Macrosystems EDDIE: Macro-Scale Feedbacks

Carey, C.C., K.J. Farrell, and A.G. Hounshell. 1 April 2019.
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http://module4.macrosystemseddie.org
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Macrosystems EDDIE
Environmental Data-Driven Inquiry & Exploration in Macrosystems Ecology

NSF

SERC the Science Education Resource Center at Carleton College

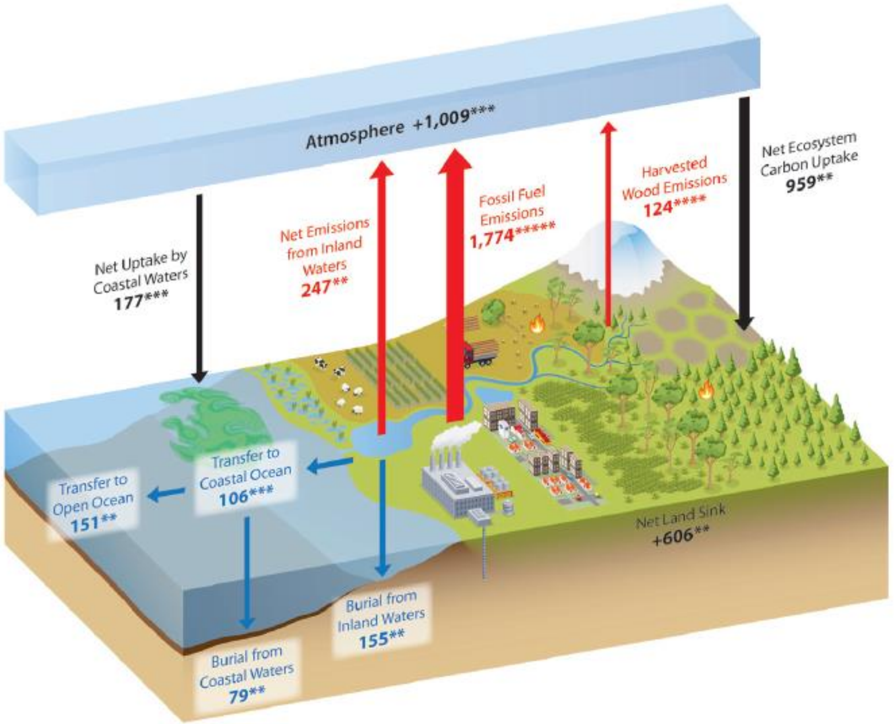
GLEON global lake ecological observatory network

Plan for today:

- Short overview on role of lakes in global carbon cycles, and how we can use a macrosystems ecology and lake modeling approach to study how their role may change with climate warming!
- **Activity A:** Run and explore a lake ecosystem model in R.
- **Activity B:** Select a climate scenario, generate hypotheses, and model how lakes respond.
- **Activity C:** Calculate global warming potentials for lakes, and make predictions about the effects of lake greenhouse gas emissions due to macro-scale feedbacks.

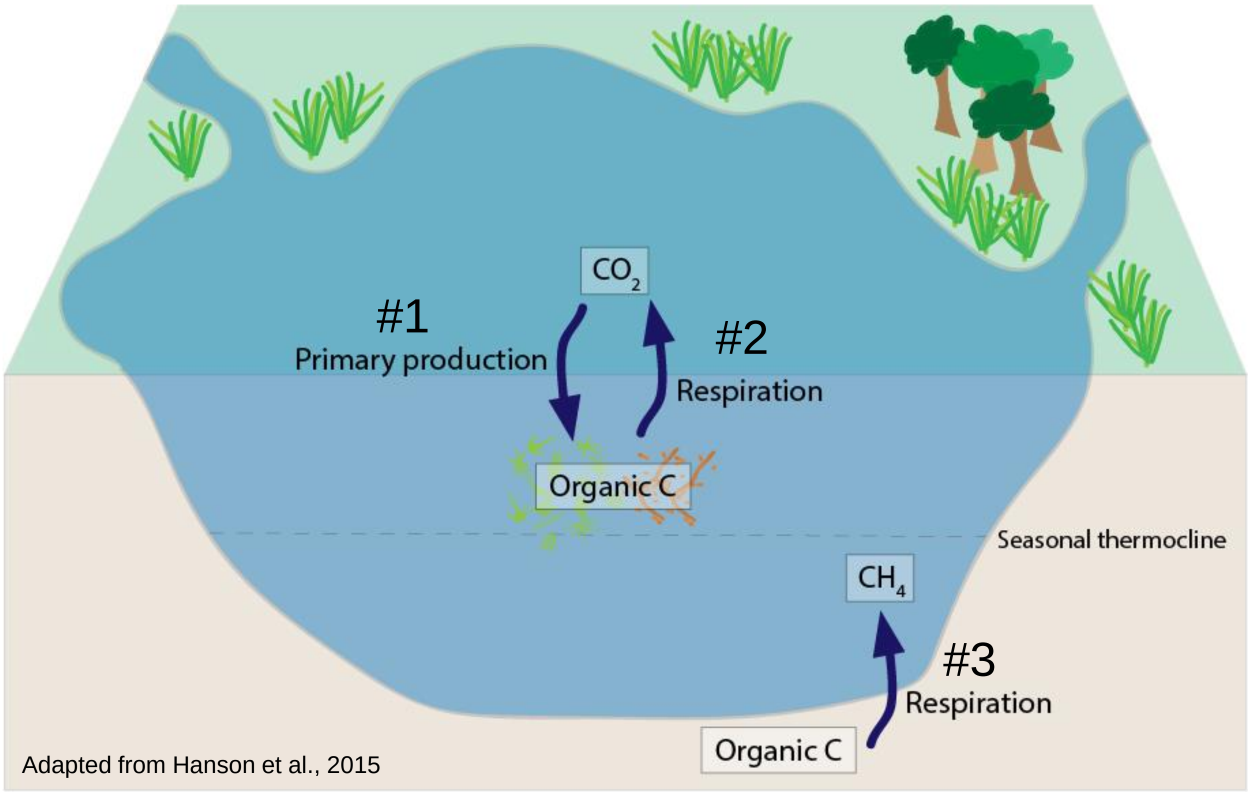
Lakes play a role in global carbon cycles

- Lakes absorb, emit, and bury large quantities of carbon (C)
- Greenhouse gas emissions (CO_2, CH_4) from lakes can be substantial and may be changing due to human activities
- Lakes often not represented in global C cycle, so understudied



Second State of the Carbon Cycle Report (SOCCR), 2018

Greenhouse gases (GHGs) in lakes: three important processes

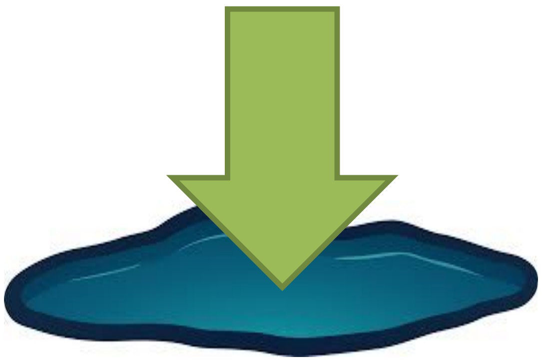


#1: Phytoplankton take-up CO_2 (carbon dioxide)

#2: <u>Aerobic</u> respiration produces CO_2 if there is oxygen

#3: <u>Anaerobic</u> respiration produces CH_4 (methane) if there is *no* oxygen

GHG fluxes in lakes are driven by diffusion gradient across the air-water interface!

