Macrosystems EDDIE:
Climate Change Effects on Lake Temperatures

Student Handout

Learning Objectives:

By the end of this module, you will be able to:

- Set up and run the General Lake Model (GLM) in the R statistical environment to simulate lake thermal structure.
- Understand how GLM configuration files, high-frequency driver data, and output files are organized and used.
- Modify the input meteorological data for one GLM model to simulate the effects of different climate scenarios on lake thermal structure.
- Interpret model output from GLM simulations to understand how changing climate will alter lake thermal characteristics.
- Use the GRAPLEr R package to set up hundreds of model simulations that vary input meteorological data, and run those simulations using distributed computing.
- Explore the application of distributed computing for modeling climate change effects on lakes.

Why macrosystems ecology?

Macrosystems ecology is the study of ecological dynamics at multiple interacting spatial and temporal scales (e.g., Heffernan et al. 2014). Macrosystems ecology recently emerged as a new sub-discipline of ecology to study ecosystems and ecological communities around the globe that are changing at an unprecedented rate because of human activities (IPCC 2013). The responses of ecosystems and communities are complex, non-linear, and driven by feedbacks across local, regional, and global scales (Heffernan et al. 2014). These characteristics necessitate novel approaches for making predictions about how systems may continue to change across time and space. Consequently, macrosystems ecologists are increasingly combining large datasets of high-frequency sensor observations with simulation models of ecological phenomena to predict how changes in climate, land use, and other factors may affect the structure and function of communities and ecosystems (Weathers et al. 2016).

Addressing macrosystems questions using models

Lakes around the globe are experiencing the effects of climate change. Because it is difficult to predict how lakes will respond to the many different aspects of climate change (e.g., altered temperature, precipitation, wind, etc.), many researchers are using models to manipulate climate scenarios and simulate lake responses. Lake simulation models provide a powerful tool for exploring the sensitivity of lake thermal structure characteristics (e.g., water temperature, stratification) to weather.

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In this module, you will learn how to set up a lake model and "force" the model with climate scenarios of your own design to examine how lakes may change in the future. While it is relatively easy to run one lake model on your own computer, it becomes more challenging to run hundreds of models, as the computational workload becomes more time-consuming. To overcome this problem, we have developed an R package called GRAPLEr (Subratie et al. 2017), which allows you to submit hundreds of model simulations through the R statistical environment, run those models efficiently and quickly using distributed computing tools, and then retrieve the model output. The GRAPLEr allows you to harness cyberinfrastructure tools commonly used in computer science to improve the computing speed that are rarely used in ecology and freshwater sciences. Ultimately, using the GRAPLEr and similar tools will allow us to improve our understanding of climate change effects of lakes.

Module overview:

1) Introduction to climate change effects on lakes; pre-readings and PowerPoint in class
2) Download and set up R software and module files on your computer
3) Activity A: Plot water temperatures from a lake model
4) Activity B: Develop a climate scenario, generate hypotheses, and model how the lake responds
5) Activity C: Use distributed computing to run hundreds of lake model simulations

Optional pre-class readings:

- Williamson, C.E., J.E. Saros, W.F. Vincent, and J.P. Smol. 2009. Lakes and reservoirs as sentinels, integrators, and regulators of climate change. Limnology & Oceanography 54: 2273-2282.
- Sahoo, G. B., S.G. Schladow, J.E. Reuter, and R. Coats. 2011. Effects of climate change on thermal properties of lakes and reservoirs, and possible implications. Stochastic Environmental Research and Risk Assessment 25.4: 445-456. [Focus on Section 1, pages 445-447]

Today's focal question:

How will lake thermal structure change in response to altered climate?

To address this question, we will use an open-source hydrodynamic model called GLM (the General Lake Model; Hipsey et al. 2014). To run GLM, we provide a high-frequency meteorological driver file that contains multiple weather variables (including air temperature, solar radiation, wind, and precipitation) for our lake. GLM also has a configuration file, or 'master script' file called a glm.nml file, which gives basic information about the lake (e.g., maximum depth, latitude, lake name, etc.), as well as instructions to GLM about how the model should be run. These instructions include the simulation start and end dates and times, the time step of the model, and the names of the high-frequency meteorological and inflow data files. From these inputs, the model will simulate water temperatures at many lake depths over time. For more details about GLM, see: http://aed.see.uwa.edu.au/research/models/GLM.

Setting up R software and files:

If you have not already downloaded R and RStudio, you will need to complete that step first. You can use the "R You Ready for EDDIE" file for help. Once you have R and RStudio installed, you'll need to download the module files for the rest of today's activities. All the files you'll need for the module are available for download online as a zip file (https://serc.carleton.edu/eddie/macrosystems/module1.html). We've organized the files within the folder to make it easy to load and run through RStudio. Follow the directions in Part C of the "R You Ready for EDDIE" file to extract and organize your files.

