Macrosystems EDDIE:
Climate change effects on lake temperatures

Carey, C.C., S. Aditya, K. Subratie, R. Figueiredo, and K.J. Farrell. 30 June 2017.
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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

Overview of today

- Short overview of lake modeling and some background on the tools we will be working with

- **Activity A:** Plot water temperatures from a lake model.
- **Activity B:** Develop a climate scenario, generate hypotheses, and model how your lake responds.
- **Activity C:** Use distributed computing to run 100s to 1000s of lake model simulations.

Lakes are changing worldwide…

- In response to altered climate, some regions are experiencing different temperature, precipitation, and wind conditions than in the past.
- Because of their position in the landscape and their thermal inertia, lakes can be powerful indicators of climate change.

Image: Wikimedia commons

Image: Wikimedia commons

Our focal question:

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

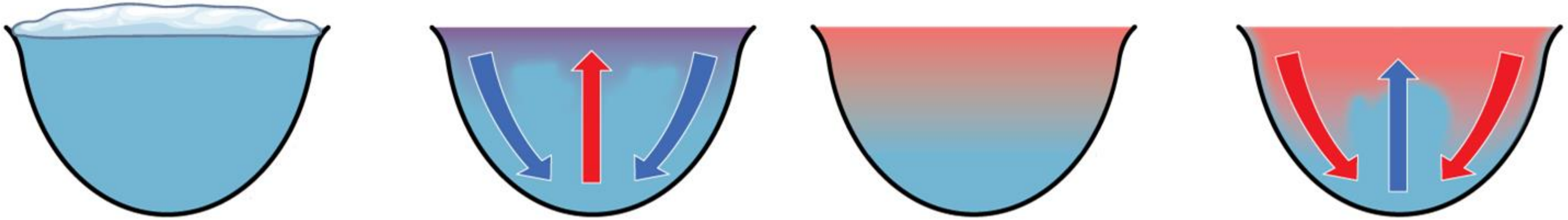
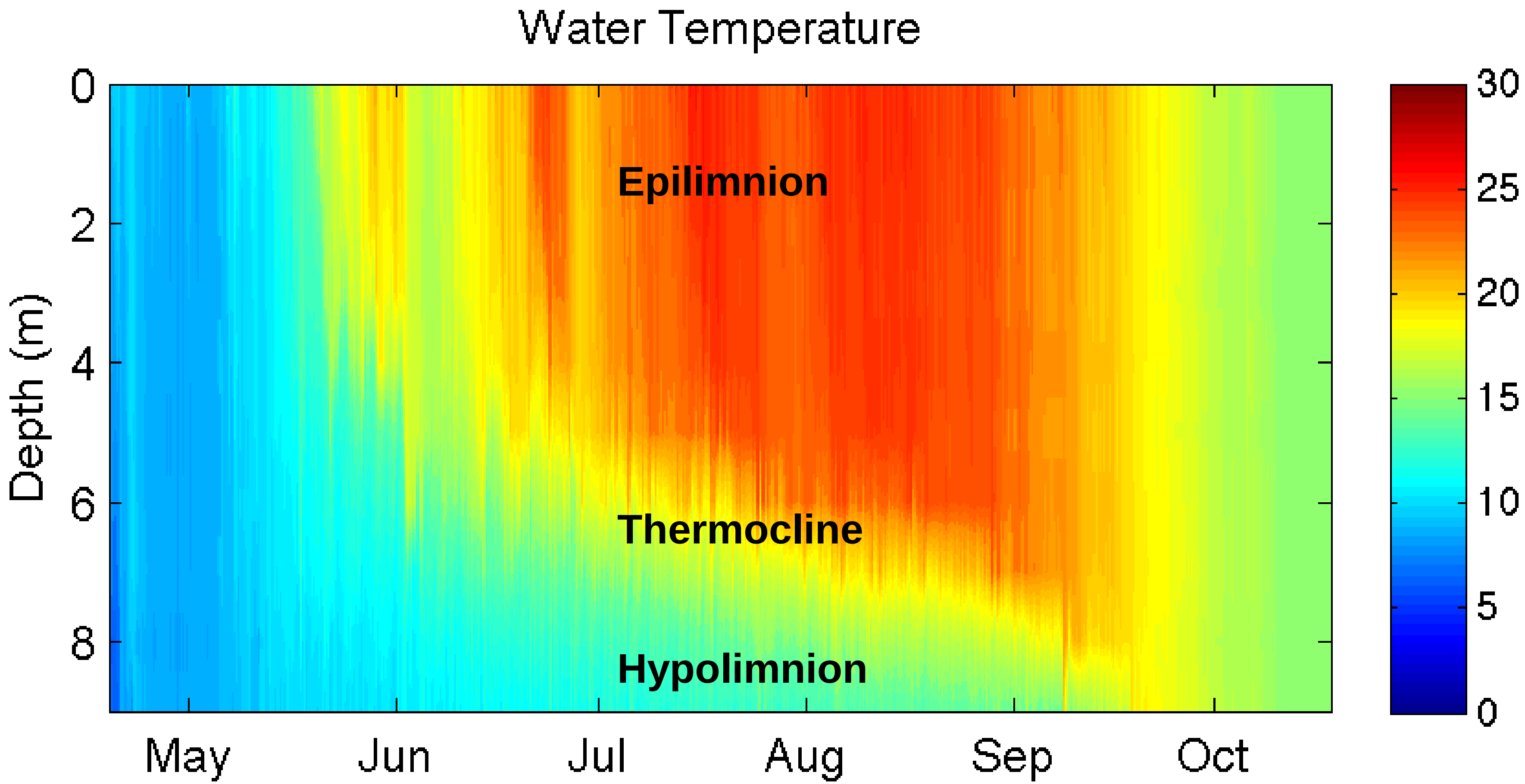


