Science of Freshwater Inland Seas (SOFIS)

Contributions from the SOFIS Working Group*

Edited by Thomas C. Johnson

Introduction

The large lakes of the world collectively represent an important, valuable, and poorly understood part of our natural environment. Although the 10 largest lakes comprise less than 1% of the continental area, they contain 61.4% of the Earth's surficial fresh water. These lakes are valuable to humans as sources of fresh water for drinking and agriculture, as fishing resources, as aesthetic resources, and, especially in the case of the Laurentian Great Lakes, as an avenue for commercial transport. Beyond their quantifiable practical value, however, large lakes have perhaps far greater scientific worth as a result of their complex interactions with the rest of nature, and as dynamic ecosystems of interest in their own right.

Despite ample motivation, there has been surprisingly little sustained or systematic study of basic processes in large lakes compared to the level of basic research activity in the oceans. Against this backdrop, a workshop on the Science of Freshwater Inland Seas (SOFIS) was held in Duluth, Minnesota on July 14 - 16, 2002. The workshop was funded by the National Science Foundation and by the Large Lakes Observatory of the University of Minnesota Duluth. The purposes of the workshop were to define the current research needs, and to develop an implementation plan that was realistic in scope and would insure the establishment of a healthy, productive and sustained research program on large lakes of the world. Attendance at the workshop was limited to 20 scientists from academic institutions from throughout the United States and Canada (Table 1). Participants were selected to achieve a balance of disciplinary expertise, and widespread geographic representation, both in terms of research areas (e.g., North and South America, Asia, Africa) and of institutional affiliation. Our objective was to represent the needs of the large lakes research community as a whole, to foster its growth, and to engender a new era of discovery in the largest and most diverse freshwater ecosystems on the planet.

Several characteristics of the world's great lakes make them ideal study sites to advance basic understanding of ecosystem dynamics.

- Large lakes exhibit structures and processes found in ocean basins (e.g., discrete coastal zones and shelf breaks, large scale circulation patterns, etc.), yet are bounded systems with inputs and outputs that are constrainable.
- Large lakes occur within all major climatic regimes of the earth, from polar to tropical, and provide a remarkable series of laboratories in which to test our

fundamental understanding of natural processes.

- Ecological research on large lakes provides us with important new insights into aquatic realms that have evolved over thousands, and in some lakes, millions, of years.
- The great diversity of ages, water chemistry, and biota in these systems provide unparalleled opportunity for both comparative and highly focused research activities of aquatic ecosystems.
- Sediments that accumulate on the floor of the deep basins of large lakes reveal how climate over significant regions of the continents changed through time, and how the lake and terrestrial ecosystems responded.

The world's large lakes are unique ecosystems integrating complex interactions between the aquatic and terrestrial environment. As such the discipline of large lakes limnology must integrate the broad fields of hydrology, biology, chemistry, fluid dynamics, and climate. It must further consider how terrestrial ecosystems and their bordering wetlands influence fundamental processes. Basic research on the world's large lakes provides more than the wonder of discovery, however; it serves as the basis for assessing human impact on large-lake ecosystems, and for developing sound policy for managing and protecting them as our global environment evolves. In essence, these large lacustrine systems offer unparalleled opportunities for environmental synthesis, addressing integrating many of the environmental research frontiers identified for the coming decade in (Pfirman and AC-ERE, 2003).

The following pages of this report address issues regarding our current state of knowledge, including recent accomplishments and identification of important gaps in our knowledge of large lakes systems. New avenues of research are proposed, and issues of infrastructure, education, international opportunities, and recommendations for implementation are addressed. We do not view this report as comprehensive in its coverage of the science. Rather our intention is to provide key examples of exciting new scientific breakthroughs and opportunities for new discovery in the scientific realm, and major recommendations for immediate implementation.

* Table 1. Participants at the Large Lakes Science Workshop (The SOFIS Working Group)

Name	Affiliation	Interests
Tom Johnson, co-convenor	Large Lakes Observatory Univ. Minnesota Duluth	Geological limnology, paleoclimate
Paul Baker, co-convenor	Dept. of Geology Duke Univ.	Geological limnology, paleoclimate
J. Val Klump, co-convenor	Water Institute Univ. Wisconsin Milwaukee	Chemical limnology, nutrients
David K. Rea, co-convenor	Dept. of Geological Sciences Univ. Michigan	Geological limnology, oceanography
Sarah Green, co-convenor	Dept. of Chemistry Michigan Technological Univ.	Chemical limnology, carbon cycles
Hans Paerl	Inst. of Marine Sciences Univ. North Carolina	Nutrients, estuarine ecology, limnology
John Janssen	Water Institute Univ. Wisconsin Milwaukee	Fish ecology
Sally MacIntyre	Marine Science Institute Univ. California Santa Barbara	Physical limnology, oceanography
Joe Niebauer	Dept. of Ocean and Atmospheric Sciences Univ. Wisconsin Madison	Physical limnology, oceanography
Elise Ralph	Large Lakes Observatory Univ. Minnesota Duluth	Physical limnology, oceanography
James McManus	College of Ocean and Atmospheric Sciences Oregon State Univ.	Chemical limnology, oceanography
Jonathon Cole	Inst. Ecosystems Studies	Microbial ecology, carbon cycles
Bob Sterner	Dept. of Ecology and Behavioral Biology Univ. Minnesota Twin Cities	Zooplankton ecology, nutrients
Bob Hecky	Dept. of Biology Univ. Waterloo	Nutrient dynamics, tropical limnology
Noel Urban	Dept. of Civil Engineering Michigan Technological Univ.	Chemical limnology, carbon/nutrient dynamics
David Jude	Dept. of Biology Univ. Michigan	Fish Ecology
Chris Scholz	Dept. of Geological Sciences Syracuse Univ.	Geological limnology, Seismic stratigraphy
Jim Churchill	Woods Hole Oceanographic Inst.	Physical limnology, oceanography
Ray Weiss	Scripps Inst. Oceanography	Chemical limnology, oceanography
John Swenson	Dept. of Geological Sciences Univ. Minnesota Duluth	Physical/sedimentary dynamics

The Circulation Dynamics of Lakes

Understanding the wide variety of motions in lakes is essential for understanding many of the biogeochemical processes that dominate aquatic ecosystems. In the past two decades, physical limnology has advanced considerably through more sophisticated analytical and numerical modeling, laboratory experiments, and field studies (Imboden, 1990) than were possible in the early years of Mortimer's classic investigations of Lake Michigan (Mortimer, 1968). Insights from physical oceanography and meteorology have strongly informed the discipline, but there are major differences between large lakes and the ocean due to the proximity of boundaries and the variety of flows made possible as temperatures in lakes approach $4^{o}C$, the temperature of maximum density of fresh water.