Negative flux	Positive flux
	
Atmosphere > Lake	Atmosphere < Lake
Lake is **SINK** of GHG	Lake is **SOURCE** of GHG

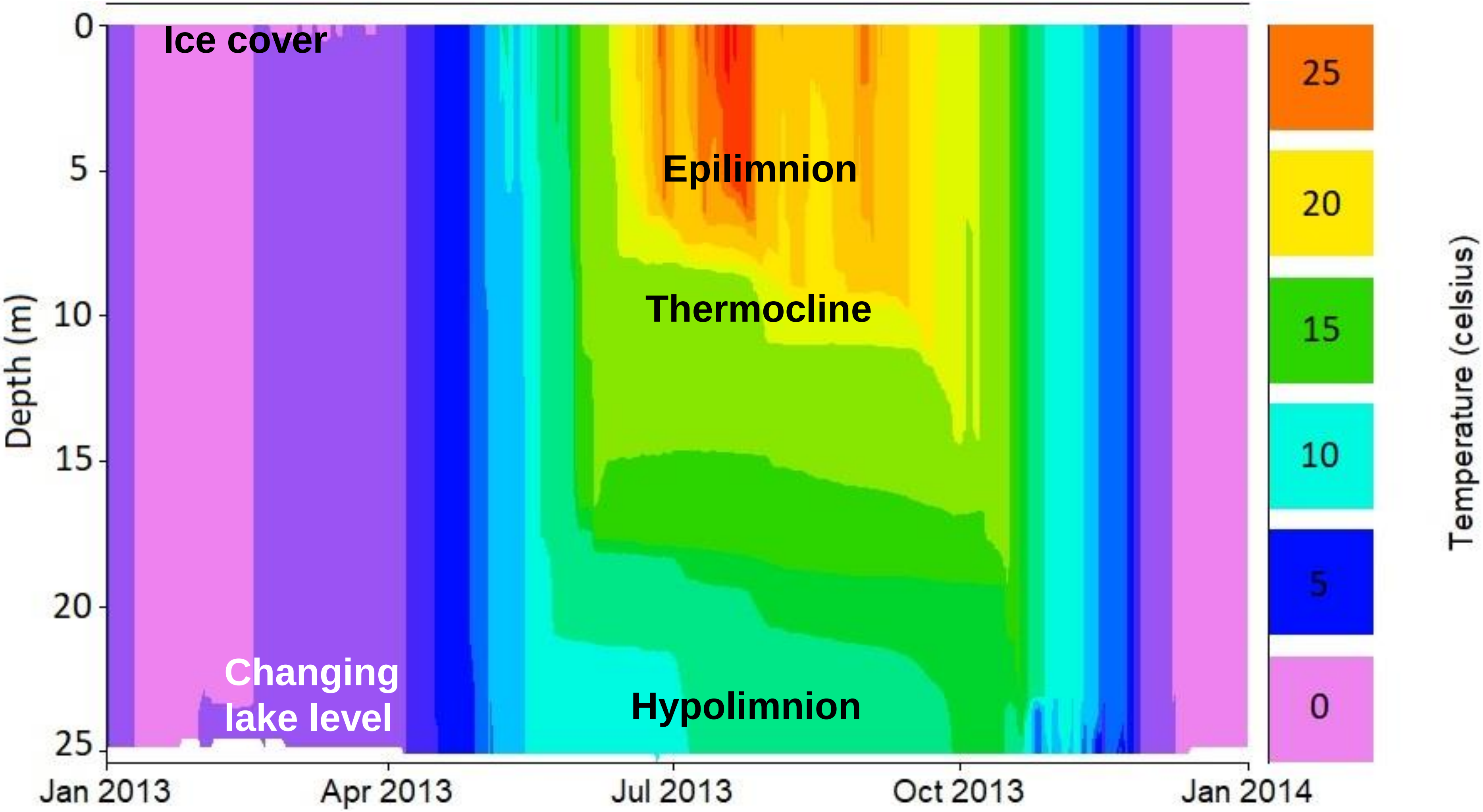
NOTE: When there is ice on the lake's surface, GHG flux = zero because the air and water are not in contact!

Lake warming may influence CO_2 and CH_4 fluxes: but likely varies among lakes and gases!

- Warmer temperatures may increase phytoplankton growth
- Warmer temperatures also increase respiration rates
- Warming water holds less dissolved oxygen (DO), resulting in lower DO concentrations

BUT, how will all of these processes interact?

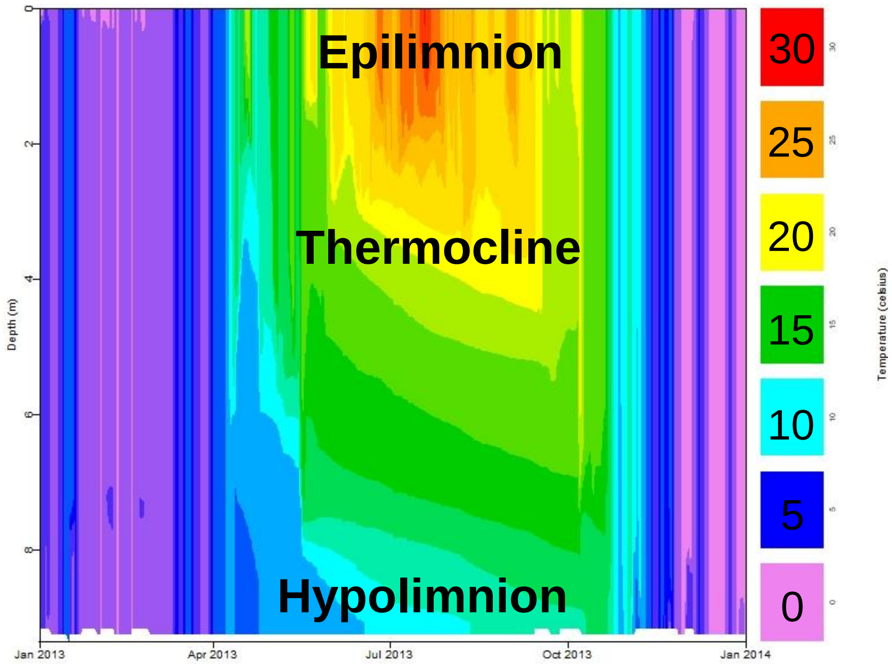
How does lake temperature vary seasonally?



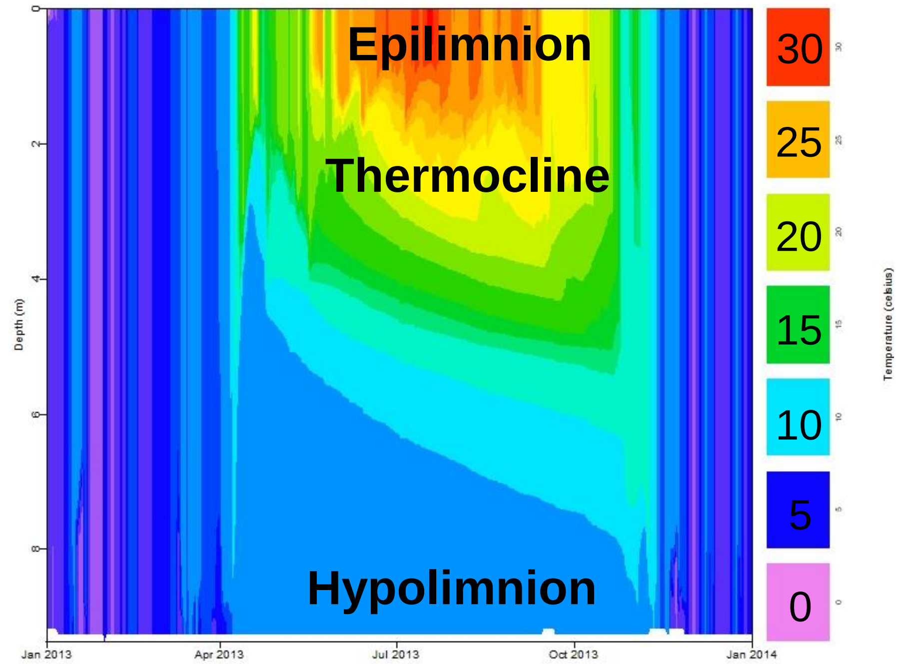
Lake Mendota, WI, USA: data from Temperate Lakes Long-Term Ecological Research

How will warming air temperatures affect water temperatures?

