Toward a Global Lake Ecological Observatory Network

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Abstract

The Global Lake Ecological Observatory Network (GLEON; www.gleon.org) is a grassroots network of limnologists, information technology experts, and engineers who have a common goal of building a scalable, persistent, international network of lake ecology observatories. Data from these observatories will help us to better understand key issues such as the effects of climate and landuse change on lake function, the role of episodic events such as typhoons or mixing events in resetting lake dynamics, and carbon cycling within lakes. The observatories consist of instrumented platforms capable of sensing key limnological variables and moving the data in near-real time, often through wireless networks, to web-accessible databases. A common web portal is being developed to allow easy access to data and information by researchers and the public. A series of web services supported by this portal are being developed to allow automation of processes associated with instrument management and data quality assurance/quality control, and to allow computation of metrics based on the high frequency data. Such metrics include, for example, estimates of rates of important processes such as gross primary production and respiration, or physical stability of the water column.

GLEON builds on a successful pilot project involving several study lakes in the North Temperate Lakes Long-Term Ecological Research program in Wisconsin and Yuan Yang Lake in Taiwan. With cyberinfrastructure support provided by members of the Pacific Rim Applications and Grid Middleware Assembly (http://www.pragma-grid.net) program, near-real time data from the lakes are available at http://lakemetabolism.org. So far, better understanding of lake responses to typhoons at Yuan Yang Lake and how the dominant drivers of dissolved gas concentration change as a function of time scales from minutes to decades have been made possible by the data from these platforms.

In March 2005 scientists and information technology experts from ten programs met to discuss extending the network. Programs represented at this meeting included: Australia, Canada, China, Finland, Israel, New Zealand, South Korea, Taiwan, United Kingdom and the US. A global network of dozens or even hundreds of automated lake observatories, each collecting and transferring data in near real time, is within our grasp in the next decade, and will offer new opportunities in scientific collaboration and understanding of lake processes.

Introduction

Freshwater lakes provide a number of important ecosystem services including supply of drinking water, support of biotic diversity, transportation of commercial goods, and opportunity for recreation. Based on past trends it is likely that these and other services will come increasingly under stress in the future. The Millennium Ecosystem Assessment project concluded that current use of freshwater for drinking, industry, and irrigation is unsustainable. Approximately 1.1 billion people lack access to clean drinking water and about 1.7 million people die annually as a result of inadequate water, sanitation, and hygiene. Global demand for freshwater doubled from 1960 to 2000 and is expected to continue increasing into the future (MEA 2005).

These sobering statistics underscore the importance of understanding how changes in land-use, human population, and climate interact to affect lake dynamics at local, regional, continental, and global scales. Developing this understanding across such scales is a formidable challenge, in part because ecological systems are characterized by high spatial and temporal variability (Kratz et al. 2003), non-linear dynamics (Carpenter et al. 1999, Scheffer et al. 2001), and coupled physical/biological processes (Hamilton and Schladow 1997). In lakes, this complexity is manifested in phenomena such as sudden and short-lived algal blooms, changes in frequency and response to disturbances such as mixing events caused by typhoons, inter-dependency of biota and biogeochemical processes, and the wax and wane of fish stocks (Carpenter 2003). Moreover, variability in ecological systems affects the general public and commands the attention of resource managers and policy makers.

To understand this complexity and variability researchers must use multiple approaches, including modeling, comparative analyses, and long-term observations. Central to all these approaches is high quality, spatially and temporally pervasive, comprehensive, well-documented and easily accessible data (Gewin 2002, NRC 2000a, b). New developments in sensor and sensor network technology promise revolutionary advances in how such data are collected. A recent report of a workshop sponsored by the US National Science Foundation stated, "*Spatially extended, intelligent networks of multi-variable intelligent sensor arrays are emerging as revolutionary tools for studying complex real-world systems. The temporally and spatially dense monitoring afforded by this technology promises to reveal previously unobservable phenomena*" (Estrin et al. 2003).

