Seminar and Brainstorming Session

Great Lakes Evaporation – Identifying Research Needs and Opportunities

Date: noon – 4pm, Tuesday, April 11, 2017 (lunch provided)
Location: U-M Graham Sustainability Institute, 214 S. State St, Ann Arbor, MI (above Sava's).
Sponsors: U-M College of Engineering, Cooperative Institute for Limnology and Ecosystems Research, and the Water Center

Measuring over-lake evaporation for large water bodies like the Great Lakes presents unique challenges but is critically important for water resource management. This co-sponsored seminar included short presentations about sensor technology, modeling strategies and ways evaporation measurements can inform lake level and weather forecasting. Discussion was encouraged throughout the seminar to explore new ideas for expanding the existing sensor network and identify collaboration opportunities.

The meeting was facilitated by Drew Gronewold from NOAA's Great Lakes Environmental Research Lab, Brad Cardinale from the Cooperative Institute for Limnology and Ecosystems Research and Lynn Vaccaro from the Water Center.

Note: The agenda and participant list are provided at the end of this summary document.

Meeting Summary Notes

Part 1. Introduction and Applications

Opportunities with CILER

- Brad Cardinale, Professor and Director of the Cooperative Institute for Limnology and Ecosystems Research (CILER)

<u>Key Points:</u>
Brad outlined some of the resources and opportunities available through NOAA's Cooperative Institute for Limnology and Ecosystems Research (CILER). Each year, CILER funds 3 or so working groups or summits, which could be a next step for this topic. He provided some advice for the group about CILER summits and working groups:

- Another summit or working group could be funded this year. Proposals should be submitted soon, at least by June 1. Recommends thinking about a workshop in late summer, early fall.
- Topic must relate to the focus areas of NOAA's Great Lakes Environmental Research Lab. Great Lakes Evaporation meets this criteria, particularly if we can show how work could benefit their forecasting work.
- Summits are for larger, shorter events – 2-3 days, 30 or so people. Typically used to help set a research agenda, identify gaps and vision.
- Working groups are for smaller group and longer events, potentially more appropriate for a data analysis exercise or proposal writing.
- Should be multi-institutional, more than just UM and NOAA.
- Emphasize multi-discipline involvement
- Engage relevant user groups that could inform and help apply any new science (USACE, NWS,

shipping industry, Dept of Transportation). Strive for co-production and joint planning process.

- Should be product oriented. Brad outlined a few example products:
    - Visioning, state of the science, gap analysis paper
    - A major proposal for a specific funding opportunity
    - A collaborative data analysis exercise, e.g., a sensitivity analysis for models to identify parameters that need more study, or new analysis of existing data.

Resources:

- NOAA's Cooperative Institute for Limnology and Ecosystems Research (CILER)
- NOAA's Great Lakes Environmental Research Lab (GLERL)

An Introduction to Great Lakes Evaporation

- Drew Gronewold, Hydrologist with NOAA's Great Lakes Environmental Research Lab (GLERL)

Key Points:

- Evaporation is an important part of the annual water budget for each Great Lake. The amount of water that evaporates from each lake is comparable to annual inputs from runoff. This is unusual and demonstrates the importance of understanding evaporation for predicting lake water level changes.
- Estimating evaporation is challenging for a few key reasons: the large scale of the Great Lakes, the lakes are an international boundary water so science needs to be coordinated carefully, and the current evaporation monitoring network is very sparse.
- All three parts of the Great Lakes water budget (runoff, precip and evaporation) have uncertainty, though runoff estimates seem to be the most uncertain.

Resources:

- Drew Gronewold's NOAA profile page
- GRONEWOLD, A.D. The Great Lakes System. In Handbook of Applied Hydrology, Second Edition. Vijay P. Singh. McGraw Hill, (2016). Available online

Implications for Water Resource Management

- John Allis, Chief of the Great Lakes Hydraulics and Hydrology Office, US Army Corps of Engineers (USACE), Detroit District.

Key Points:

- USACE and John's office help track and forecast Great Lakes water levels to inform decisions at each of the water level control points. They use a variety of models and data sets.
- John can help researchers connect with users and understand practical applications. For example, lake water levels are very important to the shipping industry because it influences how much cargo they can carry through shallower sections of the Great Lakes system.
- There are several lake water level control points on the Great Lakes:
    - Lake Superior's water levels are controlled by a series of locks, gates, hydropower facilities near Sault St. Marie.
    - Lake Ontario outflows are regulated by the Moses Saunders hydropower dam at Cornwall, Ontario.
- Both control points have recently adopted new guidelines for water level management, after extensive studies. There are international governing boards for both control points as well as

the Niagara River.
- The Great Lakes Water Level Dashboard, that NOAA developed, has been useful.
- There is a need to better understand climate impacts on water levels and evaporative processes

Resources
- Great Lakes Water Level Dashboard
- USACE Great Lakes Water levels and Forecasts
- International Joint Commission

Evaporation and Weather Forecasting
- Greg Mann, Science and Operations Officer, National Weather Service, Detroit office.

