

Process-based Aquatic Ecosystem Modeling

A wide-angle photograph of a lake at sunset. The sky is filled with dramatic, layered clouds in shades of orange, yellow, and grey. The sun is low on the horizon, casting a warm glow over the water. In the foreground, many sailboats are moored in the calm water. In the background, a city skyline with several tall buildings is visible across the lake.
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = q_0$$
$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \nabla \mathbf{v} = -\frac{1}{p} \nabla p + g + \nu \Delta \mathbf{v}$$
$$\frac{\partial P}{\partial t} = D \frac{\partial^2 P}{\partial z^2} + \lambda P \left(1 - \frac{P}{K}\right)$$



@hydrobert



WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

GLEON



supported by NSF ABI development grant, #DBI 1759865

Disclaimer

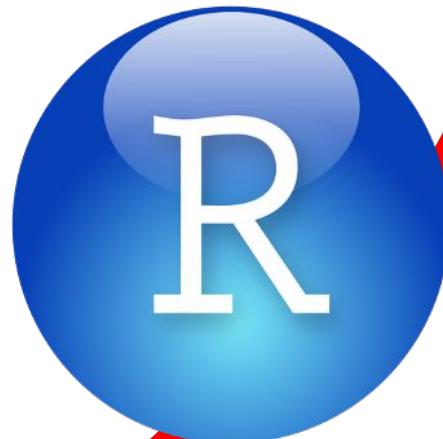
This workshop focuses solely on running the vertical 1D lake model GLM-AED2 using the scripting language R as our coding environment.



Hopefully in future iterations, we can showcase applications of PCLake, GOTM, Simstrat, MyLake, FLake, ALBM, and many more using Python, Matlab or Julia (or whatever).

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Who's who?



Robert, postdoc at
UW-Madison
modeling enthusiast

#carbon



Austin, grad
student at
UW-Madison

guest talk by DIY
model builder

Carol, PhD student at
University of São Paulo



#reservoirs



Johannes, PhD student
at TU Dresden

guest talks by two
GLM experts

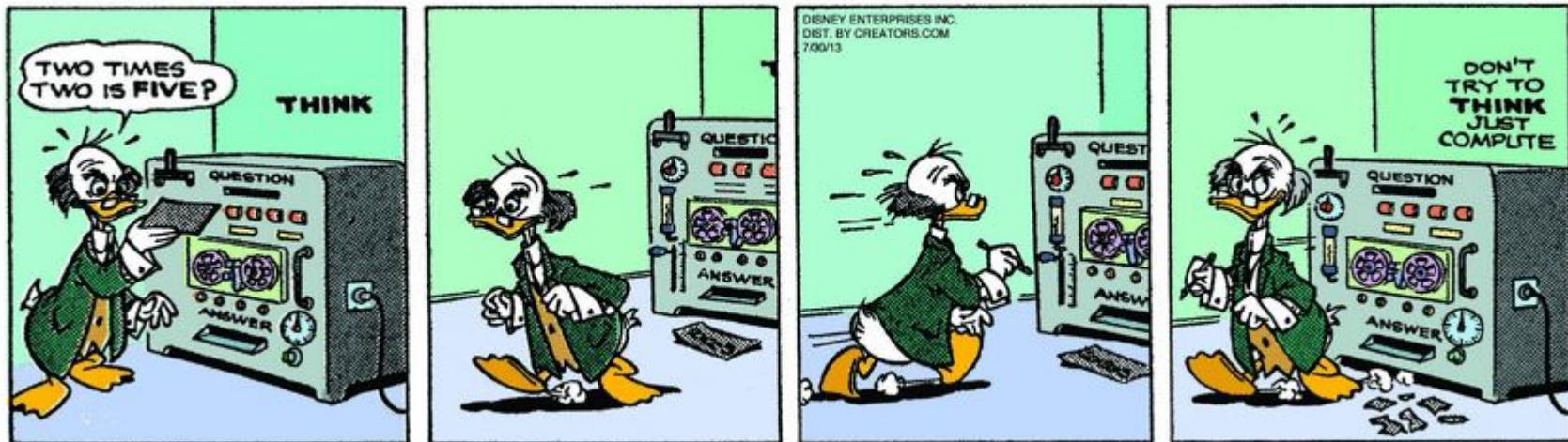
Welcome!