The challenge of understanding complex dynamics in lakes is made somewhat easier by a number of recent developments. Sensors capable of measuring key features of lakes have been developed over the past several decades and are being deployed for a variety of scientific and management objectives (NSF 2005). Coupled with advances in cyberinfrastructure (Atkins et al. 2003) including wireless sensor networks, continuous in situ measurement of variables such as water temperature, dissolved gases, pH, conductivity, and chlorophyll are becoming increasingly common in lakes worldwide. Furthermore many research groups around the world are interested in increasing the data available from lakes to provide local to regional perspectives on lake ecosystem functioning (Porter et al. 2005). During the past decade an increased importance has been placed on understanding the coupling of physical and biological lake processes, for example, how circulation patterns, internal waves and stream intrusions influence nutrient cycling, metabolism, and the wax and wane of algal blooms in lakes (e.g. Kratz et al. 2005). As a result of these advances and in particular the improvements in data input to simulation models, there is greater potential to predict how lake ecosystems respond to natural and anthropogenic-mediated events.

The Global Lake Ecological Observatory Network

In response to the challenges and opportunities for integrated real time measurements, a number of limnologists, information technology experts, and engineers have joined forces to create a new, grassroots, international network, the Global Lake Ecological Observatory Network (GLEON, www.gleon.org). The goal of GLEON is to build a scalable, persistent network of lake ecology observatories. Data from these observatories will allow us to better understand key processes such as the effects of climate and landuse change on lake function, the role of episodic events such as typhoons in resetting lake dynamics, and carbon cycling within lakes. The observatories will consist of instrumented platforms on lakes around the world capable of sensing key limnological variables and moving the data in near-real time, often through wireless networks, to web-accessible databases. A common web portal will allow easy access to data and information by researchers and the public. A series of web services supported by this portal are being developed to allow automation of processes associated with instrument management and data quality assurance/quality control, and to allow computation of metrics based on the high frequency data. Such metrics would include, for example, estimates of rates of important processes such as gross primary production and respiration, or physical stability of the water column.

The following tenets have been instrumental in guiding GLEON's development:

- Science is increasingly global in scale. Scientific issues critical to society, such as change in the quality and quantity of freshwater resources and the importance of lakes and reservoirs in regional and global carbon balances transcend national boundaries.
- Comparative lake studies are critically important. Understanding dynamics of important lake processes, such as metabolism and atmospheric exchanges, can benefit immensely from comparative studies of lakes that have different climatic, geologic, morphometric, and cultural characteristics.
- A global network of instrumented research sites is attainable in the near future. Such sites would record at relatively high frequency the dynamics of lakes and make data available in near real time to the scientific community and general public.
- Multidisciplinary partnerships are essential. A strong partnership among lake scientists, engineers, computer scientists, educators, and information technology and management experts from multiple institutions throughout the world is required to make the vision of a global network of lake observing systems a reality.

An early prototype of such a network was built in 2004, building on experiences at the North Temperate Lake (NTL) Long-Term Ecological Research site in Wisconsin, USA with automated measurements, infrastructure developed in Taiwan's EcoGrid (http://ecogrid.nchc.org.tw/), and the collaborative, grass-roots grid community of the Pacific Rim Application and Grid Middleware Assembly (PRAGMA) (Arzberger and Papadopoulos 2006). That activity led to a new observatory node in Yuan Yang Lake (YYL) in Taiwan and built a web accessible, cross-site query interface between NTL and YYL, with data available in near real time at lakemetabolism.org. An inaugural GLEON meeting was held in March 2005, when limnologists, engineers, and information technology experts representing ten programs met in San Diego, USA to discuss the scientific goals and information technology needs of GLEON (Fig. 1).