Key Points:
- Greg agrees evaporation monitoring stations should be expanded to improve estimates and weather forecasting.
- Explicit use of evaporation measurements is not taking place in the forecast offices currently.
- There is potential for using the data to validate and critique numerical weather prediction performance within the marine environment. For example, evaporation can be used as a tracer to help determine performance of boundary water schemes in their models.
- The data can aid in improving boundary layer parameterizations used in operational and research atmospheric models.
- Evaporation estimates are critical for predicting the intensity and timing of lake effect snow events, which can be very dangerous particularly for motorists.
- John Lenters indicated that evaporation measurements from the Lake Superior towers have significantly improved weather forecasting in Ontario.

Resources:
- NOAA/OAR HRRR simulations (Sensible and latent heat flux variables near bottom of table)
- NCEP NOMADS (NOAA/NCEP models - many have evaporation as an output variable)

Discussion about applications is included in final section below.

Part 2. Sensor Technology

Great Lake Evaporation Network
- John Lenters, Honorary Fellow, Center for Limnology, Univ. of Wisconsin. Email:

Key Points:
- There were essentially no over-lake evaporation “gages” in 2000.
- Currently the Great Lakes Evaporation Network includes 7 towers or sensor equipment mounted on lighthouses.
- These towers use the eddy covariance method to calculate evaporation fluxes. They also collect a variety of other meteorological data and imagery.
- Data is provided through several online weather portals with different partners (NOAA, GLOS, others).
- Initial projects were funded by the International Upper Great Lakes Study (through the International Joint Commission), with support from GLISA and GLOS. The team recently

developed a business case for maintaining and expanding the network. The field work and management are not insignificant.
- Recently have been piloting ship based sensors that also eddy covariance approach and take into account all the rocking and movement of the boat.
- John and team continue expanding buoy based weather sensors in upper Great Lakes.
- Spatial variation can be significant. Also seasonal changes in evaporation have been surprising.
- Canadian forecasters have observed a 30% improvement in downstream lake effect snowfall forecasts by integrating new evaporation monitoring results. (See article below: Deacu 2017)

Resources:
- Assessing the Impact of Climate Variability and Change on Great Lakes Evaporation: Implications for water levels and the need for a coordinated observation network. Available through GLISA.
- Predicting the Net Basin Supply to the Great Lakes with a Hydrometeorological Model (Deacu et al. 2012, article link)
- Granite Island Light Weather Station
- Great Lakes Evaporation Network

Buoy Mounted Sensors and Data Architecture for Evaporation

- Kevin Fries, graduate student, U-M Mechanical Engineering (advisor: Branko Kerkez).

Key Points:
- Kevin, along with the Kerkez lab group, is interested in new sensors and improving the data architecture to process big data sets.
- They have been estimating evaporation using energy balance approach, using a series of “energy balance” buoys that measure relative humidity, wind air and water temp and radiation.
- Also testing out new, far cheaper “drifter” buoys, and integrating weather measurements that many vessels already collect and share to estimate evaporation.
- The data architecture for these measurements like evaporation is also critical and challenging. Kevin has been using a hierarchical, web architecture with help from Amazon web services. Machine learning helped integrate all the ship based weather measurements.
- These buoy and ship based weather station measurements are messy, but hopefully with many, many data points the noise can be minimized, and analyses can identify the conditions that influence accuracy of estimates.

Resources:
- Big ship data: Using vessel measurements to improve estimates of temperature and wind speed on the Great Lakes (Fries and Kerkez 2017 - Article Link)
- Kerkez Lab Group

Exploring Ideas for Sensor Technology

- Bill Schultz, Professor, U-M Mechanical Engineering

Key Points:
- Bill outlined the key elements of an evaporation sensor and threw out some ideas for simplifying the current eddy covariance equipment to make it cheaper. Can we reduce distance between prongs, or use fewer prongs?
- Ideally we could create many, cheap and expendable evaporation buoys that could fill in the

gaps in between the towers. Bill showed one example – a Hydra 2 that is used in terrestrial applications.

- This work requires modeling a completed boundary layer – it is turbulent, two-phase, with energy and mass transfer. A complicated shoreline, waves and aerosol formation further complicate estimatations.

<u>Resources:</u>

- An integrated micro-meteorological system for evaporation measurements. (Shuttleworth 1988 - Article Link)
- Bill Schultz's UM profile page

Brainstorm on Sensor Technology is included in final section below.