Recent Accomplishments

- *Circulation Models*: Recent hydrodynamic models have incorporated our new understandings of water circulation on scales ranging from basin-wide gyres (e.g., (Beletsky and Schwab, 2001) to turbulent eddies associated with internal waves (e.g., (Hodges et al., 2000). A simulation of a March 1998 resuspension event in southern Lake Michigan as part of the Episodic Events – Great Lakes Experiment (EEGLE), (Eadie et al., 2002) exhibited many of the qualitative characteristics of the large-scale turbidity pattern seen in satellite imagery and predicted areas of sediment deposition that closely match regions of fine-grain sediment accumulation.

- *Boundary Currents*: Coastal jets are extremely important for transport in the Great Lakes. Perhaps the strongest of these, Lake Superior's Keweenaw Current, transports ~100,000 m^3 sec^{-1}, enough to circulate the volume of Lake Superior every three years. Variability in this coastal jet's dynamics is caused by interannual/global variability in the atmospheric circulation as it alters the location of regional storm tracks. The clear coupling to the migrating high and low pressure systems seen in the 1970's is not as apparent today (Niebauer and Ralph, in review). Model results (Chen et al., 2000; Zhu et al., 2000) showed that shifts in the along-shore wind direction can lead to the formation of a warm-core eddy off the northern tip of the Keweenaw Peninsula, a feature often seen in satellite imagery.

- *Coupled Regional Climate Simulation Models:* The application of regional climate models to lake circulation dynamics is in its infancy, but is much needed as we attempt to predict ecosystem response to global climate change. A coupled regional climate simulation model for Lake Victoria, East Africa, reveals that this large, shallow lake, which straddles the equator, has a memory in its momentum of about two weeks (Song et al., 2002). Because of this large inertia in the system, the lake circulation is primarily controlled by the large-scale wind patterns over the basin rather than the component associated with the diurnal land/lake breeze.

- *Near-surface processes*: Recent air-water interaction studies using instruments affixed to towers erected within lakes quantified, for the first time, the manner in which wave growth is influenced by variations in depth and development of the atmospheric boundary layer along the fetch (Donelan et al., 1992) and (Young, 1997). Data from instrumented lake towers have also demonstrated that the aerodynamic roughness of a water surface with a developing wave field is not simply a function of wind speed, as commonly assumed, but is strongly dependent on wave age and steepness (Anctil and Donelan, 1996; Donelan et al., 1993). In a landmark study using velocity measurements from the CCIW tower in Lake Ontario, (Terray et al., 1996) demonstrated that breaking waves can significantly enhance kinetic energy dissipation in near-surface waters. In what may be a consequence of the differing wave conditions in lake and ocean environments, their field measurements of CO_2 mass transfer rates in Lake Ontario were greater than measured oceanic rates by roughly a factor of two (Donelan and Drennan, 1995).

- *Deep mixing and ventilation:* Major insights into the functioning of large lakes have been made via studies of convection and other deep mixing processes. For instance, while the residence time of water in Lake Baikal (the world's deepest lake with a maximum depth of 1632 m) is ca. 350 years, measurements of dissolved atmospheric chlorofluorocarbons (CFCs) and other anthropogenic tracers have shown that the deep waters in this lake are renewed by deep mixing events from the surface waters on time scales of up to 16 years (Killworth et al., 1996; Weiss et al., 1991). These studies have shown that our classical understanding of mixing in dimictic lakes is incorrect in deep lakes where water temperatures seasonally cross the temperature of maximum density. CFC tracer studies in tropical Lake Malawi have shown that the deep anoxic waters of this great lake (maximum depth of 703 m) are renewed from the surface on time scales ranging from 8 to 26 years (Vollmer et al., 2002).

- *Enhanced turbulence at lateral margins of lakes*: One of the most important recent findings in physical oceanography and limnology is that turbulence is more prevalent at the boundaries than in the interior (DeSilva et al., 1997; Goudsmit et al., 1997; Imboden and Wuest, 1995; MacIntyre et al., 1999; Saggio and Imberger, 1998). Mixing is enhanced by up to 4 orders of magnitude compared to offshore, and leads to higher nutrient fluxes and localized increases in plankton growth (MacIntyre and Jellison, 2001; Ostrovsky et al., 1996). The internal wave dynamics cause spatially varying rates of biogeochemical processes, sediment resuspension (Gloor et al., 1994; Imberger, 1998) and enhanced diffusion of pore waters (Oldham and Lavery, 1999). Offshore transport occurs via intrusions (McPhee-Shaw and Kunze, 2002; Thorpe, 1998).

- *Fine scale structure in stratified fluids*: New instrumentation can resolve extremely small changes in temperature and salinity on spatial scales of one millimeter, and reveals structure on scales previously assumed to be well mixed. Physical measurements taken on the microscale, when coupled with fine scale optical and acoustical instruments in recent studies in fjords, revealed thin layers (10 cm scale) of phytoplankton, bacteria, zooplankton and marine snow concentrations elevated 3 to 1000 times above background. These layers occurred on small-scale density discontinuities, and persisted for days on spatial scales of kilometers. Major paradigm shifts in biological and chemical limnology are anticipated based on these findings (Fig. 2) (Alldredge et al., 2002; Hanson and Donaghay, 1998; Rines et al., 2002).

- *Climate:* Recent predictions from GCMs for CO_2 doubling scenarios, imply global warming trends that could have significant, even catastrophic impacts on large lake ecosystems. Some current models predict an increase in the length of the stratified period in the Laurentian Great Lakes by as much as 90 days (Sousounis and Bisanz, 2000). Extended isolation from the atmosphere of a potentially warmer hypolimnion could drive dissolved oxygen concentrations lower with potentially enormous impacts on nearly all segments of the ecosystem, particularly benthic metabolism, nutrient cycling, and fisheries. Lake level oscillations will undergo significant alterations as river runoff drops and evaporation increases (Mortsch and Quinn, 1996). In addition, less intuitive, indirect effects may result. For example, a climate change related to southward migration in the average wind field over the Great Lakes basin since 1980 has resulted in a decrease in water mass exchange between Green Bay and Lake Michigan. This has led, in turn, to intensified bottom water hypoxia, warmer bottom water temperatures, increased benthic metabolism within the bay, and a doubling in methane evasion from Green Bay to the atmosphere in late summer (Waples and Klump, 2002).