- If you want to run the simulations during the workshop, you will need to install the following software on your computer. If you just want to watch, ask questions, and drive from the back seat, that's fine, too!
 - Github: https://github.com/robertladwig/GLM_workshop
 - Future questions? Robert (rладwig2@wisc.edu)
-
- (1) Use the docker: <https://hub.docker.com/r/hydrobert/glm-workshop> (requires docker)
 - (a) this includes Rocker, all packages, all scripts and all data
 - (2) Clone or download files from: https://github.com/robertladwig/GLM_workshop
 - (a) you'll need R (>= 4.0) and these packages: GLM3r, glmtools, rLakeAnalyzer, tidyverse

Expectations for today

- **Introduction:** to process-based modeling intended for all skill levels and background
- **Overview and hands-on coding with state-of-the-art model:** vertical 1D hydrodynamic-water quality model (**GLM**)

Great textbook: Steven C. Chapra (2008) "Surface Water-Quality Modeling" Waveland Pr Inc

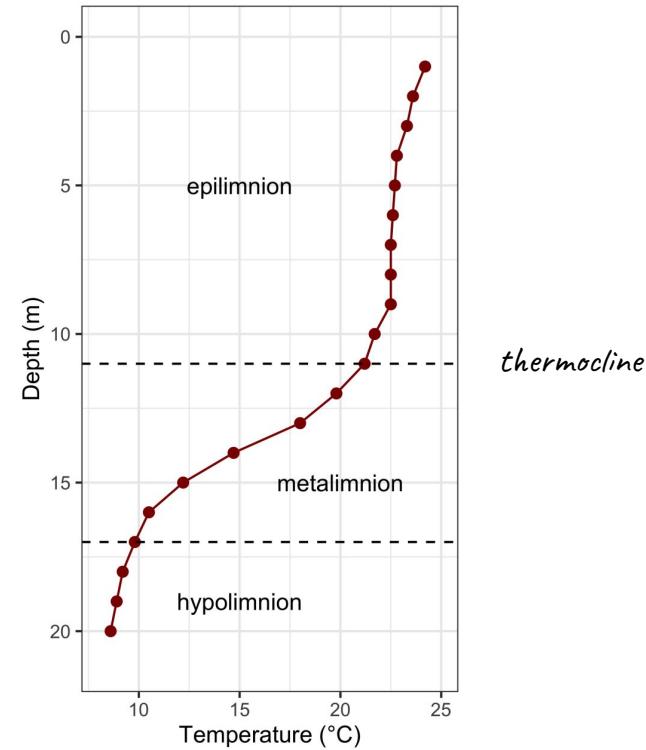
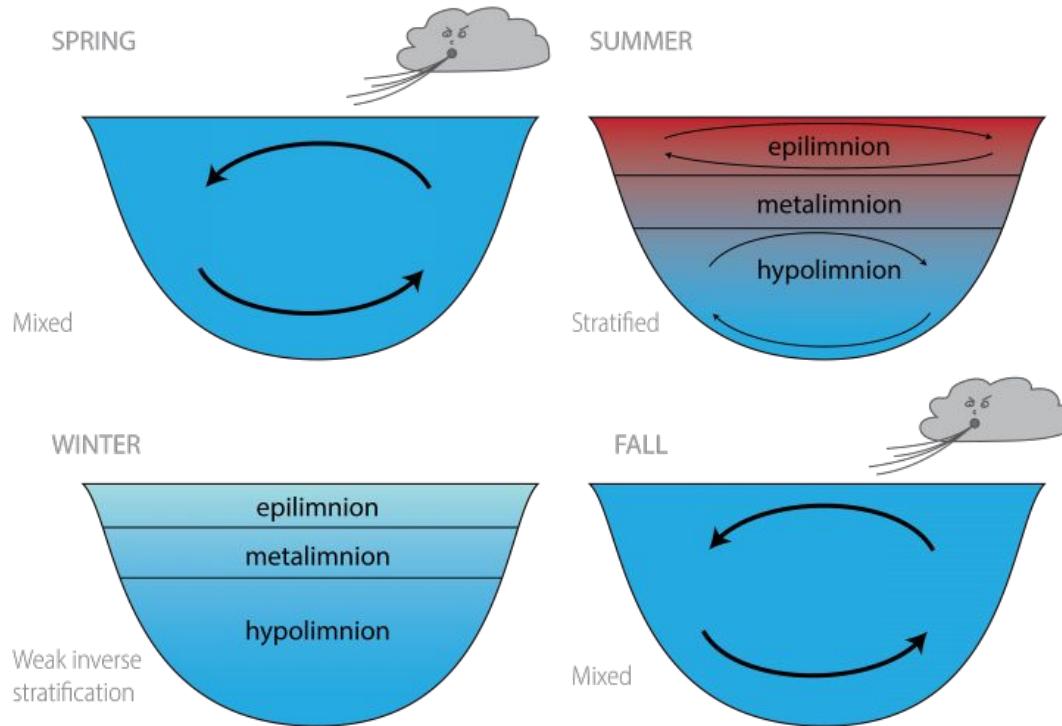