Image modified from: Figure 44.10 in “Ecology and the Biosphere” (Candela Learning)

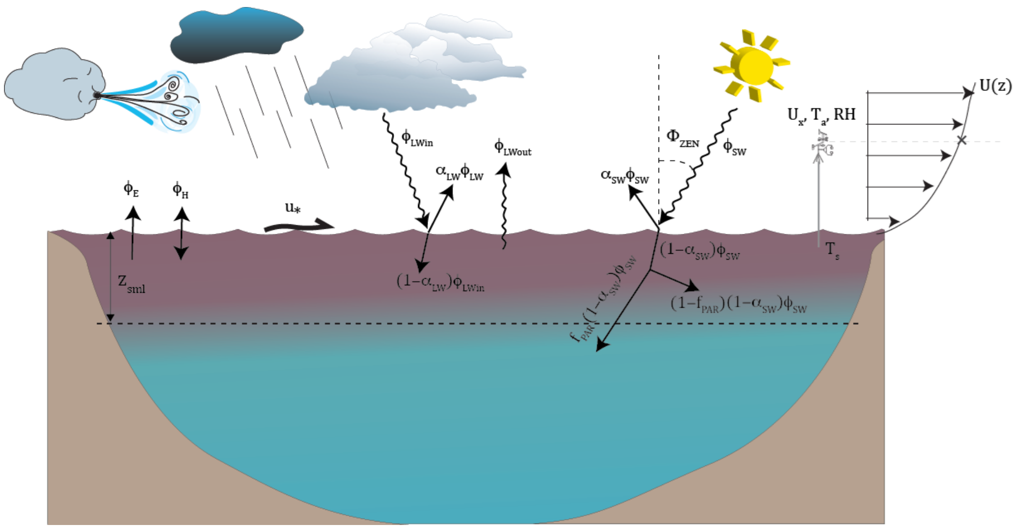
What is lake thermal structure?



Lake Sunapee, NH, USA: data from Lake Sunapee Protective Association buoy, 2012

What are the drivers of thermal structure?

- Solar radiation
- Air temperature
- Wind
- Precipitation
- Inflow & outflow streams



- All of these factors will interact to control water temperature, thermocline depth, mixing, and more!

Figure: Hipsey et al. 2014

Using a macrosystems ecology approach to study lake thermal structure

- Drivers of lake thermal structure occur at both local and regional scales
  - Local = e.g., inflow streams
  - Regional = e.g., air temperature
- Macrosystems ecologists study ecological dynamics and feedbacks at multiple interacting spatial and temporal scales
- We can study local and regional drivers using high-frequency sensor data + simulation models

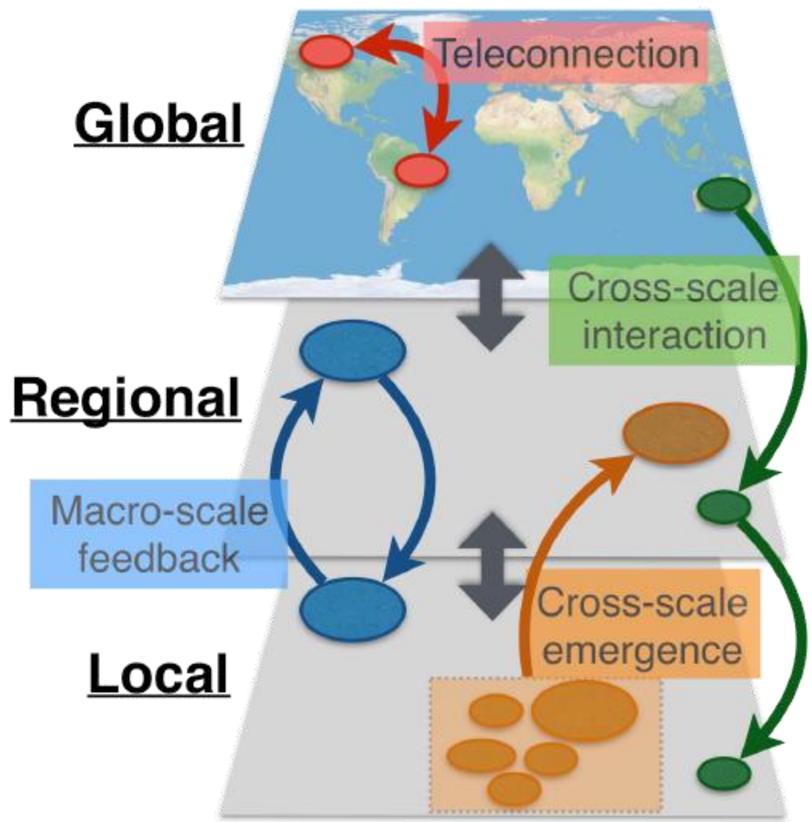
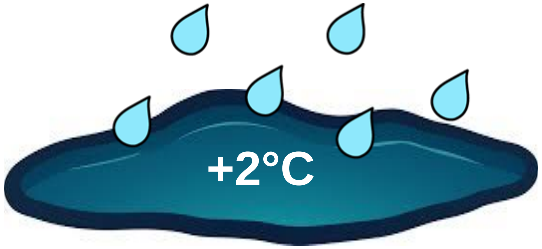
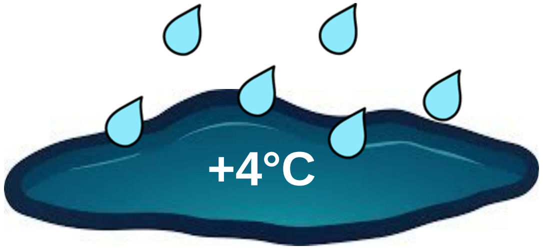