  Effects of climate change on large lake systems cannot begin to be unraveled without dependable time-series measurements. The deep waters of tropical lakes Tanganyika and Malawi have warmed over the past century (Fig. 3) but the consequences of such warming on the vertical circulation of these lakes and on the biological production, which is dependent on rates of deep water exchange with surface waters, is unknown. The lakes at present seem to be increasing in stability and rates of deep-water renewal are declining. These changes could lead to an expanded volume of anoxic water and build up of toxic gases in the deep waters, increasing the possibility of catastrophic overturns.

Future Research Directions

- *The Thermal Bar:* How are both the vertical and horizontal circulation in large lakes influenced by the fact that the temperature of maximum density in freshwaters is ca. 4 ^{o}C? The thermal bar is a well known phenomenon in higher latitude great lakes, but the order of magnitude of the vertical transport associated with thermal bar convection has not been quantified. How important is it in the annual physical and biogeochemical cycling of a large lake?

- *Mesoscale Eddies:* Recent time series measurements and spatial surveys of velocities, temperature, chlorophyll and zooplankton in Lake Superior have revealed a complex horizontal structure driven by mesoscale eddies (Fig. 4)(Ralph, in press). These are not the standing Poincare waves that Mortimer (1968) described for Lake Michigan, for some are cyclonic and others are anticyclonic. Recent oceanographic studies have shown that upwelling and downwelling in mesoscale eddies has major implications for primary productivity, especially in oligotrophic regions of the ocean

(McGillicuddy Jr. et al., 1998). Similar process studies are needed in large lakes to determine the extent of upwelling in cyclonic gyres and downwelling in anticyclonic gyres and the resultant implications for annual primary productivity and the carbon budget

- *Episodic Events:* What are the effects of episodic events on horizontal and vertical transports, and are these events more important for changes in lacustrine productivity than more averaged conditions? What impacts do major events of different time and space scales have on productivity?

- *Microwaves and gas flux:* The fundamental physics of gas flux at the air-water interface has not been fully described. While studies to understand the role of microwave breaking are underway, few have addressed the role of heat loss for gas flux.

- *Turbulent mixing:* What is the magnitude of vertical transport in a turbulent fluid? Depending on the degree of stratification (which varies by several orders of magnitude over the seasonal cycle), the turbulent eddies may be damped, and turbulence of considerable magnitude may not lead to significant transport. How does topography influence internal wave dynamics and associated turbulence and vertical transport? In which systems do 'thin layers' persist?

- *Global Teleconnections:* What are the effects of global forcing on regional climate and how does this impact lake circulation and internal wave dynamics? To understand lake hydrodynamics and possible response to global climate change, we need to quantify the relation of regional weather patterns to lake transport for all of the Great Lakes of the world on time scales of synoptic through interannual to decadal.

- *Geographical Variability:* How do physical processes in large lakes differ along a latitudinal gradient? A comparison of all the worlds great lakes using both field data and similar models will allow us to develop broad understandings of the forcing controlling circulation patterns, density structure, transports in the horizontal and vertical, and the effects of winds and buoyancy.

The Biology and Chemistry of Large Lakes

One of the most striking aspects of large lakes is their diversity in climatic setting, age, water chemistry, circulation dynamics and ecosystem development. Large lakes are oceanic in scale and process, yet many have evolved in relative isolation from other aquatic systems, offering unique opportunities for testing new theories of ecosystem evolution and dynamics.

Recent Accomplishments

- *Physical Forcing*: The recurrent sediment resuspension plume in Lake Michigan described above is extremely episodic in nature (Schwab et al., 2000), with surprising biological impact. For example, despite the extreme cold that occurs during the resuspension events (< 4º C), productivity driven by the release of nutrients and organic matter from the sediments can be comparable to summer rates (Cotner et al., 2000). Because sediments concomitantly decrease light levels while increasing nutrients, most of the stimulated productivity is heterotrophic, not autotrophic (Fahnenstiel et al., 2000).

  (Plisnier and Coenen, 2001) describe the pulsed nature of phytoplankton blooms at the north end of Lake Tanganyika at the end of the windy season each September, when the SE trade winds subside for several months. An internal wave associated with the rebounding metalimnion oscillates back and forth through the lake basin, causing subsequent, damped pulses of high productivity at roughly monthly intervals until December. The intensity and number of pulsed oscillations depends on the intensity of the SE winds in the preceding windy season, and can vary substantially from one year to the next.

- *Nutrient Dynamics:* The major plant nutrients, nitrogen, phosphorus, and silicon, are intimately tied to the carbon cycle and yet have very different and individual biogeochemical behavior. The importance of atmospheric loading to large lakes is now appreciated. In East Africa, for example, atmospheric deposition of P and N may dominate their budgets in Lake Victoria and Lake Malawi (Bootsma et al., 1996).

  Nutrient distributions in large lakes are governed by processes that can have unique temporal patterns. (Brooks and Edgington, 1994) for instance argue that nearly all primary production in Lake Michigan occurs during the spring and the limiting factors are the solubility constant and dissolution rate constant of the mineral, apatite. This source of phosphorus is an order of magnitude greater than external inputs. Hence, Lake Michigan is more productive in years when there is later stratification because there is more time for phosphate to dissolve.

- *Stoichiometry of large lakes*: An oceanic paradigm is that C:N:P ratios of different ecosystem components exhibit little variation in space and time (Falkowski, 2000; Redfield, 1958). However particles in small lakes often exhibit highly divergent ratios (Elser et al., 2000; Hecky et al., 1993). Elemental stoichiometry, in particular the C:N:P ratio of aquatic biota, influences fundamental processes such as secondary production and nutrient recycling (Sterner and Elser, 2002). Large lakes, being intermediate in scale between small lakes and oceans, are instructing us about the biogeochemical controls on C:N:P ratios across the whole size spectrum (Guildford and Hecky, 2000). In Lake Superior, for instance, the seston C:P ratio varies dramatically on a multi-year time scale (100-150 in 1996 and 1997 to 300-350 in 2000), a change with consequences for the entire food web (R. Sterner, unpubl. data).

- *Carbon balance and heterotrophy*. The world's lakes, large and small, account for a significant portion of carbon storage - roughly 54 Tg C per year (54 X 10^{12} g/y) compared to the 97 Tg C/y buried in the oceans (Dean and Gorham, 1998). Because these high carbon burial rates have been maintained throughout geologic history, and because lacustrine organic carbon is particularly energy-rich, lacustrine sediments also account for disproportionately high rates of accumulation and maturation of hydrocarbon resources (Bohacs et al., 2000).

