Organized Oral Session 43. Novel Applications of High-Frequency Sensor Data in Aquatic Ecosystems: Discoveries from GLEON, the Global Lake Ecological Observatory Network

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Presenters

Paul Hanson. "Dissolved oxygen from 20 lake observatories: changing drivers from minutes to months"

Robyn Smyth. "Diurnal mixed-layer dynamics: insights from high-frequency sensor data"

Kevin Rose. "Understanding allochthony: new techniques and tools"

Denise Bruesewitz. "Drivers of pelagic metabolism: evidence from high-frequency free-water measurements in lakes around the globe"

Gordon Holtgrieve. "Intra-diel patterns in ecosystem respiration revealed using continuous oxygen data from lakes around the globe"

Emily Kara. "Time-scale dependence in numerical simulations: predicting physical, chemical, and biological patterns in Lake Mendota, Wisconsin, from hours to weeks"

Kathleen Weathers. "Enhancing human passion and curiosity about lake ecosystem function: a case study of sensors, citizens, and cyberinfrastructure from Lake Sunapee, New Hampshire"

Introduction

Ecologists are increasingly using embedded sensor networks to monitor ecosystems threatened by climate and anthropogenic change (Arzberger 2004, Porter et al. 2005, 2009). Notable examples of sensor networks that monitor marine ecosystems include the National Ecological Observatory Network

(NEON), which will have monitoring sites distributed across the continental United States, the Global Ocean Observing System (GOOS), the Integrated Ocean Observing System (IOOS), and the Coral Reefs Environmental Observatory Network (CREON) (see Shade et al. [2009] for a more comprehensive list of sensor networks). The development of remote sensors and wireless technology is enabling observations on previously unexplored temporal and spatial scales, and synthesis of these observations are yielding new insights to ecosystem dynamics (Collins et al. 2006, Porter et al. 2009, Benson et al. 2010).

For lake ecosystems, the Global Lake Ecological Observatory Network (GLEON) is the primary organized sensor network. GLEON is an international organization of limnologists, ecologists, information technology specialists, and engineers, and currently consists of approximately 50 lake sites from 25 countries and over 300 members (www.gleon.org; Hanson 2007). GLEON's sensor network is composed of observatory platforms (buoys) deployed on lakes that are instrumented with sensors measuring high-frequency water-quality variables and are wirelessly transmitting the data in near real-time to web-accessible databases. These data are available for GLEON members to use in collaboration with the data providers as part of the network's open data access policy. Unlike many sensor networks, GLEON is grassroots; its platforms are funded independently by each site, there are no hardware or software requirements for member sites, and there is no requirement that members oversee a buoy. In addition, the network's governance structure is minimal; GLEON is led by a 14-member steering committee with diverse international representation.

We organized a special session at the 96th ESA Meeting in Austin, Texas, to highlight discoveries enabled by remotely deployed, high-frequency GLEON sensors. Because they are often located at the bottom of hydrological networks, lakes may be especially sensitive to the effects of climate or land-use change (Williamson et al. 2008); hence, sensor networks are particularly useful tools for monitoring and documenting change in lake ecosystems. Perhaps due to its international and grassroots nature, GLEON has been extraordinarily successful in catalyzing scientific collaborations and discoveries in aquatic research (Hanson 2008). Specifically, GLEON-derived data and collaborations have facilitated advances in measuring lake metabolism (Staehr et al. 2010, Hanson et al. 2011), studying microbial ecology (Shade et al. 2009), understanding the effects of episodic disturbances (Jennings et al., *in press*), applying lake modeling to ecosystem forecasting (Pierson et al. 2011, Kara et al., *in press*), and interpreting lake physical dynamics for ecological analysis (Read et al. 2011).