Time schedule today (all in UTC)

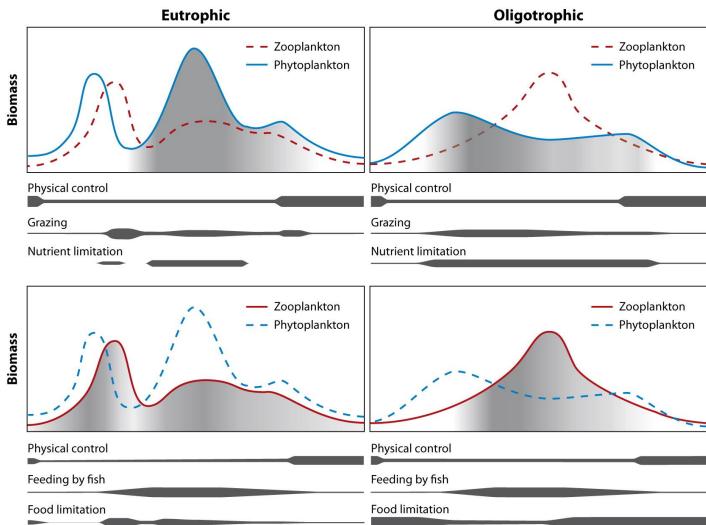
3:00-3:45	Introduction to process-based aquatic ecosystem modeling	<ul style="list-style-type: none">• What is modeling?• How to approach process-based modeling?• Why should you use modeling?
4:00-5:00	Introduction to GLM-AED2	<ul style="list-style-type: none">• Theory behind GLM and AED2• How to set up your own model• How to work with GLM-AED2 in R
5:15-6:45	Hands-on coding in R	<ul style="list-style-type: none">• Running the GLM-AED2 model in R• 6 different exercises• Work in sub-groups on either physics or biology

Introduction

Today we will talk about lake stratification ...

