THE GLOBAL LAKE ECOLOGICAL OBSERVATORY NETWORK (GLEON): THE EVOLUTION OF GRASSROOTS NETWORK SCIENCE

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A grassroots, global network to examine lake function using sensor data? Why not? That was the perspective of Drs. Tim Kratz (limnologist), David Hamilton (limnologist), Peter Arzberger (mathematician), and Fang-Pang Lin (computer scientist) in 2004 when they hatched the idea of the Global Lake Ecological Observatory Network (Fig. 1). Nine years later, with over 380 members from 40 countries, and 50 publications to its credit, GLEON is growing at a rapid pace and pushing the boundaries of the practice of network science. GLEON is really three networks: a network of lakes, data, and people (Fig. 1). While the first two underpin the scientific products and analyses that GLEON members produce (Fig. 2), explicit attention to the people network has served both GLEON science and its members exceedingly well.

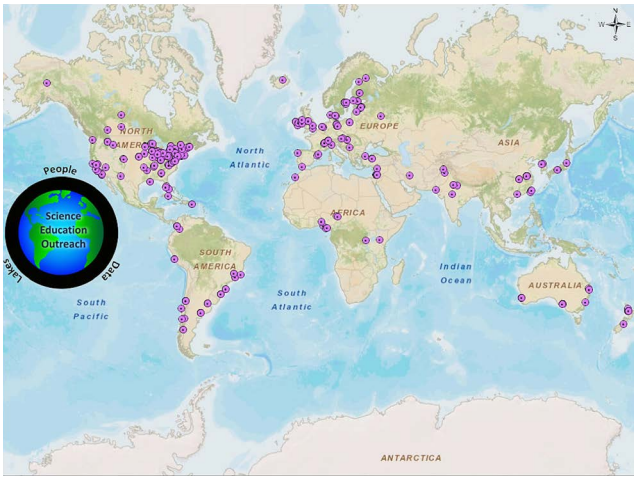

Fig 1. GLEON (www.gleon.org) conducts innovative science by sharing and interpreting high-resolution sensor data to understand, predict, and communicate the role and response of lakes in a changing global environment. More than 380 members from 40 countries form networks of people, lakes, and data. GLEON encourages participation across multiple disciplines of environmental science and information technology, by openly and informally sharing ideas, expertise, and data, and by moving ideas to products via working groups. Education, especially the training of early career scientists, and outreach are central to GLEON's activities.

Lake and Data Network - Over the past few years, GLEON research has focused on analytical tools for the use of high frequency sensor data in understanding lake function. Analyses of data from a broad spectrum of lakes across the globe have been used to address metabolism and carbon cycling in lakes (Hanson et al., 2011; Solomon et al., 2013), the role of wind and advection in lake physics (Read et al., 2012), the development of models (Staehr et al., 2010; Read et al., 2011; Kara et al., 2012) and response and recovery of lakes to extreme events (e.g., Jennings et al., 2012; Klug et al., 2012; Fig. 2). The diversity of science derives, in part, from the large gradients inherent in the world's lake ecosystems. The power of comparative research is well illustrated by these studies where the importance of lake context—for example, its watershed (Klug et al., 2012), its bathymetry (Read et al., 2012), and its meteorology is revealed. Recently, groups of GLEON members have initiated several large-scale projects and cross-site experiments. One exciting example is the Spring Blitz, a coordinated survey of biology, chemistry, and physics in GLEON lakes around the world during the onset of spring thermal stratification. The GLEON network of sensors in lakes differing in stratification regime is central to the project's design. The overarching goal of the experiment is to test whether lakes with strong stratification in spring develop higher plankton diversity.

People Network - How do we accomplish our work? GLEON advances science both synchronously – at annual meetings, and asynchronously – using a variety of cyber-enabled technologies and working group formats (Fig. 3). Face-to-face meetings hosted around the world where attendees roll up their sleeves, gather into working groups, and brainstorm are the primary mechanism by which scientific products are catalyzed and new collaborations are formed. These meetings have been supported, in part, by an NSF Research Coordination Network grant, funds from the Gordon and Betty Moore Foundation, and local meeting hosts. Research costs are born by the members, and in some cases, the organizational infrastructure and collective resources have underpinned research funding initiatives,

both in the US and abroad. Work is sustained through smaller face-to-face meetings complemented by virtual communication. Frequently, graduate students or early career stage scientists take the lead on projects and papers, with later career stage scientists providing guidance and leadership from within.

