemical contamination is a problem at various locations throughout the basin. (Unpublished figure provided by Ned Clayton, Schlumberger Water Service)

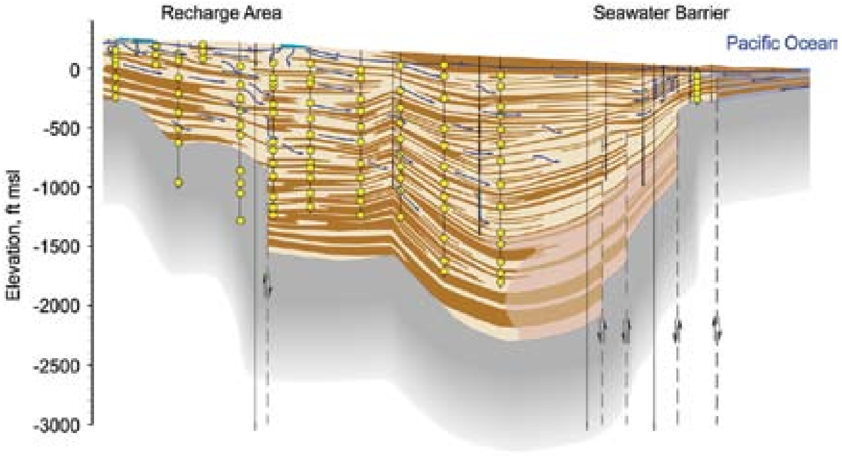
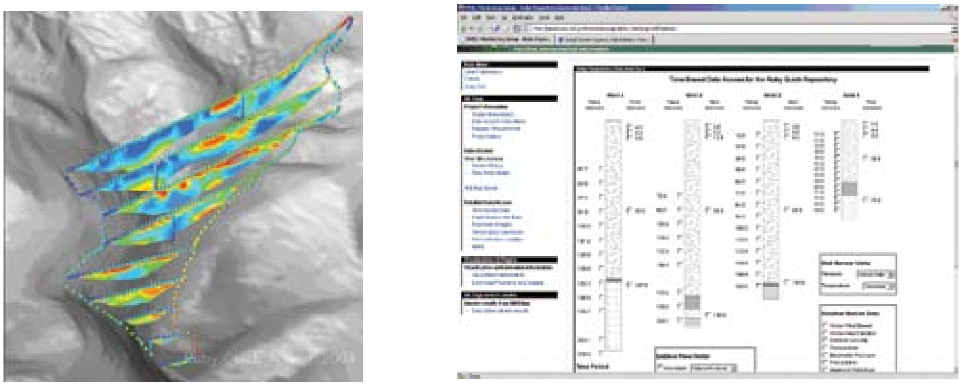


Figure 2. Cross-sectional view of the OCWD basin, showing wells located along the Santa Ana River. The left-hand side of the illustration is East. Yellow dots indicate multilevel monitoring zones; blue arrows indicate flow. The cross-section shows the many layers in which detailed monitoring has enhanced the modeling of flow from recharge areas to production wells. (Ned Clayton, Schlumberger Water Services)

Groundwater: EPA Superfund Groundwater Monitoring

The Gilt Edge gold mine is an acid-producing sulfide site in Lawrence County, South Dakota. The groundwater monitoring system at the site consists of surface and borehole measurements taken with a suite of instruments, including a 560-electrode electrical resistivity tomography array, advanced tensiometers, suction lysimeters, gas ports, thermocouples, thermistors, a weir, and a weather station. The entire system is computer-controlled and operated remotely (Versteeg et al., 2004). The data are collected and then sent automatically to a database, where they are processed and imaged. The system provides users with web-based access to data and information. Results from this system have already changed conceptual models of capped systems.

Automatically generated status images of the Gilt Edge monitoring system allow scientists and regulators to compare water data in near real time. (Versteeg et al., 2004)



A cross-sectional view of the area shows the electrical-resistivity data (left). A web-based interface (right) allows users to selectively interrogate and view different aspects of the system. Automatically generated status images of the Gilt Edge monitoring system allow scientists and regulators to compare water data in near real time. (Versteeg et al., 2004) species that researchers need. Technical capabilities must be developed to enable the use of sensors in water-saturated and unsaturated subsurface environments. Measurements of mass flux between the earth's surface and subsurface are needed so that groundwater sources and sinks can be characterized. Furthermore, measurements of micro-scale flow velocity near soil particles are important if the fate and transport of contaminants and the supply of nutrients for subsurface microbial activity are to be characterized.

As in other scenarios, the implementation of groundwater observatory sensor networks that are capable of measuring more than basic pressure, temperature, and electrical conductivity parameters is hindered by the costs of advanced sensors. For example, nitrate sensors cost about $17,000 each, and most observatories need a significant number of them to achieve sufficient spatial resolution. To be economically viable for current permanent *in situ* technologies, the unit cost must be reduced to less than $1,000. Alternatives to large and costly permanent sensor networks include programs of routine periodic well logging with sophisticated sensors or temporary deployments of automated networks. The oil and gas industry uses the latter approach when conducting one-time characterizations and performing long-term monitoring.

New sensor technologies developed in other industries can be exploited for groundwater characterization. For example, nuclear magnetic resonance (NMR) logging, used in the exploration of oil and gas, can be used to measure capillary pressure, porosity, pore-size distribution, flow permeability, and biofilms in groundwater environments.

2.5.3 Deployment

To be usable in large numbers in high-resolution networks, sensors need to be low-cost, rugged, small, reliable, and field-deployable. To keep the cost as low as possible for the analysis and support system (including power, spectrometers, and telemetry), designers need to consider ways of connecting multiple remote primary *in situ* sensors through fiber-optic cable systems to a common multiplexed analysis support system. Sensor field installations must be immune to electrical noise and other artificial sources of interference, as well as secure against vandalism and natural disruptions. Biological sensors, such as bio-capture films and evanescent detectors that sense bio-molecular surface binding through fluorescence, should be developed to overcome problems related to deployment and fouling, storage, and lifespan. These problems are common to most new sensor technologies, including chemical sensors, which typically need to be recalibrated or replaced after a limited number of measurements.

A systems approach—in which a large, spatially distributed sensor network is integrated with an information management, analysis, and modeling system—will enhance the ability of scientists to characterize, monitor, and effectively manage groundwater systems. For example, autonomous data acquisition, reporting, and information access through a website or other online means will not only significantly improve sensor response time, but also enable scientists, site managers, and regulators to react more swiftly and efficiently to changes in the groundwater system. A good example of the systems approach is the monitoring system developed for the EPA Gilt Edge Superfund site in South Dakota (see sidebar on page 16).

2.5.4 Future Issues and Recommendations

Interfaces

The time lag between the development of a new measurement principle and the appearance of sensor technology based on that principle is often long—so long, in fact, that scientists sometimes refer to it as the "Valley of Death." A similarly long lag typically follows the development of new sensor technologies before their deployment and application in the field. In the oil and gas exploration industries, among others, these gaps are closed through a coherent, integrated product development process. Stakeholder agencies such as NSF, EPA, DOE, and USGS should address the fact that sensor development requires significant financial investments and long-term commitments. Investments in sensors and monitoring systems could significantly reduce the extremely high cost of environmental cleanup, by allowing stakeholders to monitor and efficiently control remediation processes. The community needs a long-term, integrated commitment from stakeholder agencies to ensure the timely development of sensor network systems capable of adequately addressing subsurface water and geoscience research needs. A cross-disciplinary engineering technology program and center could fill this need.

In the interim, observation sites with a history of research and monitoring should make case studies available to demonstrate the value of sensor technologies developed for that site. A website clearinghouse or other form of "information distillery" could be used to post specific science and technology needs and provide responses to queries about ideas and developments. Such a resource could provide sensor experts with a way to stay current with groundwater research needs. Regular interdisciplinary workshops for researchers from a variety of disciplines within the environmental sensor community are extremely useful for developing awareness, contacts, and collaborations for new avenues of research.

Key Recommendations

- There is a great need for field network deployable sensors that are low-cost, rugged, reliable, species-specific, and secure.
- Networks of densely spaced and temporally continuous high-resolution basic surrogate sensors are critical for observing groundwater flow and simple chemistry. High-resolution measurements can be integrated with smaller numbers of chemical-, pathogen-, and contaminant-specific sensors to translate small-scale process-specific knowledge to a larger scale.
- The concept of an integrated "solution development process" is needed to overcome the long delay and high cost traditionally required to develop measurement science and new sensor technologies, and finally implement them in observatory networks. This may involve the establishment of an engineering center for sensor technology development.

Reference

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2.6 PRECISION AGRICULTURE SCENARIO

Contributing authors: Tom Harmon, Craig Kvien, David Mulla, Gerritt Hoggenboom, Jack Judy, James Hook, David Weinreich

Speakers at the Agriculture Scenario Plenary Session: Craig Kvien (Science/Needs), Jack Judy (Sensor Technology/Techniques), Tom Harmon (Deployment)

2.6.1 Science and Engineering

The science and engineering questions associated with precision agriculture center mainly around increasing efficiency in the face of global competition. A closely related and emerging need is to understand and minimize the impact of agricultural developments on the ecosystems that share the Earth (i.e., precision conservation). Agriculture provides the economic underpinnings for the majority of rural America, netting some $50 billion annually on gross receipts of $250 billion. When food and fiber shipping, storage, and processing are included, the sector becomes even larger and more diverse. In terms of area, some 46% of the nation is covered in cropland or pasture; with forestry the total rises to 75%. To prosper in a sustainable manner, U.S. agriculture must become very efficient from the perspectives of both productivity and resource conservation. Precision agriculture is rapidly evolving as an information-intensive approach, and in many ways can serve as an effective test bed for other terrestrial sensor and sensor network deployments.

Precision agriculture is an information management system that involves customizing the management of farm fields for spatial and temporal variations in crop yield and quality, soil moisture, soil fertility, weed and pest infestations, and environmental impacts. Information collected using global positioning satellites (GPS), remote sensing, yield monitoring, soil and crop sensors, and soil sampling is then converted into management decisions using geographic information systems (GIS), spatial statistics, and expert systems software. Multiscale sensor deployments are already helping many farmers to better manage their land. Closely related benefits accrue from monitoring the impact of agriculture on adjacent ecosystems. Further increases in efficiency will stem from networking sensors to elucidate important spatiotemporal patterns and integrating their data streams so as not only to display or record information, but to actuate responses. For example, satellite and airborne remote sensing can report on the spatial variability of crop biomass and leaf area index (Figure 2.6.1), yield distribution,

Figure 2.6.1. Variability of cotton growth five weeks after planting. Dark green areas indicate better growth. (Photo courtesy of Craig Kvien/NESPAL)

Figure 2.6.2. Hillslope erosion and deposition on an agricultural field in Minnesota. (Photo courtesy of David Mulla, Univ. Minnesota)

and needs in terms of nutrients (Doraiswamy et al., 2004; Jacobs et al., 2004; Lobell and Asner, 2004; Vellidis et al., 2004). This information is important and can increase farming efficiency as long as the farmer receives it in a timely manner and has the capacity and knowledge to act on it. Models of integrated sense-and-respond systems are being successfully deployed in ground-based systems. For example, tractor-mounted yield monitors, operating at the scale of individual plants, are capable of real-time protein content quantification and sorting during harvest.

There are clear immediate needs for improvement in precision agriculture sensing. Obvious needs are soil moisture, dissolved inorganics such as nitrogen and phosphorous species, and organics such as herbicides and pesticides. Requirements for sensors become less obvious as we look beyond short-term objectives. Cues from nature often suggest viable starting points. As one example, *M. Croceipes,* a tiny parasitoid wasp, locates caterpillars attacking cotton plants by keying on a complex organic volatile cocktail emitted from the plant when attacked. Heterogeneous groups of sensors, ranging from sophisticated universal detectors (e.g., mass spectrometers) to simple nodes (e.g., temperature), will provide added value. A cluster of sensors characterizing and responding to spatiotemporal patterns in weather, hydrology, pressure, motion, soil moisture, soil matric potential and fluxes, plant ecophysiology, weeds and pests (bacteria, fungi, insects, rodents), for example, could aid the agricultural manager. An emerging issue is that early warning networks may soon be necessary to protect especially vulnerable crops that rely on limited genetic strains. Related to this is the need for error-resilient systems to prevent the unwanted propagation of genetically modified organisms. Other issues include the following:

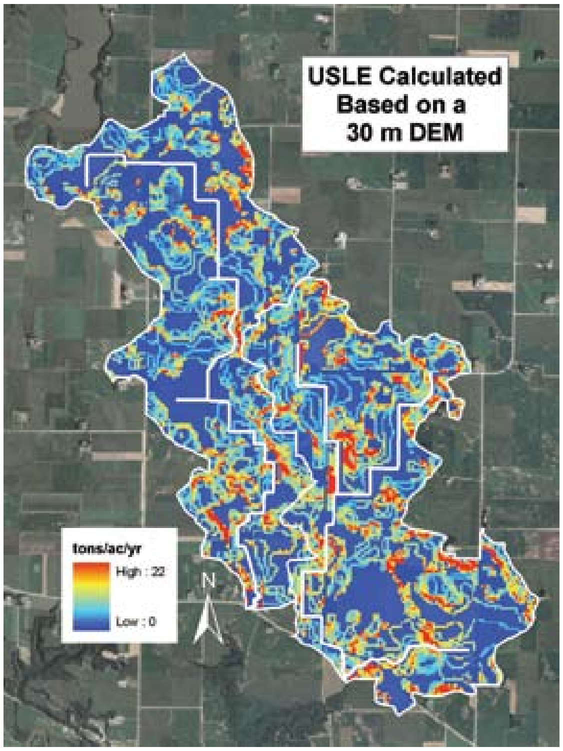


Figure 2.6.3. Watershed scale assessment of erosion risks for precision conservation in Minnesota using terrain analysis and the Universal Soil Loss Equation. (Map courtesy of David Mulla, University of Minnesota)

- Precision conservation (Figures 2.6.2 and 2.6.3)—collaboration between scientists, engineers, and social scientists is needed here to identify portions of the landscape vulnerable to environmental degradation and develop strategies to reduce their impact.
- Understanding linkages between agricultural production/ precision management and nature (genetic stock resistance to pests, effect of food web).

2.6.2 Technology

Technology developments in the areas of remote sensing, bench-scale sensors (onboard sensors), and scaleable microsensors all have a place in precision agriculture.

In order to maximize the quantity, diversity, and accuracy of information extracted from sensor-network deployment for precision agriculture, a variety of reliable, high-performance, and cost-effective sensor technologies are needed. The precision-agriculture domain provides a platform on which bench-scale analytical instruments and image-recognition systems can be deployed on the tractor platform (see following section). There are a number of examples of this strategy, including sensors that identify weeds and actuate herbicide application in real time to reduce herbicide use and save time. A greater challenge will be scaling down sensors for distributed deployments. For example, sensors to accurately detect ionic concentration in the groundwater and soil (e.g., the nitrogen cycle) are needed, as well as sensors capable of analyzing a cocktail of volatile organic compounds. Consequently, there is an increasing interest in miniaturizing both highly specialized chemical sensors (e.g., nitrate sensors for soil and groundwater—see Bendikov et al., 2005) as well as generalized chemical sensors (e.g., gas and liquid chromatography—see Figure 2.6.4). Development work on micromachined electrochemical ionic sensors (e.g., nitrate) is progressing quickly and should be translated into deployed sensor networks in the near future (Kim et al., 2004). Similarly, impressive progress is also being made on micromachined liquid chromatography systems, and their near-term deployment is also foreseen (He et al., 2004). However, the accurate discrimination of complex organic compounds, with the sensitivity levels needed, has yet to be realized and is an active area of research.

2.6.3 Deployment

The level of sensor reliability, sensitivity, complexity, miniaturization, and cost must be considered when determining the most appropriate deployment technique. As is the case in all environmental domains, the long-term deployment of chemical and biological sensors poses a major challenge, both above ground and particularly below ground, where access will be limited. For many agricultural problems, sensor deployments on a short-term basis (e.g., critical periods within the growing season) may be sufficient, creating deployment possibilities for short-lived sensors. This then creates a need for the use of environmentally benign materials, as such sensors might be considered disposable.

Sensors and sensor networks supporting precision agriculture can be broadly categorized in terms of their deployment mode: (1) remote sensors, (2) autonomous mobile systems, referred to as networked infomechanical systems (NIMS, see Kaiser et al., 2004), and (3) embedded, networked systems (ENS). Remote sensing via satellite and airborne sensors (e.g., LIDAR, hyperspectral imaging) are accessible to the farming community at increasingly high resolution, and, with some expertise, can provide useful spatial data on soil and vegetation. Down-scaling regional ground-based remote sensing, such as ground-penetrating radar (GPR), can provide more insight into the subsurface. Spatially continuous snapshot information gleaned from remote-sensing deployments is most useful when adequately coupled with data collected using spatiotemporally continuous ground-based ENS and NIMS technologies. Precision agriculture has been using effective NIMS technologies for years in the form of GPS-guided tractors equipped with onboard sensor systems.