Presentations

Paul Hanson opened the session by demonstrating how aquatic sensors and new signal-processing techniques can enable novel discoveries about lake dynamics. Most lake ecosystems exhibit patterns at multiple temporal scales, indicating that the drivers of ecosystem processes are scale dependent. For dissolved oxygen in lakes, scales between daily dynamics driven by light cycles and annual dynamics driven by seasonal temperature changes are not well explored. In a study using sensor data from 17 GLEON lakes, Hanson and his collaborators discovered that complex patterns exist over scales of days to months. At scales of 10–20 days, variability in light and water column stability were good predictors for high-latitude lakes; however, low-latitude lakes had more complicated patterns that were not easily predicted at any time scale.

Lake metabolism is an ecosystem-scale assessment of primary production and respiration within a lake and is crucial for understanding a wide range of processes, from food webs to global carbon cycling (Hanson et al. 2004). Lakes currently are not widely represented in the carbon cycles of most Earth system climate models; however, new data indicate that lakes may play a significant role in global carbon cycling (Cole et al. 2007, Tranvik et al. 2009). As a result, GLEON researchers are developing new modeling techniques to estimate metabolism from high-resolution sensor measurements (Staehr et al. 2010). Denise Bruesewitz and colleagues synthesized GLEON data from 25 lakes across the globe to calculate metabolic rates and found that gross primary production (GPP) and community respiration (CR) were tightly coupled. GPP was driven primarily by total phosphorus concentrations, and the relationship between GPP and CR was strongest in low-nutrient lakes. In addition, Bruesewitz found strong relationships between catchment land use and GPP, which are likely due to nutrient loading.

To estimate lake metabolism from dissolved oxygen sensor data, it is necessary also to measure wind speed, water temperature, and the mixed-layer depth (Staehr et al. 2010). Lake metabolism studies typically calculate the mixed-layer depth from depth profiles of temperature to determine what proportion of a lake is represented by a fixed oxygen sonde, and when corrections must be made for gas exchange with the atmosphere. However, high-frequency data from sensors show that lakes are very dynamic in their stratification and mixing patterns (Coloso et al. 2011). Robyn Smyth and colleagues showed how comparisons of the vertical profiles of temperature and the dissipation of turbulent kinetic energy derived from temperature gradient microstructure (both measured with high-frequency sensors) revealed that turbulent mixing is suppressed at temperature gradients considerably weaker than those commonly used to define mixed-layer depth in studies of lake metabolism (e.g., Staehr et al. 2010, Coloso et al. 2011). Smyth concluded that limnological constants, especially mixed-layer depth constants calculated from manual measurements, may need to be updated as sensor technology and availability improves the spatial and temporal resolution of observations.

Continuing on the theme of using new methods and updating old methods to determine lake metrics related to carbon cycling, Kevin Rose and colleagues compared several techniques that can be used to understand the degree of allochthony, or the degree of terrestrial resource subsidies, to lakes. These techniques include the ratio of dissolved organic carbon (absorbance) to chlorophyll (Webster et al. 2008), isotope ratios (e.g., carbon and hydrogen [Doucett et al. 2007]), and fluorescence (McKnight et al. 2001), as well as new techniques Rose is developing, including spectral slopes (e.g., Helms et al. 2008) and attenuation (K_d) ratios. Absorbance, chlorophyll, and attenuation ratios can all be measured with in situ sensors, providing the ability to characterize allochthony in near real-time. Rose described each of these methods and analyzed the differences among them by comparing them across a suite of western U.S. lakes. He found that some techniques consistently provided a better fit for the data than others, especially when including lakes with glacial flour and high dissolved organic carbon concentrations. His findings, which provide critical information on the relative strengths and weaknesses of these indicators of allochthony, will help refine measurements of GPP and respiration by adding lake optical characteristics to ecosystem models.

Using the same 25-lake GLEON data set described by Bruesewitz, Gordon Holtgrieve discussed his investigation of how variation in the rates and patterns of nighttime dissolved oxygen consumption is indicative of ecosystem respiration characteristics and related ecological conditions among lakes.