Baseline



+6ºC Climate Scenario

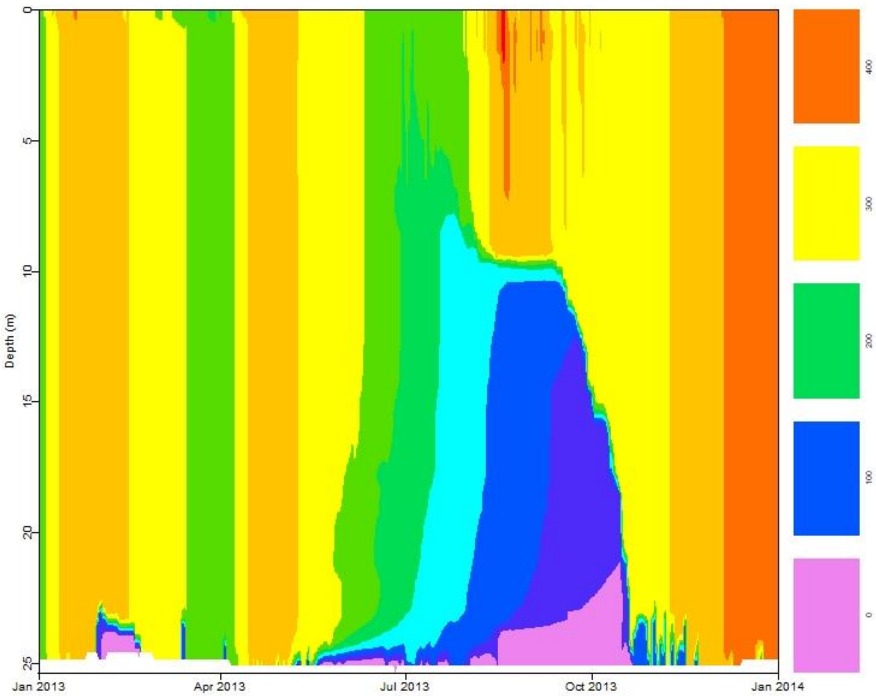


- Warmer epilimnetic waters yet cooler hypolimnetic waters

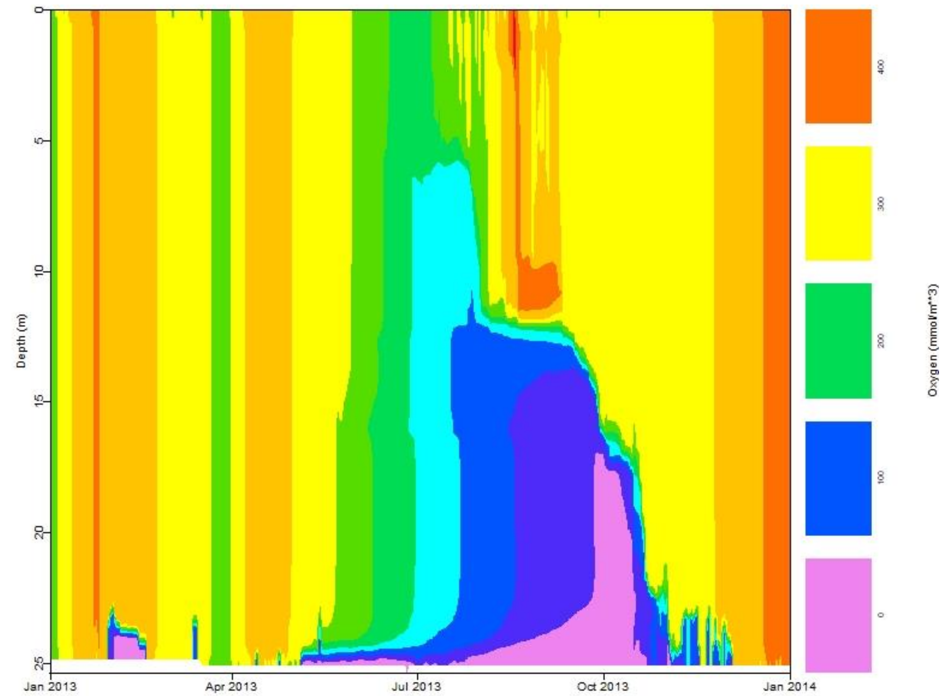
Model output from Falling Creek Reservoir, VA

How will warming air temperatures affect dissolved oxygen?

Baseline



+6^{o}C Climate Scenario



- CO_2 will be produced from respiration when there is oxygen
- CH_4 will be produced from respiration when there is *no* oxygen

Lake Mendota, WI: data from Temperate Lakes Long-term Ecological Research

Using a macrosystems ecology approach to study greenhouse gas fluxes

- Drivers of fluxes occur at both local and regional scales
  - Local = e.g., lake characteristics
  - Regional = e.g., weather
  - Global = e.g., climate change
- Macrosystems ecologists study ecological dynamics and feedbacks at multiple interacting spatial and temporal scales
- We can study local, regional, and continental drivers using high frequency sensor data + simulation models