2.6.4 Future Issues

These efforts serve as a mature platform for further developments (application-specific robotics, visualization systems, chemical and biological sensors). The seamless integration of the NIMS-based platforms with the geospatial

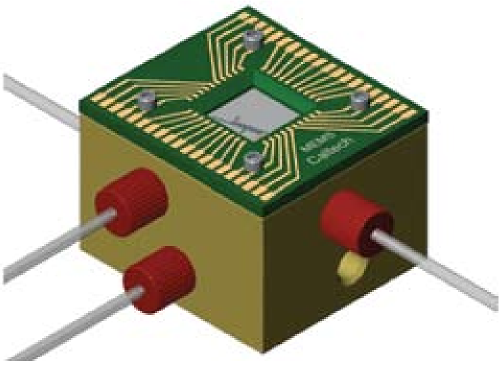


Figure 2.6.4. Drawing of prototype ion chromatograph on-a-chip (left) and proof-of-concept chromatogram generated under laboratory conditions. (Y-C. Tai, California Institute of Technology and the Center for Embedded Networked Sensing)

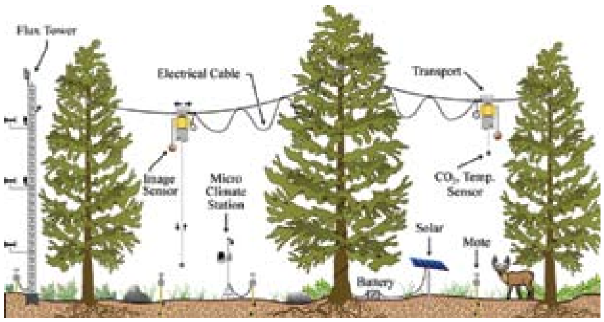
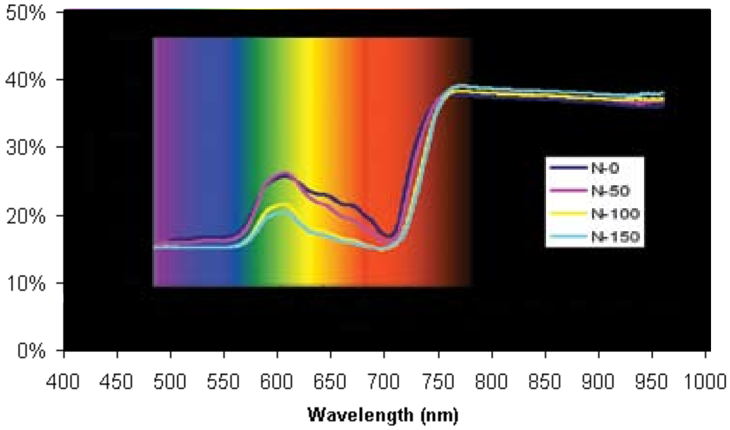


Figure 2.6.5. A hypothetical NIMS deployment in a forest canopy set in the context of a stationary sensor network. (Drawing by Jason Fisher, UCLA/Cal-CLEANER)

Precision Agriculture

The Nutrient Management Group in Lincoln, Nebraska seeks to develop sound nutrient management practices through work performed by scientists from the Soil and Water Conservation Research Unit (http://arslincoln.unl.edu/swcru/) of the Agricultural Research Service (ARS), an agency of the United States Department of Agriculture (USDA) and faculty from the Agronomy and Horticulture Department at the University of Nebraska at Lincoln. Foundational research was performed by John Shanahan and Jim Schepers at ARS, and the project was led by Robert Caldwell at UN-L with support from Holland Scientific (http://www.hollandscientific.com/) in developing the sensor technology through a cooperative research agreement with ARS. Various remote sensing technologies were used in the project to improve the use of N in corn cultivation. The goals were to optimally manage N application and reduce both grower fertilizer costs and environmental contamination.

Starting from small-scale tests with *in-situ* chlorophyll meters, the Nutrient Management Group worked with a suite of remote sensing tools, including spectroradiometers, aerial photography and satellite imagery. Researchers have been able to accurately assess N needs in crops and plan remediation with little waste. Such methods have the advantage of using available data in new ways, but may be limited by interference from weather and/or cloud cover. Calibration is also critical to account for variation in species, cultivars, and stages of development. Hence there is a need to augment such approaches with *in-situ* testing that can be applied at a broad scale.



Canopy reflectance as determined with a hyperspectral radiometer and integrating sphere in the visible (400-750 nm) and the near-infrared or NIR (750-1000 nm) electromagnetic spectrum for corn receiving four different N fertilizer rates.

In 2000, the team finished an initial cycle of testing on an enhanced multispectral Holland Scientific passive sensor system, and has since evolved to using an active sensor system that generates its own source of modulated light and can operate in full sunlight or darkness equally well. The system is designed to interface with a real-time-differential global positioning system (DGPS) for mapping crop canopy reflectance over entire fields. By selecting the appropriate photodiodes, sensors can measure light reflected off the crop in various bands of the visible and NIR spectrum, which provide the greatest measure of difference between adequately fertilized and N-stressed corn canopies. Early findings suggest that the sensors are capable of detecting variations in leaf chlorophyll or N status induced by varying levels of N application, since variation in the sensor readings (expressed vegetation index) were highly correlated with ground-based chlorophyll meter readings for plants measured at early vegetative growth stages, when N fertilizer can be optimally applied.

High-clearance vehicle configured with canopy sensors, drop nozzles and controller, which has been designed to deliver liquid N fertilizer based on sensor-determined crop needs.

Such sensors can further be coupled with high-clearance applicator vehicles configured with a controller and drop nozzles to apply N fluid fertilizer based on crop need. Additional research is needed to determine the appropriate control algorithm to translate sensor output into corrective action for the fertilizer applicator. (http://agronomy.unl.edu/nmgt/proposal.htm) imaging data created by remote sensing will be an important step toward optimizing deployments. Another form of deployment, that of distributed and embedded (soil- and vegetation-based) sensor networks, can be used to provide ground-truth data for higher-level sensors as well as detailed data on specific chemical and biological facets of agricultural problems (Figure 2.6.5). For example, remote sensing and NIMS-based GPR may identify the onset of nitrogen deficiencies, but soil-based sensors can be used to assist in the optimal application of fertilizer, avoiding overuse and potential releases to groundwater and surface water. Vegetation-based deployments will certainly evolve to help move toward optimal timing on harvest and sorting according to quality and optimal use of resources such as minimizing water use and pesticide application.

For embedded sensor networks, key issues include sensor robustness in the face of environmental conditions (reliable, rugged, low power requirements), *in situ* calibration needs (resistant to degradation, signal drift), and monitoring network design strategies (sufficient coverage at least cost). Overall, the integration and interplay between the various modes of sensor-network deployment will be critical to future precision-agriculture developments. The Internet is rapidly becoming the backbone supporting these agricultural sensing and control systems. A key strategy will involve exploiting data from lower-order sensors to trigger higher-order sampling and analysis. Those mastering these and other sensor network management schemes will succeed in producing crops in greater quantity and at higher quality while minimizing cost. With the exponential increase in sensors and sensing capability, there will be an increasing need for information and decision support systems to help analyze and interpret the data to allow for efficient and timely management by farmers.

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2.7 TERRESTRIAL ECOLOGY SCENARIO

Members of the Terrestrial Ecology Scenario Committee: Barbara Bond, John Sechrest, Roland Kays, Mike Hamilton, Stuart Gage, John Porter

Speakers at the Terrestrial Ecology Scenario Plenary Session: Barbara Bond (Science), Terri Fiez (Technology), Roland Kays (Deployment)

2.7.1 Science

Terrestrial ecological research incorporates a wide range of topics, temporal and spatial scales, and research approaches. An enormous amount of effort has gone into defining today's most urgent questions in terrestrial ecology. In 2000, the National Academy of Sciences (NAS) surveyed thousands of scientists and asked them what they perceived as the most critical questions in environmental research. The responses led to the identification of eight "grand challenges," each of which is pertinent to terrestrial ecology (the news release is available at http://www4.nationalacademies.org/news.nsf/isbn/09252000?OpenDocument). Subsequent to the release of the report in November 2004, planning groups sponsored by the American Institute of Biological Sciences (AIBS) released a series of summary reports on these major questions as they pertain to environmental observatories (http://ibrcs.aibs.org/NEON-workshop-series/). In the first half of 2005, additional working groups will define how an observatory should be constructed to address these questions. Examples of the "grand challenges" in terrestrial ecology and related critical science questions include the following:

- *Land use change*—What are the dynamics and consequences of land changes—which are coupled environment systems—at regional and continental scales?
- *Climate Variability*—How will variations in climate influence ecosystem structure and function at scales ranging from the landscape to the continental? What are the consequences of these variations for society?
- *Biogeochemistry*—How can ecosystem losses or degradation of ecosystem services be predicted via altered movements and distributions of biologically important elements?
- *Infectious disease*—Where and when will infectious diseases of humans, non-human animals, and plants emerge?
- *Invasive Species*—What species are most likely to become invasive and how can they be managed? How can rates of population growth and spread of invasive species be predicted?
- *Biodiversity*—Can the impacts of changes in biodiversity and human activities on ecosystem function and services be forecasted?

Each grand challenge will require its own approach regarding technology, deployment, and its future issues. As it is impractical to summarize these approaches for each grand challenge in this report, some illustrative examples will be discussed.

Terrestrial ecology sensors can be grouped into two broad categories: (1) sensors deployed on ground-based towers using eddy covariance techniques, and (2) sensors at ground level, attached to stationary mounts or free-ranging animals. Each grand challenge may be addressed by one of these types of sensors. Because it would be impractical to summarize the different approaches needed for each challenge in this report, illustrative examples have been used below in each of these categories. Current applications for collecting and synthesizing data, examples of relatively small changes that could facilitate important advances, and areas where major new developments in technology are needed are discussed where appropriate.

2.7.2 Applications and Technology: Ground-Based Towers

Satellite sensors have been in place for decades, and they are providing important insights into the detailed characteristics of the land surface—for example, leaf area and species composition in natural and managed ecosystems—as well as revealing changes in these attributes over time. As future strategies are developed for terrestrial sensors, it is critical to recognize the wealth of information already available through remote sensing. Sensors are providing continuous information about changes in ecosystem phenology on regional scales—consider, for example, the "greening" of the boreal forest, which is associated with global warming and indicates enormous change in carbon cycling in these regions. Sensors also are providing insight into changes in sea level, properties of coastlines, and changes in the physical characteristics of landscapes such as urban boundaries, deforestation, and afforestation.

Sensors deployed on ground-based towers are used to measure ecosystem processes using eddy covariance techniques (Figure 2.7.1). More than 50 Fluxnet sites are currently in place around the globe; sensors at each site continuously measure the net exchange of energy, CO_2, water

Figure 2.7.1. (left) Metolius, Oregon flux site in 70 year old ponderosa pine. (Source: http://public.ornl.gov/ameriflux/Site_Info/siteInfo.cfm?KEYID=us.metolius_int.01)

Figure 2.7.2. (right) The global flux network. (Source: http://daacsti.ornl.gov/FLUXNET/)

vapor, and often other gases between terrestrial ecosystems and the atmosphere (Figure 2.7.2). Most Fluxnet sites include a large number of ancillary sensors that measure such ecosystem properties as moisture in the soil, sap flux in trees, and respiration rates from soil and vegetation.

2.7.3 Future Issues: Ground-Based Towers

Eddy flux towers and remote sensing technologies are powerful tools for measuring ecosystem processes and landscape change; however, they have important limitations. Remote sensing provides information at relatively coarse temporal and spacial scales, and most remote sensing is limited to the properties of landscapes that can be viewed from above. An intriguing area for future development is to use the technologies employed in satellite remote sensing for local, ground-based sensors.

Flux towers are expensive to build and maintain; therefore they are built at widely distributed points, which only provides "point in space" information. The actual points sampled are also limited by cost and technology: eddy covariance techniques can only be used in relatively uniform, relatively flat terrain and towers tend to be clustered within "wealthy" nations. Hence, many of the world's most productive and fragile ecosystems are thus not represented. Finally, remote sensing and eddy covariance alone usually provide little insight into the processes behind the properties being observed.

New sensors and methods of deployment will provide environmental scientists with significant tools for understanding fundamental ecosystem processes. Micrometeorological measurements at fine spatial scales will help scientists understand how microclimate is—and is not—coupled with broad-scale changes in global climate, and how microclimate controls ecophysiological processes. Sensors mounted on trams or other mobile platforms may provide information over a broader range of spatial scales. These measurements are possible with existing technology. However, new technologies are needed to measure and monitor belowground processes such as respiration and nitrogen cycling. New technologies are also needed to measure fluxes in mountainous areas and structurally complex ecosystems. One promising arena for development using newer sensor technologies is the *in situ* measurement of stable isotopes in CO_2 and water vapor (http://basinisotopes.org/basin/BASIN_workshops/ParkCityUT.html).

Figure 2.7.3. Acoustic sensing in Crescent Meadow, Sequoia National Park, yields information about the presence and activities of wildlife in the area. (Source: Stuart Gage, Michigan State University)

Figure 2.7.4. Automated radio telemetry systems (ARTS) aid in tracking larger animals. (Source: Roland Kays, NY State Museum)

2.7.4 Applications and Technology: Ground-Level Sensors

Terrestrial ecology sensors are increasingly used to detect behaviors and changes in animal and microbe populations. Such detection is critical for addressing four of the environmental grand challenges identified by the NAS: invasive species, biodiversity, ecological response to climate change, and ecological response to land use change. Most assessments of flora and fauna are currently conducted via manual surveys, but many opportunities exist for automating these processes. Three classes of sensors in use today to survey biota offer the potential, in the short term, for deployment as a network: acoustic, visual, and radiotelemetry. Other sensors that have the potential to detect changes in biota— olfactory/chemical, tactile, and genetic sensors, for example—are currently in more experimental phases of development.

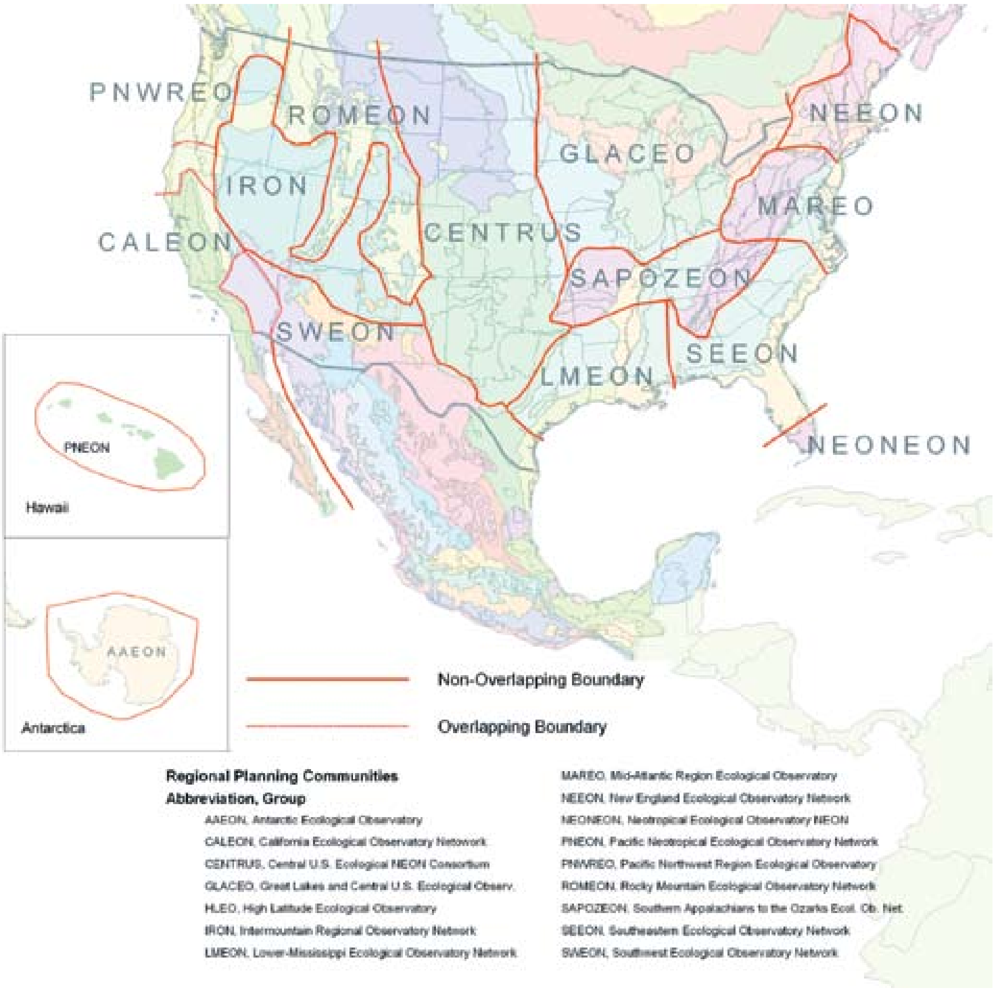
Terrestrial Ecology

The National Ecological Observatory Network (NEON) is a major initiative proposed by the National Science Foundation (NSF) to establish a national platform for integrated studies on natural processes at all spatial scales, time scales, and levels of biological organization. NEON will provide the resources and infrastructure for fundamental biological research that will enhance our understanding of the natural world, improve our ability to predict the consequences of natural and anthropogenic events, and inform our environmental decisionmakers. (Source: http://ibrcs.aibs.org/neon/index.html)

As the NEON concept has developed, regional groups have self-organized to create partnerships, inventory existing infrastructure, and explore how NEON can enhance research capacities within their regions. The NEON regions are based loosely on ecoregions and represent the major biomes of the United States and Antarctica.

Throughout the United States there are now fifteen such groups. They vary in their formal organizational status — some are just starting to meet formally, whereas others have been organized for several years. Regional group meetings have aided in building momentum by creating a forum for the NEON community to consider how this national research platform can improve our ability to understand ecological phenomena.