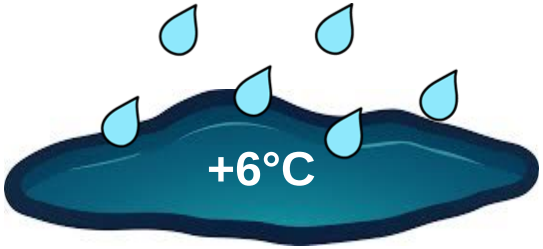
Figure modified from: Heffernan et al. 2014

Models to understand multiple drivers

- How can we test the effects of drivers from different scales on lake thermal structure?
  - Impossible to experimentally manipulate all possible drivers in a lake!
- Simulation modeling allows us to explore what would happen if we changed one driver, or multiple drivers at once
  - For example, how would lake thermal structure change if air temperatures were 2°C warmer than they are now? 4°C? 6°C?
  - What if rain also increased 50% on those 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/

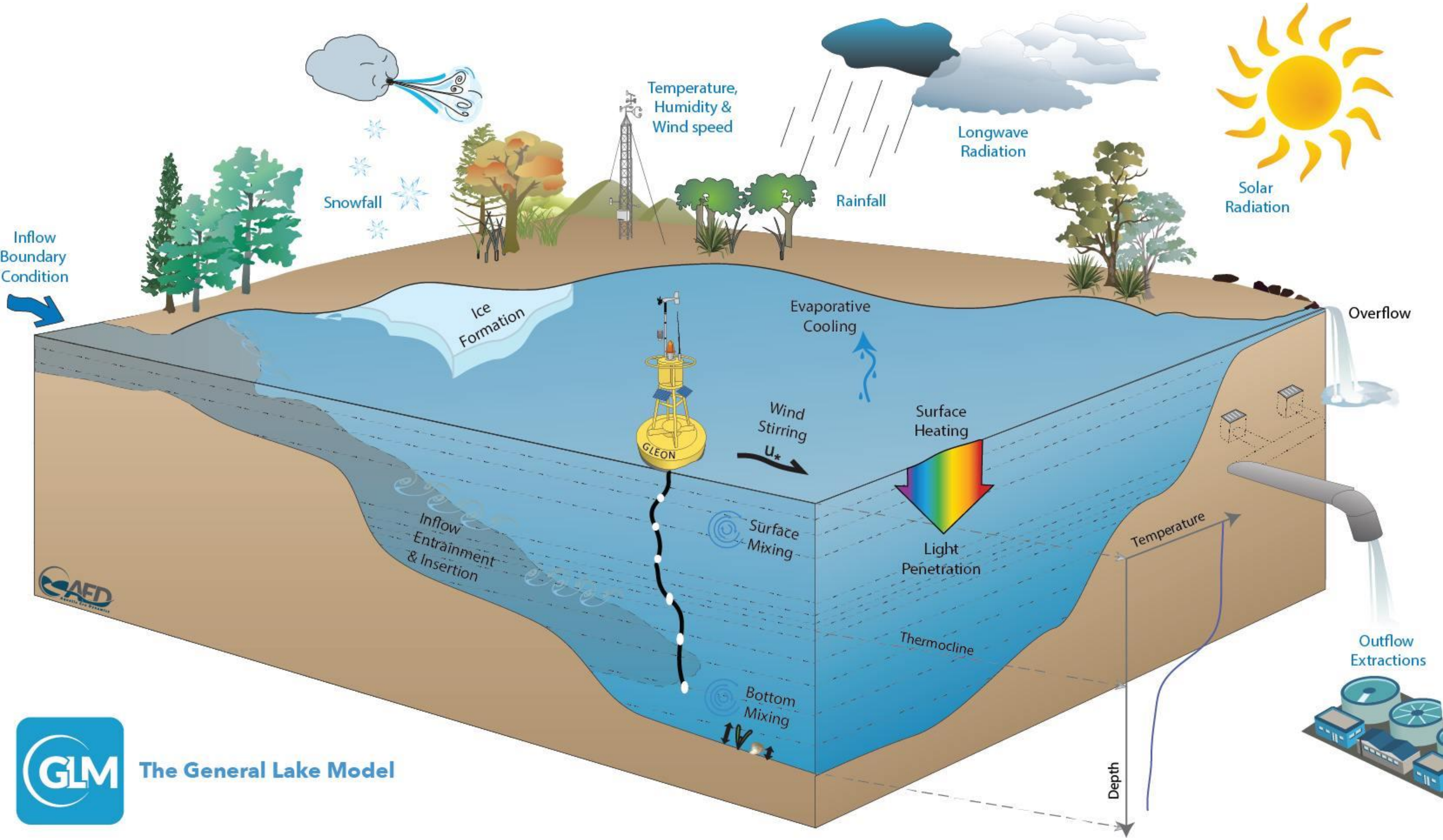


Figure: Hipsey et al. 2014

Basic structure of the model

- You need to create a new folder (directory) on your computer.
- Within this folder, you will have:
  1) A high-frequency meteorological CSV file (‘met file’) that forces the model
     - e.g., “met_hourly.csv”
  2) An ‘nml’ text file that acts as a ‘master’ script
     - glm2.nml
  3) High-frequency Inflow/outflow CSV files that specify the temperature and flow rate of connected streams
     - Today we’re studying a closed lake without inflows or outflows