Attention to organizational structure and operations has enabled GLEON to learn and adapt to the network's needs. Governance and overall leadership are provided by a GLEON-elected, 14-member Steering Committee (SC) with 3-year renewable terms. One seat is reserved for the chair of the GLEON Graduate Student Association (GSA) and another for chair of the GLEON Collaborative Climate Committee (CCC). Both of these committees are central to the vibrancy and operation of GLEON; both also grew organically from members and in response to perceived opportunities or challenges. Over 30% of GLEON members are students, many of whom have led or participated in the analysis and writing for GLEON manuscripts. The GSA organizes some GLEON all-hands' meeting sessions, holds a graduate student workshop to train leadership skills and complex data analysis tools, has facilitated site exchange visits for students to broaden skill sets, and runs the Network Partners Program, which matches mentors (those familiar with GLEON meetings) and mentees (those new to GLEON meetings) for all-hands' meetings. The CCC evolved to guide the activities and advise governance of GLEON, promote diversity of engagement and inclusivity, and explore the best practices of the science of team science. The CCC has been instrumental in such activities as training Working Group facilitators and creating processes that encourage maximum participation and open dialogue by members (e.g., world café –style discussions).

Diverse and distributed leadership for a suite of activities is encouraged throughout GLEON, and we are developing tools and programs to assess the value of network science to early-career, as well as all-career stage scientists. These latter activities are supported both by the RCN and Moore Foundation awards, and through a recent NSF Macrosystems Biology Graduate Student Training award.

The importance of network science: Does network science lead to innovative research? While traditional field-based science remains a hallmark of limnology, there is broad recognition of the need for interdisciplinary science and more extensive collaboration that crosses institutional and even political boundaries. Whether the promises of network science are realized will depend on how well we are able to confront issues of global importance – rapid degradation of water quality, profound changes in biodiversity and invasion by exotic species, and availability of water to support a growing world population. Confronting these issues requires skills in data integration, modeling, and a suite of social skills necessary to harness the communities' resources (Porter et al., 2011). These skills, as well as the training necessary to develop them, are difficult to find at any one institution but are a key attribute of the cumulative expertise and knowledge of GLEON members. Perhaps the best of GLEON's science is just now emerging and is exemplified by a combination of the physical sciences (Read et al., 2012), the ecological sciences (Klug et al., 2012; Solomon et al., 2013),