The graphic below maps the tentative layout of NEON regions as of July 22, 2004. The boundaries were initially determined at a meeting of key leaders from each of the regions that took place at the Conservation Research Center in Front Royal, Virginia, on Jan 27-29, 2004. Since that meeting, new regions have emerged and boundaries have evolved. It is likely that they will continue to do so. (Source: http://ibrcs.aibs.org/neon/regional-index.html)



Acoustic sensors such as microphones have the potential to monitor any fauna that vocalize, especially birds, bats, amphibians, and insects, as well as the potential to quantify human influences. Such sensors were recently utilized to verify the existence of ivory-billed woodpeckers in the Big Woods of Eastern Arkansas when visual sensors proved too coarse. Prototype automated acoustic monitoring systems are presently used to capture sounds at regular intervals; the information is then transferred to central processing hubs. The sensor community should encourage important short-term sensor improvements and deployments, including automation of species identification, improvements in network infrastructure, and triangulation of animal location.

Coupling current visual sensing technologies with improved information and communications systems offers the potential for major scientific progress. For example, 35 mm "camera traps" used to monitor mammal biodiversity and density could be automated with $5 digital cameras and the appropriate communication network. Time-series photographs from these same cameras might also be used to quantify change in understory vegetation, which usually cannot be detected in remotely sensed imagery.

Animals marked with passive or active tags can be monitored through radiotelemetry or satellite-based tracking systems. Existing GPS tags offer fantastic opportunities to track big animals over large areas, but such sensors are currently too large to be fitted on most animals. If satellites were fitted with the appropriate radiotelemetry technology, smaller animals could be tagged with 1 g radio transmitters and then tracked; ecological observatories should make this technique a priority. Fine-scale tracking of tagged animals has recently been developed through the Automated Radio Telemetry System (ARTS); a network of these systems would provide relevant data for these grand challenges.

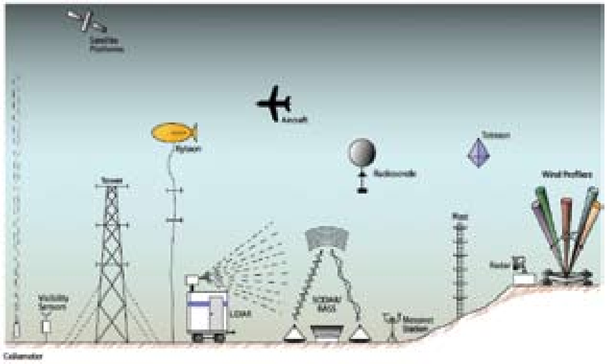


Figure 2.8.1. A schematic of an atmospheric flow sensor deployment in a field campaign. This figure provides guidance for sensor deployment in an instrumented urban airshed where the functioning of different sensors can be coordinated through a cyber network.

2.7.5 Future Issues: Ground-Level Sensors

Existing and emerging technologies offer many opportunities for tracking and monitoring populations of previously identified organisms. However, setting up a system that will identify invasive species is proving to be difficult. In principle, the techniques used to track these species should be no different from those used to track other organisms; the challenge lies in setting up monitoring systems that are capable of detecting unknown organisms before they appear at a particular location. The successful detection of invasive species will depend on a combination of predictive models and rapid sensor deployment. When predictive models alert researchers to the possibility that a particular species is moving into a particular space, the researchers can deploy the appropriate sensor system to detect and monitor that species.

Power requirements are one of the most serious barriers to the widespread deployment of sensors in terrestrial ecology. Even sensors with ultra-low power requirements will eventually run out of power if they are battery driven; the costs of the crews required to replace such batteries throughout an extensive sensor network are prohibitive. Creative and environmentally friendly technologies are urgently needed to provide lasting, reliable power for sensor networks.

2.8 METEOROLOGY AND URBAN AIR POLLUTION SCENARIO

Members of the Meteorology and Urban Pollution Scenario Committee: Joe Fernando, James Cogan

Speakers at the Air Pollution in Urban Settings Scenario Plenary Session: Joe Fernando (Science), Jim Cogan (Enabling Technologies), Lenny Montenegro (Deployment)

2.8.1 Science

The community of scientists working on research questions in meteorology and urban air pollution face two major issues: (1) how to assess and predict atmospheric flows and thermodynamic structure accurately and rapidly on scales appropriate for transport and dispersion in an urban area, and (2) how to determine the sources of polluting materials accurately.

Because researchers cannot cover a city with a large number of sensors—for technical as well as financial reasons—microscale and meso-gamma models are required to conduct urban meteorology and air pollution research. In addition, real data are needed to initialize those models and maintain

Figure 2.8.2a. A high-resolution data tower that records atmospheric flow and turbulence. This is located at the premises of the Mountain View high school in Mesa, Arizona, and it communicates with a cyber network based at the ASU CLEANER site. In addition to providing data for research, this tower also acts as a facility for high-school student projects. The modus operandi for the ASU CLEANER network is shown in Figure 2.8.2b.

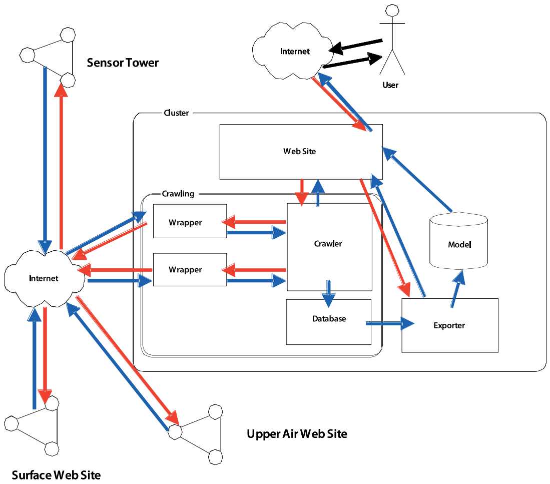


Figure 2.8.2b. The cyberinfrastructure of the ASU CLEANER demonstration facility. The data are continuously acquired and locally stored. The user may request specific data or model runs from the network via Internet/web. A signal is then sent to the crawlers, which decide upon the type of sensors and sensor networks to be contacted for the specific job. Then the required data is sent to the user directly or the data can be temporarily stored in the database for immediate use of the models. Since data from different networks are inhomogeneous, they are made model-ready at an exporter. The model is then initiated, executed, and the results are delivered to the user via web/Internet. The surface and upper air sensor sites are operated by public agencies.

their accuracy. Sensors that are currently available and in development—including lidars, profiling radars, sodars, RASS, microwave radiometers (temperature and humidity), sonic anemometers, and more conventional meteorological sensors—can provide the relevant data (Figure 2.8.1). To be effective, they must work together as a network and with the models to cover the entire area of interest. The models have to run as close to real time as possible, at temporal and spatial resolutions that are currently produced by computational fluid dynamics (CFD) models, which are not presently achievable. The models can in turn provide information that researchers can use to place and operate the sensor network more effectively.

A properly designed network of sensors tied to appropriate models will provide first responders and decisionmakers with the information they need to make informed decisions in response to general pollution episodes or specific catastrophic events, and when locating power plants, highways, and other infrastructure. Without such a system, first responders and decisionmakers operate with incomplete information or—worse—with no information at all, risking consequences that range from unnecessary disruptions to the creation of a larger problem with even graver consequences.

2.8.2 Applications and Technologies

Researchers must employ a combination of experiment and simulation if they are to fully understand the processes that occur in the atmosphere. Relevant techniques include simulation of atmospheric flows in the laboratory using wind tunnels and specially designed water "tunnels;" computer simulations using appropriate models and data assimilation methods; and experiments in the real world using sensor networks, models, and the methods that connect them. Development of theoretical analyses and parameterizations are also an integral part of the development of science in this area.

The following technologies should be pursued in order to achieve the goals described above:

- computer simulations on high-performance computers to help design the systems, determine representative

Clear Lake, California. (Photo courtesy of Bill Boyd, UC Berkeley)

Meteorology and Urban Pollution

The Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER) encompasses four general aspects:

1. Field Network

The backbone of CLEANER will be a series of well-instrumented Environmental Field Facilities (EFFs) situated in either distinctive stressed environments or environments that are representative of a common set of conditions and/or stressors. For example, the PCB-contaminated portion of the Hudson River is a distinctive stressed environment whereas Clear Lake in California could represent a shallow, highly impacted lake in mining and agricultural areas. Site selection will be driven by problems associated with anthropogenic stresses on environmental systems.

EFFs will be monitored with an appropriate array of remote and onsite sensors combined with sample collection and analysis both locally and off site. Innovative monitoring methods will be developed based upon specific site characteristics and targeted stressors. This will apply real-time data acquisition with wireless transmission and newly designed sensors in the field. Monitoring endpoints will be chosen based upon the specific problems identified for individual sites and upon inputs required for development and calibration of engineering models useful for extrapolation of results. Material balance approaches will allow a systematic and dynamic evaluation of ecosystem conditions and flows across and within media. Data collected will be analyzed for quality control prior to incorporation into a networked database.

2. Data Network

The data network will include a virtual repository for data and models as well as a network to facilitate collaborations.

The virtual repository will include collection and organization of existing data for the EFFs within a unified database structure. The database will allow inter- and intra-site queries and facilitate new developments in data mining. Further, the CLEANER organization will standardize input format for newly collected data and include specific structures to test and validate new data with mass balance and statistical approaches.

placements of sensors, and establish the interactions between the various components

- appropriate sensor networking designs capable of achieving the most effective measurement, analysis, and prediction capability
- data compression methods to allow the rapid transfer and processing of large data sets
- embedded sensor technology to allow autonomous or near-autonomous operation of sensors, as well as onboard QAQC and other pre-processing functions
- scalable, flexible, and robust networks that make use of Met-Spaces (Java Spaces) and "browser-like" or web crawler methods for handling ad hoc networks where nodes may be static or mobile and may enter or leave the net at random (Figures 2.8.2a & 2.8.2b)
- small, lightweight, low-power, and low-cost remote sensors for both atmospheric variables and the detection of hazardous materials

CLEANER will include the development of new models and the integration of existing models based upon the data collected within the virtual repository. Existing watershed, ecosystem, and regional models will serve as building blocks for integrated CLEANER modeling efforts. Modular and open architecture will allow optimization and modification by a large number of researchers. Models will be evaluated, validated, and calibrated using the large database of existing and new data. Models will also be used for retrospective and prospective research on the EFFs.

The combination of models and data will be used to identify data gaps and suggest the need for new measurement methodologies and sensor technologies. The data network will allow extensive access to results from multiple researchers' data. This access will promote collaborative planning of experimental approaches across sites. Researchers will be able to benchmark solutions and integrate studies on multiple sites.

3. Integrated Activities

The activities pursued within CLEANER will integrate research, education, and environmental analysis, decisionmaking, and management. The instrumented sites and virtual repository will enable the development of collaborative and multidisciplinary research projects. Specific research projects will be investigator-instigated and will both respond to and drive the design of site instrumentation. The accessibility of data and models will allow modeling to be a central component of both experimental design and analysis and will facilitate the integration of information within and among CLEANER sites, including field-based comparisons of similar sites with different stressors or different sites with similar stressors.

The data and models derived from research at CLEANER sites will support the elaboration of technical and policy options for site protection, remediation, or restoration. These activities will require collaboration among engineers, scientists, social scientists, urban planners, stakeholders, and community members.

Education will be a component of all CLEANER activities. The design and implementation of site instrumentation will promote community education, and the instrumented sites will offer opportunities for experiential learning (e.g., through visitor centers).

4. Collaboration

CLEANER will facilitate collaboration between industry, policymakers, the academic community, non-governmental organizations, the public, and other stakeholders. It specifically addresses the programmatic gaps in the current NSF environment portfolio identified by the National Science Board. For example, CLEANER can support research in materials flow accounting and analysis, both at local and global scales; human perturbations to natural materials flows; urbanization; transportation; land use; and product and process life-cycle assessment. Environmental and energy implications of emerging technologies and trends, such as switching to alternative fuels or industrial restructuring toward a service economy, can be evaluated from economic, engineering, and sustainability perspectives. Consequently, CLEANER can be used, for example, to help industries understand their local and broader environmental impacts by relating their outputs to the fate, transport, and impact of their releases into the environment. This could include localized pollutants as well as larger-scale concerns, such as CO_2 emissions and their global climate effects. The data repository and associated models will enhance pollution prevention as well as remedial efforts. CLEANER's network can also be used for improved public information and education, especially as an "early warning" for system contamination.

2.8.3 Future Issues

The sensor-model system requires effective assimilation of data in close to real time and rapid feedback for modifying sensor deployment. The individual sensors needed include

- lightweight, low-power, remote sensors, including lidars and other instruments, to provide a 3D picture of the atmosphere at fine temporal and spatial scales
- low-cost, low-power sonic anemometers
- affordable mobile profiling sensing systems (e.g., small sodar, lidar, or radar)

Prior to the successful development and deployment of sensor networks and models for the study of meteorology and urban air pollution, the sensor community must successfully address a range of relevant issues. Chief among these are the quality and quantity of data. Put simply, numbers do not equal data. Without appropriate data handling systems or the means to compress and decompress those data, data will be difficult to assimilate into models and will not be useful to scientists. Furthermore, without a flexible and robust network, virtually any extensive system will be overwhelmed and system crashes or lock-up are inevitable. Interactive tools such as graphical user interfaces (GUI) are required, although the required level of operator intervention and the methods by which developers and users will observe system performance remain to be established.

Large, scattered networks in urban locations also have inherent issues of security, autonomy, and power. Vandalism is a real threat at any location, and cyber security is essential for maintaining an effective network. If a network requires extensive "care and feeding," the reliance on a large team of technicians and others could make the entire sensor network unaffordable. Although extensive cable networks will be suitable for static sensor sets in many cases, they are less suited for mobile sensor networks. The feasibility of alternative power sources such as solar, wind, or battery have yet to be determined. Additionally, any solution to these problems depends in no small part on achieving "buy-in" from local communities. Ideally, the local population will accept and even help protect the sensor network. Education and community outreach are important to achieving success in urban deployments.

Another key issue is the interaction between models and the sensor system. Scientists need to determine how model outputs should be used to adjust sensor placements so that the fate of hazardous materials can be assessed as rapidly and accurately as possible. An automated, real-time feedback loop between the sensor system and the model (or models) is needed.

In solving the problems associated with these issues, a systems approach is assumed. Isolated sensors or small groups of sensors will not provide the density of data required for good assimilation. Without integration into a network and without models, individual sensors will provide only isolated, highly localized information for use with dispersion models.

The main challenge in atmospheric modeling and sensing at this time is to garner the political will to properly support the development and deployment of technology that is already available or in the pipeline. Without that support in funding and personnel, none of the above will happen any time soon.

Chapter 3. Shared Issues in Sensing Science, Education, and Collaboration

3.1 INTRODUCTION

Among the common themes identified in the *Sensors for Environmental Observatories* workshop, attendees placed much importance on the crosscutting issues related to sensor science, development and deployment, education and outreach, and interagency and international collaborations. Key observations include the following:

- There is a need to couple models and data, both to build better informed models and to strategically place sensors.
- There is a big opportunity for education, using data from sensor networks in the classroom and building an exchange of people among observatory projects.
- It is important to think and act globally, to harness and share expertise, observations, and resources with the international community.

3.2 SHARED SENSOR SCIENCE: REQUIREMENTS AND OPPORTUNITIES

Attendees at the *Sensors for Environmental Observatories* workshop considered an extremely diverse set of environmental systems ranging from oceans to urban atmospheres and from lakes to estuaries to oceans, and from agricultural lands to forests. Although specific sensors are needed to address many of the scientific requirements in these diverse systems, the discussions revealed several issues that cut across the sensor application scenarios addressed in the workshop's scenario breakout sessions (see Chapter 2). The following issues were deemed most salient:

- modeling and data management
- spatial coverage
- design for ultra-low power consumption
- use of environmentally benign materials to build sensors
- measurement of proxies in lieu of organisms or chemicals
- requirements for flux-based and profiling sensors
- means for sharing expertise across fields

Collaborating and exchanging ideas with researchers in other fields can lead to great benefits and leveraging of resources. The workshop participants discovered that the more extensive and more accurate the sensor networks are, the greater chance they have of improving our knowledge and predictive ability, to the benefit of society. By advancing knowledge, we are reducing uncertainty. Note, however, that undirected data collection—whether using current methods or new sensors—does not automatically translate to an advancement of knowledge.

3.2.1 Modeling and Data Management

Models—conceptual, graphical, mathematical, or simply verbal—can be used to characterize both current knowledge (in "now-casting" mode) and future knowledge (in forecasting mode); thus, models should serve as the framework for assessing the value of new information from sensor data as well as for forecasting future events. With mathematical models, sensitivity analyses can be used to provide a ranking of uncertainties in the model that should be the focus of future data collection. Workshop participants proposed that models be used as the basis for designing the deployment of sensor networks to collect new data, with the goal of reducing uncertainty as represented in the model.