The role of inland water bodies in the global carbon budget touches on the fundamental processes of organic matter production and breakdown, as well as the connections between lakes and their watersheds. Evidence that lakes may be net producers of carbon dioxide (i.e. are net heterotrophic), due to an import of terrestrially derived DOC from their watershed, and mineralization within the lake, has been much discussed (Cole, 1999; Cole et al., 2000; Del Giorgio et al., 1999; Schindler et al., 1997). Though most evidence for net heterotrophy comes from smaller water bodies, large lakes and even some portions of the world's oceans have surface water supersaturated with CO_2 and undersaturated with O_2, suggesting that even these regions are net heterotrophic. On the other hand, some lakes such as tropical, eutrophic Lake Victoria have surface waters that are undersaturated with CO_2 through most of the year.

Carbon and nutrient budgets are attainable in principle, but remain an unsolved mystery for most large lakes around the world. In Lake Superior, for example, three to four times more oxygen is respired in the deep waters than can be accounted for with our present best estimates of annual primary production and of carbon input from the surrounding terrain (McManus et al., in review; Urban et al., in review). This observation suggests that our few sparse measurements of primary production have missed important temporal and spatial variations in biological activity, of scales varying from days/kilometers to years/basin-wide (Fig. 9).

- *Plankton Dynamics:* One of the more intriguing observations to come out of Lake Superior recently is the biomass spectrum of zooplankton in the eastern basin (Zhou et al., 2001). This shows a surprisingly high zooplankton biomass, equivalent to or higher than most biologically active marine regions, such as the California Current and Norwegian fjords. The slope of the biomass spectrum for the Lake Superior zooplankton suggests faster individual growth and lower mortality than in the historically more productive marine environments (Zhou et al., 2001). How can this be in such an oligotrophic system such as Superior?

- *Invasive Species:* Introductions of exotic species can be extremely disruptive ecologically and economically (e.g. sea lamprey and zebra mussels) and need to be stopped. However, we have learned much about the ecology of inland seas and ecosystems by studying the impact of invasions. Recent examples include substantial changes in the community structure in the Great Lakes attributed to the invasion of the predaceous spiny water flea (Bythotrephes cederstromi) (Lehman and Caceres, 1993) and the zebra mussel (Dreissena polymorpha) (Nalepa et al., 1996; Strayer et al., 1999) (Howell et al., 1996). These invasions will undoubtedly challenge the validity of current models of nutrient transport and cycling and trophic state in the Great Lakes. Similar biological perturbations to large lakes worldwide are inevitable and ongoing.

- *Evolutionary Biology:* One of the more controversial discoveries to come from a large lake in the past decade, with important implications for evolutionary biology, was that Lake Victoria completely dried up during the last glacial maximum (Beuning et al., 2002; Johnson et al., 2000; Johnson et al., 1996). Yet, Victoria, the largest lake by area in tropical Africa, harbors more than 500 endemic species haplochromid cichlid fishes (Fig. 5).

  Geophysical evidence indicates that the Lake Victoria basin began to refill with water about 14,700 years ago, which implies that most of the species of cichlid fishes evolved within this short span of time. This is an unprecedented rate of evolution, contrasting dramatically with the mere 14 species of Darwin's finches that are thought to have evolved over the course of one to two million years. The discovery of Lake Victoria's recent desiccation and its implication for rapid speciation has generated considerable controversy in the biological literature (e.g., (Fryer, 2001)), and provides a striking example of the biological surprises that lie in the sedimentary archives of these large tropical lakes, awaiting discovery. Phylogenetic analyses of DNA sequences of the mitochondrial control region of the East African cichlids indicate that the Lake Victoria cichlid flock originated in Lake Kivu (Verheyen et al., in review). The timing and exact migratory pathway of cichlid fishes from Kivu to the Victoria basin remains to be discovered, for it no longer exists.

- *Tracers in Large Lakes:* The exploitation of a wide variety of biogeochemical tracers in large lakes have enormous potential to elucidate the physics, chemistry and biology over time scales spanning several orders of magnitude. In some instances, the confined nature of large lakes has provided elegant demonstrations of the power of these techniques. The distribution of the atmospheric pulse addition of fallout Cs-137 in the sediments of Lake Michigan, for example, changed dramatically over the course of a decade in a manner that was not anticipated by burial and decay alone (Edgington and Robbins, 1990). There are also important quantitative links between the rates of deep mixing and ventilation as determined by time-dependent chemical and isotopic tracers (see above section) and the rates of carbon, nutrient and oxygen cycling and other biogeochemical processes within the water column (e.g. Weiss et al., 1991).

  The application of radionuclide geochronologies in the Laurentian Great Lakes (Hodell et al., 1998; Robbins and Edgington, 1975; Schelske and Hodell, 1995) and tropical great lakes (Johnson et al., 2001; Verschuren et al., 2002) has confirmed the existence of high-resolution sedimentary records of environmental change for continental regions at decadal to even annual time scales. Sediment cores from Lake Ontario, for example, provide a beautiful high-resolution record, spanning the past 160 years (Hodell and Schelske, 1998; Hodell et al., 1998)(Fig. 6).

Stable isotopes of carbon and nitrogen also have demonstrated utility to map food webs in terms of the major carbon flows and trophic relationships (Hecky and Hesslein, 1995), as well to track contaminant movements through food webs and sediments (Graney et al., 1995; Kidd, 1998; Kidd et al., 2001). The stable isotopic composition of bulk organic matter in sediments of Lake Victoria (Talbot and Laerdal, 1999) has provided a fascinating history of aquatic productivity as the basin re-filled following late Pleistocene desiccation. The $\delta^{15}N$ composition of bulk organic mater raining out of the water column in Lake Malawi exhibits seasonal variability in excess of 4.5 per mil, as well as substantial interannual variability (Francois et al., 1996). The stable isotopic composition of lacustrine carbonates is one of the major proxy tools used in paleolimnology (e.g. (Hodell et al., 1998; Ricketts and Johnson, 1996; Talbot and Kelts, 1990), providing signals of past hydrologic balance, primary productivity, and other climatically influenced lake processes.

Trace element abundances in sediments have provided important clues to past environmental change. The Nb/Ti ratio in the sediments of northern Lake Malawi serve as a paleoanemometer, indicating when north winds prevailed over the basin (Johnson et al., 2002)). Shifts in the relative abundance of redox-sensitive metals in sediment cores can provide information about past fluctuations in the chemocline of large lakes (Brown et al., 2000), and past rigor of deep water renewal (Ricketts et al., 2001). The strontium isotopic composition of fossil molluscs and gastropods in deposits of the White Nile have provided a strong signal of past changes in river outflow from volcanic versus crystalline basement terrain in East Africa, and clearly indicates when Lake Victoria refilled at the end of the Late Pleistocene, becoming once again the source of the Nile (Talbot et al., 2000).