Part 3. Modeling Strategies

Heat Flux Modeling

- Eric Anderson, Oceanographer, NOAA Great Lakes Environmental Research Lab

<u>Key Points:</u>

- The NOAA GLERL lab provides forecasts for a range of lake parameters - wind, waves, ice, water temperatures, water levels etc.
- Recently added heat flux estimates to suite of forecasting products. This includes latent and sensible heat flux and long and short wave radiation, mapped across the Great Lakes, in Watts/meter2.
- Evaporation estimates are one component of the heat flux estimates (latent heat), but the end goal of this work for NOAA is to better describe lake processes (circulation, thermocline parameters etc.)
- The hydrodynamic models (FVCOM and POM) use similar algorithm to atmospheric models (WRF, HRRR) for surface turbulent heat exchange
- Eric's group reviewed a range of existing models and algorithms and chose two – UZL (SOLAR) and COARE 3.0 – to test their performance for Great Lakes, both of which estimate bulk transfer coefficients. However, most algorithms are based on measurements from the open ocean, and represent fully-developed ocean conditions, which may differ significantly from conditions in the Great Lakes, e.g. wave steepness, wave age, etc.
- Paper is in review comparing the heat flux outputs for the Great Lakes using a variety of models. Also looking at heat fluxes as an output of evaporation.

<u>Resources:</u>

- Great Lakes Coastal Forecasting System (GLCFS) and Next-Gen GLCFS
    - o Original GLERL method (UZL)
    - o COARE 3.5 flux algorithm
- Experimental heat flux point forecasts
- Experimental whole-lake heat flux forecasts
- Eric Anderson's NOAA profile

Lake Ice and Thermodynamic Fluxes

- David Richter, Assistant Professor, Civil & Environmental Engineering & Earth Sciences, University of Notre Dame.

Key Points:

- Background is in fluid mechanics and has used large eddy simulations as a tool for understanding fluxes.
- Ocean spray and aerosols can be important at certain wind speeds and distances. Lots of surface evaporation is from the aerosol particles.
- The influence of ice formation processes is also of interest. For example, in arctic studies, measurements and flux parameterization methods vary depending on ice cover. What happens if sensors are integrating ice and non-ice areas?

Resources:

- Richter Research Group
- Parametrizing turbulent exchange over summer sea ice and the marginal ice zone (Andreas et al. 2010 - Article Link)
- Ocean spray: An outsized influence on weather and climate (Ricther and Veron 2016- Article Link)

Two Phase Flow and Turbulence Modeling

- Jesse Capecelatro, Assistant Professor, Mechanical Engineering, U-M.

Key Points:

- Jesse described himself as a traditional fluid mechanician that relies on computational approaches. He is just getting into the topic of Great Lakes evaporation.
- Currently "bulk algorithms" for surface fluxes lump several processes and local conditions into a small number of parameters and coefficients.
- A "bottom up" approach to describing the underlying physical processes could be applied to Great Lakes evaporation predictions. Several academic questions could be tackled this way:
    - To what extent does turbulence retain memory of upstream roughness and how does this affect evaporation rates?
    - What role do aerosols play in evaporation?
- One potential outcome of this would be to improve hydrodynamic / atmospheric forecasting models (e.g., FVCOM and POM) to not rely as heavily on evaporation monitoring sensors.
- Jesse outlined some ideas for simulations of processes at different scales that could be used to develop physics-based models. This could include building on work that simulates:
    - turbulence transitions over roughness (e.g. shoreline)
    - interface tracking, which can resolve air-water interactions
    - turbulent sprays, which can capture droplet-turbulence interactions

Resources:

- Capecelatro Research Group

Part 4. Science Questions and Potential Next Steps

There was a lot of discussion to help the group understand each other's disciplines and perspectives on the topic and identify questions, knowledge gaps and opportunities. Note: some of the questions identified below may be known, but could be addressed through a science synthesis exercise to help guide next steps.

Brainstorm and Discussion

<u>Introduction and Applications</u>

- How much do evaporation estimates vary spatially and temporally, what are the patterns? Where and when are estimates most uncertain? Where and when are evaporation processes most influential for applications - like lake effect snow and water level predictions?
- It's helpful to remember the applications of evaporation numbers: improving water level predictions and management (for example, for shipping and lake control decisions) and improving weather forecasting (lake effect snow leads to high car accidents rates in affected states). Canadian forecasters started using evaporation data points from flux towers – and it improved forecasts by 30%!
- Which of these ideas will have a measurable impact of the quality of NOAA's models and evaporation numbers for these applications? Dave Schwab suggests for NOAA's goals:
    - Long term – more monitoring and improved modeling is needed
    - Short term – better calibrate and link hydrodynamic lake models and atmospheric/meteorological models to improve numbers now.
- Consider current political climate and use of terms like climate change. Suggested title: Making the Lakes Great Again
- Do we need to show relevance at national or global level? Great Lakes evaporation affects weather and commerce for a large number of people regionally, this should be enough? Ocean evaporation doesn't have as clear an impact on weather that affects people.
- There would be a benefit to forecasting water levels if evaporation could be better forecasted. Can evap forecasts be created with any skill based on expected monthly temperature, current water temp, etc?