Images: Wikimedia commons

Example met file

	A	B	C	D	E	F	G
1	**time**	**ShortWave**	**LongWave**	**AirTemp**	**RelHum**	**WindSpeed**	**Rain**
2	2009-01-01 00:00	0	237.0800018	-12.32001343	71.3469252	11.25574053	0
3	2009-01-01 01:00	0	237.0800018	-13.0000061	70.61931244	11.61440932	0
4	2009-01-01 02:00	0	237.0700073	-13.66998901	69.5395646	11.9717879	0
5	2009-01-01 03:00	0	212.8999939	-14.35001221	68.17292338	12.33103782	0
6	2009-01-01 04:00	0	212.8899994	-14.85999146	68.26885627	12.45128543	0
7	2009-01-01 05:00	0	212.8899994	-15.37000122	68.22720667	12.58038186	0
8	2009-01-01 06:00	0	178.0099945	-15.88001099	68.07701147	12.71270623	0
9	2009-01-01 07:00	0	178.0099945	-15.82999268	68.560877	12.30275177	0
10	2009-01-01 08:00	0	178.0099945	-15.78000488	69.0241756	11.90672061	0
11	2009-01-01 09:00	0	175.9700012	-15.72998657	69.46721996	11.50951766	0
12	2009-01-01 10:00	0	175.9700012	-15.91000977	70.3181745	11.37918273	0
13	2009-01-01 11:00	0	175.9600067	-16.10001221	71.21325022	11.24893784	0
14	2009-01-01 12:00	0	154.0700073	-16.28000488	72.06085374	11.12530937	0
15	2009-01-01 13:00	77.08799744	154.0700073	-16.13999023	71.84831464	11.38470936	0
16	2009-01-01 14:00	196.1999969	154.0700073	-16.0000061	71.65033449	11.65082869	0
17	2009-01-01 15:00	317.9200134	146.8600006	-15.85001221	71.39024308	11.91713029	0
18	2009-01-01 16:00	391.9039917	146.8600006	-15.13001099	72.36215735	11.65626426	0
19	2009-01-01 17:00	429.428009	146.8699951	-14.41000977	73.02151614	11.40773869	0
20	2009-01-01 18:00	371.394989	153.4600067	-13.69000854	73.38292443	11.16527203	0