Finally, to get started on the module activities, chose the script file that's appropriate for your computer (PC or Mac). Read through the annotation for each step in the R script so that you understand what is happening in each of the lines of code that you are running, which align with the questions below.

References:

Heffernan, J.B., et al. 2014. "Macrosystems ecology: understanding ecological patterns and processes at continental scales." Frontiers in Ecology and the Environment 12.1: 5-14.

Hipsey, M.R., L.C. Bruce, and Hamilton, D.P. 2014. GLM - General Lake Model: Model overview and user information. AED Report #26, The University of Western Australia, Perth, Australia. 42 pp.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Page (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Eds.). Cambridge University Press, New York, NY.

Subratie, K. C., S. Aditya, S. Mahesula, R. Figueiredo, C. C. Carey, and P. C. Hanson. 2017. GRAPLEr: A distributed collaborative environment for lake ecosystem modeling that integrates overlay networks, high-throughput computing, and WEB services. Concurrency and Computation: Practice and Experience 29: doi: 10.1002/cpe.4139.

Weathers, K. C., P. M. Groffman, E. Van Dolah, E. Bernhardt, N. B. Grimm, K. McMahon, J. Schimel, M. Paolisso, R. Maranger, S. Baer, K. Brauman, and E. Hinckley. 2016. Frontiers in Ecosystem Ecology from a Community Perspective: The Future is Boundless and Bright. Ecosystems 19:753–770.

As you go through the module, you'll answer the questions below and turn in your answers at the end of the activity.

Name: ___________________________

Activity A: Plot water temperatures from a lake model

1) With a partner, set up the GLM files and R packages on your computer (Objective 1). Load the files for Awesome Lake and answer the following questions (Objective 2).
    a. Where is your lake located? (e.g., what is the latitude and longitude?)

    b. What is the lake's maximum depth?

    c. Awesome Lake is based on a real lake on the globe. Use a mapping program (e.g., http://www.latlong.net/Show-Latitude-Longitude.html) to locate Awesome Lake using the latitude and longitude you extracted from the nml file. What is the name of the water body that Awesome Lake models?

    d. Do the meteorological plots look reasonable for the latitude and longitude of your model lake? Why or why not?

2) Run the model and explore the output for lake water temperature (Objective 3).
    a. What do you notice about seasonal patterns in water temperature?

    b. Look at the color gradient scale: when during the year is lake water temperature warmest? What is the value of the maximum temperature?

3) Compare your model output with the observed high-frequency field data for Awesome Lake (Objective 4). The black circles on the figure represent real observations of temperature.
    a. How do the water temperatures and thermocline depths compare between the modeled output and the field data?

    b. Would you consider the modeled output to be a good representation of the observed lake water temperatures? Why or why not?

Activity B: Develop a climate scenario, generate hypotheses, and model how the lake responds

With a partner, discuss how different aspects of climate change may affect lake thermal structure. Your climate scenario could involve an extreme event (e.g., a hurricane), a more gradual change (e.g., +2°C increase of observed air temperature), or a scenario completely of your own design! If you need ideas for a climate scenario, check out http://climatedata.us/. For global projections, visit http://climatemodels.uchicago.edu/maps.

4) Describe the climate change scenario you are creating for Awesome Lake:
    a. Which meteorological variables (air temperature, precipitation, wind) will you modify, and by how much?

    b. When during the simulation (for a specific day or month(s)? the entire simulation period?) will you modify the variables listed above?

5) How do you expect your climate change scenario will affect thermal structure in Awesome Lake, in terms of both water temperatures and stratification timing and strength?

Modify the input data (met_hourly.csv file) to create your scenario, then run the model and analyze the output to determine how your scenario altered lake thermal structure (Objective 5).

6) Describe how your climate scenario changes the thermal structure of the lake:
    a. What differences do you observe in the surface and bottom water temperatures of the climate change scenario model output in comparison to the observed data?

    b. How does the depth of the thermocline change? How does the strength and timing of stratification change?

7) Did the output from the climate change scenario support your hypothesis (Q5 above)? Why or why not?

After you have analyzed the model output and plotted some figures of your lake's new thermal structure, create a short presentation about your climate scenario to share with the class (Objective 6). Make sure your presentation includes: (1) an introduction of your climate scenario (what you changed and why: include a figure of the climate scenario's meteorological driver data), (2) your hypothesized changes in lake thermal structure, (3) some figures of the model output, and (4) whether the model output supports or contradicts your hypotheses.