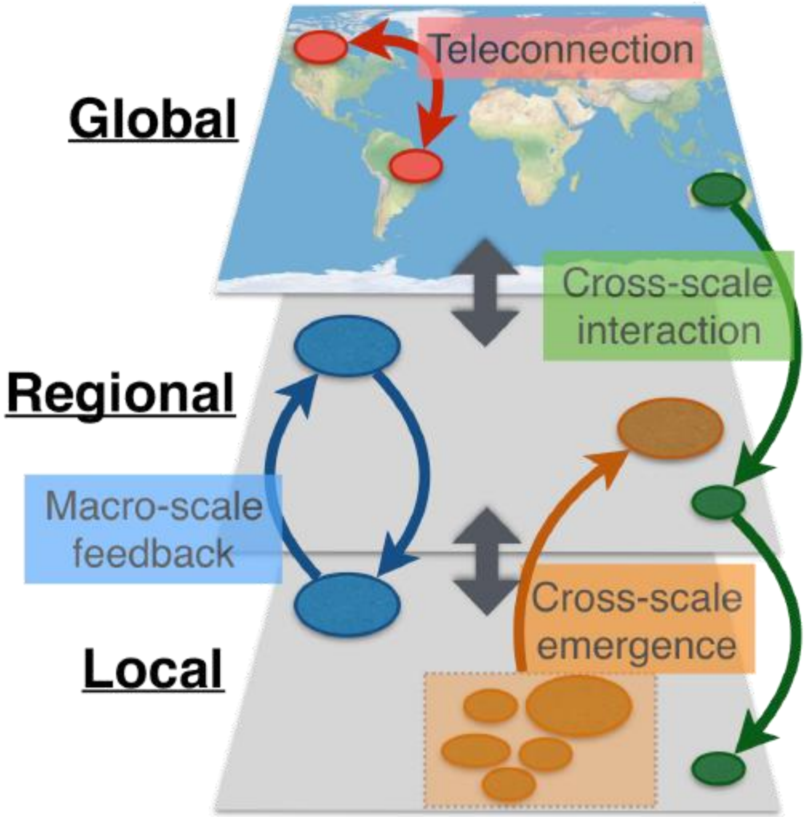
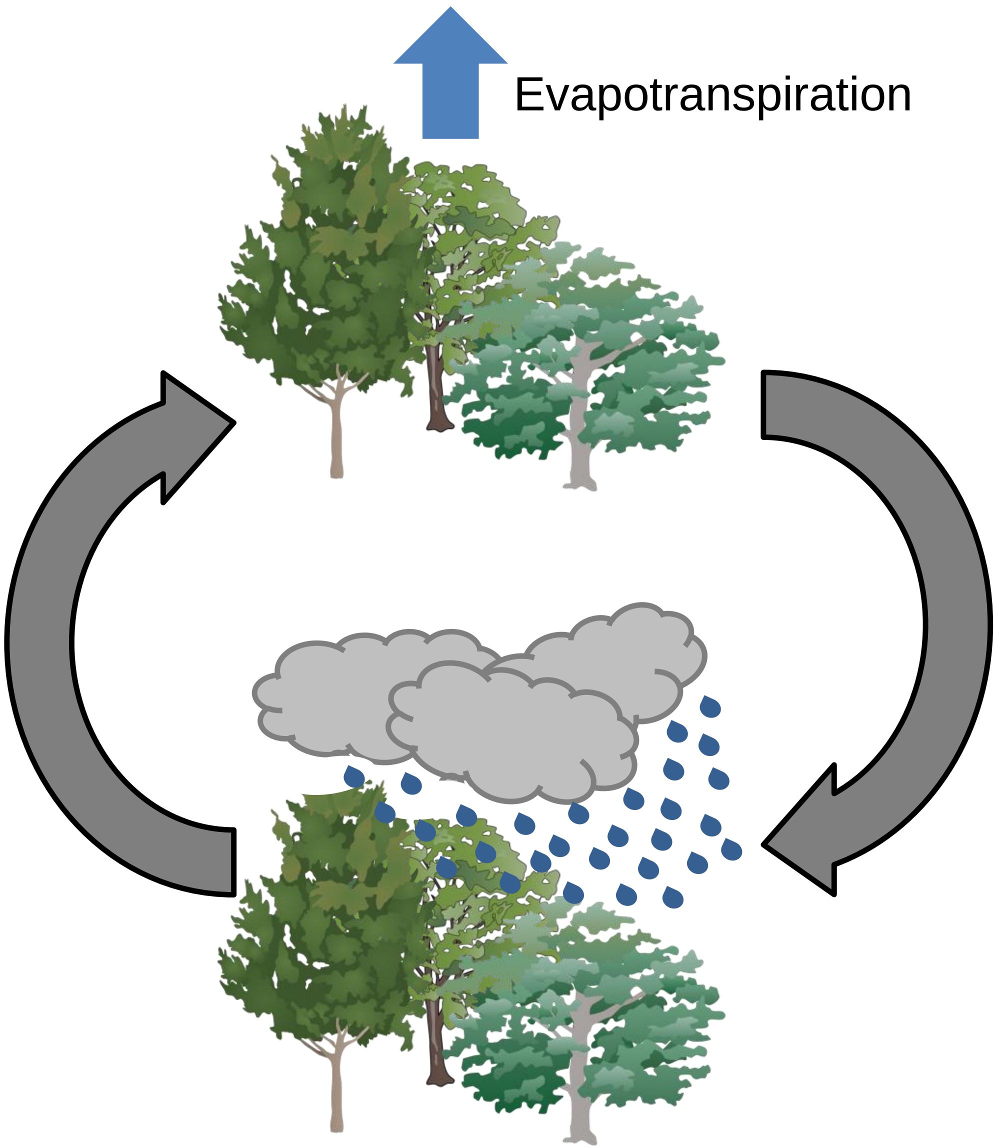


Figure modified from: Heffernan et al. 2014

Macro-scale feedback

- Processes occurring at different scales (i.e., local, regional, or global) can either amplify (positive feedback) or diminish (negative feedback) each other
- Example:
  - Local vegetation both influences, and is dependent on, regional precipitation, creating a feedback loop



Heffernan et al. 2014

Macro-scale feedbacks in lakes

- Lake GHG fluxes are impacted by: Local lake characteristics *and* Regional air temperatures
- Warming air temperatures, due to climate change, can lead to either an increase or decrease of GHG emissions from lakes
- This will result in a ***macro-scale feedback*** by either <u>increasing</u> **or** <u>decreasing</u> GHG concentrations in the atmosphere, which could subsequently intensify or mitigate global climate warming

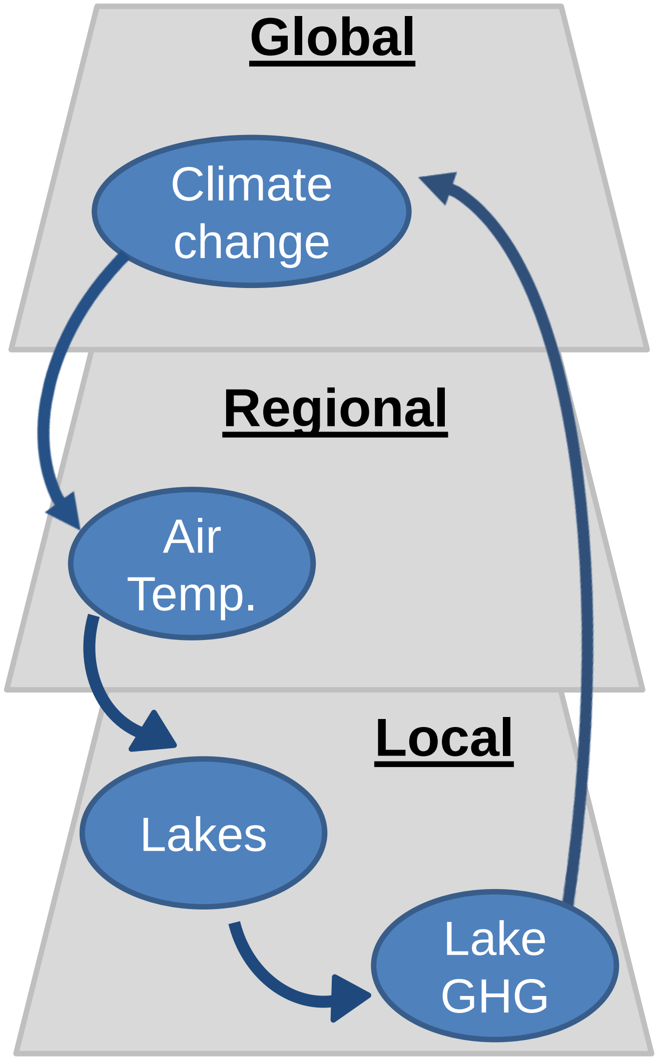


Figure modified from: Heffernan et al. 2014

Studying macro-scale feedbacks in lakes is needed to predict future climate change

- Lakes play an important role in the global C-cycle
- Under warming conditions, lakes may play an even larger role as either a source or sink of GHGs to the atmosphere, but this remains unquantified
- May be important in either intensifying or mitigating atmosphere GHG concentrations
- BUT, we currently don't know the answers!

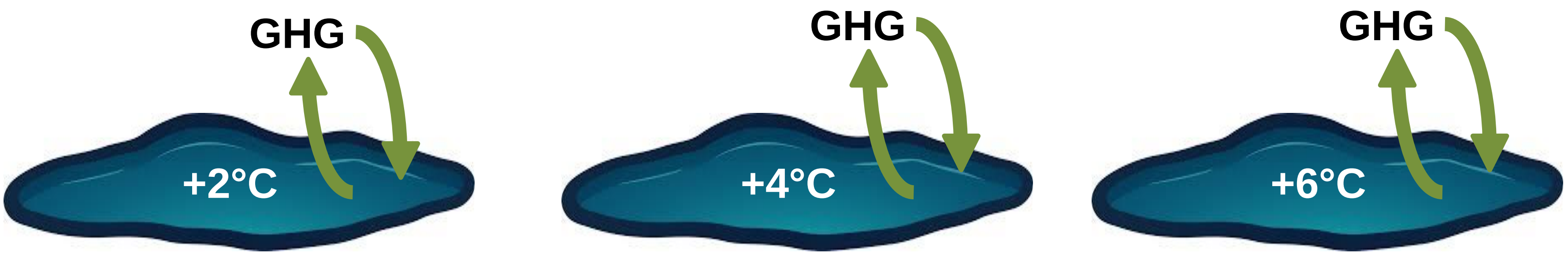
Our focal question:

How will warming temperatures and local lake characteristics interact to create **macro-scale feedbacks** by altering lake greenhouse gas fluxes?