Holtgrieve and colleagues tested the GLEON data set with a comprehensive ecosystem metabolism model and found that frequent occurrence of nonlinear dynamics in respiration rates were related to physical drivers, such as photosynthetically active radiation and water temperature, most likely because of their effects on labile carbon pools and reaction rates. With a greater mechanistic understanding of respiration over a wide diversity of lakes, researchers may be able to use GLEON sensor data to better predict the ecosystem effects of anthropogenic changes on aquatic ecosystem metabolism.

While Bruesewitz, Smyth, Rose, and Holtgrieve highlighted the utility of GLEON data for metabolism applications, Emily Kara described how high-frequency in situ sensor data and long-term manual observational data can be used to parameterize, calibrate, and evaluate a one-dimensional coupled hydrodynamic–biogeochemical model. Kara and colleagues modeled physical, chemical, and biological variables of Lake Mendota, Wisconsin, specifically focusing on the prediction of phytoplankton biomass because of its implications for water quality. Kara found that traditional goodness-of-fit metrics indicated that physical variables were more accurately predicted than chemical or biological variables in the time domain, which was confirmed by wavelet analysis in both the time and frequency domains. For example, chlorophyll *a* fluorescence spectral characteristics were not reproduced by the model for key time scales, while both predicted and observed global wavelet spectra for temperature were closely related (Kara et al., *in press*). Although the magnitude and timing of physical and biological changes can be simulated adequately at the seasonal scale through calibration, time-scale specific dynamics may be difficult to reproduce, even when calibrating with high-frequency sensor data.

Finally, Kathleen Weathers connected the scientific data and findings described by the earlier speakers with applications for local communities. Weathers, colleagues, and citizens in the Lake Sunapee, New Hampshire, region, a GLEON site, have codeveloped web tools for watershed residents. This cyberinfrastructure is being designed to make GLEON data accessible and in a form that nonscientists can understand. By conducting a number of workshops aimed at connecting GLEON science and scientists with GLEON watershed homeowners, Weathers found that GLEON high-frequency data, resultant science, and the scientists themselves present a wonderful opportunity for enhancing public awareness and understanding of lake function. After creating tools that translated GLEON data into readily understood variables (e.g., dissolved oxygen in milligrams per liter can also be described as the amount of oxygen that fish need to survive, on a numerical scale), Weathers and colleagues found that many local homeowners were able to understand and engage with the GLEON data.

Discussion

There were several recurring themes that were highlighted by the speakers within the session. First, GLEON sensor data as a whole are very powerful for enabling novel discoveries about lake dynamics previously unrecognized by traditional sampling and data analysis methods. Hanson, Bruesewitz, Smyth, Rose, and Holtgrieve all described unprecedented observations and ecological relationships that would not have been possible without access to high-frequency, long-term data from a diversity of lakes. GLEON data have been essential for answering many lake metabolism research questions, which is important, because respiration and gross primary production are critical ecosystem processes linked to food webs, biogeochemical cycles, and trophic state. Second, these novel discoveries may force us to question long-standing limnological principles. As Smyth pointed out, her findings demonstrate that sensors may enable new findings about lakes, but they also demonstrate the need to reassess older standards that are based upon intermittent manual lake sampling (e.g., mixed-layer depth criteria). Third, real-time, high-frequency data are an effective tool to connect lake ecosystem function with nonscientists for outreach and education, as demonstrated by Weathers.

Nonetheless, there are also several challenges ahead for the network. Maintaining and developing the underlying GLEON cyberinfrastructure is critical for making data available for scientists and community members. Both Bruesewitz and Holtgrieve found that working on the GLEON lake metabolism data set provided the opportunity to examine variation in gross primary production and respiration on multiple time scales (daily to annual), but temperate lakes were overrepresented within their data set. Despite these challenges, however, GLEON is on its way to achieving its goal of creating a scalable, persistent network of global lake ecology observatories, and we believe that this ESA special session was only a first glimpse of the groundbreaking research that will be conducted using GLEON's scientific and human infrastructure. As many of the speakers pointed out, there are still many unexamined questions within this field, so undoubtedly GLEON will enable exciting research for years to come. For more information about GLEON, its science, and how to become a member, visit http://www.gleon.org.

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