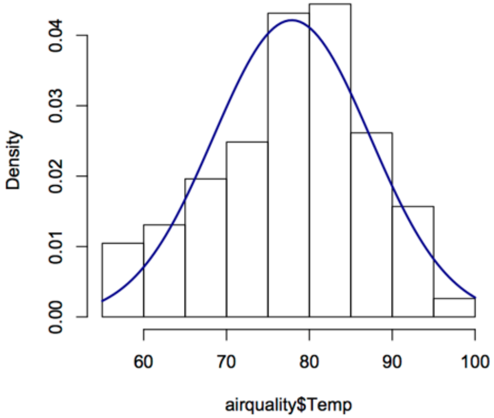
Example .nml file

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
```

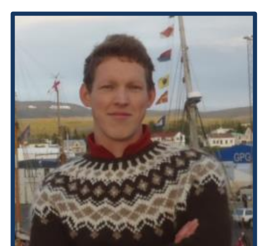
We will run GLM using R

- 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!)
- R is the programming language of choice for most ecologists



GLM-associated R packages

- **GLMr**: holds the current version of the GLM model and allows you to run GLM on any operating system
- **glmtools**: has different functions for analyzing and plotting GLM output from GLMr
- Developed by Jordan Read and Luke Winslow
- Available from: https://github.com/GLEON & https://github.com/USGS-R/glmtools



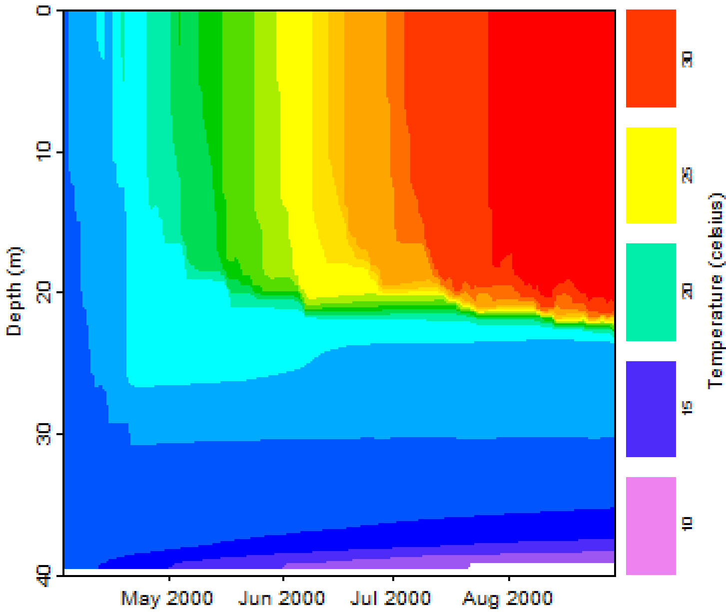
Learning objectives of today's module

- 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

Activity A

With a partner (work in pairs):

1) Download the zipped folder of R scripts and other files to run this module. Extract to your Desktop
2) Download GLM files and R packages onto your computer
3) Run the model and look at the thermal output
4) Examine how your model output compares to the observed field data for your lake



Activity B

- Develop a climate scenario for any region and explore how it will affect lake thermal structure