Image: K.J. Farrell

Models to understand macro-scale feedbacks

- How can we test the effects of warming temperature and local lake characteristics on GHG emissions?
  - Impossible to experimentally manipulate all possible climate drivers in real lakes!
- Simulation modeling allows us to explore what would happen if we changed one driver, or multiple drivers at once:
  - For example, how would GHG emissions change if air temperatures were 2°C warmer than they are now? 4°C? 6°C?
  - How would this change for different lake ecosystems?



Global warming potentials (GWP)

- Provide a way to compare CH_4 and CO_2 fluxes from different ecosystems on global warming
- CH_4 is a more potent GHG (86x more potent than CO_2 over a *20-year time span*!)
- GWP can be used to convert CH_4 and CO_2 fluxes to the same warming equivalents
  - Positive GWP = the lake is emitting heat-trapping gases to the atmosphere (intensifying climate change) **= NET GHG SOURCE!**
  - Negative GWP = the lake is a net sink for heat-trapping gases and is offsetting global warming **= NET GHG SINK!**

GWP data from Myhre et al. 2013

Global warming potentials (GWP)

- We can calculate a lake's GWP by:
  1. Summing the mass of CO_2 emitted over one year

     i.e.) mmol m^{-2} d^{-1} → mmol m^{-2}
  2. Summing the mass of CH_4 emitted over one year

     i.e.) mmol m^{-2} d^{-1} → mmol m^{-2}
  3. Multiply each mass by lake area

     i.e.) mmol m^{-2} x m^2 = mmol
  4. Convert units to kg
  5. And scale to GWP
     a. Multiply CO_2 by 1
     b. Multiply CH_4 by 86
     c. Sum CO_2 GWP + CH_4 GWP

NOTE: GWP is unitless!

Pre-module activity: Changing GHG concentrations in lakes

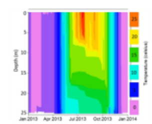
 [1]

Warming air temperatures

 [1]

Increase phytoplankton growth
(Process #1 on conceptual diagram)

[CO_2]
Increase
Decrease
No Change



Warming water temperatures

 [2]

Increase microbial respiration

If oxygen present
(Process #2 on conceptual diagram)

[CO_2]
Increase
Decrease
No Change

If oxygen absent
(Process #3 on conceptual diagram)

[CH_4]
Increase
Decrease
No Change

Increase thermal stratification

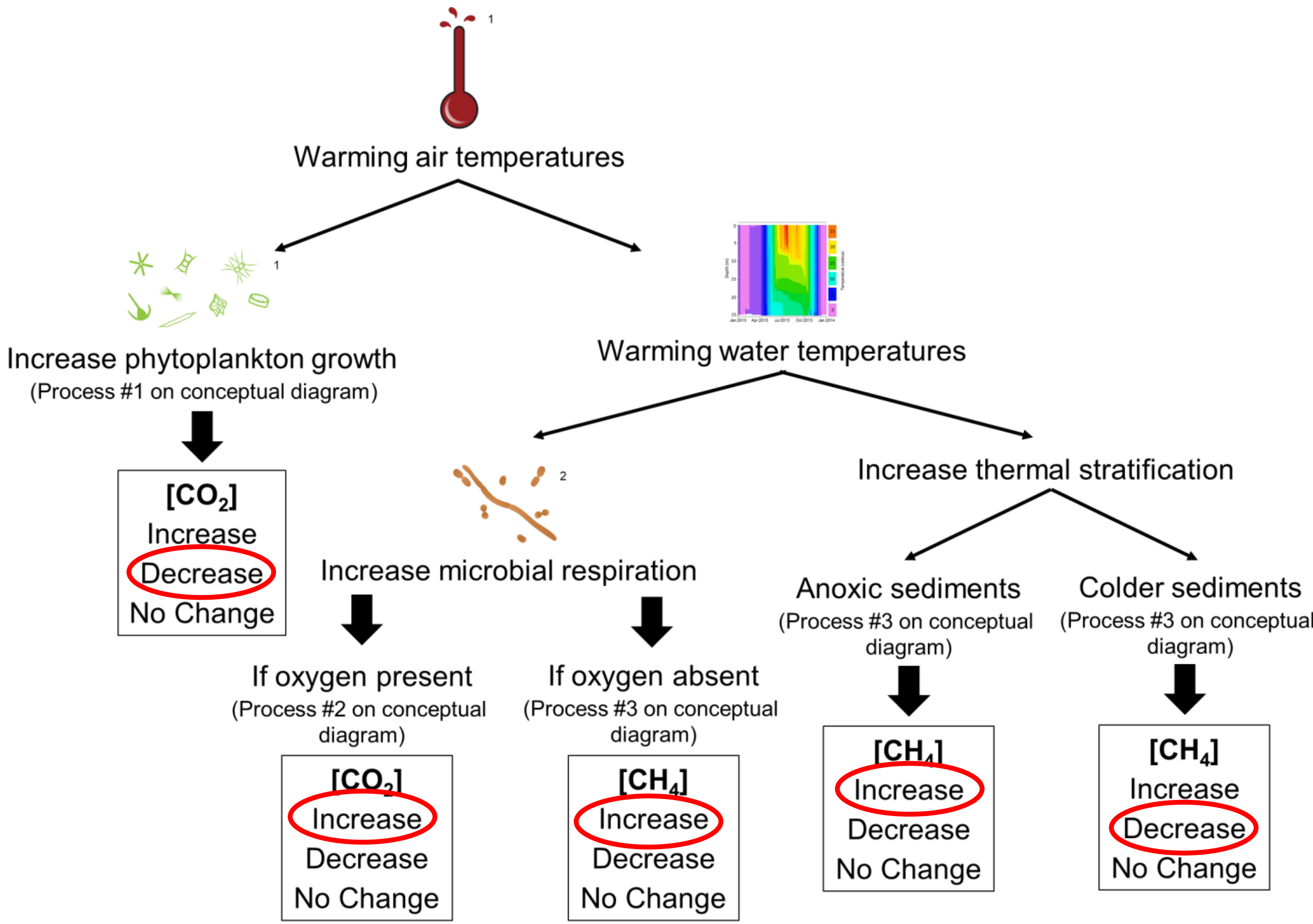
Anoxic sediments
(Process #3 on conceptual diagram)

[CH_4]
Increase
Decrease
No Change

Colder sediments
(Process #3 on conceptual diagram)

[CH_4]
Increase
Decrease
No Change

Pre-module activity: Changing GHG concentrations in lakes



GLM: General Lake Model

- **Authors:** Matt Hipsey, Louise Bruce, and David Hamilton

- The **General Lake Model** (GLM) is an open-access model for simulating lake dynamics. It simulates vertical stratification and mixing and accounts for the effect of inflows/outflows, surface heating and cooling.
- GLM has been designed to be an open-source community model developed in collaboration with members of the **Global Lake Ecological Observatory Network (GLEON)** to integrate with lake sensor data.
- Available from: http://aed.see.uwa.edu.au/research/models/GLM/