Future Research Directions

- *Ecosystem Structure*: Large lake ecosystems are more species-rich than those of smaller lakes and they have an enormous range of geological ages. Hence, they provide fertile grounds to test the generality of theories derived from other habitats about genetic diversity, biodiversity, and ecosystem function. In addition, manipulations of fish populations through intentional or accidental introductions or extinctions have profoundly altered community structure in many of these systems. Thus, these studies have great interest both for development of management plans and for the advancement of ecological theory.

  Food webs in large lakes are associated with substrate both near their shores and on mid-lake rises. Trophic transfers in the latter may be important to whole lake metabolism and to fish production (Ackerman et al., 2001). Because of their large extent, complex morphology, and heterogeneity, large lakes and inland seas offer unique aspects to the study of benthic-pelagic couplings, and require landscape-level approaches.

Experimental and theoretical tools now exist to answer major questions about the structure of large lake ecosystems. The explosion of genomic technologies over the past decade offers the possibility of investigating species diversity at scales never before imagined, ranging from a full survey of the microbial community to tracking relatedness of individual fish. DNA microarrays offer the possibility of identifying the expression of specific genes within a microbial or plankton community. Large lake researchers should be poised to both benefit from and contribute to these exciting developments.

- *Nutrient Dynamics:* How does biogeochemical cycling change with differing hydrodynamical regimes? For many deep lake systems, the annual mixing of nutrients from the deep waters is the primary source of nutrients that support "new" biological production (e.g., (Dymond et al., 1996; Hecky et al., 1996), and the extent of mixing can vary substantially from year to year. Comprehension of the coupling of climate, lake physics, and biogeochemical cycling is essential for understanding year to year variability in the present lakes as well as the impacts of global change.

  The world's large lakes are ideal systems in which to test coupled physical and biogeochemical, 3-D time-dependent numerical models. New modeling efforts are building from oceanographic models while incorporating the high resolution and specific biogeochemical parameters required for large lakes (Chen et al., 2002) and show much promise for guiding future experiments.

  Yet to be included sufficiently in field work or in models is the interactions of large lakes with their watersheds and overlying atmosphere. River-derived constituents are critically important to the health and vitality of many lake ecosystems, yet the biological availability or fate of these components is largely unknown. The reactivity and seasonality of dissolved organic nutrients, for example, remains an important but virtually unknown area for research in lacustrine systems.

  Related questions involve the biogeochemical functioning of atmospherically dominated lakes. Are there different time scales of forcing? Does the stoichiometry of atmospheric loading differ from that of terrestrial runoff? Are connections to climate change greater in these atmospherically "sensitive" locations, or does their large size impart to them more inertia and resistance to change?

  These issues require the combination of aquatic ecosystem and hydrodynamic modeling with the landscape level approaches that are now accessible with satellite imaging and geographic information systems (GIS).

- *Carbon Balance and heterotrophy.* The amount of carbon buried in large lakes comprises about 10% of the total carbon buried in all lakes. These large lakes provide interesting systems on an intermediate scale between oceans and small lakes in which to test ideas of carbon cycling, and in which to observe the response of the aquatic carbon cycle to global warming. Despite the relative importance of lacustrine carbon burial, the chemical factors that contribute to carbon burial are still poorly understood. Burial rate, rates of primary and secondary productivity, basin morphometry, and degree of anoxia, to name a few, have all been proposed to control rates of carbon burial (e.g., (Einsele et al., 2001; Katz, 1990)). However few studies have focused on the specific effects of diagenetic pathways on lacustrine basin carbon preservation. The pore-water geochemistry of the warm, deep African rift lakes, for example, is undoubtedly unique and dramatically different from the deep sea, yet has been all but neglected.

How does net heterotrophy occur in the Laurentian Great Lakes, which have long water residence times and relatively little input from land? This paradox will only be resolved through efforts on three fronts: first, we can apply newly developed technology to obtain high quality gas saturation data with extensive spatial and temporal coverage. Second, we must collect simultaneous measurements of primary productivity and respiration using current methods with particular focus on seasonality. For example, quantification of under-ice production and decomposition is essential to resolving questions about heterotrophic-autotrophic balance. Third, evaluation of components of the food web that produce organic C (principally phytoplankton and macrophytes) and decompose it (principally bacteria and microzoans) is critical if we are to compare the whole to the sum of the parts.

Dissolved organic carbon (DOC) is now recognized as a vitally important component of the organic carbon cycle in aquatic systems (e.g., (Biddanda and Cotner, in press; Pomeroy, 1974; Roland and Cole, 1999; Wissmar et al., 1977) and many others). DOC in lakes is both autochthonous and allochthonous in origin and both components are actively recycled within the water column of aquatic systems (e.g., (Baines and Pace, 1991; Cole and Caraco, 2001; Cole et al., 1982). The diversity of climatic settings and watershed and air shed loadings in large lakes of the world present exceptional opportunities for investigating the constraints on processing and producing DOC. DOC is modified by exposure to UV light, but, as the major chromophore in most systems, it also controls light penetration into the water column.

- *Species Diversity:* Large lakes and inland seas typically have higher species diversity than small lakes. However, relative to the immense diversity present in most of the world's oceans, large lakes hold a manageably small community. The simplicity of a food chain can be useful for testing hypotheses (e.g., in Lake Baikal (Yoshii et al., 1999)). Large lakes offer extremely fertile environments in which to develop links between geological scales of speciation and ecological processes. In general evolutionarily old suites of fish species in very old large lakes (sometimes endemic to that lake) are well adapted to lake conditions. In contrast, in large lakes that are geologically young, stream fish species often occupy open lake niches. This observation raises many intriguing questions. For example, are geologically young lakes more susceptible to invasion than those with locally adapted suites of species? Some large lakes, for example Lake Victoria, are becoming biologically impoverished while others, such as Lake Superior, are acquiring numerous exotic species and are thus becoming more species rich (Table 2). What ecosystem effects do we expect from these trends?

- *Ecological Stoichiometry:* Fundamental questions about limits to primary productivity and growth at higher trophic levels are waiting to be addressed in large lakes research. Time scales of change in the stoichiometry of the seston, such as those of Lake Superior, are as yet poorly understood. Understanding such excursions in C:P is vital to resolving differences in behavior between oceans and small lakes (Elser and Hassett, 1994). This approach is also beginning to suggest answers to questions of resource competition, foodweb feedback loops, and short-term /long-term stability of ecosystems.

Table 2. Fish species richness and change due to introductions and extinctions (R. E. Hecky)

Insert table near here.