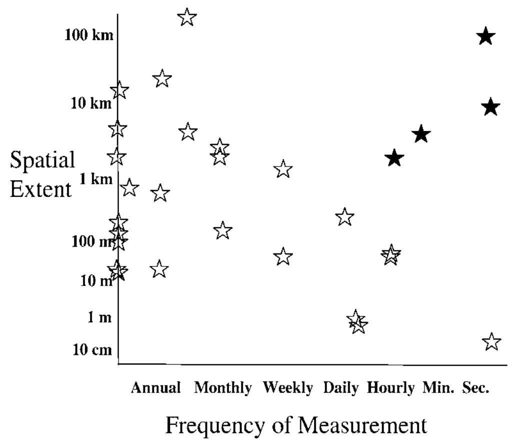


Figure 3.2.1. Results from analysis of 30 papers randomly chosen from the journal *Ecology* in 2003. Sixteen papers contained information on both spatial extent and frequency of sampling (open stars). Stars overlapping the origin on the frequency axis had one-time sampling. Wireless sensor networks, discussed in this paper, are represented by solid stars. Currently, and without sensor networks, most ecological data is collected either in small areas, or at a low frequency. Wireless sensor networks allow data to be collected both at high frequencies and over large spatial extents. (Porter et al., 2005)

Modern predictions from environmental modeling are compromised by serious inadequacies of data—too few, too infrequent, over too small a geographic area. In the ecological sciences, for example, a recent review of papers from the Ecological Society of America publication *Ecology* showed that most current published results are either spatially sparse or temporally infrequent (see Figure 3.2.1). However, with the increased availability over the next five years of low-cost sensors capable of measuring a variety of parameters of interest and capable of being deployed over large areas, model-supported science could change dramatically.

Ideally, the process whereby scientific knowledge is advanced and scientific uncertainty is reduced is a continuous one. The results of experiments and monitoring are used to revise and improve the model, which in turn acts as the framework for the design of new data collection. The result is an adaptive and integrated model-building and data acquisition process. Data assimilation to the models is another technique that can improve the model performance by using *in situ* data. Because new sensor development is focused on variables that are of critical concern in the model, the opportunities for improving both models and the resulting knowledge are increased significantly.

Aside from modeling, several other data-related sensor issues cut across the application scenarios. New sensors are expected to lead to a broader array of experiments than previously possible. Wide-ranging spatial deployment will mean that researchers will have access to wider spatial statistics to perform geospatial analysis. Creative ideas are needed for ways to calibrate sensors by both sensor self-assessment and cross-comparisons among sensor “nodes” in the network.

3.2.2 Increasing Spatial Coverage

Workshop attendees proposed two methods for providing broad spatial coverage of sensors: nested suites of sensors and core sets of sensors. Networks with multiple layers of inexpensive, simple sensors capable of measuring temperature, radiance, and other environmental variables can be placed at many nodes. Expensive, special-function sensing systems such as air flux towers and flow cytometers can be located more sparsely. Models can be used to help determine the optimum location for specialized sensors, and by using simple proxies derived from the higher density network, the placement of specialized measurements can be interpolated and extrapolated. This approach requires investment in the development of robust proxies and technologies that directly measure critical parameters.

In order to increase spatial coverage, effective design and deployment of a sensor network must start with a “core” set of proven sensors that provide quality-controlled data. Other sensors can be added to the core when the development of the core and its associated data streams has been completed.

3.2.3 Designing for Ultra-Low Power Consumption

The sensors, communication devices, mobile platforms, and tracking components used in remotely deployed sensing systems—that is, systems that are off the grid—require ultra-low power consumption. The power budget is one of the key determinants of both mission longevity and duty cycle (frequency of measurement) for sensor operation during a mission. Advances in electronics that reduce power consumption, as well as technological improvements that both increase battery capacity and reduce battery size, are high priorities for all fields. Also, improved methods are needed to transmit continuous data both in real time and in burst, using minimum power.

3.2.4 Materials Issues

Some sensing systems will be deployed in environments where recovery is difficult or impossible. As a result, workshop attendees expressed interest in the development of environmentally benign, or even decomposable, sensing systems, materials, and power sources such as batteries and fuel cells. On the other hand, materials used in hostile environments—such as those with corrosive fluids, temperature extremes, and biofouling—must be able to resist rapid degradation.

3.2.5 Measurement of Proxies in Lieu of Organisms or Chemicals

Sensors often measure a proxy for the true quantity of interest—for example, a reading on a gauge that reflects a quantity of interest. Workshop attendees expressed a general concern that many existing sensors use proxies of changing and even unknown reliability. This issue presents engineers and scientists with the challenge of clearly understanding and quantifying the relationship between proxies and the underlying variables.

Although this issue is a general concern across many classes of parameters, perhaps the most compelling case is in the area of biological variables, where typically few sensors measure biological processes or biological community structure directly. For example, to understand changes in biotic structure resulting from changes in land use, climate change, and invasive species, sensors must be able to detect changes in the individual species occurring over spatially broad areas. Currently, sensors are unable to detect such changes. This will be a particularly challenging area for sensor research; successful solutions would greatly increase our understanding of the processes driving biotic community change.

Another area where proxy measurement is needed is in aquatic systems, where more types of chemical sensors are needed to track the source, movement, and fate of key solutes. In particular, as several workshop breakout groups noted, our understanding of land/water interactions over broad spatial scales would greatly increase if sensors had an increased ability to measure total nitrogen and phosphorus, and not just the inorganic fractions that are being measured today.

3.2.6 Requirements for Flux-Based and Profiling Sensors

Finally, in many systems there is a need to understand multiple processes that occur across profiles or gradients, whether upward from the land surface into the atmosphere, downward from the water surface through a water column, or across a particle/fluid interface. Because multiple variables are often of interest, sensor packages capable of sampling multiple key variables across the gradients are needed. The fact that sensors are suited to a specific scale is a challenge. For example, large-scale optical sensing for terrestrial vegetation or aquatic plant biomass is based on reflectance measurements, whereas small-scale measurements may be based on fluorescence or other optical parameters. A rigorous analysis is needed of bias as introduced by the use of different sensor types for different scales.

3.2.7 Means to Share Expertise Across Fields

The analytical detection systems used to study environmental variables often share a high degree of commonality across many environments, whereas the "handling" systems that are used for sample extraction, preparation, and delivery are often specific to the particular environment. One example of a suite of variables that are important across a range of environments—including ocean, freshwater, soil, and atmosphere—is that of combined nitrogen compounds, both total nitrogen and specific nitrogen species. The detection of nitrogen compounds may be based on absorption spectroscopy, mass spectroscopy, fluorescence, and by other means.

In order to use limited financial and human resources most effectively, new mechanisms that facilitate the rapid sharing of technological advances for detection systems—such as the miniaturization of detectors, reductions in power consumption, improved long-term stability, and self-calibration protocols—are a high cross-cutting development priority. By combining the individual efforts to improve common detection systems, more resources can be allocated to solving problems related to environment-specific handling protocols.

3.3 CHALLENGES OF THE INTERFACIAL ENVIRONMENT

In addition to the above technical issues that cut across many or all of the scenarios, there are also new opportunities in science, especially as related to interfaces such as atmosphere-water or water-soil. Such interface areas add to the challenges at the frontier of the environmental sciences. This section provides a brief overview of the issues surrounding interface environments.

Interface environments include atmosphere-water, water-sediment/soil, and air-soil as well as the boundaries between fluid masses of sharply different characteristics. These boundaries are important because they call for the measurement of flux. Fluxes—especially of key carbon species such as CO_2 and CH_4, nitrogen species such as NH_4^+, N_2O, and NO_3^-, sulfur, and many important metals—are very important for understanding local, regional, and global biogeochemical processes.

The processes that occur within environmental systems and interfaces are varied and complex; they include adsorption, absorption, biochemical/chemical oxidation, growth processes, replication, flow equalization, extractions across phases, filtrations, aggregations, hydrolysis, precipitation, thermal, density, and partitioning. In general, environmental scientists are interested in measuring changes at interfaces and within boundaries (volumes). Fundamentally, the exchange of matter, energy, and information is of paramount importance. The rates, fluxes, and transport across boundary layers and process dynamics—for example energetics, kinetics, reaction rates and transformations—inform our understanding of change. Researchers are interested in being able to identify the scale, both temporally and spatially, of the interface. The typical procedure begins with an understanding of the microsystem process dynamics, which eventually yields progress on environmental macrosystems.

With a few exceptions, satisfactory *in situ* sensors do not currently exist. Moreover, the need to measure flux requires sensor suites that either implicitly or explicitly quantify transport as well as concentration. Moreover, as these environments typically exhibit sharp chemical and physical gradients, sampling must be performed across small spatial scales or, in the case of eddy covariance measurements, at high frequency (< 1/sec) to infer transport and flux. In cases where fluxes are inferred from gradient measurements, sensor localization must be particularly accurate.

Interface boundaries often span aerobic/anaerobic environments wherein different redox potential exists in close proximity. In such boundary areas, higher metabolic activities, diversity, and densities of microbes and macrofauna exist relative to the more homogeneous media that are distant from the boundary. This layer is often the home of key microbial transformations of chemical species; for this reason, parallel measurements of the biotic community are needed in tandem with those of the chemical and physical environment. For those biotic measurements that are not feasibly obtained using *in situ* probes, data could be obtained using modular high-resolution collection devices that feed into a remote analysis instrument. As is evident from the issues discussed here, measurements at interfaces present a particularly complex and challenging set of problems. However, the resolution of these problems will provide great scientific payoff.

The interface question will determine the scale at which the technology will have to operate, which will include the modes and types of technology, the heterogeneity of the technology, the instrument interface, sensor fusion, strategy, power needs, and the models to be used. A technical solution to interfacial dynamics monitoring may involve a mixture of platforms, sensors, and integrative models. One leading model currently under development is the Adaptive Oceanographic Sampling Network (AOSN) sponsored by the Office of Naval Research (ONR). This configurable network approach utilizes heterogeneous technologies, such as remotely operated vehicles (ROVs) and sensors, is dynamic in operation and composition, and relies on a systems approach. The objective is to design and build an adaptive coupled observation and modeling and prediction system that can integrate coupled observational and modeling systems, employ multiple oceanographic modeling and assimilation schemes, and use forecasts to "inform" sampling patterns. This technological strategy may also be effective for sampling and characterizing volumes and interfaces in other environmental media.

Several factors emerge when attempting to deploy heterogeneous sensing network technologies in the interfacial environment. Logistics and management of the various technologies must become more sophisticated. Agencies—ONR, the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA), among others—must streamline interagency cooperation, as targets, objectives and products from these sensing networks may be similar. The physics, biology, and chemistry communities must establish new and more effective collaborations across traditional boundaries. The choice of appropriate technology scenario and predictive model becomes more critical once the complex environment of interfaces is factored in. Furthermore, the data must be properly fused in order to provide the "right picture." Finally, the complexity of the interfacial environment requires complex technological solutions—which means major financial investment. The return, however, will greatly advance our understanding of the environment and the changes that occur within it. It may be worthwhile to explore the topic of interface science and technology at a future workshop.

3.4 SENSOR-RELATED COMMUNITY DEVELOPMENT, EDUCATION, AND OUTREACH ISSUES

Education is critical if the general public is to become aware of the science of sensor networks. Aggressive educational outreach should be pursued beyond the immediate community of sensor professionals for a variety of important reasons:

- recruitment of new scientists and engineers into sensor R&D efforts
- wider dissemination of technologies
- greater public buy-in and understanding
- acquiring financial and volunteer support

The combined efforts by researchers and educators will contribute to developments in the area of environmental observatory science.

3.4.1 Involving the Community

Workshop participants agreed that a very large and interdisciplinary community of scientists should participate in research involving environmental observatories (EObs) in order to address the issues noted above. In this report, the term "community" refers to the scientists who participate in sensor research, development, and deployment. Because the success of the observatories will require a completely new way of "doing science"—including significant collaborations among specialists representing a broad range of sciences—creative methods for assembling and maintaining a vital community will be needed. Discovery- and observation-based sciences will meld in the EOb groups, and frequent interactions among the scientists will permit the entire community to progress more quickly. Real and perceived institutional barriers that inhibit participation will need to be removed. Incentives should be offered to top scientists to entice them to participate in these programs.

The barriers and incentives would differ according to each scientist's career stage. For early-career scientists, the most important barriers are associated with the promotion and tenure process. Many institutions expect junior scientists to author a specified number of papers; it often "counts against" them if they co-author papers with scientists in other disciplines. Also, it is increasingly common for institutions to expect junior faculty to obtain a minimum amount of grant money. To overcome these barriers, workshop participants recommend a proactive policy within the community to encourage first authorship by junior faculty and establish mentorship programs within EObs. In addition, workshop participants encourage scientific leaders in the EObs to be supportive of talented early-career faculty who are proceeding through the promotion and tenure process. NSF can also assist by developing programs with support for early-career faculty who seek to work on EOb projects.

For tenured faculty who are now being asked to accept new ways of doing research, the barriers are different; for example, they must learn new processes and assume the risks that are associated with the decision to commit to working with a large group of collaborators. To overcome these barriers, workshop participants recommend that the mid-career and senior faculty participate in invited seminars and workshops, and exchange graduate students and postdoctoral fellows. Additionally, NSF can play an active role in supporting senior faculty by establishing formal methods of recognition, such as pre-sabbatical grants for use in visits to network centers. Leaders of professional societies can enhance interest and participation by writing articles for leading journals that explain and extol the value of research involving EObs.

The greatest incentive for mid-career and senior scientists to participate in research collaborations is the availability of funding. Workshop participants recommended that NSF program staff continue to develop cross-disciplinary funding opportunities that encourage multidisciplinary cooperation in research involving EObs. Researchers can take advantage of already existing opportunities, such as the Integrative Graduate Education and Research Traineeships Program.

EOb members and NSF staff can increase awareness of environmental issues and of the importance of research in EObs by disseminating news and information about environmental observatories and their projects. Information should be distributed to students of all ages through academic channels and to the general public through mass media outlets.

3.4.2 Audiences

Education and outreach involves the dissemination of information to a variety of audiences, including policymakers, Congressional staffers, scientists, engineers, resource managers, the general public, the media, and administrators, educators, and students at various formal and informal educational institutions. Formal education includes grades K–16 schools, research institutions, community colleges, and adult basic education/adult literacy programs. The informal audience is extremely large and includes (but is not limited to) zoos, museums, aquaria, and nature centers. The more people researchers in EObs can reach, the more likely they are to trigger interest, and the more legitimate it will be to continue to seek funding for research in EObs.

3.4.3 Products

Four primary types of education and outreach products have been identified as outcomes of sensor networks: technology, data, people, and curricula.

Technology

Practical application of knowledge gained in environmental research can lead to a new capability. Members of the general public usually take technology as a given and work with what they are given. Thus, if they perceive technology that allows data to be collected in sensors as useful, they will start using the technology. Educators will be able to use the new technology. Workshop participants envisioned new classroom tools that would allow teachers and students to access, analyze, and display data from multiple sensors in real time, and enable them to communicate with experts.

Data

The data coming from the sensors are going to be a rich and valuable resource for many audiences. Because each audience will apply or integrate the data uniquely, applications should address a wide variety of vocational and recreational uses of the data—for example, to provide beachgoers with daily weather information.

Sensor networks hold the potential to produce amazing and engaging data sets that can enliven a science classroom and provide students and teachers with new ways to perceive and interact with science. Instead of just reading about the ocean and currents, students with real-time access to coastal observing data coupled with satellite imagery can actually see a real current in motion, and can study its effects as they happen.

People

Researchers, scientists, faculty, and others who participate in sensor network projects serve as role models for students, and they can also help students explore career pathways in technology and science. For those reasons, education and outreach efforts should emphasize the role of people who are involved with all aspects of sensor networks. Students who study and use these networks will improve both the level of participation in, and our understanding of, environmental processes. This type of outreach is also a key strategy for enhancing international collaborations (see section 3.5).

Curricula

Information and lesson plans must be provided to educators in a tiered fashion; that is, at varying complexities and in formats that accommodate a wide range of learning stages and styles. Curricula should include accurate and engaging information about the reasons for collecting environmental data and the many ways that researchers use it. The curricula can contain specific lesson plans and experiment guidelines that utilize data acquired by sensors. The hands-on experiments, as well as use of data directly relevant to the audiences, will entice them to engage in EOb activities.

Workshop participants discussed ways of making all data and lessons available to anyone with both a level of interest and access to the Internet. A key goal would be to reach a diverse audience, especially populations that are underrepresented in the sciences. Therefore, profiles of scientists who are currently involved with the sensor networks should be included, to enable them to serve as role models for educators and students who are considering a career path in science. This "packaging and delivery" of data and information is also an extremely attractive option for disadvantaged school districts, which may not have resources to purchase the types of materials that typically encourage student interaction with science.

There are not nearly enough students in the pipeline today to support the network infrastructure of tomorrow, and with the continued declining interest in the sciences as career choices, the available workforce currently looms as one of the bigger limiting factors to the development and deployment of sensor networks. In order to increase the success rate of attracting students into the field in the long run, it is necessary to expose students of all ages to the complexity of sensor networks and engage them in ongoing activities. These activities can range from participation in fieldwork to working with project team members in planning for meetings. Additionally, establishing formal or informal mentoring relationships can help students to create relationships with professionals. This method, often successful in different disciplines, is a useful tool especially for students participating in interdisciplinary research; they can learn first hand, often in an informal setting, of the experiences and the hardships of the researchers in the field.

Outreach programs should engage students and citizens in the generation and use of the data. For example, the Satellite Lake Observatory Initiative in the upper Great Lakes states of Wisconsin and Minnesota engages volunteer "citizen scientists" who take measurements at predetermined times and submit them electronically. These measurements provide ground truth for remote sensing, thereby enriching the scientific data that are obtained. These data are made available on a website, http://www.lakesat.org.