  - **Develop a hypothesis** about how climate change (e.g., altered temperature) may alter lake thermal structure
    - Create a corresponding meteorological input file
  - Run your model and examine the lake's response:
    - How does your scenario alter the temperature profile in your lake over time?
    - How does the thermocline depth change?
    - How does the timing of stratification and evaporation change?
  - Compare the modeled output to the observed data
  - **Create a few figures to highlight your climate scenario and share with the class!**

Need ideas for a climate scenario?

- Check out climatedata.us
  - Temperature & precipitation predictions for US across the year under different emission scenarios
  - For global projections, try: climatemodels.uchicago.edu/maps

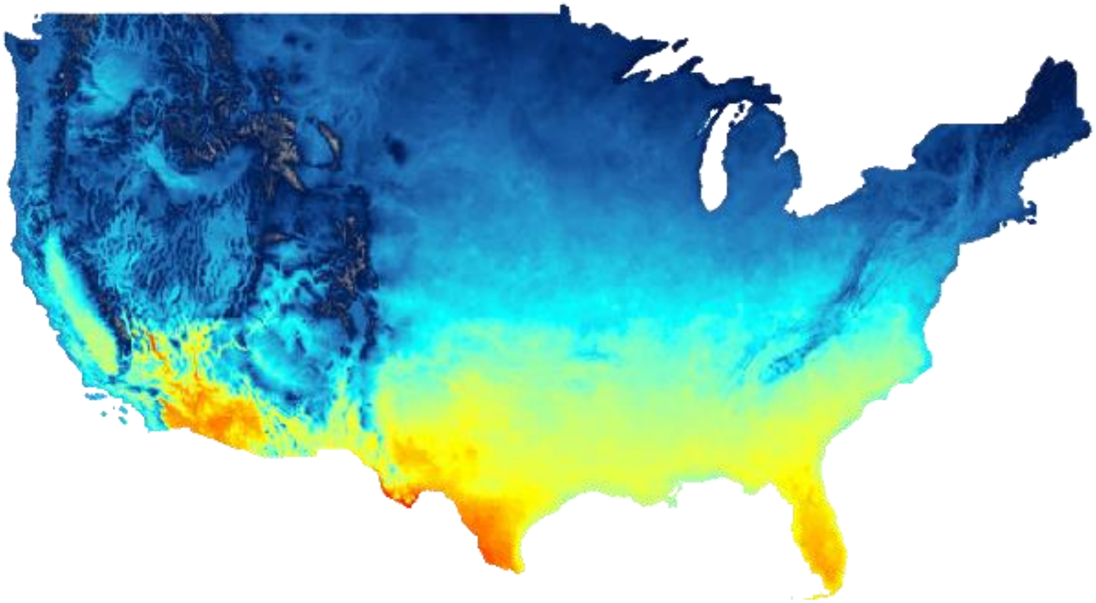


Image: climatedata.us

Converting units?

As you edit the met_hourly file to create your climate scenario, keep the following units in mind!

Variable	Unit	Example	Conversion
AirTemp	°C	20.05	
WindSpeed	meters · sec^{-1}	1.87	To convert from miles per hour, multiply by 0.447
Rain	meters · day^{-1}	0.000592	To convert from inches per day, multiply by 0.0254

Activity C