- *Non-equilibrium Forcing:* Episodic growth and transport of organisms may be significant on time scales ranging from hours to years. The observed mismatch between our best estimates of carbon supply (from primary productivity and import from the drainage basin) versus carbon dioxide production from heterotrophic processes suggests that we are missing important events of primary production, on unknown spatial and temporal scales. Could there be years of unusually high productivity that build up the DOC pool in a lake such as Huron, for example, that can fuel the heterotrophic microbial machine for several years afterwards? Is the annual primary production dominated by brief events associated with mesoscale eddies that last for only a few days or weeks and are only a kilometer or two in areal extent?

  The most likely explanation for the unusually large zooplankton population observed by Zhou et al. (2001) in eastern Lake Superior is that their measurements were made at an unusual time, during a period of exceptional zooplankton growth. Do such boom times for zooplankton occur every year, or is there substantial interannual variability? The interannual variations in the stoichiometry of the seston suggest the latter. Such variability may contribute substantially to the dramatic interannual rise and fall of the fisheries observed in virtually every large lake in the world. These observations demonstrate the importance of characterizing the temporal and spatial variability of the food web in lakes of different size, morphology and climatic setting if we are to successfully manage fish resources and develop useful predictive models of future ecosystem dynamics.

- *Organic Geochemistry:* The general area of organic geochemistry has perhaps the greatest potential for major breakthroughs in the development of new tracers of modern processes and of past ecosystem dynamics in large lakes. Recent advances in instrumentation are allowing stable isotopic analysis of specific organic compounds, which will undoubtedly refine our ability to characterize food web dynamics and past environmental conditions.

- *Coastal Dynamics:* The coastal boundary dominance of large lakes make these systems highly subject to episodic, storm-generated local resuspension and horizontal advection of sediments, nutrients and biogeochemically important materials. Onshore – offshore coupling, coastal trapping, and the role of embayments in the attenuation and sequestration of material fluxes are complex physical, geochemical and biological phenomena that are poorly understood, in nearly all aquatic environments. The differences in the physical and chemical character of lakes and oceans make coastal dynamics in large lakes fundamentally different from oceans in many respects, and they can provide intriguing contrasts that will enlighten both the oceanographic and large lakes research communities.

GEOLIMNOLOGY

Recent Accomplishments

Geological research on the great lakes of the world has advanced significantly in the areas of paleoclimate, human impact, continental rift dynamics and sedimentary dynamics during the past decade.

- *Paleoclimate:* The sediments of large lakes provide a unique record of global climate history, distinguished from their marine counterparts in three important ways. First, the lacustrine records provide information on past precipitation amount, probably the single key climatic variable and one that is not easily reconstructed from marine sediments, with the exception of a few marginal basins such as Cariaco and Santa Barbara Basins. Second, lake records provide site-specific information on continents, where most people live and where, arguably, we most need paleoclimate information. Third, because of their relatively high rates of accumulation and low degree of bioturbation, lacustrine sediments provide much higher temporal resolution than do marine deposits.

  Lake sedimentary records have the added advantage of duration that surpass the longevity of small lake records, of tree rings, and of glacial ice records, by several orders of magnitude. The deposits of these large lake basins are undoubtedly among the most exciting, untapped reservoirs of environmental history yet to be sampled and analyzed (Fig. 7).

To date, the geologic history of the water cycle has been a particularly difficult aspect of past climate systems to decipher. And yet it is perturbations in the hydrologic cycle, not temperature, associated with global climate change that will have the most immediate impact on future human welfare. Understanding mesoscale patterns of precipitation variability, past and future, is of key importance to human survival.

Examples:

- Results from coring Lake Titicaca and the large paleolake, Salar de Uyuni on the South American Altiplano, depict the paleohydrology of not only the Altiplano, but also of a large portion of Amazonia that can be related to sea surface temperature patterns in the equatorial Atlantic (Fig. 8) (Baker et al., 2001a; Baker et al., 2001b).

- Glacial-interglacial cycles are clearly imprinted on the sedimentary record in Lake Baikal, demonstrating that the deep interior of the Asian continent responds not only to variations in insolation, but to the nonlinear response of the oceans and ice sheets as well (Colman et al., 1995; Kashiwaya et al., 2001).

- Paleowind records, which are unattainable in the sediments of small lakes, have been recovered from Lake Malawi sediments in the southern tropics of East Africa. They link the African monsoon on a millennial scale in the late Pleistocene to the Greenland ice core record of temperature ($\delta^{18}O$) (Johnson et al., 2002), and on a centennial scale with the Little Ice Age and Medieval Warm Period of the Northern Hemisphere (Johnson et al., 2001).

- Varved glacial-lacustrine sediments provide compelling evidence for ENSO variability in the early Holocene record of Lake Huron (Godsey et al., 1999), in counterpoint to other published studies that suggest that ENSO was globally inactive during that time.

- *Human Impact:* While large lakes are immense, with water residence times of decades to centuries, they are surprisingly vulnerable to human impact (Cohen et al., 1996). Are such changes such as the eutrophication of Lake Erie and the drying of the Aral Sea unique, and unparalleled by natural variability? The sedimentary record can answer this important question.

Lake Victoria, Africa's largest lake by area, underwent dramatic change, from a diatom- to blue-green algae-dominated system sometime between the 1960's and the 1980's. Bottom waters became permanently anoxic and several hundred endemic species of cichlid fishes were eradicated. The paleolimnological record of fossil diatoms and midges reveals that ecological change had actually begun in the 1930's as the human population in the lake basin began its ten-fold (!) rise to the present 30 million people (Verschuren et al., 2002). This sedimentary record of environmental change is unlike any change observed in the sediments spanning the previous 13,000 years. The population in this basin is projected to rise to 53 million people by 2020 (Nations, 1995). What does this portend for the lake's future welfare?

- *Continental Rift Dynamics:* Seismic stratigraphic studies of rift lakes, especially the East African rift lakes, have shed new light on the early history of continent-to-ocean rifting and the geometry of passive continental margins, such as along the Atlantic Ocean (Rosendahl, 1987). Such information is of great interest to the petroleum industry as new models of the reservoir and source rocks are developed for ancient lacustrine basins, which currently provide about 20% of the world's hydrocarbon production (Bohacs et al., 2000).

  Subsurface imaging of large lakes over the past decade has unveiled a unique stratigraphic architecture, relative to marine systems, dominated by profound facies shifts, discontinuities and lithologic variability driven by both tectonic and climatic forcing (e.g. (Carroll and Bohacs, 1999; Cohen et al., 1993; Colman, 1998; Moore et al., 1997; Scholz, 1995; Scholz et al., 1993).