In addition to the efforts described above, ongoing professional development activities must be supported as well. Professional development opportunities could be provided remotely through Internet-based applications or face to face at meetings and professional conferences. Such opportunities will hopefully provide the various audiences with a venue for new applications of sensor networks. On-the-job training in using database management systems is also crucial to ensuring that educators, resource managers, policymakers, scientists, and engineers continue to use the data effectively.

The area of environmental observatories also has potential to attract students from underrepresented groups. The students in these groups have chosen their careers based on usefulness to their community. Their desire to contribute to their community is strong; as environmental problems have been known to affect people from underrepresented groups, it is an opportunity to attract these students into the field.

3.4.4 Providing Data to Audiences

The real-time data generated from sensor networks—one of the key educational and outreach products of sensor networks—is inherently compelling. The keys to effective communication with the public are (1) to deliver the information to the public through a user-friendly interface, and (2) to demonstrate practical, everyday applications of the data. As network groups are formed, they should include at least one educator whose job is to deliver data and information to the public. Ideally, a single website could serve as a central resource for users, providing access to as many data sources as possible. On the other hand, competing resources could fracture the potential user community and possibly discourage members of the public from using the information.

3.4.5 Recommendations for Education and Outreach

The development of curricula and tools for teachers and students of all levels should be emphasized to encourage connections between observing systems and target audiences. Software and education modules should make use of real-time data that are accessible to students, teachers, and the broader public. The development of educational materials should be coordinated to avoid wasteful duplication. Coordination efforts should be established as soon as possible, so that they align with the rollout of new observing systems and networks. Educational programs within particular environmental systems should consider coordinating their materials, taking a "systems approach" to their development. For example, a lesson on water temperature off the coast of Maine would be useful for educators and the public, but it would be much more useful if those data were part of a larger lesson on water temperature in which the user could select from among many such data sets, combining them at will. Such an approach would maximize the potential inherent in the coordination of data generated by environmental observing systems. The observing systems should be proven to be reliable, accurate, and accessible sources of data before suitable educational materials that use their data are developed.

Attempts also should be made to integrate data gathered by observing systems into familiar everyday activities. For example, a weather forecast, embraced by the public and educators, is an extremely useful, succinct summary of enormous amounts of modeling and observing data. Obviously, not all data collected through observatories will be as pertinent to the public; nevertheless, the effort should be made to create or document the many practical applications of scientific information.

The development of support materials will require a coordinated, long-term commitment and should likewise have long-term expectations—perhaps as long as the processes under investigation. Projects in this area should be encouraged, and in some cases required, to have explicit education and outreach activities.

Supplemental funding should be provided for the purpose of engaging secondary-level (grades 9–12) teachers and community college faculty in projects. This will have the benefit of allowing the instructors to convey their own experiences to students in addition to the data and information from sensor network projects. Professional development for educators should not be limited to a single point of contact. Research indicates that educators require up to three years to incorporate or adopt new materials into their curricula, especially when computers and new technologies are involved. The funding should be ongoing in nature, and it could provide venues for communicating about updates as networks evolve.

Sensor network organizations should work with local agencies to create "citizen scientists" (see the example described above). Every effort should be made to work through existing organizations to avoid duplicate efforts. For example, the EPA's National Directory of Volunteer Monitoring Programs (http://yosemite.epa.gov/water/volmon.nsf/Home?readform) offers a collection of existing water quality programs. A comprehensive database of ecological systems where sensor networks are or will be deployed could be assembled immediately and maintained for use by all audiences.

Finally, sensor network organizations must remember to strongly encourage diversity among the participants in their funded activities.

3.5 INTERNATIONAL COLLABORATION

Environmental processes do not respect political boundaries, and the decline of biodiversity, or spread of pollution in the United States, cannot be managed within the confines of the country alone. Sensor networks are needed that cross U.S. boundaries and monitor regions that influence U.S. interests. U.S. scientists should be prepared and willing to collaborate with other multinational sensor initiatives including global sustainability, advancement of fundamental science and technology, and educational experiences. Furthermore, as articulated in the new book by Thomas Friedman, *The World Is Flat, A Brief History of the 21st Century* (Friedman, 2005), we live in an age where we can bring together resources and intellect from anywhere, and redistribute the those resources to other parts of the world. It is incumbent on the U.S. research community to engage internationally to address global environmental challenges. The National Science Foundation's Office of International Science and Engineering (OISE) may play an active role in coordination of such initiatives.

3.5.1 Global Sustainability

International collaboration can provide a greater resolution and understanding of global processes like global climate change, so that the impacts, including ecological, physical, social, and economic, can be better predicted. Unique regions of the world will experience intense development pressures. The ability to monitor, analyze, and understand these unique regions with colleagues there and throughout the world will enrich our understanding and create lifelong collaborations. Furthermore, the presence and involvement of international collaborators often allow local officials to react to the data that are being produced in a timely manner.

Other collaborative applications of environmental observatories, all with large human impact, include disaster forecasting, mapping regions of key biodiversity, and identifying regions that are susceptible to natural disasters. U.S. watersheds that are being “restored” should be compared to “almost-pristine” watersheds elsewhere that are just beginning to experience development. New knowledge could be gained about the conservation and sustainability from such studies.

3.5.2 Advancement of Fundamental Science and Technology

International collaborations between U.S. researchers and their counterparts in other countries provide access to technologies, research facilities, infrastructure, and scientific expertise not available in the United States. For example, Japan is poised to become a global leader in micromachines; both Europe and Asia produce middleware for cyberinfrastructure and sensor nets that could be adapted by researchers in the United States. Sharing these skills and knowledge can lead to more effective use of resources, and may result in new discoveries.

3.5.3 Educational Experiences

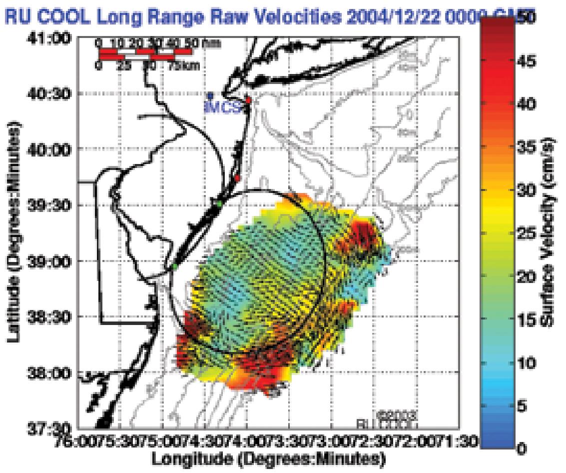
Research programs in environmental observatories can provide undergraduate and graduate students and postdoctoral researchers with opportunities to have meaningful international field and in-class experiences. Students who participate in student exchange programs can be equipped with the language knowledge that would allow

Education: The COOLRoom

In 1997 scientists at Rutgers University’s Coastal Ocean Observation Laboratory (RU COOL) established a website, called the COOLRoom (http://www.thecoolroom.org), to serve as a command post for studies being conducted on a cross-section of the ocean off the New Jersey coast, and as a place for general-interest users—including fishermen, boaters, and swimmers—to find real-time data on coastal New Jersey’s underwater weather. The data are pulled together from satellites, coastal radars, and underwater weather stations and made available through personalized interactive web-based interfaces.

The companion educational website to the COOLRoom is the COOL Classroom (http://www.coolclassroom.org), which allows students and teachers to virtually explore the waters off New Jersey along with scientists who are embarked on research trips. Through exercises, study guides, and interactive programs, students learn how to identify weather patterns, make predictions, and observe the ocean from 500 miles above the earth and 15 meters below the surface.

The image below (left) depicts raw, averaged ocean surface current velocities off the New Jersey coast. Data like these are made available through the COOLRoom website. To the right, teachers board a Rutgers University research vessel to perform some “old fashioned” oceanographic sampling, which students and teachers will observe remotely. (Source: Rutgers University’s Coastal Ocean Observation Laboratory)



them to be competitive in an increasingly global workforce. Furthermore, many examples can be provided in which students and/or postdocs establish initial bridges between U.S. researchers and international sites that end up lasting past the individual's tenure there. An example of this is the Pacific Rim Undergraduate Experiences program (PRIME, http://prime.ucsd.edu). This program funded the Pacific Rim Application and Grid Middleware Assembly (PRAGMA; http://www.pragma-grid.net) project, which enabled researchers at the Taiwan EcoGrid project (http://ecogrid.nchc.org.tw) to establish a link with the researchers in the ROADNet project at University of California, San Diego (http://roadnet.ucsd.edu). In this way undergraduates can be links (and create technology transfer) between development groups in the U.S. (e.g., ROADNet) and overseas (e.g., EcoGrid). The PRIME/PRAGMA relationships fund the students and make the linkages. See also section 3.5.4. for the other NSF opportunities.

Existing programs that draw together instructors and graduate students from several institutions also could be used as models. Three examples are the programs of James Ehleringer at the University of Utah, the Flathead Lake Biological Station at the University of Montana, and the Centro EULA Graduate Summer School, University of Concepción, Chile. An international collaboration of this type could be accepted as satisfying the foreign language requirement of some Ph.D. programs and would provide students with an opportunity to demonstrate competency in a foreign language while obtaining a meaningful professional and cultural experience.

3.5.4 Recommendations for International Collaboration

The recommendations of workshop participants focused on opportunities for student, researcher, or teacher exchanges. A program should be created that allows scientists to undertake short-term travel and bilateral exchanges. This program should include the means whereby observatories and programs establish deeper collaborations that continue past the period of travel or exchange. NSF's Office of International Science & Engineering may be able to provide assistance in this regard.

Research should be sponsored that supports students and postdoctoral researchers, perhaps using sensor deployment at paired research sites. This could take the form of a global IGERT and emphasize the importance of programs such as the NSF Pan American Advanced Study Institute. Since the workshop in November 2004 NSF has created an exciting new program, the Partnerships for International Research and Education (PIRE; http://nsf.gov/pubs/2005/nsf05533/nsf05533.txt) which has attracted an incredible response from the community. It is hoped that this program will be expanded, and will attract innovative and stimulating projects in sensors for environmental observation.

Finally, possible links with other international programs from diverse origins, such as the Fulbright program or the Nature Conservancy, should be investigated.

3.6 KNOWLEDGE-SHARING: CROSS-FERTILIZING THE OBSERVING NETWORKS

Unlike many professional meetings in which attendees tend to know each other or their work, *Sensors for Environmental Observatories: A Framework for Progress* brought together people from many backgrounds, professions, and disciplines, most of whom were meeting each other for the first time. Through presentations and discussions, the initial steps toward cross-disciplinary collaboration were taken. For example, lake ecologists expressed an interest in applying biosensors that have been developed for ocean and coastal studies, and researchers with expertise in rivers were able to share their knowledge and experience with colleagues specializing in "built" aquatic environments.

The Science, Education and Collaboration breakout group noted that sensor networks provide unique opportunities for knowledge-sharing, and that these will revolutionize the way sensor science is done. The recommendations outlined below are aimed at accelerating the community's progress along the path of technology deployment and usage.

To effectively harness the funds that are available, ideas must be shared so that efforts are not duplicated and so good ideas from other communities, whether in the United States or elsewhere in the world, are leveraged properly. Accordingly, the workshop attendees offered two major recommendations, one calling for continued information exchange and the other encouraging multidisciplinary team research.

The community, including NSF, should continue sharing information, cross-fertilizing ideas, and establishing bridges between researchers, technicians, system builders, and broader observing communities. This can be done by providing funds that would be used to allow people to move between projects for varying lengths of time. For example, researchers could apply for mini-grants that would allow them to be embedded in another observing system for periods ranging from weeks to months. Funding could be made available to postdocs to enable them to migrate between various observing systems, thereby allowing them to act as idea exchange conduits between systems.

Information sharing and collaborations could also be encouraged through the provision of funds for intensive short courses such as summer institutes that would bring together researchers and students to focus on a topic in depth. Funds should also be provided for the creation of information-sharing resources such as those developed by National Weather Service Training Portal (http://www.nwstc.noaa.gov/nwstrn/), or Meteorology Education and Training (http://meted.ucar.edu).

Funds should also be allocated for the development of a facility where people could be technically trained. As a longer-term goal, a "center" could be established to develop technologies, host workshops, and provide training for observing systems. The meteorological community trains its people on new technologies in this fashion. The community should also consider establishing a peer-reviewed journal or an e-journal on environmental sensors, or on sensors in general regardless of the application. The journal should strive for a high frequency of publication.

Multidisciplinary team research, another recommendation of the workshop attendees, must also be encouraged. In its proposal solicitations, NSF should strongly encourage the formation of multidisciplinary teams to address key problems. Although this is happening to some extent, for example in the biocomplexity in the environment priority area, the workshop attendees encouraged NSF to continue with this approach in the future. There is no one strategy for the formation of such teams; options should be left open. Funds should also be provided to help researchers retool, to provide specific expertise, and to encourage more bridge building between communities.

3.7 THE NOPP MODEL FOR INTERAGENCY COLLABORATION

The scale of the problems related to the deployment of effective sensor observatories is larger than individual scientists, institutions, agencies, and even countries. NSF, as part of the community, should find ways to foster interactions and collaborations among government agencies that will focus support on the development and deployment of sensors and sensor networks for environmental observations.

The *National Oceanographic Partnership Program* (NOPP, http://www.nopp.org) can be a model for interagency collaboration. NOPP is a collaboration of fifteen Federal agencies whose mission is to provide leadership and coordination of oceanographic research and education programs throughout the United States. An innovative program established by Congress in Fiscal Year (FY) 1997, NOPP facilitates new interactions among Federal agencies, academia, and industry; increases visibility for ocean issues on the national agenda; and achieves a higher level of coordinated effort and synergy across the broad oceanographic community. NSF chose NOPP as an established model for continuing to grow interagency collaborations and increasing its funding resources and its impact in this interdisciplinary field.

Through NOPP, the public and private sectors are brought together to support larger and more comprehensive projects; to promote the sharing of resources; and to foster community-wide innovative advances in ocean science, technology, and education. Using a peer-review process, NOPP identifies and funds the most scientifically and technically meritorious research that clearly demonstrates public/private sector partnerships within that year's areas of interest. In an era of declining science literacy, the ocean readily provides an exciting vehicle to stimulate learning and promote math and science education. NOPP strongly encourages projects to incorporate components that explicitly address public education. NOPP is also a sponsor of the National Ocean Sciences Bowl (NOSB), a national academic competition for high school students on topics related to the study of the oceans.

The following agencies and organizations participate in NOPP:

- U.S. Navy
- National Oceanic and Atmospheric Administration
- National Science Foundation
- National Aeronautics and Space Administration
- Department of Energy

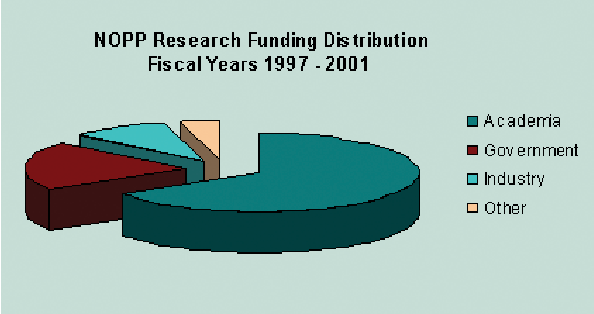


Figure 3.7.1. NOPP Research Funding Distribution, FY 1997 to FY 2001. (Source: NOPP Program Overview, http://www.nopp.org/Dev2Go.web?id=205277&rnd=11807)

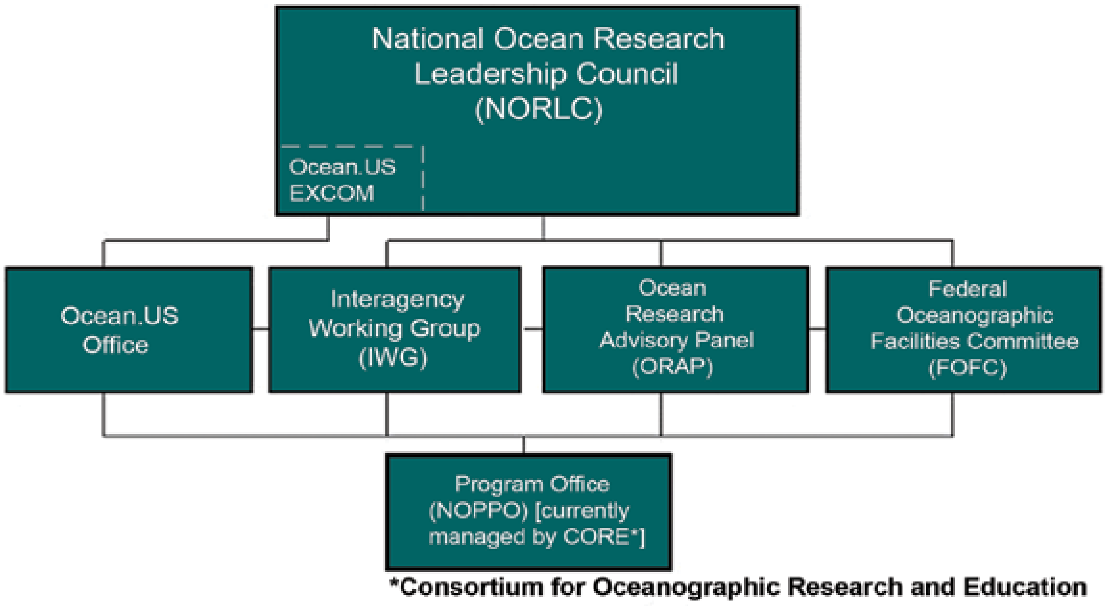


Figure 3.7.2. Organization of NOPP governance. (Source: http://www.nopp.org)

- Environmental Protection Agency
- U.S. Coast Guard
- U.S. Geological Survey
- Defense Advanced Research Projects Agency
- Minerals Management Service
- Office of Science and Technology Policy
- Office of Management and Budget
- Department of State
- U.S. Army Corps of Engineers
- Department of Homeland Security

NOPP distributes funds for programs of interest between academia (the largest share), government, industry, and “other” programs, as illustrated in Figure 3.7.1.