<u>Sensor Technology</u>

- Desire to design and test cheaper sensors. More sensors to fill in the gaps, expand network.
- LIDAR can be used, looking across to horizon.
- Aircraft campaigns are also possible, but their flight is restricted to particular heights.
- Scintillometers can measure sensible heat flux
- Techniques used to measure density differences of jet propulsion (synthetic Schlieren?)
- What about remote sensing options? Modeling techniques used in the remote sensing community could have relevance here – e.g., how to best up-scale measurements?
- Remote sensing has been well developed for evaporation estimates from terrestrial areas, but lakes would require a different methodology. NASA is working on developing humidity profiles.
- CYGNSS Mission has UM involvement, they are focusing on wind. Gretchen suggests it may be difficult to retrieve other information reliably.
- What mounting sensors on birds? Can we learn from the way birds sense humidity and other

physical variables?
- There are opportunities to do lab and field scale experiments to test new ideas against existing measurements. Granite Island weather station is now managed by Northern MI University as a research station.
- GM has donated their wind tunnels to Western Michigan University, which are available for projects now. (Charles Petty has these connections.)
- Opportunities to bring in ocean-atmosphere community. Chris Fairall (NOAA Boulder) was mentioned. New sensor ideas that could come from marine community.

<u>Modeling Strategies</u>

- Is diffusion induced convection a factor for evaporation fluxes? Evaporation is a mass transfer problem, which means both convection and diffusion are at play (though not of equal importance). In other mass transport questions "anomalous diffusion" can be significant, but can be explained by convection processes. (Q from Charles Petty)
- Evaporation seems like a well understood physical process. The challenge is to incorporate the stochasticity of wind, waves etc.
- There is an operational wave forecasting model. Could models be linked in a different way?
- Drew suggested that we need a framework that integrates all of this. For example, NOAA's current model doesn't incorporate Branko and Kevin's evaporation estimates (drifter buoys, ship based weather estimates), or the smaller scale models Jesse described.
- Dave believes that processes when wind speeds are close to zero could be influential and not well captured in models or measured. For example, ice forms only at low-wind speeds; evaporation is high just before ice forms. Ice and wind processes could influence each other. This might elevate the importance of anomalous diffusion.
- How important is the variation in processes that occur within a grid cell used for large scale Great Lakes models? What are the important spatial and temporal scales for evaporation?
- Predictive models are a way to synthesize data that is available at a range of scales. They can constrain large scale flows, let small scale parameters take over. Can do a sensitivity analysis to determine importance of variables and modeling attributes.
- Opportunities to bring in ocean-atmosphere community. NOAA GLERL's current lake models were developed by marine community and have been adapted for the Great Lakes. However, algorithms for turbulent heat flux were developed based on experiments in the open-ocean, where significant differences from the Great Lakes are likely, e.g. fetch-limited waves. Updating these algorithms with lake-based experimental measurements, as well as incorporating additional processes may be fruitful.

Meeting Agenda

Noon	**Lunch and Introductions** – Jen Read, U-M
12:45	**Introduction and Applications** • A next step opportunity with CILER – Brad Cardinale, CILER • An introduction to Great Lakes evaporation – Drew Gronewold, NOAA • Implications for water resource management, John Allis, US Army Corps of Engineers • Evaporation and weather forecasting, Greg Mann, National Weather Service *Discussion objective – How can we best demonstrate real world needs?*
	Sensor Technology • Great Lake Evaporation Network, John Lenters, Univ. of Wisc. • Buoy mounted sensors, Branko Kerkez and Kevin Fries, U-M • Exploring ideas for sensor technology, Bill Schultz, U-M *Discussion objective – What technology could help expand the existing sensor network?*
2:15	**Break**
	Modeling Strategies • Heat flux modeling, Eric Anderson, NOAA Great Lakes Environmental Research Lab • Lake ice and the thermodynamic fluxes, David Richter, Notre Dame • Two phase flow and turbulence modeling, Jesse Capecelatro, U-M *Discussion objective – What modeling strategies could improve evaporation estimates?*
	Next Steps – Brad Cardinale, CILER • The role of CILER summits and workgroups • Brainstorm – goals, products, timeframe, participants • Other funding opportunities and considerations
4:00	**Adjourn,** optional happy hour

Participant Contact List

(This list includes a few individuals that registered but were unable to attend.)

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