- How do you run 1000s of lake simulations quickly? Is there a more efficient way to submit and analyze lots of different simulations than editing met files manually?
- YES! = GRAPLEr
- An R package that allows you to create 1000s of simulations, submit them to run via a suite of distributed computing tools, and then return the GLM output

GRAPLEr: a new R package

- **Authors**: K. Subratie, S. Aditya, S.S. Mahesula, R. Figueiredo, C.C. Carey, and P.C. Hanson

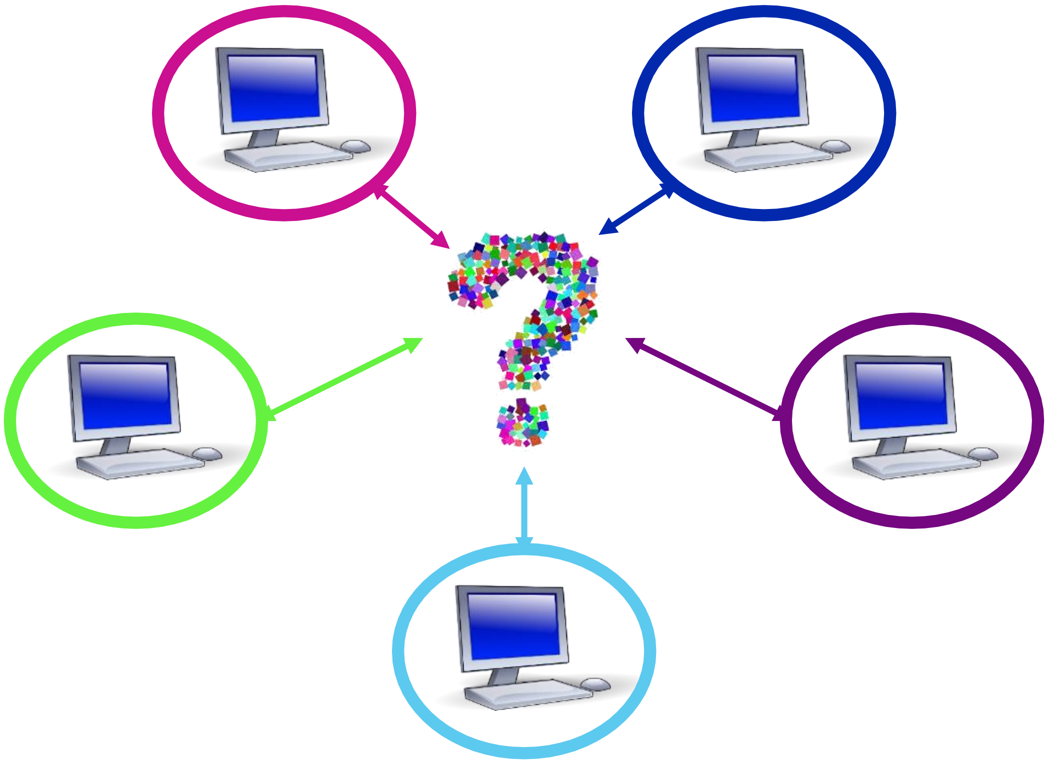




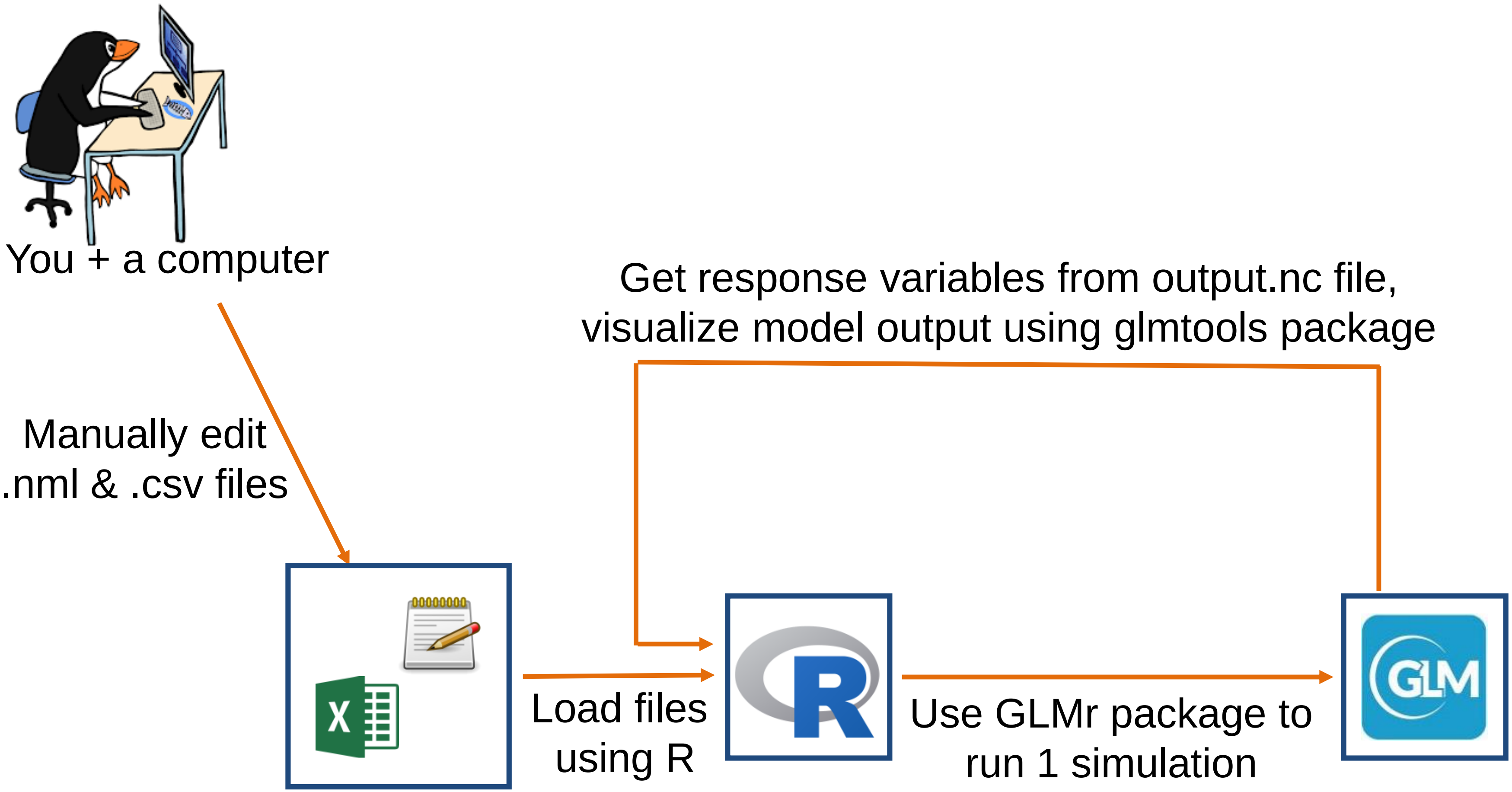

- Creates offsets for GLM met file variables (e.g., add +2ºC to all temperature values in a met file), submit the jobs via a Web service to run on other computers, and then analyze the output
- See: http://graple.org/

What is distributed computing?

- A model of computing where multiple networked computers work together towards a single problem, dividing the problem into many parts that are solved by different computers

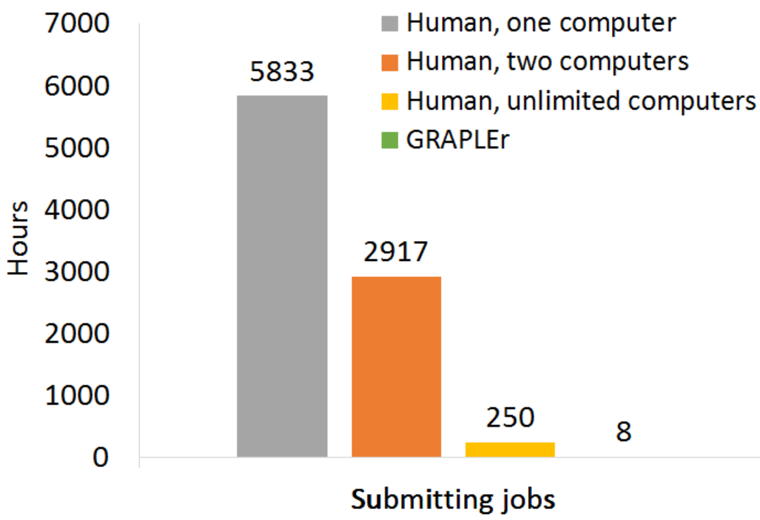


GLM in your computer

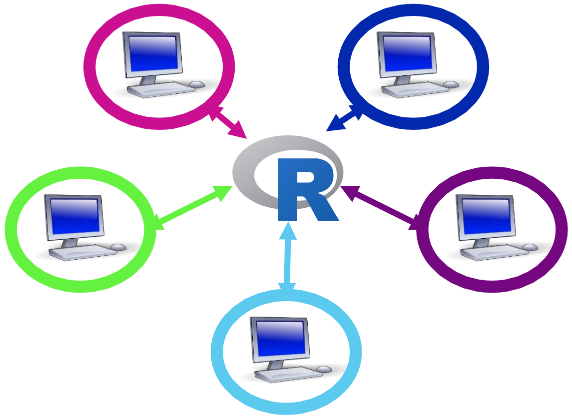


GRAPLEr expedites simulation modeling

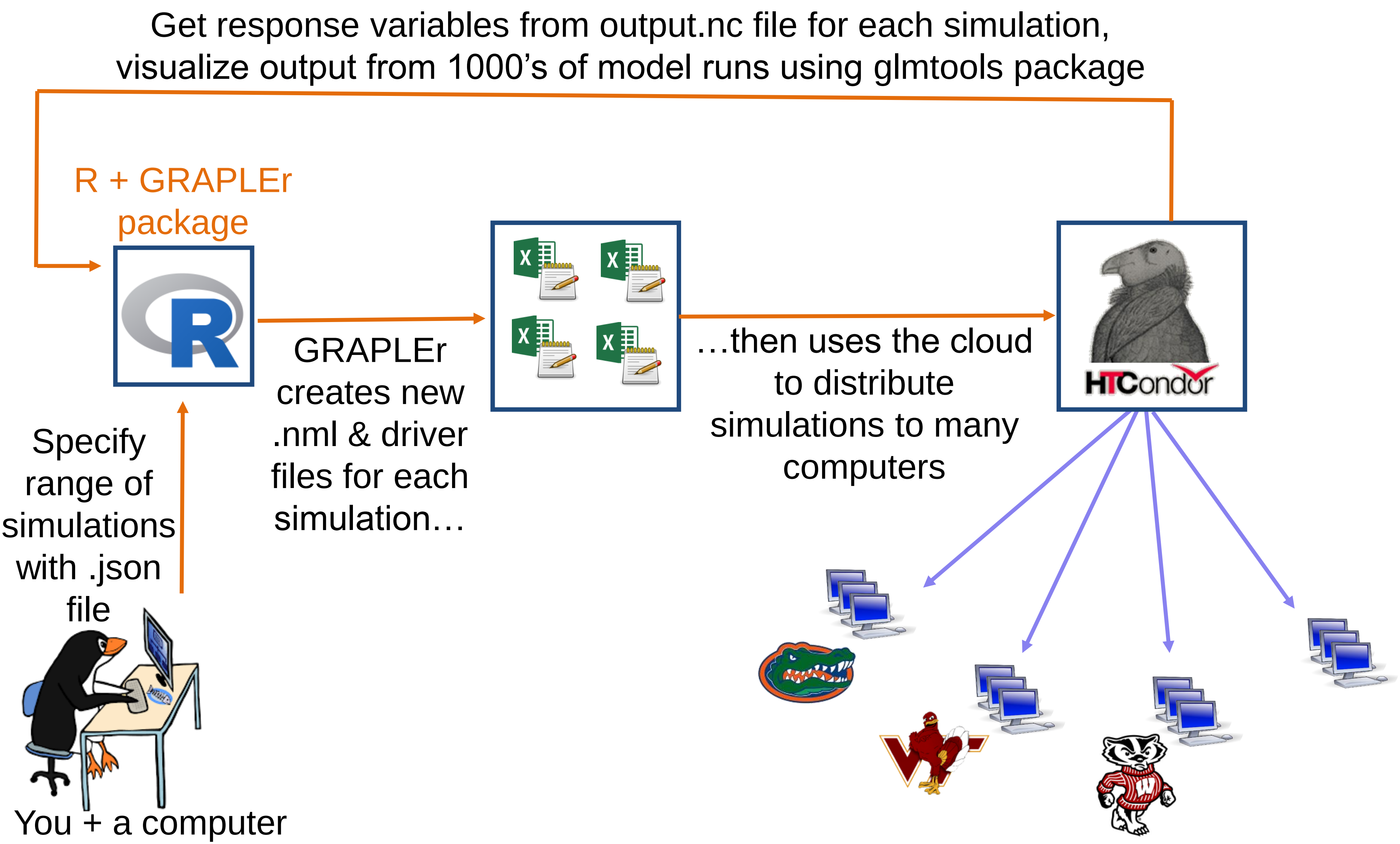
- Enter distributed computing:
  - Run 100s to 1000s of GLM jobs