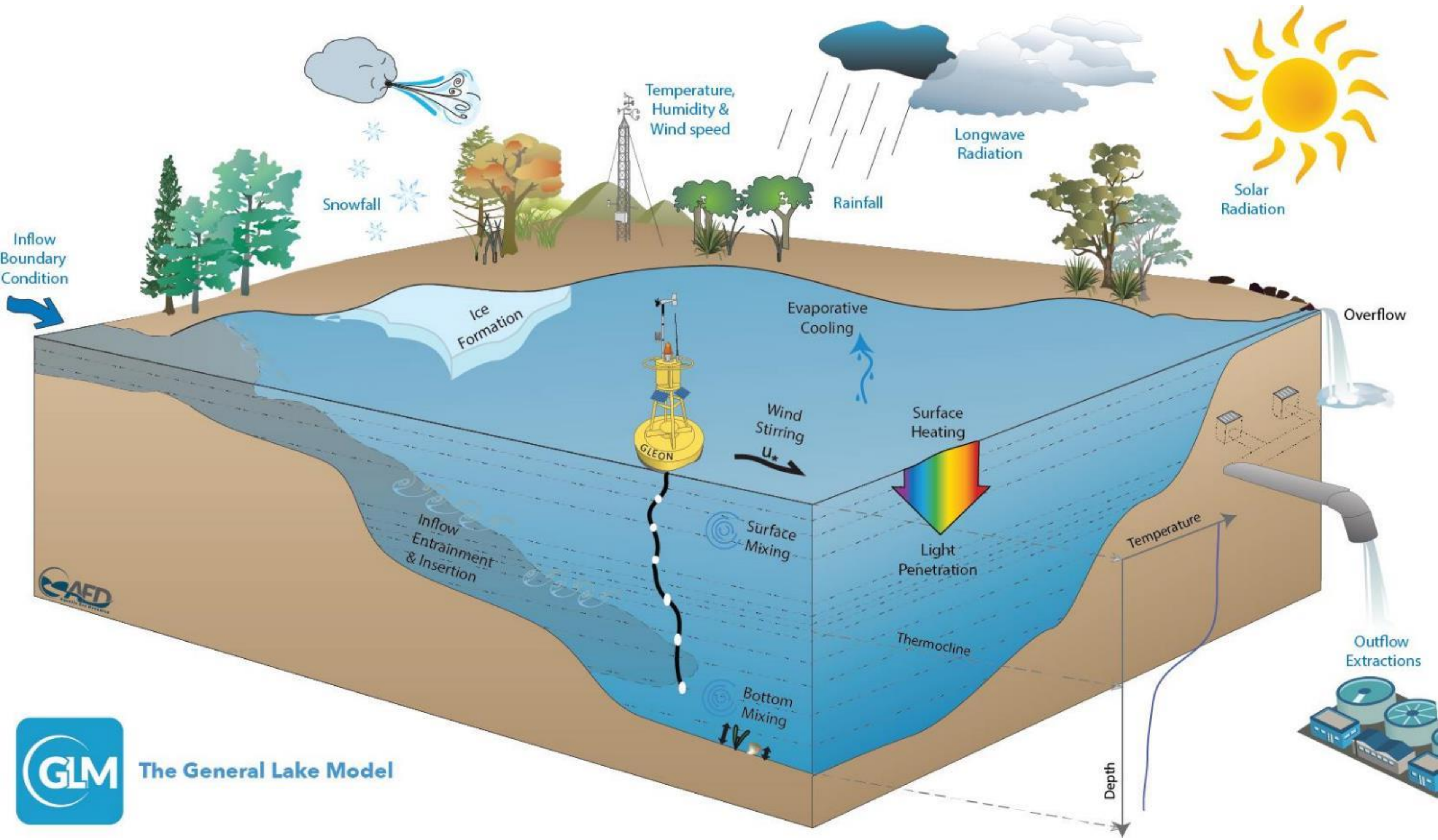
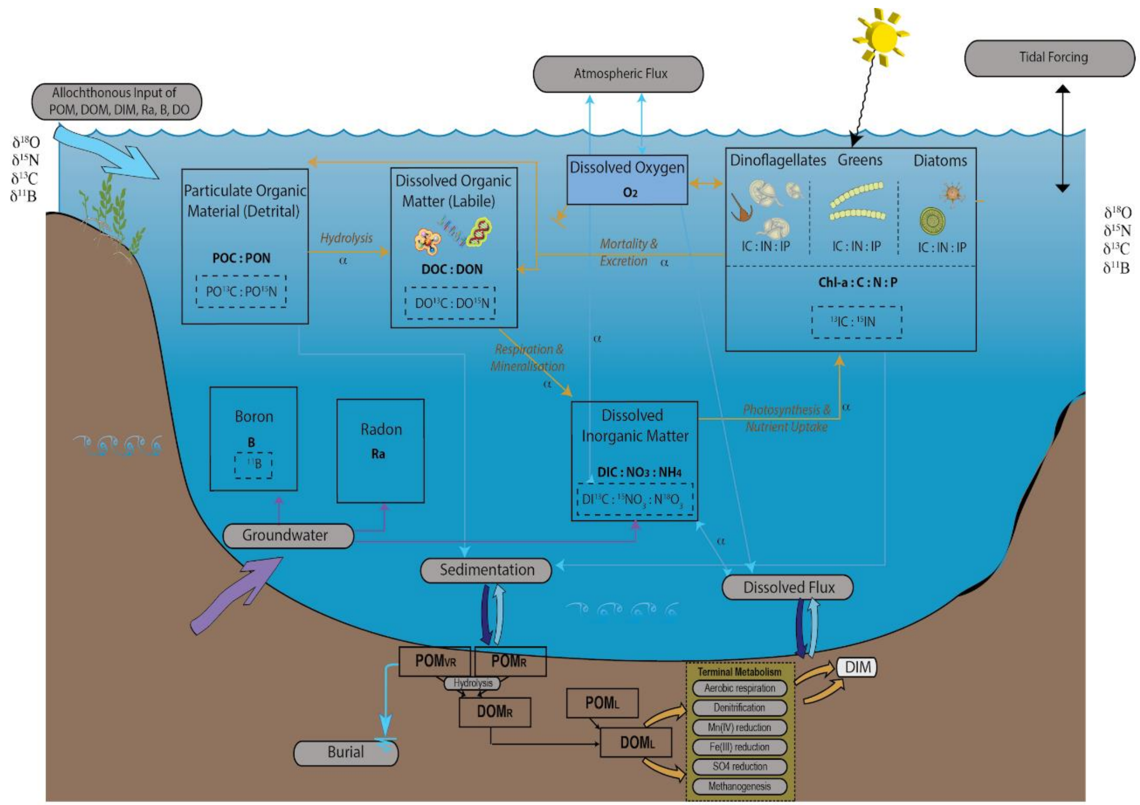


Figure: Hipsey et al. 2019

AED: Aquatic EcoDynamics

- The Aquatic EcoDynamics (AED) module couples with GLM to model changes in water chemistry and biology
- Can model nutrient, phytoplankton, and zooplankton dynamics
- Today, we'll focus on carbon dioxide (CO_2) and methane (CH_4) fluxes at the lake-atmosphere interface



Isotope-enabled carbon & nutrient ecosystem model

Figure: Hipsey et al. 2013

Basic structure of the model

- You'll create a new folder (directory) on your computer when you unzip the module folder.
- Within this folder, you will have:
  1) A meteorological CSV ('met') file that forces the model (e.g., met_hourly.csv)
  2) 'nml' text files that act as 'master' scripts for the model (e.g., glm2.nml, aed2.nml)
  3) Inflow/outflow CSV files that specify the temperature, flow rate, and nutrient concentrations for streams entering and leaving the lake

Images: Wikimedia commons

Example .nml file

glm2.nml

```
!-------------------------------------------------------------------------------
! lake details
!-------------------------------------------------------------------------------
!
! name                 [string]
!                        name of the lake
! latitude             [float, minimum = -90, maximum = 90, unit = deg North]
!                        latitude
! longitude            [float, minimum = -360, maximum = 360, unit = deg East]
!                        longitude
! base_elev            [float]
!                        base elevation (m)
! crest_elev           [float]
!                        crest elevation (m)
! bsn_len              [float]
!                        basin length at crest (m)
! bsn_wid              [float]
!                        basin width at crest (m)
! bsn_vals             [integer]
!                        number of depth points on height-area relationship
! H                    [float]
!                        elevations (m)   (comma separated list, len=bsn_vals)
! A                    [float]
!                        area (m2) (comma separated list, len=bsn_vals)
!
!-------------------------------------------------------------------------------
&morphometry
   lake_name  = 'Mendota'
   latitude   = 43
   longitude  = -89.41
   bsn_len    = 9500
   bsn_wid    = 7400
   bsn_vals   = 15
   !   H(m)  A(m2 * 1000) V(m3 * 1000)
   H = 375.00640,376.79166,378.57691,380.36217,382.14743,383.93269, 385.71794,387.50320,389.28846,3
   A = 0.00000,2827226.39,5654452.79,8481679.18,11308905.58,14136131.97, 16963358.37,19790584.76,22
```