- *Sedimentary Dynamics:* Understanding depositional patterns in lakes and the sediment transport pathways that lead to those patterns is a necessary prerequisite to understanding most problems related to pollution, as nearly all pollutants travel adsorbed onto sediment particles. Unfortunately large lakes are complex depositional systems, not just simple collection bowls for anything entering at the edges. The past decade has seen the formulation of quantitative descriptions and numerical models of sediment dynamics in some, but only a few, of these systems (e.g., southern Lake Michigan and Lake Erie (Edgington and Robbins, 1990).

<u>*Future Research*</u>

- *Paleoclimate:* More than 4 km of sediments have accumulated in many large tectonic lakes on the continents, providing long continuous records of past climate that are unsurpassable in their combination of duration and temporal resolution. Such records will allow us to understand the response of lakes and regional climates to larger-scale forcing on a variety of time scales, from interannual (ENSO) to decadal, to millennial (Little Ice Age, Younger Dryas, Dansgaard-Oeschger events), to orbital (glacial-interglacial stages), and longer (pre-Quaternary). In some cases we will even be able to approach critical questions of seasonality.

  In order to fully exploit this resource, we need high resolution, long time-scale climate reconstructions from lakes on all continents, especially from lakes that are old enough to contain sediments representing periods of different mean states of global climate (for example, the last glacial maximum and older periods).

  What will be the impact of global warming on lake temperatures, hydrologic balance, biological productivity, ecosystem structure, and water quality? And conversely, what will be the effect of lakes on the climate of surrounding regions? The application of improved mesoscale climate models will increasingly provide insight into these issues.

- *Linking Modern Lake Processes to the Sedimentary Record:* The paleoclimate community is in great need for modern process studies in large lakes that will establish unequivocal links between climate forcing and sediment composition. Instrumented moorings (with thermistor arrays, current meters, in-situ monitors of the biota and dissolved gases, and sediment traps) are needed in all of the large lakes that are known to produce promising paleoclimate records.

- *Geochemical Proxies of Past Conditions:* New geochemical proxies of past environmental conditions need to be developed in lake sediments. One of the most promising avenues of research is in organic geochemistry due to the increasing availability and sensitivity of modern analytical techniques. Lacustrine organic material is a complex mix of organic compounds, some of which can be keyed to unique sources (Meyers and Ishiwitari, 1995). The potential exists to discover a lacustrine analog to marine alkenones, which have provided a valuable paleothermometer to the paleoceanographic community. Compound-specific analyses for light stable isotopes will undoubtedly become routine in paleolimnology, and will provide more quantitative information about past environments than we presently are able to produce.

- *Sediment Dynamics:* A particularly exciting opportunity involves using large lakes to connect process (sediment dynamics) with product (sedimentary strata) and test fundamental aspects of stratigraphic theory. Attempts to test stratigraphic theory on continental-margin strata are fraught with difficulty due to poor age control and limited independent knowledge of the history of basin boundary conditions (Paola, 2000). In contrast, laboratory-scale, physical experiments, i.e. “sand-box” experiments, conducted under precisely known conditions, circumvent the above difficulties but are limited by inherent scaling issues (Paola et al., 2001). Large lakes, with their potentially well-constrained boundary conditions and high-resolution chronologies, have the potential to bridge the gap between continental-margin-scale, field-based studies and laboratory-scale experiments. This concept of "process and product" applies to the sedimentary architecture of the lake basins, in extensional settings (e.g. Lakes Baikal, Malawi and Tanganyika), along transform faults (e.g., the Dead Sea) and along convergent plate boundaries (e.g., Lake Issyk Kul). Stratigraphic forcing mechanisms in large lakes include high amplitude and high frequency lake level changes, rapid rates of tectonic subsidence, and tightly coupled hydrologic and sediment delivery systems.

  Large lakes exhibit immense diversity in basin physiography, water density (from the fresh waters of Lake Superior to the hypersaline Dead Sea, with a water density of about 1.25 g/cc, and climatic setting. As such, they provide a spectrum of wave climate and circulation patterns necessary to understand the controls on shallow water sedimentation.

  By thoughtfully exploiting the similarities and differences between lacustrine and marine settings, we have a tremendous opportunity to improve our knowledge of process sedimentology and stratigraphy. The absence of a salinity barrier in most large lakes permits the frequent plunging of rivers with modest sediment loads. This renders such settings ideal for studying the dynamics of hyperpycnal flows (Mulder and Syvitski, 1995). Due to the relatively delicate nature of large-lake hydrologic budgets, variations in lake level are characterized by rates and magnitudes appreciably different and often larger than those of sea level. Through careful analysis of seismic stratigraphy in large lakes, we can gain tremendous insight into the stratigraphic response to rapid, large, and well-known changes in base level, which should have important sequence-stratigraphic implications.

- *Acoustic Remote Sensing:* Most large lakes of the world have been mapped with seismic systems in only a reconnaissance mode, if that. Ship track spacing on the best mapped lakes is too great to unravel fault geometries and buried sedimentary features as large as several kilometers across. The potential exists to make major advances in our understanding of rift evolution, and even to map, in greater detail than is possible outside of lake basins, the geological structures in the ancient crust underlying many large lakes such as the Laurentian Great Lakes.

  There has been no multi-beam sonar mapping undertaken on most of the world's great rift lakes, and very little on the Laurentian Great Lakes of North America. Yet such imaging of the lake floor provides a wealth of new insight into modern sedimentary processes and sediment facies development (Fig. 9).

Needs of the community.

- *Time Series Platforms:* Spurred by the impending implementation of an ocean observatory network, the Laurentian Great Lakes and other large lakes offer ideal natural laboratories as "instrumented ecosystems," providing real time data on physical, chemical, and biological conditions. Long term trends in such phenomena as thermal structure, seasonal transitions, and ice cover may be characterized as subtle changes with significant impacts. The data generated by such networks will be widely used by local, national and international agencies interested in management of large lakes ecosystems, as well as by scientists studying the fundamental processes driving the systems.

  Multiple moorings and meteorological stations are required in large lakes to understand spatial as well as temporal variability. At a miminum, moorings require thermistors with high accuracy (0.001 ^{o}C), current meters, and fluorometers. Acoustical equipment will detect layering of organisms within the water column and transmissometers are needed to describe sediment resuspension events, plume development, and intrusions. Conductivity-temperature-depth platforms for both time series and process studies must be outfitted with state-of-the-art oxygen, pH, fluorescence, and optical equipment. There have been exciting new advances in *in-situ* instrumentation with high temporal measurement frequency, remote telemetry capabilities, either via fiber optic cable or links via satellites or cellular phone, and a variety of measurement capabilities. These include *in situ* biomonitoring, acoustic hydrophone networks that track fish and zooplankton populations, *in situ* chemical/physical analyzers, *in-situ* seismographs, and optical systems. The efficiencies and advantages of these technologies include reduced man-power requirements, real time or near real time data collection and display, and high frequency collection and observation.