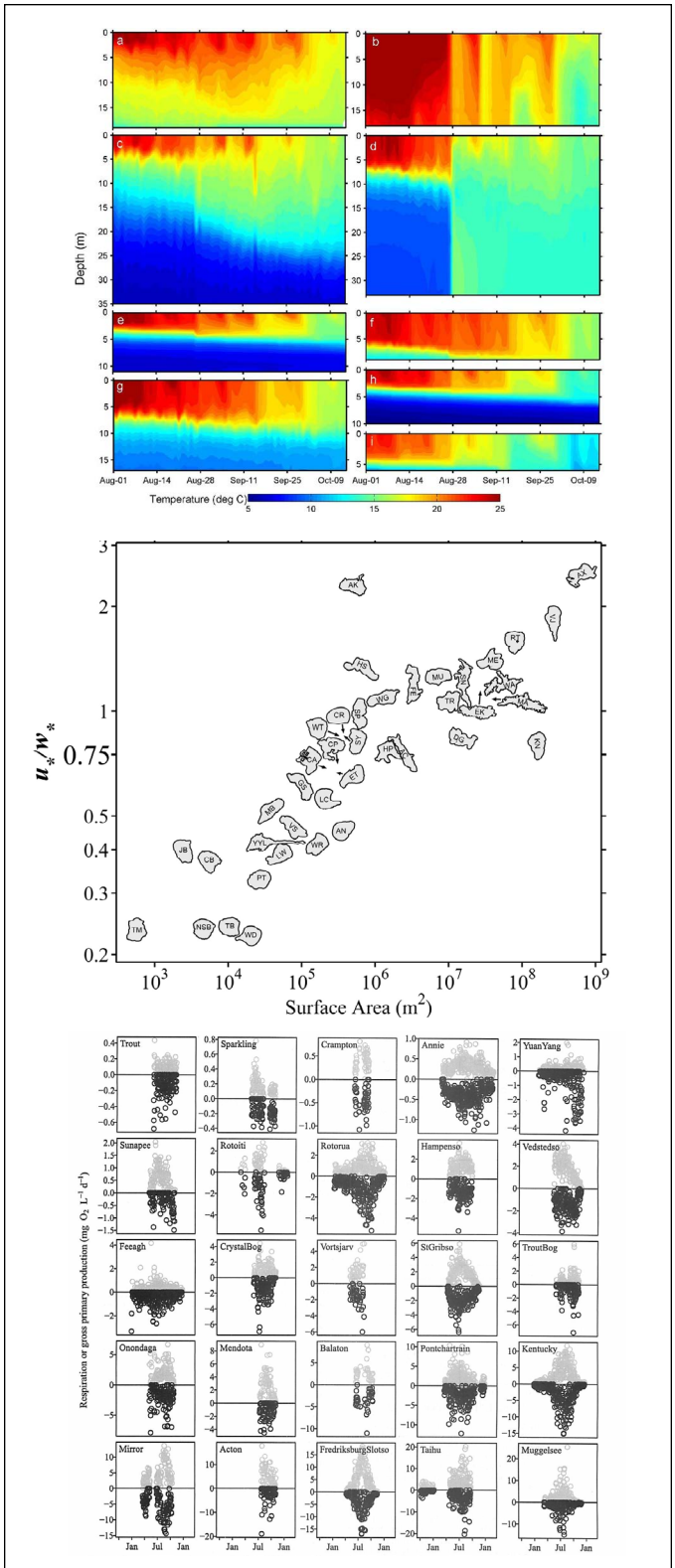

Fig 2. Examples of GLEON network science, including (a) the impacts of tropical storm Irene on thermal stratification in 9 lakes in northeastern North America (Klug et al., 2012, reprinted courtesy of ACS); (b) ratio between the temporally-averaged velocity scales for wind shear (u*) and convection (w*) for 40 GLEON lakes (Read et al. 2012, reprinted courtesy of AGU); and (c) rates of gross primary production (GPP; gray points) and respiration (black points, plotted on negative scale to facilitate viewing) estimated at a daily scale in 25 lakes (Solomon et al., 2013, reprinted courtesy of ASLO).

as well as the perspectives of members on issues of future water quality (Brookes and Carey, 2011; http://newswatch.nationalgeographic.com/2013/03/07/warming-lakes-climate-change-threatens-the-ecological-stability-of-lake-tanganyika/). While the future cannot be predicted, often organizational structures dictate the nature and methods of how science is accomplished (Uriarte et al., 2007). As GLEON pays careful attention to the process of team science (e.g., http://sites.nationalacademies.org/DBASSE/BBCSS/CurrentProjects/DBASSE_080231#.UbtTyPkce8A), it is facilitating an organizational structure

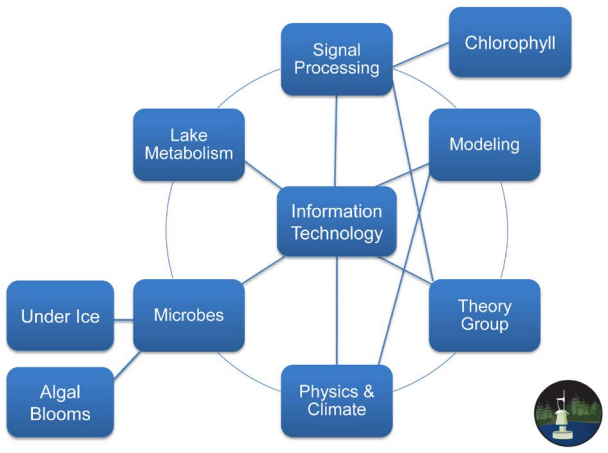

Fig 3. Current structure of GLEON working groups (WG). The groups are open to participation and have evolved, in grass-roots fashion, from GLEON meetings and workshops. The core groups are depicted in the circle (Signal Processing, Modeling, Theory, Physics and Climate, Microbes, and Lake Metabolism). Subgroups and projects have evolved from the WGs (e.g., with more specific foci on Chlorophyll, Under Ice dynamics, and Algae Blooms). Group activities and products are supported and enhanced by Information Technology (IT) (e.g., in support of virtual communication, sharing models, and data sharing).

adapted to training and producing talented network scientists and innovative scientific products.

Organizations, technologies, and the scientific enterprise change rapidly. GLEON is a powerful example of both a learning organization, as it seeks to continually reevaluate both its weaknesses and strengths and adjust accordingly, and a working example of the emerging field of the science of team science. In short, GLEON is an ever-evolving organization whose successes are attributable to the network of members. Our strengths and opportunities, as well as some of our challenges, are intimately tied to the facts that: no one person's career and identity is wholly interwoven with GLEON (unlike, say, an investigator-initiated research program), we are bound by a common mission (Fig. 1) and are committed to sharing data and ideas openly, we encourage broad leadership, and we are learning by doing network science. The rapid growth in membership, scientific productivity, and reputation of GLEON is a testament to its current timeliness. Its subsequent longevity will depend on its ability to continue to learn, innovate, and be inclusive of new ideas and new people.

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