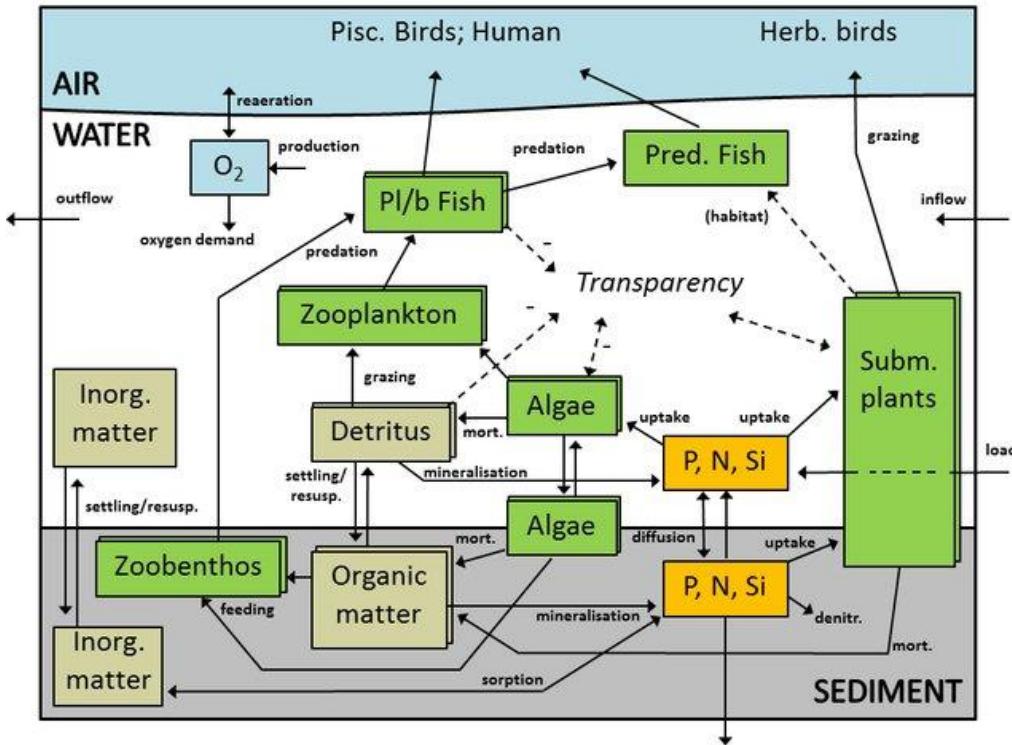


... and aquatic food webs



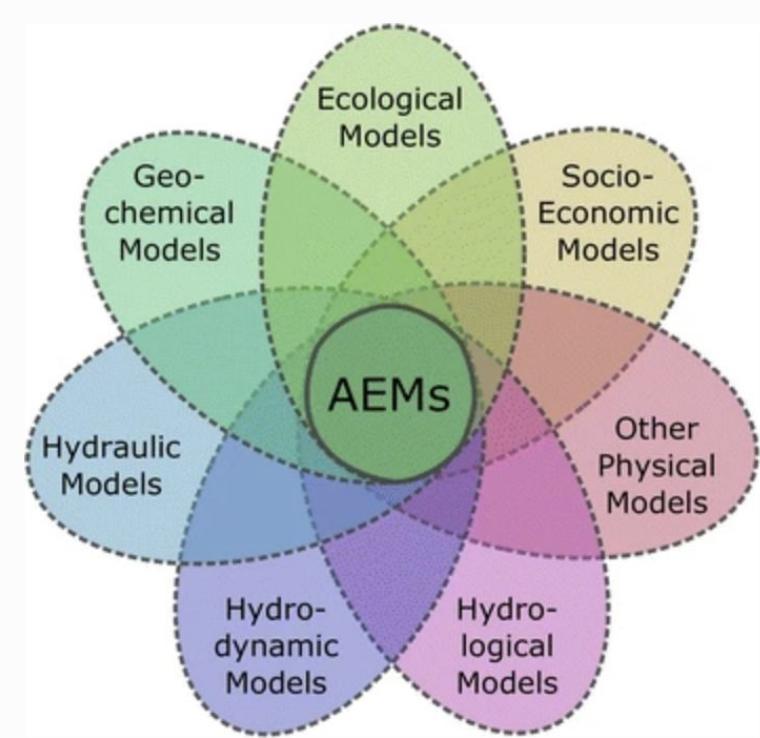
 Sommer U, et al. 2012.