  - Take each GLM job and dispatch to a different computer across the Internet
  - Shorten execution times for large numbers of model runs (e.g., climate change offsets)
  - A superhuman could manually submit <100 simulations in an 8-hr day



- Distributed computing is not easy– but GRAPLEr makes it easy for you!
  - Can submit jobs directly from R user interface



GRAPLEr in action



GRAPLEr in action

- **Web service**: A server takes requests from you through R
- **IPOP network overlay**: Aggregates computers across the Internet as if they belong to the same domain within the cloud
- **HTCondor**: Distributes GLM jobs to the computers connected by IPOP so they can run concurrently and finish faster

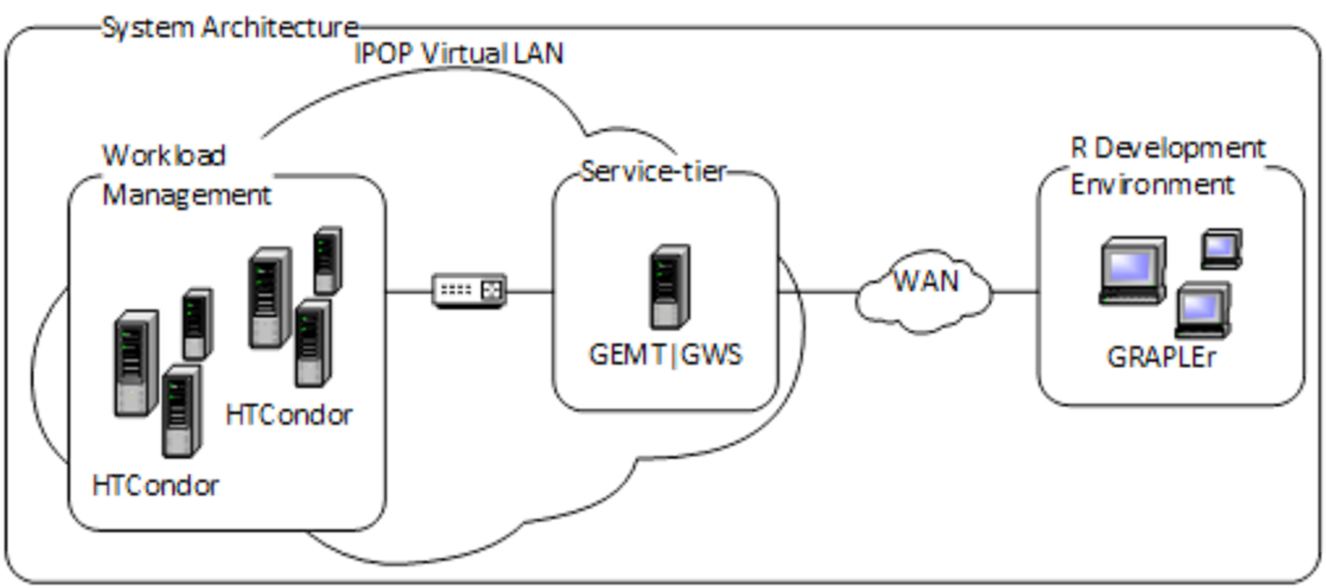


Figure: Subratie et al. 2017

Activity C

- Go through the GRAPLEr demo in the R script
- Once you have finished the demonstration, design your own simulation "experiment" with your partner and use the GRAPLEr to examine the offsets of a meteorological variable and magnitude of your choice.

m day^{-1}

- **Create some figures from your simulation and share them with the class.**

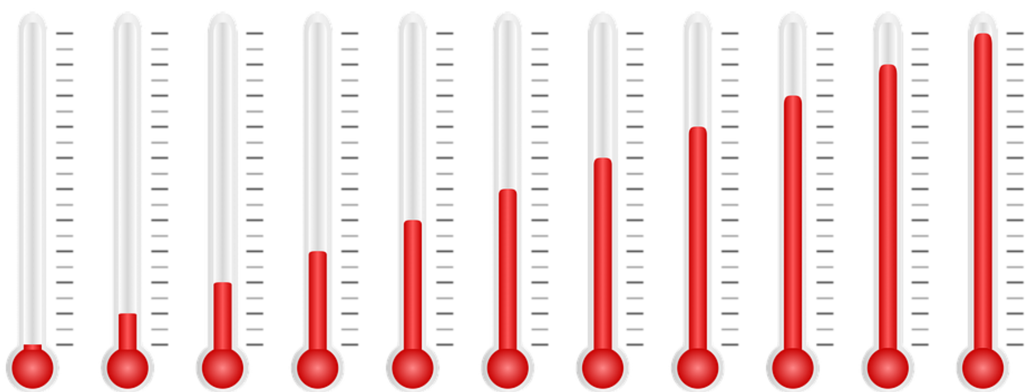


Image: Pixabay public domain

Thank you for participating!