3.7.1 Governance

The current organization of NOPP is illustrated in Figure 3.7.2. Each of the components is described in detail below.

The **National Ocean Research Leadership Council** (NORLC) is the decisionmaking body of NOPP. The council confirms program activities and funding opportunities. It is composed of the heads of fifteen Federal agencies that conduct or fund ocean research or develop ocean research policy.

The **Ocean Research Advisory Panel** (ORAP) provides advice and scientific guidance to NOPP. It is composed of representatives from the National Academies, ocean industries, state governments, academia, and other organizations/communities as appropriate.

The **Federal Oceanographic Facilities Committee** (FOFC) advises the NORLC on policies, procedures, and plans relating to oceanographic facility use, upgrades, and investments. Membership is composed of Federal oceanographic facilities managers.

The **Interagency Working Group** (IWG) performs staffing functions assigned by, and on behalf of, the NORLC. Membership reflects that of the NORLC.

The **Ocean.US Executive Committee** (EXCOM) serves as the oversight body for the Ocean.US Office. Membership is composed of NOPP agencies that are party to the Ocean.US Memorandum of Agreement and that have provided personnel or other resources to the Ocean.US Office.

The **Ocean.US Office** serves as the national focal point for integrating ocean observing activities. Its goal over the next decade is to integrate existing and planned elements to establish a sustained ocean observing system to meet common research and operational agency needs.

The **National Oceanographic Partnership Program Office** (NOPPO) was established by the NORLC to assist in the management of NOPP and provide daily administrative support. Using competitive procedures, a contract for the operation of the NOPPO was awarded to the Consortium for Oceanographic Research and Education (CORE) on 14 July 1997.

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Chapter 4. Enabling Technology Issues

4.1 INTRODUCTION

The goal of the enabling technologies breakout session was to identify those technology gaps, between current and needed sensor capabilities, that if filled could lead to new scientific understanding. Because the priority parameters to measure had been agreed upon in previous community workshops, the participants of this working group tried to look for similar demands in sensors across multiple environmental settings, including land, air, water, and biota. Finally, the group talked about what the National Science Foundation (NSF) can do to encourage greater migration of technology across the media. The group participants identified and classified new opportunities for environmental observatories to use sensors, with the intention of creating a new "vision" for observatory-based sensor science. The group also addressed crosscutting sensing solutions. Participants concluded that the wider science community should categorize sensor technology requirements into near-, mid-, and long-term needs:

- Near-term technologies will be available within the next several years.
- Mid-term technologies will, with small incremental changes, yield large observational benefits.
- Long-term technologies will result in major changes in sensor observatories' "vision," or sensing perspective.

Specifically, the group was charged with answering the question, "What are the primary existing sensor network application(s) and/or development efforts?" Initially, the group divided the applications by environment (lithosphere, hydrosphere, and atmosphere) in parallel with the overall workshop; participants attempted to identify the sensors that were needed for each application and the proxies that could be sensed as alternatives. However, given the interest in the identification of sensor technologies across traditional boundaries, the group decided that a function-based classification (physical, chemical, and biological) was more appropriate. Sensors could be deployed across any of the classifications with some modifications (e.g., in packaging) for the particular environment.

4.2 PHYSICAL SENSOR TECHNOLOGIES

Physical sensor technology, in general, is more mature than either chemical or biological sensor technologies. A large industrial base exists for the manufacture of temperature, pressure, and physical property sensors, and consequently there are more examples of these types of sensors than others. However, current physical sensor technology does not provide 3D parametric physical information for air, water, soil, and groundwater over spatial scales ranging from the micro (e.g., pore volume) to the mega (e.g., kilometer scale volumes). New 2D and 3D imaging techniques for physical parameters would be able to assist in mapping the fluxes in environmental volumes and interfaces. For example, atmospheric turbulence sensing requires 3D flow field measurements that are within 10 cm of the surface; the sensors must be environmentally robust for long-term observations, and sensitive to ±0.1 cm/s. Water column sensing requires 3D flow fields quantified at the ±5% level throughout the water column, in order to understand the turbulent transport and flux of gases and chemicals in the water and at the water-air interface.

The breakout group identified a number of other requirements for physical sensing:

- 1D and especially 3D flow field (transport, fluid velocity) information in air, water, soil, and groundwater.
- Microturbulence measurements.
- Instruments to quantify the relationship between turbulence in the water and coupled turbulence in the air directly above the surface.
- Standards for accuracy of eddy covariance fluxes, most critically in friction velocity.
- UV low-power optical systems.
- Accurate techniques to measure particle backscattering for small angles (0.01°).
- Standardization for field physical sensing devices.
- Continued miniaturization in physical sensors, electronics, and packaging.
- Discrimination of particles and nanoparticles, including the discrimination of non-biological and biological composition.
- Particle size distribution and shape sensors with near-real-time response.
- Carbon dioxide mapping. Range-resolving lidars need to be developed to measure carbon dioxide scalars and fluxes in the atmosphere close to the surface (within 50 m).

Sensor systems must be able to accurately establish the sensor's orientation within the environment. Orientation is the largest uncertainty in hydrological observations, for example. As submersible robots become increasingly available, knowledge of their exact location and orientation will become critical. An error of alignment within ±0.1 degrees or ±0.5 cm will substantially degrade the utility of bio-geo-chemical observations. Remote or high-altitude observation sites require orientation sensors with ±0.1 degree accuracy, because off-axis errors propagate into the measurements.

4.3 CHEMICAL SENSOR TECHNOLOGIES

Chemical sensors are urgently needed for a wide range of inorganic, organic, and biochemistry sensing applications in all environments (e.g., the atmosphere, soils including crop soils, sediments, groundwater, fresh and marine waters). To date, few sensors are robust enough to measure key or fundamental chemical compounds and ions in sustained operations at sufficiently high acquisition rates, precision, and sensitivity. Requisites to be measured in an observatory mode of operation include oxygen, basic nutrients, hydrogen sulfide, pH, CO_2, NO_x, SO_x, CO, O_3, Fe, Mn, and trace metals. Several electrochemical and optical oxygen sensors are known to be prone to biofouling in short periods of time. Currently, nitrate content can be measured in water by UV spectroscopy, but only at levels greater than 1-10 micromolar, which are well above the levels found in the surface ocean. Furthermore, no available sensors are robust or sensitive enough to measure ammonia, nitrite, or phosphate in waters, soils, and sediments at the desired levels or acquisition rates.

In addition, there is a clear need for sensors that are capable of detecting organic compounds of both small (< 300 Da) and large (>300 Da) molecular mass. Small molecules include methane, xenobiotics such as halogenated hydrocarbons, and toxins. Compounds of large molecular mass, which have hitherto been largely ignored, include dissolved organic compounds (DOC), dissolved organic nitrogen compounds (DON), aerosols, and nanoparticles. Scientists see research into both types of organic compounds as an emerging area in need of greater understanding.

Sensors with multi-element and/or chemical speciation capability[1] at the same spatial and temporal resolution are highly desirable for elucidating complex environmental processes in 3D. These sensors are based on fundamental analytical methods that include spectroscopy (e.g., UV, IR, Raman, laser-induced breakdown [LIBS], and X-ray), electrochemistry (e.g., voltammetry), radiochemistry, mass spectrometry, and separation techniques.

Sensors that can serve as chemical proxies for biological processes until appropriate sensors come online are also desirable. For example, because iodate and nitrate reduction of organic matter have similar thermodynamics, the onset of iodide detection after oxygen consumption in sedimentary porewaters is an indication of denitrification. In hydrothermal vent systems, the detection of hydrogen sulfide can be an indicator of the presence of chemosynthetic organisms, whereas no detection of hydrogen sulfide indicates the absence of chemosynthetic organisms.

Lastly, some chemical sensors, including those based on electrochemistry (potentiometry using ion selective electrodes and voltammetry); spectroscopy using derivitization reagents after sampling; radiochemistry; and mass spectrometry may be capable of taking measurements in all media. However, more investigation into adaptive sensor interfaces will be needed before analytical techniques are able to cross the boundaries between media.

4.4 BIOLOGICAL SENSOR TECHNOLOGIES

Biological sensors are used to measure biological reactions and physiological functions in both natural and built (that is, engineered) ecosystems, providing a complete "fingerprint" of ecosystem structure and function over time. Perhaps the least developed of the three sensor types, biological sensors can provide key information on the function, structure, and composition of biologically influenced ecosystems in real time. As with the other types of sensors, the signals produced by biological sensors need to be processed in ways that allow for adaptive sensing. Furthermore, the sensors need to be capable of long-term deployment, and should be capable of integration with other sensing devices. Biological sensors need to be developed for monitoring all levels of biota, from the microbiological to the highest levels in the eukaryotic domain. Although some aspects of sensor deployment may vary when implemented across different media—air, water, land, and biota—the sensor development needs are considered to be similar for all.

The group identified several existing and new technologies that need further development and improvement before they are ready for field deployment:

- *Genomic-based sensors that identify community structure through phylogenetic fingerprinting methods, or detect biological function through gene expression.* Knowing the

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[1] Chemical speciation includes different oxidation states of an element (Fe^{2+}, Fe^{3+}), different molecular ions (HS^-, $S_2O_3^{2-}$, SO_4^{2-}, NH_4^+, NO_3^-, NO_2^-) and metal complexes with different inorganic and organic compounds (ligands).

dynamics of a community structure can validate chemical information as well as inform the interpretation of chemical data. Measuring the expressed levels of key genes can indicate whether and to what degree certain functions are turned on.

- *Proteomic-based sensors that measure protein expression patterns in biota.* Because proteins—the functional elements in cells—are amenable to significant post-translational modifications that are not captured by functional genomic sensors, proteomic-based sensors are expected to give information that relates better to function at the ecosystem's macroscale. However, extensive investment will be needed to achieve the automation of proteomic methods.
- *Metabolomic-based sensors that measure metabolic byproducts produced by functional biota.* This new method relies upon nuclear magnetic resonance (NMR) or mass-spectrometry to detect the known metabolic byproducts or "fingerprints" that are generated in response to external environmental influences. This technology is considered the ultimate method for detecting biological function and physiology, though it is the youngest and least well developed "-omic" technology available today.
- *Sensors that measure biotic morphology.* The shape and look of an organism being monitored may, in turn, relate to biotic function; this is because morphology can change in response to stress or relief from stress.
- *Sensors that provide reliable quantitative growth rate information.* Knowing kinetic information allows for quantitative predictions about the ecosystem being monitored. Respiration measurements are a very reliable method for achieving growth rates, but other methods are also needed. Furthermore, *in situ* growth rate information is critically needed because physiology influences growth kinetics; *ex situ* estimates often yield very different information that is not useful.
- *Sensors that detect the initiation and extent of primary production.* These sensors are needed to connect environmental perturbations or variations with primary production events in real time.
- *Sensors that detect levels of predation.* These sensors are needed to tease out changes in population numbers, so that ecosystem structural dynamics can be better understood in the context of environmental changes.
- *Sensors that indicate the initiation of or relief from stress.* These sensors will allow researchers to establish correlations between natural and human events and identify their impact on ecosystem health. This technology also captures toxicological responses.
- *Sensors that detect pathogens and invasive species.* These sensors can be used to detect pressures that reduce population diversity.

Several of these sensor technologies are already fairly well developed, while others still need significant development before they can be made field-deployable. In the meantime, current monitoring needs can be addressed through the use of established measurement practices and sensing methods as proxies of biological phenomena. This approach can also lead to new discoveries that will inform new biological sensing technology needs.

New biological sensor technologies must be able to capture bioavailability and toxicological data. If a perturbation event is detected but it is largely not bioavailable to the biota, the perturbation will have minimal impact on the biota. A biological sensor that does not correct for bioavailability could be too sensitive and yield a false positive response. Similarly, sensors that incorrectly model bioavailability could result in false negative responses. Therefore, researchers need to pay close attention to the methodologies and technologies used to detect and correlate biologically relevant events.

4.5 NANO- AND BIOTECHNOLOGIES

Miniaturized technology is an encompassing concept that includes not only micro- and nanotechnology but also advanced information technologies. Advances in meso- and microscale systems built from nanoscale technologies create new sensor systems modes for sensor networks, and efforts to integrate "smart" electronics into sensors will permit adaptive, intelligent and robust networks.

Miniaturization research will continue to enable low-cost systems, reducing system power requirements; create new materials; and help minimize reagent consumption. Microelectronics and advanced information technology insertion will evolve smart sensors, autocalibration and self-test capabilities, and allow digital processing and control functions in the field. New knowledge in the biosciences and biotechnology fields will provide models and information for new ecosystem diagnostics and probe developments. All combined, new nano-bio-info knowledge will sustain a revolution in systems technology, directly affecting environmental sensor networks. To be successful in creating the new distributed sensing networks, transfer of technologies from the nanotechnology, biotechnology, and information technology fields will have to be supported.

4.6 USE OF SENSORS ACROSS MULTIPLE SCENARIOS

All environmental media have similar requirements for sensor technology, whether optical, spectroscopic, electrochemical, separations, acoustical, mass, or other. One of the important requirements is that the sensor be able to probe a variety of changes for a variety of parameters. Sensor technologies that rely on radiation, acoustics, fields, or mass transfer can be applied to the various media. However, the enormous number of potential environmental targets reduces the opportunities for the development of crosscutting sensors.

Each of the existing major sensing technologies has advantages and limitations:

- Spectroscopic techniques can cut across all fields, but they are dependent on the excitation wavelength; furthermore, interferences in the environment limit the resulting informational content.
- Eddy correlation for fluxes in the air or at the water/ sediment interface is a promising technique, but the sensor systems require modifications to be able to be active in a desired environment.
- Mass spectrometry is a very promising ubiquitous sensor technology, but new interfaces need to be developed to sample the various media.
- Radionuclide analysis is the most ubiquitous and has the most potential for crosscutting applications, but its ability to provide desired information about physical, chemical, and biological change is limited.

Furthermore, key questions remain to be answered, in part through the development of adaptive sensor interfaces and adaptive packaging concepts:

- What are the issues that most concern systems and network designers as they attempt to develop or deploy sensor networks?
- What are the key sensor characteristics—for example, cost, sensitivity, size, selectivity, or power—for their application of interest?
- Can developments occurring in one media sphere transfer across to other media?

In general, it is difficult to demonstrate the existence of any sensor or sensing technology that is highly effective in all media. Environments are highly variable, whereas sensor technology systems tend to be constrained by their specificity to a particular application.

Multisensor packages capable of measuring many physical, chemical, and biological parameters are possible; when they are available, they will be in demand. The breakout group deemed multisensor packages to be essential, but such sensors will likely require miniaturization before they can be practically implemented.

Mobility of sensors through passive or active means is an important theme of future systems, and a key capability in support of adaptive and model-driven sampling. These technologies include mobility of microsystems as well as integration of sensors with mobile platforms and vehicles (e.g., AUV technologies).

The technology breakout group identified a clear need for better exploration and support for the transfer of systems across atmospheric, terrestrial, and marine environments. Areas to be explored include new materials capable of operation across all media, and new packaging schemes that will ease the insertion of sensor systems into multiple environments. Although the group had difficulty identifying sensors that can provide single solutions across the various media, the possibility that configurable multisensor packages may yield a more tractable path towards crosscutting sensor systems and solutions was recognized. Miniaturization efforts in technology will further help advance solutions in this topical area.

Chapter 5. Long-Term Deployment, Calibration, and Quality Assurance Issues

5.1 INTRODUCTION

No discussion of sensing for environmental observatories is complete without addressing the complex issues related to the deployment of sensors in a broad spectrum of environments. Many of the environments are harsh, and all environments offer unique challenges related to sensor reliability and calibration. Sensors and sensor networks require comprehensive testing to determine their efficacy and performance in real-world applications including long-term autonomous deployment. The purpose of this section is to consider fundamental science and sensor enabling technology and to summarize discussion regarding sensor deployment strategies to gain insight and ability to test new hypotheses as applied to dynamic environmental systems. The breakout group that discussed deployment issues focused on limitations and requirements for long-term deployment of sensors. Specifically, in this context, deployment issues regarding sensor power, ruggedness, calibration drift, quality assurance and control, integration, synergy, specificity in design requirements, and sensor security were discussed. In addition, strategies for deploying sensors across media and interfaces were developed and presented. Specific topics associated with media and interfaces included systems approaches to sensor deployment, sensor community collaboration, and commercialization and manufacturability of sensors. Data management and infrastructure strategies for sensor deployment were also discussed, with focus on data standardization and cyberinfrastructure issues.