R Annu. Rev. Ecol. Evol. Syst. 43:429–48



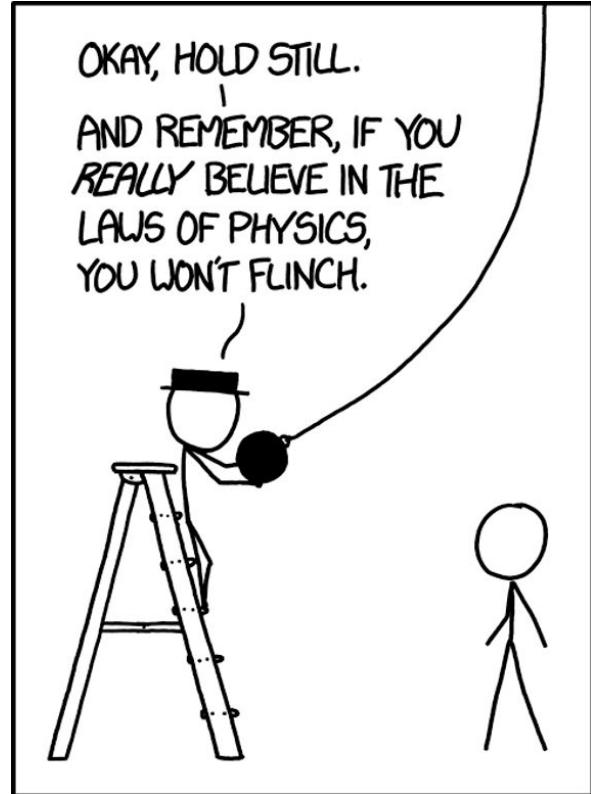
And then we have an aquatic ecosystem model (AEM)

- aquatic ecosystem modeling: *a formal procedure by which the impact of external or internal forcing on aquatic ecosystem state(s) can be estimated*
- two distinct classes of AEMs exist:
 - direct mathematical relation between forcing and state (statistical models)
 - formulated in terms of the processes underlying this relation
(process-based models)



First, what is modeling?

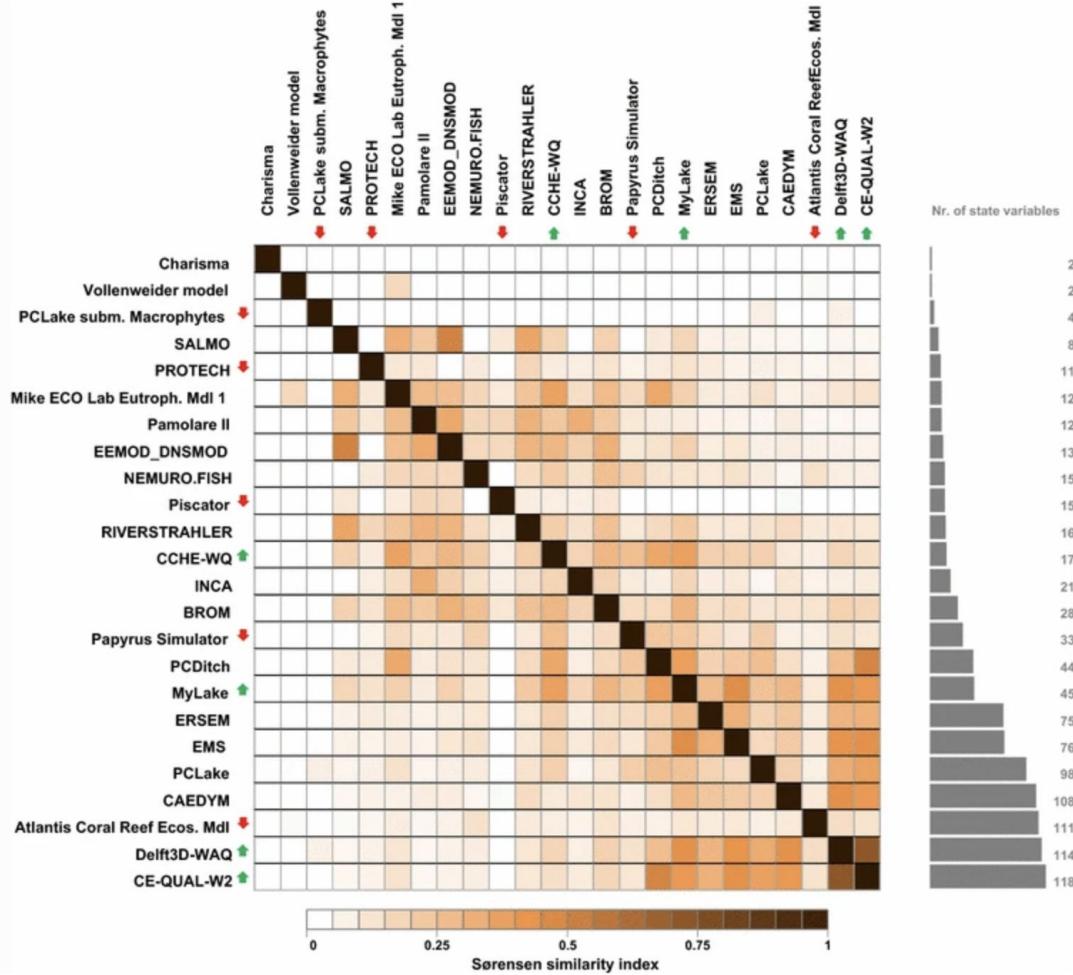
- Models are simplified reflections of reality
- Deterministic (events at next time step depend on events from previous time step)
 - and describe processes with mathematical equations
 - that are either based on empirical knowledge or physical principles
- Numerical models need time and space discretization
- As well as initial data (to start from) and boundary data (as driving data)