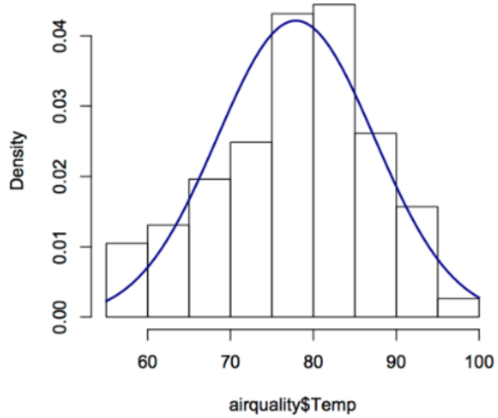
Example met file

Climate scenarios:
+2°C, +4°C, or +6°C

	A	B	C	D	E	F	G	H
1	time	ShortWave	LongWave	AirTemp	RelHum	WindSpeed	Rain	Snow
2	2011-09-01 00:00:00	34.33	386.25	30.84	50.04	1.90	0	0
3	2011-09-01 01:00:00	0.00	386.25	28.84	55.67	1.31	0	0
4	2011-09-01 02:00:00	0.00	386.24	26.84	62.03	1.21	0	0
5	2011-09-01 03:00:00	0.00	366.02	24.84	69.22	1.70	0	0
6	2011-09-01 04:00:00	0.00	366.02	24.09	71.30	1.33	0	0
7	2011-09-01 05:00:00	0.00	366.02	23.35	73.40	1.26	0	0
8	2011-09-01 06:00:00	0.00	358.33	22.61	75.56	1.54	0	0
9	2011-09-01 07:00:00	0.00	358.33	21.82	78.48	1.91	0.001	0
10	2011-09-01 08:00:00	0.00	358.33	21.03	81.52	2.47	0	0
11	2011-09-01 09:00:00	0.00	359.96	20.24	84.69	3.13	0	0
12	2011-09-01 10:00:00	0.00	359.96	20.17	86.02	3.02	0	0
13	2011-09-01 11:00:00	0.00	359.96	20.10	87.36	2.93	0	0
14	2011-09-01 12:00:00	84.08	391.87	20.04	88.66	2.89	0	0
15	2011-09-01 13:00:00	229.97	391.87	23.59	75.43	3.37	0	0

We will run GLM-AED using R

- R is a statistical environment that can run on different computer operating systems (PC, Mac, Linux)
- R is reproducible, free(!), and easy to download
- R can run stats, make figures, and do a suite of different analyses in many disciplines
- Many packages for R to merge with other tools (including GLM!)
- We'll walk you through each step of the script, so don't worry if you're new to R!



Lakes we're going to model today, using a suite of available continental datasets

neon
National Ecological Observatory Network

LTER NETWORK

GLEON
global lake ecological observatory network

Learning objectives

- Understand the concepts of macrosystems ecology and macro-scale feedbacks, and how different ecological processes can interact at local, regional, and continental scales
- Simulate greenhouse gas fluxes in multiple lakes using ecosystem models set up with publicly-available high-frequency sensor datasets (Activity A)
- Test the effects of a climate scenario on the different lake models and examine how the timing and magnitude of greenhouse gas fluxes change with climate warming (Activity B)
- Examine how local conditions may alter the timing and magnitude of greenhouse gas fluxes from lakes to affect global climate change (Activity C)
- Predict how lake greenhouse gas fluxes may both respond to and amplify changing climate

Discussion questions embedded in your handout

- Everyone will need to turn in the completed handout with question answers written out at the end of the module today.
- We encourage you to work with your partner to complete the questions!

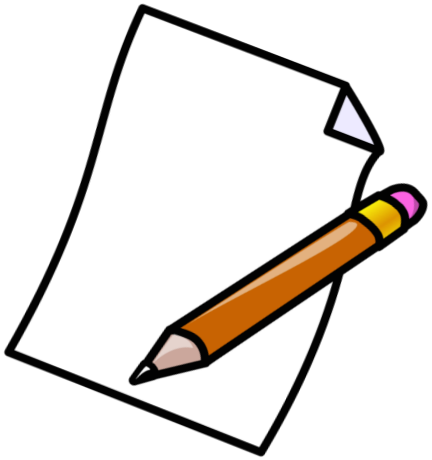


Image: newsfrom4j.wikispaces.com

Download the module files

- Navigate to the Macrosystems EDDIE Module 4 website
  - http://module4.macrosystemseddie.org

- Scroll down to Teaching Materials and click Files for Running the Module

Teaching Materials:

Note: We continue to update our lake model calibrations, so check back frequently to make sure you have the most up-to-date zip folder of files to use!

- Files for Running the Module (Zip Archive 2.1MB Nov2 18)– Zipped folder of all files needed to run the module in RStudio
- R You Ready for EDDIE? Module 3 (Microsoft Word 2007 (.docx) 23kB Oct4 18)– Step-by-step guide to download R, RStudio, and module files

- Save the .zip folder to your Desktop

A few important notes about R

- Lines of code that start with # are not read by R
  - These lines include important notes about how and why the R script is running, so be sure you're reading them!

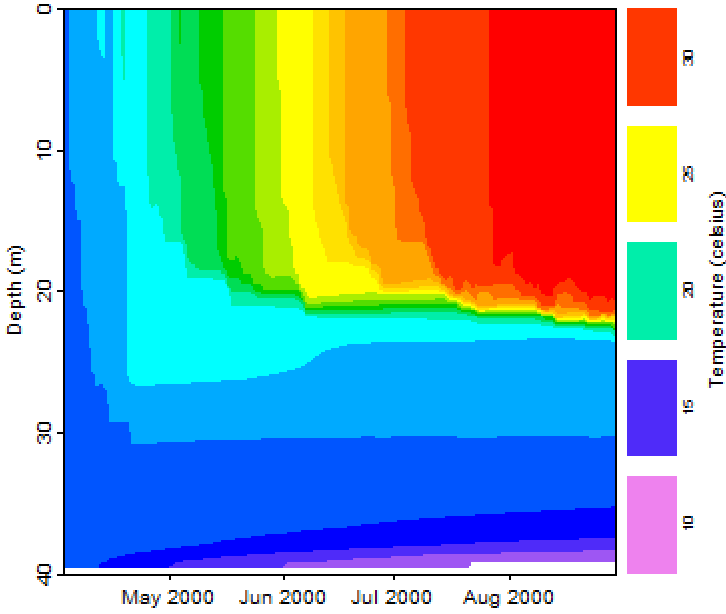
- Lines with ##!! indicate lines of code where you need to modify something for it to run

- In the glm2.nml file, ! indicates lines that are not read by the GLM model (tricky!)
  - When you need to modify your glm2.nml file in Activity B, make sure you're not changing the value in a line that starts with a ! or your changes won't be read by GLM

Activity A: Run a lake model!

With a partner (work in pairs):

1) Find your lake on a satellite map, and examine land use in the watershed
2) Download the zipped folder of R scripts and other files to run this module. Extract to your desktop
3) Download GLM-AED files and R packages onto your computer
4) Run the model and look at the output for water temperature and fluxes of CO_2 and CH_4 for your lake (make sure you save your plots as you go!)



Activity B: Climate change scenario

1) Working with your partner, **select one** of the pre-made climate change scenarios for air temperature. **Develop hypotheses** about how changing air temperatures may affect water temperatures and greenhouse gas fluxes in your model lakes

2) Modify your glm2.nml file to test your hypothesis
   - Analyze the model output to determine how the scenario changed water temperature and fluxes of CO_2 and CH_4

3) **Create a few figures** (save them as you go!) to examine your climate scenario:
   - Does the model output support or contradict your hypothesis?
   - How does the output from CO_2 and CH_4 compare?
   - Would you predict more or less warming in the future based on the CO_2 and CH_4 output? Why?