Figure 1. GLEON participants as of March 2006. 1. Trout Lake Station, University of Wisconsin, NTL-LTER, US; 2. Academia Sinica; National Center for High-performance Computing, Taiwan Forestry Research Institute, TWN; 3. Centre for Biodiversity & Ecology Research, University of Waikato, NZ; 4. Center for Lake Management Research, Kangwon U, KOR; 5. Centre for Ecology and Hydrology, UK; 6. Centre for Water Research, U Western Australia, AUS; 7. Dorset Environmental Research Centre, Inland Lakes, Ontario Ministry of the Environment, CAN; 8. Lammi Field Station, U Helsinki, FIN; 9. Kinneret Limnological Laboratory, Israel Oceanographic & Limnological Research Ltd, STAV-GIS, ISR; 10. Nanjing Institute of Geography & Limnology, CHN; 11. Archbold Biological Station, USA. 12. Lake Sunapee Preservation Association, New Hampshire

What science issues is GLEON addressing?

Measurements from lake sensor networks have the potential to enable development of new estimates of ecosystem rates, better calibration of new and existing physical and biological models, and identification of key controls over ecosystem processes across multiple scales. The following examples, from institutions participating in GLEON, demonstrate the use of in situ sensors for physical, biological, and multi-scale observations.

Lake metabolism: Lakes are important sinks for the earth's organic carbon, storing more than 50% as much as is stored by the oceans annually (Dean and Gorham 1998). And yet, as a rule, lakes are net sources of CO_2 to the atmosphere (Cole et al. 1994). The confounding characteristics of lakes as organic carbon sinks and inorganic carbon sources derive from a complex set of internal carbon cycling processes, mediated in part by carbon fluxes from the landscape and atmosphere (Hanson et al. 2004). The metabolic balance between production and respiration in lakes has profound consequences for lake biomass structure (del Giorgio et al. 1999, del Giorgio and Williams 2005) and food webs (Pace et al. 2004). High-frequency, free-water measurements of dissolved oxygen and CO_2 can be used to quantify lake metabolism (Cole et al. 2000). Such measurements were made from automated buoys in a survey of lakes in northern Wisconsin. Surface waters generally had respiration in excess of gross primary production (Hanson et al. 2003), suggesting that lakes are important sites for mineralization of terrestrial organic carbon. However, the scale at which free-water gas dynamics are driven by biological versus physical phenomena may depend on a lake's hydrology, geology and landscape setting (Hanson et al. 2005), and its energy inputs (MacIntyre et al. 2002). This complex suite of factors may be manifested differently in various regions of the globe. Developing a sensing approach to metabolism that generalizes well to a diverse set of lakes around the globe will require measurements and models that take advantage of the existing and growing global data infrastructure of GLEON.

Drivers across scales: In addition to resolving patterns at high frequencies, prolonged sensor measurements can show patterns at different temporal scales, with each pattern being driven by a different process. Dissolved oxygen (DO) data collected from sensors in Trout Bog (Wisconsin) show patterns at scales ranging from minutes to seasons (Fig. 2).

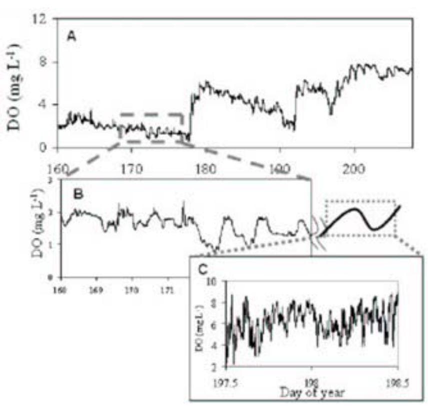

Figure 2. Dissolved oxygen time series from Trout Bog Lake, Wisconsin. (A) Full DO (y scale) series over 50 days (x axis) shows step changes due to storms; (B) Diel cycles are driven by photosynthesis and respiration. (C) High frequency oscillations at about 1 hour periods are due to internal waves.

At periods of minutes, the DO signal is driven by internal waves, whereas the diel signal is driven by the balance of primary production (PP) and respiration (R). At periods of weeks, weather fronts disrupt the thermal stratification, leading to mixing and a slower change in the DO state of the surface waters (Hanson et al. in press). Water temperature data show similar patterns across temporal scales (Appt et al. 2004). We are only beginning to understand the importance of related phenomena that occur at corresponding time scales, such as the dynamics of gas exchange at the air-water interface (MacIntyre et al. 1995), or the influence of horizontal and vertical advection and mixing. The spatial patterns throughout the lake are even more complex, but may be clarified by three-dimensional circulation models calibrated with data from sensor measurements. How variables important to both biological and physical processes respond to external drivers will be a function of many factors, including the geological and climatic settings of the lake. The diverse lakes and their settings, represented in GLEON, will provide opportunities for comparison of fundamental relationships of responses and drivers.