Various models exist

Which to choose?

- depends on aim
- depends on availability
- depends on your skills
- depends on the required output
- depends on key processes
- depends on your collaborators (supervisor, lab)
- depends on your budget

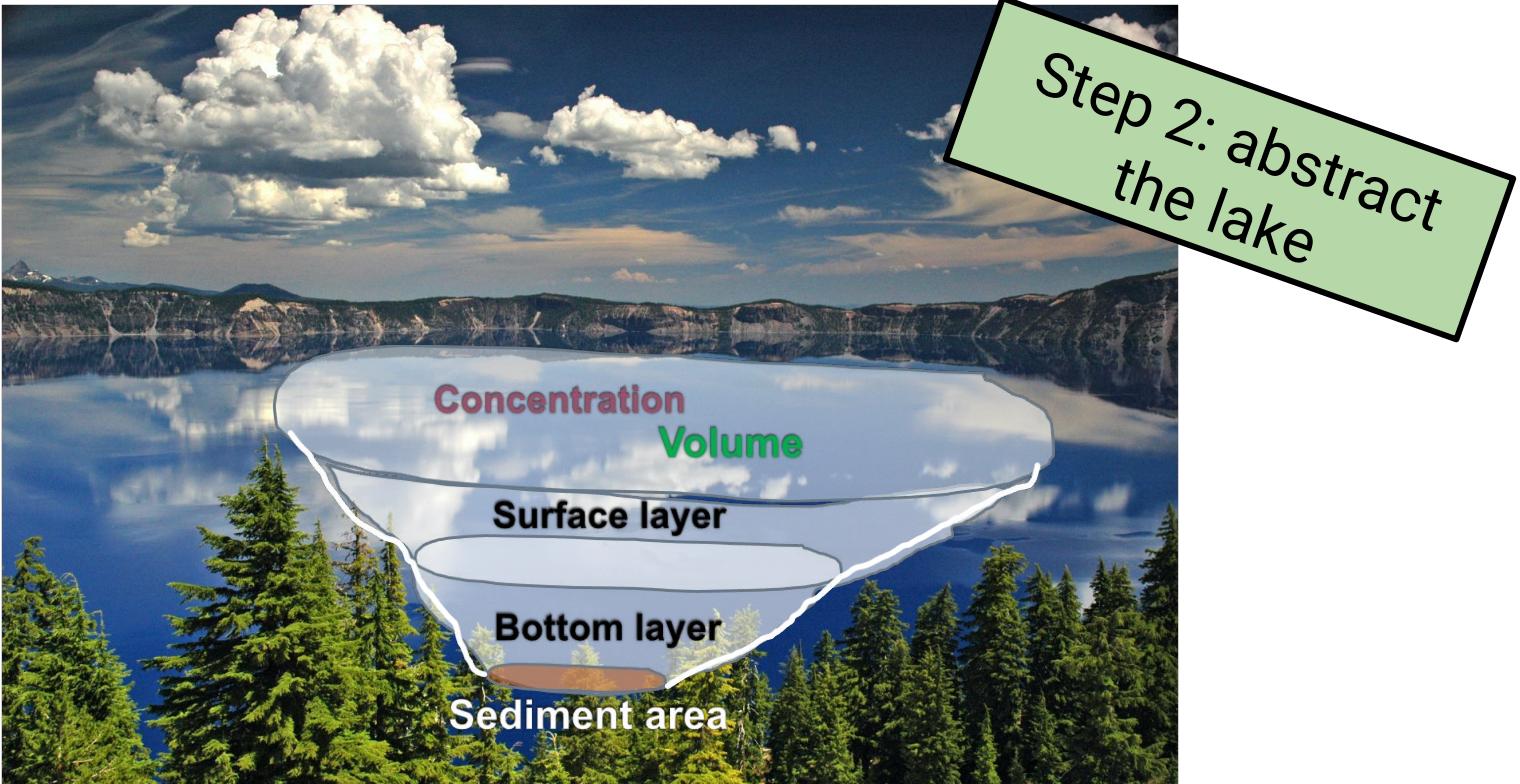


Process-based modeling in a nutshell

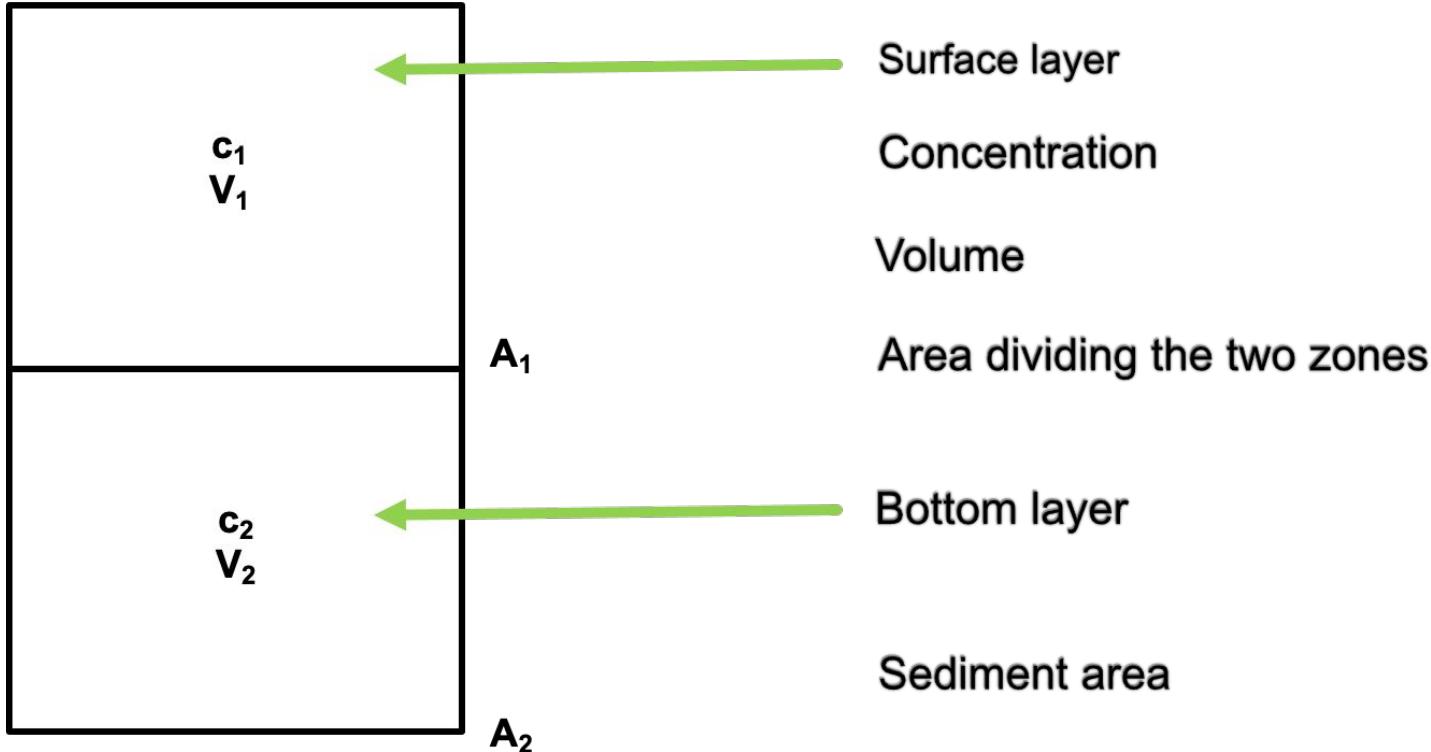


*Step 1: imagine a
(nice) lake*