- *Remote Sensing from Satellites and Aircraft:* Satellite imagery has revolutionized oceanography and has had a substantial impact on large lakes research. The capabilities of satellite- and aircraft-borne sensors are expanding rapidly and represent the most powerful tools available for large-scale synoptic studies on large lakes. New platforms with additional band and spatial resolution will significantly improve the analytical capabilities of satellite and aircraft borne remote sensing, and will produce a wealth of data in real time. Major challenges include development of local algorithms and their validation for individual lakes, and the handling and archiving of large data sets.

- *Improved Models:* At present, much of the modeling work conducted in large lakes has employed primitive equation models such as POM and ELCOM (Estuary and Lake Computer Model). All such models are imperfect estimates of the true state of the lake, thus specifying and minimizing errors in the models must be a priority. The most skillful models in oceanographic and meteorological research are made by coupled model-observation systems with data assimilation and real-time adaptive sampling. Additional theoretical modeling will aid in a deeper understanding of processes within large lakes.

- *Research Vessels:* Ultimately, enhanced, more capable research vessels will be essential for the large lakes research community. While these vessels will not have to stay away from port for long periods (typically, no longer than 1-2 weeks), multi-disciplinary field programs will require berthing for 12 or more scientists, ample laboratory space, and sufficiently large working decks to deploy sophisticated moorings and to carry specialized research vans (e.g. for 'clean' techniques, preparation of samples for isotope analysis, or biological incubations).

- *Drilling Operations:* Large lakes are currently being drilled for long sedimentary records. The recovery of a 5-million-year record from Lake Baikal has for the first time provided a detailed picture of cyclic variability in climate on orbital time scales deep within the interior of the largest continent (Williams et al., 1997). Lake Titicaca was just drilled in 2001 and Lake Malawi is on the schedule to be drilled in early 2004. These drilling operations are exceedingly expensive, and weigh heavily on the existing NSF budget for terrestrial paleoclimate research. Dedicated funding for lake drilling projects would avoid the perception that they tax the other research efforts supported by the Earth System History program at NSF.

Recommendation

The preceding pages of this report have highlighted just a few of the opportunities for growth and expansion within the science of freshwater inland seas. These systems are complex integrators of watershed hydrology, biology, biogeochemistry, and regional climate. These interactions thus combine under a discipline that does not fit in well under the umbrella of a single existing program at the National Science Foundation. However, there are clear ties to a wide array of subdisciplinary communities that the workshop participants recognize and appreciate. Bringing these subdisciplines together under a common theme would offer further synergy to a science that is only beginning to break through its frontier. The science of large lakes offers tremendous opportunity for major cross-disciplinary scientific discovery.

The participants at the SOFIS workshop recommend the formation of an umbrella initiative at NSF that will combine the complex physics, chemistry, biology, and geology that occur within the watersheds of large lacustrine systems. Ideally this initiative will be overseen by a NSF program manager who will assemble a steering committee with rotating terms to assist with program development and evolution. After much discussion, a recommendation was put forth that a 10-year initiative be established with a level of funding at $3-4M in the first year, and ramp up to $10M annually in year 4. It is proposed that the initiative be reviewed in year 6, under the guidance of NSF, to evaluate its overall success, recommend course corrections, and advise on continuation of the program beyond 10 years.

We envision annual expenditures of $10 M, approximately as follows:

- *The Core Program: Investigator- conceived, basic research* - $3.5M
  The heart of any program in basic research lies in support of the innovative science that is conceived by individual (or small groups of) investigators who compete effectively for an identified pool of research funds. The $3.5M per should be balanced among disciplines (e.g., biology, chemistry, geology, physics, atmospheric science). This amount would support on the order of 20 - 30 principal investigators per year.

- *Major Initiatives: Time-series observations and interdisciplinary focus on selected lakes - $3M*
  Many of the large lakes of the world are in remote settings where adequate transportation, research vessels, and shoreside facilities are lacking, and access to research permits and local governmental support requires advance planning. Multi-disciplinary expeditions to such lakes can ease the logistical burden imposed upon individual investigators, and will result in more science accomplished for the amount of money expended. The $3M per year would support time-series observations on perhaps four lakes world-wide ($2M) and one major expedition to a lake of focus each year ($1M).

- *Instrumentation and Facilities:* - $3M

The Gt. Lakes research community currently has only one UNOLS research vessel, the 87 ft, 200 GWT, R/V Blue Heron, operated by the Large Lakes Observatory at the University of Minnesota Duluth (Fig. 12). Ship operations in the Laurentian Great Lakes will cost $1 M per year. As the level of research activity picks up on the Great Lakes in response to this new program, the need for one or more larger, more capable research vessels will undoubtedly arise. The cost of new ship construction is not included in this budget.

The large lakes research community expects to install moored instrumentation as part of its long term studies, in lakes spaced across the substantial latitudinal gradient from the tropics to the high temperate/subpolar regions of Canada and Russia. The community expects to play an active role in the development of the new seafloor observatory program, with modification as needed for application to large lakes systems. ($1M)

Drilling operations on large lakes for paleoclimate research are expensive. The Earth Systems History (ESH) Program at NSF has co-supported lake drilling programs with the International Continental Drilling Program (ICDP), but deep lake drilling operations cut equally deep into the ESH budget as it currently stands. A drilling program is planned for Lake Malawi in January 2004, for example, that will cost approximately $2.5M for a 60-day project. This will allow drilling and sampling at four sites to a sub-lake-floor depth of only about 500 m – far less than the 4 km thickness of sediments that underlie this tropical rift lake. It is recommended that the new large lakes program contribute to lake drilling costs in the future, in conjunction with ESH and ICDP. ($1M)

- *Graduate and Postdoctoral Fellowships:* - $0.5M
  Future stewardship of the large lakes of the world will require a new generation of researchers, teachers, managers and policy makers who have formal training in the highly technical aspects of large lakes systems. If we are going to attract the most talented students into graduate study, it will be important to provide financial support to the most promising students to cover the costs of tuition, fees and living expenses. We recommend support for approximately 5-7 graduate students per year, allocated on a competitive basis. In addition, it is proposed that a postdoctoral fellowship program be established, patterned after the very successful NOAA Postdoctoral Global Climate Change Fellowship Program. The program would provide prestigious awards to approximately 5 postdoctoral scholars per year. New Ph.D.'s in any of the natural sciences will be able to compete for the postdoctoral fellowships, to work with a large lakes research group anywhere in the country. The postdoctoral scholars and their advisors will meet at a workshop annually to make presentations of their science and to establish ties for future collaboration in the large lakes scientific community.

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