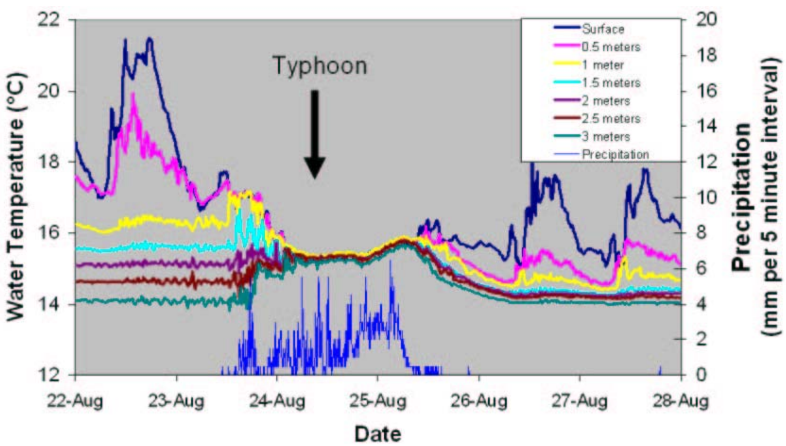

Figure 3. Disruption of thermal stratification, represented by temperature from sensors at several depths, during a typhoon at Yuan Yang Lake, Taiwan.

Disturbance: Long records of high-frequency measurements are needed to capture rare events that can dramatically alter physical and biological properties of aquatic systems (Kirchner et al. 2004). Although we are familiar with large seasonal changes, due, for example, to mixis and stratification (Wetzel 2001), we have much less information about how idiosyncratic external drivers affect lakes. In Yuan Yang Lake (Taiwan) (Fig. 3), both the chemical and the biological characteristics of the system are reset periodically when typhoons deposit up to a meter of rainfall in the catchment (Porter et al. 2005). The lake nearly doubles in depth and the water column mixes fully. Within a few days, the lake restratifies, but the dissolved organic carbon concentrations and the microbial community have changed dramatically. The effects on lake physics of this disturbance are clear, but the effects on the medium- and long-term chemical and biological dynamics remain to be discovered. In the absence of these sensor data, however, changes to the chemistry and biology would appear random and remain unexplained. As extreme weather events become more common (Osborn et al. 2000), these disturbances may play an increasingly important role in shaping aquatic ecosystems.

Scaling up: A global network of lake sensors, coupled with models that span local to global scales, will improve our predictive capabilities (Clark et al. 2001). Empirical data show lakes, to a certain extent, vary synchronously at regional (Benson et al. 2000, George et al. 2000, Järvinen et al. 2002) and global scales (Magnuson et al. 2004). This synchrony points to the broad-scale effects of climate on the physics (Arhonditsis et al. 2004) and biology (George 2005) of lakes. Lakes may also play an important role in balancing regional energy budgets of climate models. The large spatial scale of regional and global mechanistic models often requires that smaller scale processes be lumped in the parameter estimation process (Beven 2002). This lost resolution obscures spatial and temporal patterns that may be evident and important at local or regional scales. Thus, a large gap exists between the scale at which measurements are made and the scale at which regional and global models are parameterized. Although variables that respond slowly and operate over broad scales may constrain the long-term dynamics in many ecosystems (Carpenter and Turner 2000), we are only beginning to understand how finer-scale processes contribute to the short- and long-term dynamics of lake ecosystems (Harris and Heathwaite 2005).