Activity C: Global warming potential

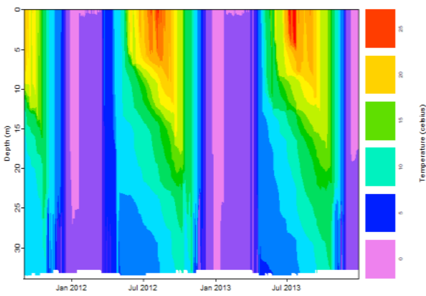
1) Working with your partner, you will now calculate the global warming potentials (GWPs) of your model lake under baseline and warming conditions to assess the relative effect of CH_4 and CO_2 fluxes.
2) Following the directions in the R script, calculate the mass of CO_2 and CH_4 flux and the GWP of your model lake for baseline and warming conditions. Record these values on your handout.
3) **Create a few figures** (save them as you go!) to highlight your 2 scenarios & share with the class!
   - Do these data support or contradict your hypotheses about the relative importance of CO_2 and CH_4 fluxes on global warming?
   - What is the net effect of the lake on the atmosphere in the baseline scenario? How might this change with climate warming?
4) Predict how lake GHG emissions will change future GHG concentrations in the atmosphere. How will this further effect GHG emissions from lakes in the future?

Evidence for Macro-Scale Feedbacks?

- GHG emissions from lakes at the local scale interact with regional scale warming conditions.
- Lake GHG emissions can further alter global atmospheric GHG concentrations by exacerbating or mitigating a warming climate.
- Do you see:
  - Changing GHG emissions from lakes under the warming scenario?
  - Changing GWP of lake emissions under the warming scenario?

Given the changes in lake GHG emissions you observed in this module due to macro-scale feedbacks, how do you expect lakes will affect global climate change in the future?

Thank you for participating!



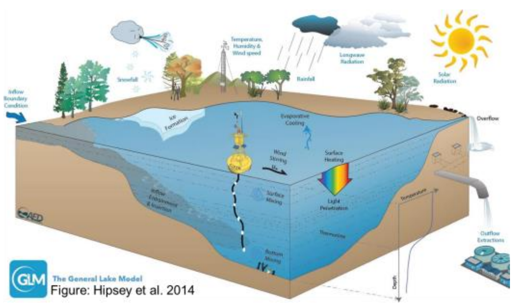


Figure: Hipsey et al. 2014


Wikimedia commons

Additional slides for instructors to use

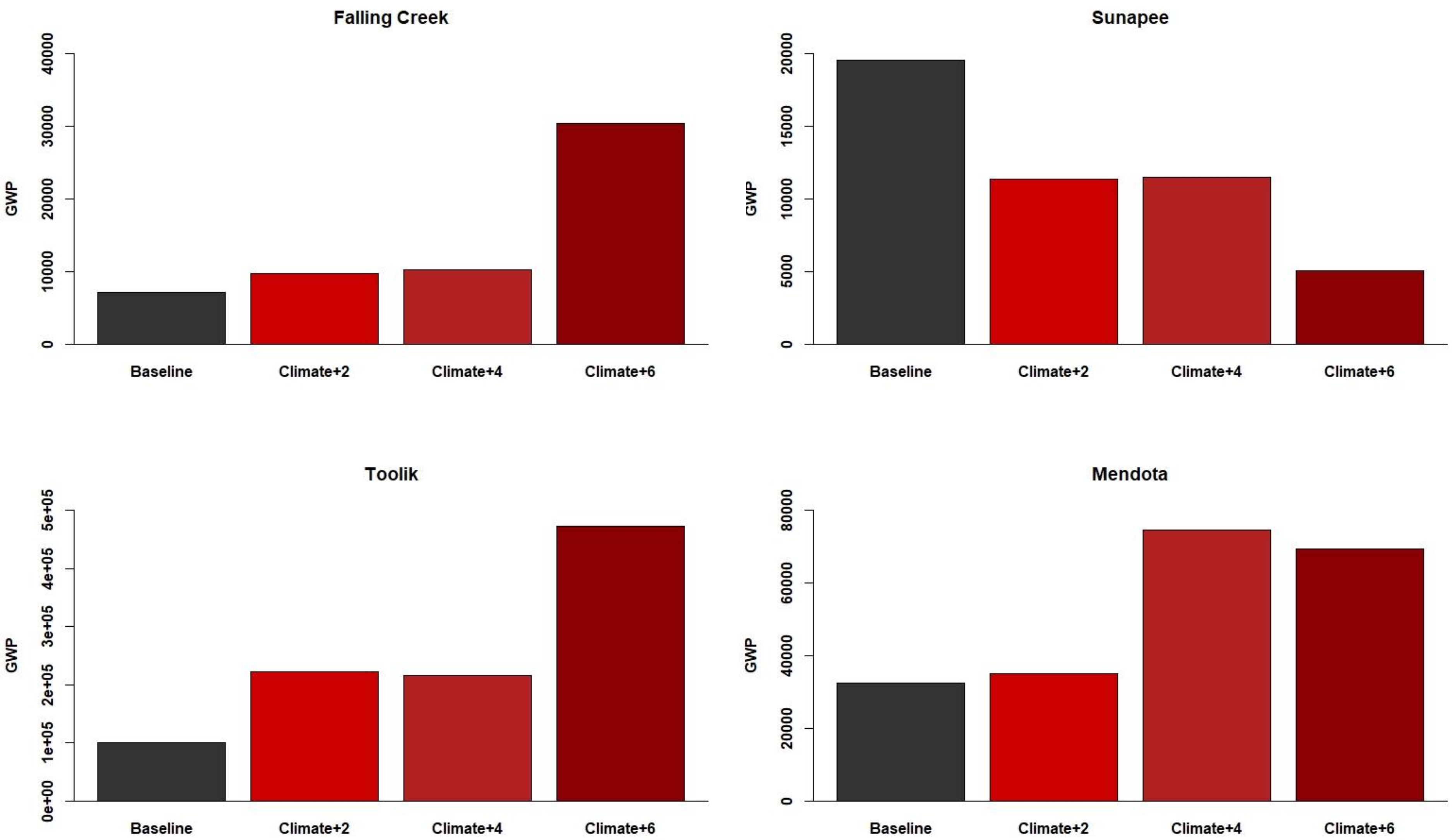
Model lake descriptions

Lake Name	Falling Creek	Mendota	Sunapee	Toolik
State (USA)	Blue Ridge, Virginia	Madison, Wisconsin	Sunapee, New Hampshire	Alaska
Latitude & Longitude	37.30, -79.84	43.11, -89.42	43.38, -72.05	68.63, -149.61
Mean annual temperature (°C)	+13.9	+7.9	+7.5	-8.0
Surface area (km^2)	0.12	39.39	16.74	1.46
Water quality	Eutrophic (high nitrogen & phosphorus)	Eutrophic (high nitrogen & phosphorus)	Oligotrophic (low nitrogen & phosphorus)	Oligotrophic (low nitrogen & phosphorus)
DOC (mg L^{-1})	2.59	4.87	2.00	5.02
Data providers	C. Carey & GLEON	P. Hanson, North Temperate Lakes Long-Term Ecological Research, & GLEON	K. Weathers, Lake Sunapee Protective Association, & GLEON	G. Kling, Toolik Long-Term Ecological Research, & NEON

Presentation guidelines

- Please put together a quick, 5-minute presentation on your baseline + climate scenario results for your individual lake and selected climate scenario
- We suggest you include:
  - A temperature heatmap of your baseline + climate scenario
  - A DO heatmap of your baseline + climate scenario
  - Ice thickness for your baseline + climate scenario
  - CO_2 and CH_4 flux for your baseline + climate scenario
  - GWP for your baseline + climate scenario
- We'll use question #15 in the student handout to guide discussion about your results!

Activity C: Lake GWPs



Activity C: Lake Greenhouse gases