5.2 LIMITATIONS AND REQUIREMENTS FOR LONG-TERM DEPLOYMENT OF SENSORS

Although sensors have long been deployed successfully for brief periods lasting days or weeks, scientists and technologists face considerable challenges attempting to enable them to perform for extended deployments that last from months to years. Desirable features for sensors to be used on long deployments include sensor intelligence, synergy within sensor networks, and flexibility in deployment scenarios.

Long-term sensor deployments are constrained by a number of issues that must be successfully addressed, particularly power, environmental ruggedness, calibration drift, quality control, manufacturing costs, and security. Each of these issues is discussed in more detail below.

5.2.1 Sensor Power

The issue of sensor power crosscuts all disciplines and deployment scenarios. The current method often requires researchers to send students into the field to physically change the batteries, which is not an effective use of time. Effective power management may require the development of new software and hardware tools capable of facilitating efficient operation. Other potential power management solutions await the development of techniques for extracting energy from the environment, such as radio frequency (RF) acoustic energy harvesting, microbial batteries, or other novel electrochemical power packs for ultra-low-power applications.

5.2.2 Environmental Ruggedness

Sensors must be able to withstand the natural processes that occur within the environment, including biofouling, electrochemical corrosion, sedimentation, and severe weather conditions. Biofouling refers to the undesirable effects of the accumulation of marine biota (microorganisms, plants, and animals) on submerged surfaces. The most commonly used preventative or anti-fouling agent tributyltin (TBT) is being phased out of use in the oceans for environmental reasons. As a result, copper is an appealing alternative for use on sensor intake screens and tubing because of its observed resistance to biofouling, although the actual mechanism is not well understood. For applications where optical clarity is essential, new non-toxic surface modifiers and UV light could be important breakthroughs for the control of biofouling. The detrimental effects of corrosion on sensors deployed in aquatic environments can be mitigated through careful selection of materials that are similar in galvanic voltage. Where applicable, completely inert materials, such as plastics like Delrin®, nylon, and PVC should also be used to prevent corrosion outright. Sensors placed where the weather conditions are harsh also need to be able to stay put and not drift away.

Although sensors must be able to withstand the ruggedness of the environment, they should also be environmentally benign. Materials remaining from "ghost" sensors and their power sources should not pose a threat to the environment.

5.2.3 Calibration Drift

Most *in situ* sensors are inherently unstable when deployed unattended over an extended period, making drift, repeatability, and accuracy of collected data critical issues for extended deployments. When intrinsic drift is combined with fouling, sensor data can quickly become uninterpretable. Auto- or self-calibration will be an essential feature of sensors that are deployed for longer than their intrinsic stability scale, or when biofouling interferes with signal quality. In some cases, internal electrical calibration would be an option, though in most cases the use of an external calibration standard will be necessary.

Some sensor developers are beginning to incorporate a method for introducing external optical standards such as dye in transmissometers, chemicals in nutrient sensors, and crystals. Each of these methods has its own limitations, and each requires further research and development.

5.2.4 Quality Assurance and Control

Quality assurance and quality control (QAQC) methods are typically based on statistical measures of the signal that allow researchers to identify and control critical variables or noise that degrade signal quality. For example, QAQC statistical parameters could be measured as deviations from a set of specified target values such as a running mean, a spline fit, FFT (Fast Fourier Transform), or other runtime calculations during data streaming. Ideally, sensors would have sufficient intelligence to detect and correct drift (low frequency) and spurious data values (high frequency) while incurring minimal loss in data content. Sensor networks themselves should also be designed to use multiple measurements of similar quantities as an *in situ* external QAQC. Data quality could be evaluated remotely by interrogation via periodic downloading of raw and processed data. In addition, rigorous methods of QAQC must be integrated into the sampling scheme.

5.2.5 Integration, Synergy, and Specificity in Design Requirements

In addition to performing autocalibration and QAQC, on-board intelligence could also be used to detect episodic events and respond to them by increasing the sampling frequency or by changing the gain and offset. As a hypothetical example of a highly integrated sensor design with onboard data processing, consider a high-resolution imaging system such as a submersible flocytometer (FlowCAM from Fluid Imaging Systems, Inc.) designed to capture images of plankton or other organisms, extract appropriate features, and classify each target through a support vector machine (SVM), all at a rate of 60 Hz. The output would be a stream of taxon identifiers rather than raw images, thereby allowing data compression on the order of approximately 10,000:1. Although this kind of technology is possible in the future, it still requires further research and development in the present.

In some applications, synergy among sensors that are deployed on multiple platforms—whether the platforms are vehicles in the ocean or wildebeest on a prairie—would allow cross-correlation between sensors for the purposes of redundancy, quality control, and efficient communications to central data servers. Deployment platforms are often opportunistically located on a standard tract—a cellular phone tower, for example, or a ferry boat. Sensors therefore need to be adaptable to a variety of platforms and deployment scenarios.

The deployment breakout group recognized that specific sensors fall into one of several categories related to both the *deployment scenario* and the *environmental conditions.* These categories will dictate requirements for the level of autonomous operation with respect to duty cycle, internal calibration, power management, and the ability to perform remote configuration and achieve synergy with other sensors. For example, if a nutrient sensor were deployed on a cabled observatory in the ocean, it would require externally configurable power, sampling frequency, and calibration; if the same sensor were deployed in a remote terrestrial application where bi-directional communications were unavailable, the sensor would need to be able to perform autonomous self-calibration and duty cycling to conserve power and minimize bandwidth. Furthermore, a sensor deployed in a built environment—for example, at a wastewater treatment plant—will have fewer power management issues, yet must be able to resist biofouling and corrosion and be able to self-adjust the sampling frequency.

5.2.6 Security

Long-term deployments require sensors that can be made secure from physical abuse, data loss, and tampering from outside and within the cyberinfrastructure. With the expanded use of the Internet Protocol, we have experienced over the years serious security breaches within computer networks as a result of malicious intent. The development of the sensor cyberinfrastructure that invariably will be tied to the public network will need to address security issues in order to prevent malicious attacks and other unintended use of the sensor network. System redundancy, especially in cases where the sensor network will be used in decision support systems relating to problems of national security, will have to be built in. Sensors often will be deployed in remote locations where the risk of physical tampering is higher or in areas of heavy human traffic (e.g., dredging, trawling, recreation), increasing the risk of physical damage. The mechanical design and construction of these sensors will need to consider these factors. Preventative strategies will have to be devised in the developmental stages of the individual sensors that will be included in the network. Such strategies could include development of "sacrificial sensors" (low cost, easily replaceable), electrical warning systems, or rugged tamper-resistant mounts, to name a few.

5.2.7 Manufacturing Efficiencies (Costs)

Even when all of the above issues in deployment have been addressed, if it is too costly to manufacture, then the sensors cannot be useful to researchers. Furthermore, until sensors can be manufactured in large quantities and at low cost, most of these deployment requirements will not be realized. Advances in miniaturization and mass production, along with developments in sensor technologies in the biomedical, homeland security, and other fields, will help achieve the goal of cost-efficient sensors.

5.3 STRATEGIES FOR DEPLOYING SENSORS ACROSS MEDIA AND INTERFACES

Many disciplines face the challenge of identifying and understanding behavior at the boundaries of, and at the interfacial regions between, environmental media. They require sensor and sensor networking technologies that are able to quantify fluxes across, and reactions within, interfaces at multiple scales.

An important example of interfacial research is the quantification of carbon dioxide flux from soil, also called the soil respiration rate. Measurement on the terrestrial side of the interface is complicated by the spatial heterogeneity of the materials—the soil and the canopy litter—and by spatio-temporal variations in soil moisture. On the atmospheric side, interface measurement is complicated by hydrodynamic complexities caused by meteorological conditions and the canopy structure. While sensors for measuring flux already exist and have improved over time—flux chambers, for example—they remain relatively expensive and are not scaleable.

Scaleable sensors that are capable of quantifying mass flux are highly desirable. In the absence of direct flux measurements, however, strategies are needed that use networked sensors. In the example of carbon dioxide flux quantification described above, such an approach would include the collaborative interaction of flux towers and micrometeorology sensors installed above ground with networked temperature, carbon dioxide, and moisture sensors embedded below ground.

Communication and collaboration are needed across disciplinary boundaries to prioritize potential technological developments. Furthermore, collaborations and technology transfers between the research community and the commercial sector are necessary for ensuring that high-priority sensors are successfully scaled up.

5.3.1 Systems Approaches to Sensor Deployment

A systems approach to sensor development is an approach whereby a multidisciplinary group of experts develops strategies for using sensors to characterize processes and phenomena within and across natural media and interfaces, across both temporal and spatial scales. The "system" includes the environment being sensed as well as the observing system—the sensors and the sensor network infrastructure—itself. The experts include researchers and technicians who develop the sensors. The participating experts must work together to elucidate scientific objectives, identify appropriate sensing technologies, and establish key system properties. There are currently several groups that already take this systems approach. The steps that should be followed in this process are as follows:

1. Identification of the problem and its significance. This includes background, scientific and economic importance, and reasons for establishing environmental observatories.
2. Definition of the boundaries of the system, including geographical extent, temporal extent, types of questions, and available resources.
3. Identification of the essential elements of the system (such as fluxes and feedback between system components) and the required measurements (such as flux magnitudes and directions). The result of this identification process would be a system diagram that forms a visual quantitative model of the system.
4. Development of a simulation-optimization model that can be used to identify alternatives and/or scenarios for deploying robust observing systems. This model will help to identify issues and problems that were not initially considered during the previous steps.
5. Iterative adjustment of long-term deployment strategies and decisions regarding configurations and/or technologies, based on assessments of how well the current observations support the science objectives. Adaptive sensing strategies would allow scientists to apply the results of current and historical observations to future assessments, while accounting for uncertainties in the data and the model. Short-term, highly-specific plans should be developed as phases of a longer-term, less-specific plan.

Other systems components that would support the larger-scale integration of sensors for observatories include the following:

- Development of a sensor forum and an associated e-journal for environmental sensors.
- Establishment of mechanisms for developing a systems approach in university educational programs. Such an approach would encourage the development of courses in which engineers and environmental scientists teach sensor application concepts and implementation for environmental monitoring and assessment applications.

During this entire process, it is crucial to make sure that there is continued involvement and collaboration among the team members.

5.3.2 Community Collaboration

Although cross-disciplinary collaboration was discussed in detail in Chapter 3, the long-term deployment breakout session participants also addressed the ways that the National Science Foundation (NSF) and the community might better communicate experiences and key issues related to deployment and cross-disciplinary collaboration. The group identified several possible mechanisms for improving communication and, for NSF, potential funding strategies for future sensor research. In addition, established community relations will help to move research along and allow for better communication.

The breakout session participants identified three primary actions for improving interdisciplinary communication among the diverse communities engaged in sensor development and deployment. The first two actions focus on the use of networked information resources. The group recommended that NSF

- Create a "clearinghouse" website that would link sensor development projects and related resources.
- Create an electronic journal that would provide a rapid mechanism for conveying sensor development concepts, techniques, and technologies to the community.
- Initiate an annual conference on sensor development and deployment. This conference would provide the diverse, multidisciplinary groups working on environmental sensors with a forum to discuss advances and lay out new strategic directions.

Discussion of the actions that NSF could take to increase funding for sensor research and development focused on the many stakeholders in the process and on the challenges that integrative and interdisciplinary proposals currently face in the merit review process. The group recommended that NSF

- Explore ways that increased collaboration between agencies, directorates, and industry could improve the funding of sensor development.
- Develop programs that foster systems-based approaches to the development and deployment of environmental sensor systems. Program announcements would focus on an integrative systems approach, rather than on discipline-specific technologies.
- Ensure that proposals for environmental sensors that are funded through the solicitation clearly identify the project's potential scientific impact as well as the system's robustness, and specifically answer the questions "What will it do?" and, "Will it work?"

5.3.3 Commercialization and Manufacturability of Sensors

To obtain the smaller, more powerful, inexpensive sensors that are needed for advanced research, the environmental sensor community must harness the power of the marketplace. NSF-funded research can be connected to commercial development through means such as

- adding incentives for SBIR-like supplemental opportunities
- creating channels for commercial involvement in grants
- enhancing opportunities for commercial partnerships

Supplemental programs, similar to the Mountain Lake Biological Station's Research Experiences for Undergraduates (REU) program (http://mlbs.org/REU.html), could be created. Also, grant applications could include information on ways to make the instrument more widely available. Finding ways to share common sensor platforms can create a greater demand for sensors, which can in turn lower development and production costs.

The National Strategy for Physical Protection of Critical Infrastructure and Key Assets (text available at http://www.whitehouse.gov/pcipb/) is an example of a program that could support dual-use sensor deployments. If a large program like this were to use a sensor platform that met the needs of NSF researchers, then overall development costs could be kept lower. Additional such opportunities exist for coordinating sensor use and funding between agencies. If the sensor community actively takes advantage of these and similar opportunities, the prospects for cheaper sensors become greater. As researchers and organizations partner with private companies on joint sensor projects, the sensor's commercial viability can be enhanced through prearranged licensing and intellectual property agreements akin to those used in the Small Business Technology Transfer (STTR) Program. By facilitating the shared use of common tool platforms and enabling collaborative commercial partnerships, NSF and universities can accelerate the development of smaller, cheaper, more widely deployed sensors that will substantively improve the infrastructure and capabilities of long-term ecological observatories, measurably improve the quality and quantity of the scientific data they obtain, and dramatically improve our knowledge of the environment.

5.4 DATA MANAGEMENT AND INFRASTRUCTURE STRATEGIES

Issues related to sensor and network data management include the establishment of metadata standards, data storage, data distribution, data QAQC, and data archiving. Session participants expressed the view that much of value could be learned from the experiences of other data-rich cyberinfrastructure networks, such as in the transportation industry. Data analytical tools should be able to connect sensors with models while being interoperable and customizable to meet diverse user needs. Metadata standards are also needed for models. Because the sharing of data and models is a new paradigm for many people, cultural changes will be required in many cases.

5.4.1 Data Standardization

The environmental sensor community would benefit from the availability of modular, interoperable sensors because such sensors would likely be less expensive and easier to work with. Defining an application platform interface (API)—the interface between various components of a sensor's cyberinfrastructure—also increases the sensor's value and productivity. However, standardization and interface protocol issues are complex.

Many standards for communication protocols, document and information exchange, and networks exist. Some of the most widely used communication standards include Ethernet, RS422, and ZigBee; common data standards include XML, Dublin Core, and EDI. How these existing standards could be applicable to the process of environmental data collection has not yet been studied in depth.

A premature emphasis on standards development can result in poorly developed systems. Currently, there is no process for evaluating and recommending standards against the requirements of the environmental sensor community. Though many existing standards might be useful for current sensor systems, issues like special power needs may require the development of new interfaces. The environmental sensor community should establish a process whereby the creation, adoption, and revision of interface definitions can lead to appropriate standards. This process might include conferences, workshops, web portals, experimental test bed evaluations, the comparison and contrasting of reports, and possibly the establishment of a committee process.

Organizations such as IEEE and ISO provide many places to start with this discussion. It is important to engage in the conversation to come to interfaces that work well as a common tool, and to stop using custom one-of-a-kind definitions that have to be reworked for each deployment. An initial starting point might be one or more environmental sensor conferences or workshops focusing on the issue of communications, sensor data transmission, standardized data formats, and other related issues.

5.4.2 Cyberinfrastructure Issues Related to Sensor Deployment

A *cyberinfrastructure* is a system of computers, data, networks, and software that support geographically distributed teams of researchers and educators. (See [Atkins, 2003] for the vision of cyberinfrastructure that underpins many other efforts, such as the CIBIO [2003] report for a vision in the biological sciences.) Cyberinfrastructure must be carefully designed via structured, user-centered design methodologies to meet the needs of the community it is intended to serve. The workshop participants represented a number of separate environmental communities that are not yet functioning as a single community. Therefore, the establishment of a true cyberinfrastructure for the environmental sensor community depends on the identification and agreement among community members as to common needs. Some of these cyberinfrastructure needs of environmental observatories and the issues associated with developing cyberinfrastructure to support observatories were discussed at the Biocomplexity in the Environment: Cyberinfrastructure for Environmental Observatories Meeting held in December 2004.

Accordingly, the deployment working group recommends that a group be established, most likely with joint sponsorship from a number of professional organizations active in these communities, to begin addressing common cyberinfrastructure needs and issues, in order to do the following:

- Sponsor meetings, workshops, conferences, an e-journal, and an online clearinghouse as forums for discussing cyberinfrastructure needs and issues, sharing lessons learned, and setting common policies. These forums should include members of other communities who have substantial knowledge and experience with cyberinfrastructure, as well as experience with issues relating to collaborative development across disciplines.

- Create policies for the availability of, and access to, data and other resources within these communities. The policies must address issues such as timeliness, access restrictions, and the transfer of observatory control to other groups. The policies would then be enforced through access rules established throughout the cyberinfrastructure.
- Create layers of abstraction, potentially leading to standards, for the data and knowledge created by collaborators. These layers would include data from sensor output specification, the creation of a consistent metadata vocabulary, common network specifications, data storage, data distribution, data QAQC, data archiving, model archiving and metadata, other analytical tools, and common collaboration tools that will allow different communities to communicate more effectively.
- Organize training workshops or courses that facilitate cultural changes within communities, thereby easing their transition into the new paradigm of sharing data, models, and other knowledge among collaborative organizations, as well as extending the collaborative foundations to address global processes such as climate change.