Information Technology Issues

GLEON raises a number of formidable information technology challenges. At the scale of the individual observatory, there are significant challenges associated with assuring data quality, capturing metadata, and automating the process of moving data from sensors in the field to accessible, persistent databases. At the scale of a network of observatories, cyberinfrastructure challenges include development of tools that will allow resource discovery, access, and utilization. These resources include databases and collections, analytical tools and models, and environmental sensors and sensor streams. The infrastructure for such a collaborative research network is being developed today but exists only in pieces and mainly due to ad hoc efforts by a disparate set of research groups. One of the values of GLEON is that it provides a compelling need for developing the cyberinfrastructure that will be necessary for larger, more complex environmental observing systems being planned in the US such as the National Ecological Observatory Network (NEON, www.neoninc.org) and elsewhere.

Years of experience in deploying sensors and retrieving data in the US Long-Term Ecological Research network in general, and at the North Temperate Lakes LTER site in particular, have exposed two key challenges that need immediate attention and are the current foci of GLEON cyberinfrastructure development. These challenges arise from the dynamic nature of the ecological science itself, where sensors are frequently being added to expand the long-term monitoring infrastructure, and reconfigured and redeployed to accommodate the transient interests of projects with specific, short-term needs.

First, we are automating the process of adding/changing a sensor deployment and ensuring its rapid integration into the network topology and database schema. Currently, a field technician deploys a series of sensors, usually attached to a datalogger. Via wireless telemetry the data move from the node (datalogger) to a base computer and then manually or through an automated process into a database accessible by researchers, managers or the public. Adding or changing sensors or dataloggers requires coordinating the activities of research scientists, field technicians, programmers, and information managers to design sampling protocols, program dataloggers, configure data transport, adjust database schemas, and implement data quality assurance. While this manual process is adequate for reasonably small numbers of sensors and dataloggers, it does not scale to the hundreds or thousands of sensors expected to be deployed by large-scale projects in the near future. A current activity of GLEON is to automate moving data from field-deployed sensors to accessible databases in a way that accommodates new generation sensors as well as legacy sensors and dataloggers currently used in the environmental science community.

Second, we are automating and making more powerful the process of screening data for quality assurance (QA). Field-deployed sensors are capable of collecting large amounts of data. When the number of sensors is limited, it is possible to screen data using standard range checks, graphs, and other forms of visual inspection. But as the number of sensors grows, manual methods are no longer feasible. We are developing a set of sophisticated, context-dependent intelligent agents capable of using disparate data sources to learn, make decisions, and provide early warning of sensor malfunction, instrument drift, or novel relationships among sensor data.

In general, we are working towards extending the range of resources available to the environmental sciences community by developing an integrated observing system cyberdashboard. This cyberdashboard will integrate a variety of tools and resources for observing system management and provide a one-stop portal for the international community of lake observing system scientists and engineers. We are building a web-services based portal and application framework that provides services for resource registration (publishing data, analytical, and sensing resources), discovery (locating relevant resources within the distributed community), and resource utilization (data acquisition, analysis, modeling, near-real time monitoring, and decision support). For examples of these concepts, see http://scirad.sdsc.edu/datatech/files/CLEOS-GoogleEarth-Cyberdashboard-poster.png or NEON's Networking and Informatics Baseline Design, http://www.neoninc.org/documents/NIBD2006Jan27.pdf (see page 18). These cyberinfrastructure tools will be designed to be compatible with, and prototypes for, other planned large observing system initiatives and operations, in particular, NEON and Ocean Research Interactive Observatory Networks (ORION; www.orionprogram.org). The cyberdashboard will extend data management services to new classes of data beyond sensor-based measurements, to include images and possibly remote-sensing data products. The cyberdashboard will also provide a publish-subscribe component to support near-real-time alerts of system changes and updates, including environmental event detection, e.g., abnormal metabolism measurements. A key component of this activity will be the use of this application to explore community-based policies and models for cross-site observing system resource discovery, access, and utilization. Thus, this prototype will provide critical insight into governance and provenance issues in cross-observatory operations as well as a functional system for integrating current studies of global lake metabolism.

Final Comments

The value GLEON is in its collective data, models, tools, expertise, and scientific inferences. GLEON is a grass-roots, community effort to better understand lake dynamics at multiple spatial scales. We encourage participation of groups interested in and willing to contribute to this effort.

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