5.5 SHARED CHALLENGES IN SENSOR DEPLOYMENT: A SUMMARY

Sensor technology is currently available for a wide variety of environmental applications, and users are very interested in applying this technology to the study of many media: biota, air, land, fresh water, estuaries, and oceans. However, it is likely that sensor deployment will be limited until a number of issues can be addressed. Clearly, the most significant issue is the high cost of sensor development and deployment. Cost reduction is somewhat of a “Catch-22;” manufacturers will not be able to reduce costs until a large and stable market of users can be demonstrated to exist, while users are reluctant to purchase large quantities of sensors until prices can be reduced.

In addition to the cost issue, users have a long list of desirable sensor features and such add-ons are not going to contribute to cost reduction if they are required. Such desired additional features include the following:

- low maintenance requirements
- low power consumption and/or use of renewable energy
- environmentally benign components and operation
- flexibility of platform location
- intelligent and synergistic operation
- data and physical security
- ruggedness
- ability to query sensors remotely

In addition, a host of calibration and quality assurance issues need to be addressed, including sensor accuracy, auto-calibration, calibration of sensor networks, robustness of legacy data in the face of changing technologies, and automated QA/QC for streaming data.

Discussions revealed that improvements in information-sharing across media—for example, the application to freshwater streams of sensor technology developed for oceans—could also lead to advances in sensor deployment. Participants recommended that a professional society, or better yet a group of professional societies, inaugurate an annual sensor technology conference that would facilitate media cross-fertilization in an open forum setting. In addition, a web-based clearinghouse and e-journal could be set up to provide a location for timely information exchange. NSF could foster collaboration by (1) developing programs that foster integrative and systems approaches to sensor development, and (2) exploring interagency and intra-agency collaborations and relationships with industry to fund sensor development.

A key to the successful deployment of sensors within a network is the systems analysis mode of thinking for network design. This is an iterative process that includes simulation-based observing system design combined with the use of sensor test beds in an iterative process that will enable the development of optimal sensor deployment strategies constrained by financial and human resources required to operate and maintain the overall sensing system.

A number of sensor manufacturers participated in the workshop, and there was quite a bit of discussion about ways to improve partnerships between academia and industry. Perhaps NSF could support a system of supplements like the REU program to allow universities to pull in manufacturing partners at appropriate points in a project. To address the cost issue, NSF and universities could help broaden the market by combining small user groups together to make their needs known to manufacturers. Manufacturers could then find more opportunities to be involved with the university R&D process and application development at an earlier stage.

Although it was not the intent of this workshop to address the cyberinfrastructure required to move data from sensors to the user's computer screen, it quickly became apparent that cyberinfrastructure was a major issue related to effective sensor deployment. A host of issues related to cyberinfrastructure have yet to be addressed, including sensor interoperability, standardization of sensor connections, and design criteria for standardization.

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Appendix B. Workshop Agenda

SENSORS FOR ENVIRONMENTAL OBSERVATORIES

30 November to 2 December 2004
University of Washington
Seattle, Washington
Draft version 15 Nov 04
http://wtec.org/seo/

Session: Each Scenario Session has been constructed to introduce science questions and provide the current state sensing to obtain data needed to gain insight into the scientific processes. One area of sensing technology is discussed, related to the scientific question, noting trends in that area of technology development. Finally, issues of deployment and maintenance are discussed.

Duration of each Scenario Session: Each session is scheduled for one hour. To encourage dialog, 15 minutes of each session should be reserved for discussion. Thus, in a session with three speakers (science, technology, deployment/maintenance), each speaker should limit remarks to 15 minutes.

Speakers: Each speaker should strive to give an overview of the area. For ***science,*** what are the compelling questions that need new types of sensors or new strategies for deployment to make breakthroughs? What cannot be done now at all, or not effectively or efficiently? What is the societal impact of addressing successfully or ignoring the science? For ***enabling technology,*** what are the trends that in technologies, and what are potential cross-over technologies (applied in one area that might be relevant in others)? For ***deployment,*** what are issues that need to be addressed for sustainable deployment of sensors? What can be gained by adopting a systems approach to deployment? Thus a session may be organized like:

Scenario 1: Oceans: TITLE—*Jules Jaffe, SIO, Session Lead*

Speaker 1: Science (and Societal Need) TITLE—speaker

Speaker 2: Technology TITLE—speaker

Speaker 3: Deployment/maintenance TITLE—speaker

Discussion

Note: Session Leads have the flexibility to restructure the sessions to better meet the goals of the meeting. For example, perhaps two speakers could cover these topics more efficiently.

Tuesday 30 November 2004

0830–0900	Breakfast
0900–0930	Welcome: Host Rationale for this workshop as seen from a NSF perspective: *Alexandra Isern, Elizabeth Blood, Patrick Brezonik* Overview of Goals, Outcomes, Structure of Meeting: *James Bonner (Texas A&M), David Fries (USF), Arthur Sanderson (RPI), Peter Arzberger (UCSD)*
0930–1030	Scenario 1: Oceans: "Sensors for Environmental Observatories: Ocean Science Needs"—*Jules Jaffe, Scripps Institution of Oceanography, Session Lead* Tim Cowles, Oregon State University (Science) Jules S. Jaffe, SIO/UCSD (Technology) Scott Gallagher, WHOI (Long term deployment)
1030–1045	Break
1045–1145	Scenario 2: Rivers to Estuaries and Coastal Waters: "Applications of Sensors in Surface Water Quality Assessment – Neuse River, Estuary and Pamlico Sound"—*Ken Reckhow, Duke University, Session Lead* Ken Reckhow, Duke (Science) Hans W. Paerl, UNC (Enabling Technology) William Showers, NCSU (Deployment Strategies)
1145–1200	Group Discussion: Commonalities
1200–1300	Lunch
1300–1400	***Breakout Session 1*** Science: David Fries and Peter Arzberger Technologies: Art Sanderson Systems Deployment: James Bonner See below for specific questions to be addressed by each group

1400–1500	Scenario 3: Lakes: "Sensing Lake Dynamics"–*Tim Kratz, North Temperate Lake LTER, U Wisconsin, Session Lead* Tim Kratz, North Temperate Lakes (Science and Needs) Sally MacIntyre, UCSB (Science and Needs) Rich Axler, U Minnesota (Deployment and Education)
1500–1530	Break
1530–1630	Scenario 4: Ground Water and SECURE Earth : "The SECUREarth Initiative"—*Russ Hertzog Idaho National Engineering and Environmental Laboratory, Session Lead* John Barich, Technical Liaison, USEPA Region 10 (Science and Societal Need) Ned Clayton, Petrophysicist, Schlumberger Water Services (Technology) Rick Johnson, Oregon Health and Science University/OGI (Deployment)
1630–1730	Scenario 5: Agriculture: "Precision Agriculture: An Information and Sensor-Intensive Approach to Agriculture"–*Tom Harmon, University of California Merced, Session Lead* Craig Kvien, Coastal Plain Experiment Station, University of Georgia (Science/Needs) Jack Judy, Electrical Engineering, UCLA (Sensor technology/techniques) Tom Harmon, UC Merced (Deployment)
1730–1800	Discussion (common themes from Day 1) Overview of Day 2
1800–1900	Mixing event
1900–2100	Dinner (separate groups)

Wednesday 1 December 2004

1 December:	"Mixing Events". Breakout groups focused on key "cross-cutting" issues
0830–0900	Breakfast
0900–1000	Scenario 6: Terrestrial Ecosystems : "Terrestrial Ecosystems"—*Barbara Bond, Oregon State University, Session Lead* Barbara Bond, Oregon State University (Science) Terri Fiez, Oregon State University (Technology) Roland Kays, New York State Museum (Deployment)
1000–1100	Scenario 7: Air, Pollution: "Air Pollution in Urban Settings"—*Joe Fernando, Arizona State University, Session Chair* Joe Fernando, Arizona State University (Science) Jim Cogan, Civ, ARL/CISD (Enabling Technologies) Lenny Montenegro, Arizona Department of Environmental Quality (Deployment)
1100–1130	Break
1130–1200	Interfaces: "Science Drivers for Sensing at the Sediment-Water Interface"—*David Fries University of Southern Florida*
1200–1230	Discussion Synthesis of what we have heard Goals for Breakouts (explicit products of groups)
1230–1530	***Breakout Groups Session 2*** (Work over lunch) Science, Technologies, Systems Deployment See below for specific questions to be addressed by each group
1530–1600	Break
1600–1700	Feedback from breakout groups [15 minutes per group—slides preferred]
1700–1730	Reflections and Unexpected Insights Overview of next day, Assignments
1800–1900	Mixing event Social
1900–2100	Dinner (separate)

Thursday 2 December 2004

2 December:	Synthesis (do we have more in common than we thought)
0830–0900	Breakfast
0900–1100	Breakout Groups Session 3: Scenario Groups: Finalize Scenarios Executive Summary Group
1100–1130	Break
1130–1230	Feedback from groups
1230–1300	Final Discussion: Input for the Writers on Key points
1300	End for Participants (lunch provided to those interested)
1400–1800	Steering and Writing Committee Finalized First Draft.

Expectation on Scenario Session Chairs:

- Identify one or two other people to flesh out each session on science, enabling technology, deployment.
- Ensure one paragraph for each layer, that is three for the session, is generated and provided to the organizers by ***Monday 21 November,*** to be placed on the web site (http://wtec.org/seo/). These paragraphs should address the questions raised above in the instruction to the speakers.
- Chair the session and keep people on time.
- Chair breakout/writing group on Thursday 2 December morning.
- Participate in writing group on Thursday afternoon.
- Review final draft.

Breakout Groups Session 1:

This is a preliminary session for Breakout Groups 2. This Breakout Groups session falls along the themes of science and societal needs, enabling technologies, and deployment, will allow for the mixing of the science/societal need driven scenarios. The key goals of this preliminary session include

- Feedback from group on missing scenarios, technologies, and deployment issues.
- Initial Plan for structuring discussion on Day 2 in Breakout Groups Session 2.
- Preliminary homework.

Breakout Groups Session 2:

The breakout groups fall along the themes of science and societal needs, enabling technologies, and deployment, and will allow for the mixing of the science/societal need driven scenarios. Some key questions that the groups, respectively, should answer include:

- ***Science (David Fries, Peter Arzberger):***
  - What are successful strategies to bring together and nurture a multidisciplinary group of scientists, engineers, and researchers at different stages of their careers to focus on and produce solutions to challenges based on the driving science question?
  - Identify several "interface" challenges (e.g. aquatic-terrestrial interface) for the next decade, identify sensor and deployment needs.
  - What can NSF do to encourage team building to address these interface challenges?
- ***Enabling Technology (Arthur Sanderson):***
  - What are the new sensors that need to be developed? Possibly consider sensors by medium: air, land, water, biota.
  - Are there demands for a similar sensor across multiple scenarios?
  - What can NSF do to encourage greater migration of technologies across scenario boundaries?
- ***Deployment Strategies (James Bonner):***
  - What are issues in deploying sensors for long-term studies? What role does calibration and quality assurance play in deployment and maintenance?
  - What are key strategies in developing and deploying sensors that can be shared across scenarios?
  - Give examples of systems approach to deployment of sensors. A systems approach looks at the entire set of tools to gather the desired data by using a variety of approaches that reflect the reality of the environment.
  - What can NSF or the community do communicate experiences on deployment or address the key issues of raised by this working group?

The issues addressed in these breakouts will feed directly into the report (see below).

NOTE: Each breakout group should have an individual who makes notes (powerpoints) as the group discusses the topics.

Breakout Group Session 3:

The purpose of this session is to complete a draft of each scenario, addressing the questions raised to the speakers, on:

- ***Science***
  - What are the compelling questions that need new types of sensors or new strategies for deployment to make breakthroughs?
  - What cannot be done now at all, or not effectively or efficiently?
  - What are the societal impact of addressing successfully or ignoring the science?
- ***Enabling technology***
  - What are the trends that in technologies relevant to the science?
  - What are potential cross-over technologies (applied in one area that might be relevant in others)?
- ***Deployment***
  - What are issues that need to be addressed for sustainable deployment of sensors?
  - What can be gained by adopting a systems approach to deployment?
- ***Interface***
  - What are the challenges of the future at interfaces of disciplines, and what sensors or systems are needed?

Possible Outline of the Report (version 2)

- Executive Summary
- Background and Rationale for meeting (this can be pre-written)
- Key Findings and / or Recommendations
- Scenarios: Driving Science (rough drafts can be pre-written)
- Technologies: Common Opportunities
- Deployment Issues: Shared Challenges
- Future: Community Building, Addressing Interfaces
- References

Appendix C. Workshop Abstracts

The following is a list of abstracts submitted in advance of the November 30–December 2, 2004 workshop. Full text of the abstracts is posted on the workshop website (http://wtec.org/seo/).

Scenario 1: Oceans

Sensors for Environmental Observatories: A Perspective on Ocean Sensors (Jules S. Jaffe, Scripps Institution of Oceanography)

Networked Oceanographic Sensor Array (NOSA) for Sensing the Chemical and Biological State of the Ocean (Zbigniew Kolber, Monterey Bay Aquarium Research Institute)

Ocean Sensor Gateway (Kendra Daly, University of Southern Florida)

Scenario 2: Rivers to Estuaries and Coastal Waters

Applications of Sensors in Surface Water Quality Assessment – Neuse River, Estuary, and Pamlico Sound (Kenneth H. Reckhow, Duke University)

Enabling Technology by Deploying and Integrating Real-time, Physical-Chemical-Biotic Indicators of Water Quality on Ferries and Other Ships of Opportunity (Hans W. Paerl, University of North Carolina, Chapel Hill)

Development of a Real Time Watershed Water Quality Monitoring Network in the Neuse River Basin, NC (William J. Showers, North Carolina State University)

Scenario 3: Lakes

Sensing Lake Dynamics: Big Science Questions and Sensor Needs (Tim Kratz, North Temperate Lakes)

Recognizing Change in Lacustrine Ecosystems: Implications for Sensor Networks (Sally MacIntyre, University of Southern California, Santa Barbara)

Using Time–Relevant, Intensive Lake and Stream Data for Training Technicians and Educating Citizens, Students, Resource Agencies and Decision-Makers (Richard Axler et al., University of Minnesota)

Scenario 4: Groundwater and SECUREarth

Session Introduction (Russel Hertzog, Idaho National Engineering and Environmental Laboratory)

Science & Societal Needs: Values, Competition, Efficiency (John Barich, U.S. Environmental Protection Agency)

Groundwater Sensor Technologies: Current Trends with Perspective from the Oil and Gas Industry (Ned Clayton, Schlumberger Water Services)

Deployment of Real-Time Physical and Chemical Sensors in Groundwater (Rick Johnson, Oregon Health and Science University/OGI)

Scenario 5: Sensors and Sensor Networks in Precision Agriculture

Current State and Emerging Needs (Craig Kvien, University of Georgia)

Sensor Technology Needed and Evolution (Jack Judy, University of California, Los Angeles)

Deployment Strategies and Challenges (Tom Harmon, University of California, Merced)

Scenario 6: Terrestrial Ecosystems

"Big Science" Questions in Terrestrial Ecology – and an Alternative Approach for Defining the Scientific Needs and Values of a Terrestrial Environmental Sensor Network (Barbara J. Bond, Oregon State University)

New Horizons for Environmental Sensing and Terrestrial Ecology (Terri Fiez, Oregon State University)

Strategies and Pitfalls for Sensor Development in the Terrestrial and Animal World (Roland Kays, New York State Museum)

Measuring Photosynthetic Performance and Primary Productivity in Terrestrial Ecosystems Using a Network of Remotely Controlled Instruments (Zbigniew Kolber and Denis Klimov, Monterey Bay Aquarium Research Institute)

Sensors for Environmental Observatories Workshop: NEON (Bruce P. Hayden, University of Virginia, Charlottesville)

Estimation of Spatially Distributed Latent Heat Flux Over Complex Terrain From a Raman Lidar (Daniel I. Cooper, Los Alamos National Laboratory)

Scenario 7: Air Pollution in Urban Settings

Science and Critical Issues (H.J.S. Fernando, Arizona State University)

Enabling Technologies (James Cogan, Army Research Laboratory)

Deployment of Sensors (Leonard Montenegro, Arizona Department of Environmental Quality)

Additional Abstracts

Interfacial Processes – The Complexity Challenge Waiting Over the Horizon (Harry Hemond, MIT, and David Fries, University of South Florida)

CENS: New Directions in Wireless Embedded Networked Sensing of Natural and Agricultural Ecosystems (Michael P. Hamilton, Center for Embedded Networked Sensing)

Eddy Correlation – An Effective Technique for Measuring Oxygen Exchange Between Sediments and Water Column in Aquatic Ecosystems (Peter Berg, University of Virginia, Charlottesville)

A Life Cycle Perspective on Sensors for Environmental Observatories (Stuart H. Gage, Subir Biswas, Michael Shanblatt and Jiaguo Qi, Michigan State University)

An Outline of Considerations for Sensors to Observe Earth's Processes (Stuart H. Gage, Michigan State University)

EARTH (Education and Research: Testing Hypotheses) (George I. Matsumoto, Monterey Bay Aquarium Research Institute)

Electrochemical Analyzers to Monitor Chemical Speciation in Diverse and Extreme Freshwater and Marine Environments (George W. Luther, University of Delaware)

Sensor Networks – the Data Challenge (J.M. VanBriesen, Carnegie Mellon University)

Automated Environmental Monitoring: the Georgia Experience (Gerrit Hoogenboom, University of Georgia)

Multipurpose Sensor Networks for Environmental Research (John H. Porter, University of Virginia)


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