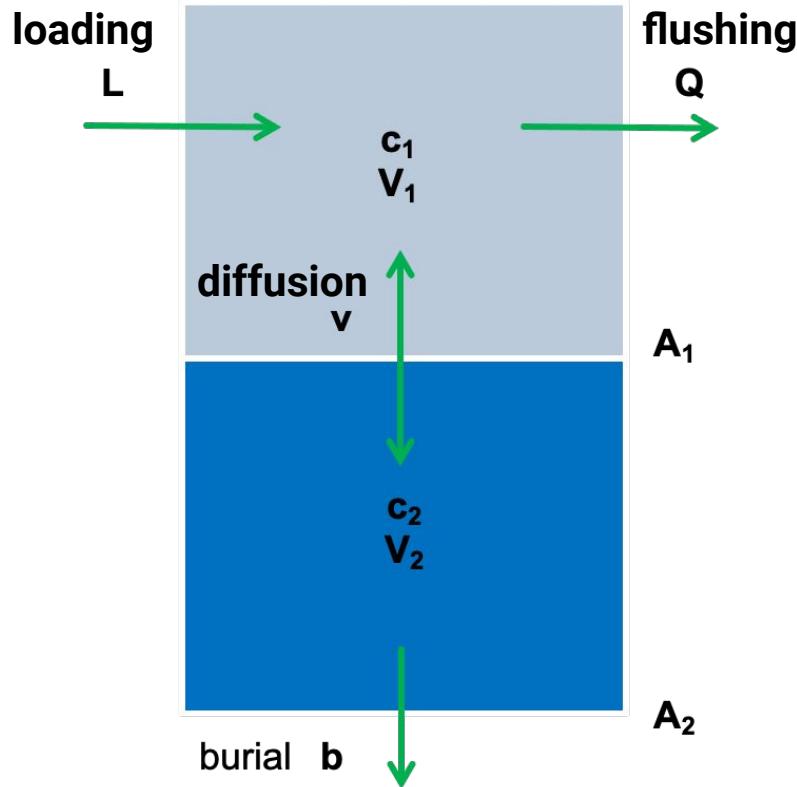
Process-based modeling in a nutshell



Process-based modeling in a nutshell



Process-based modeling in a nutshell

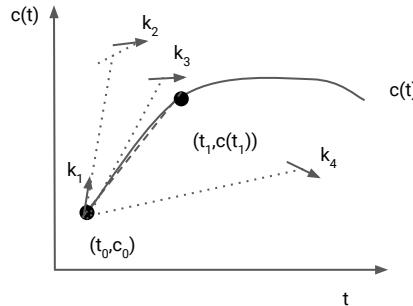
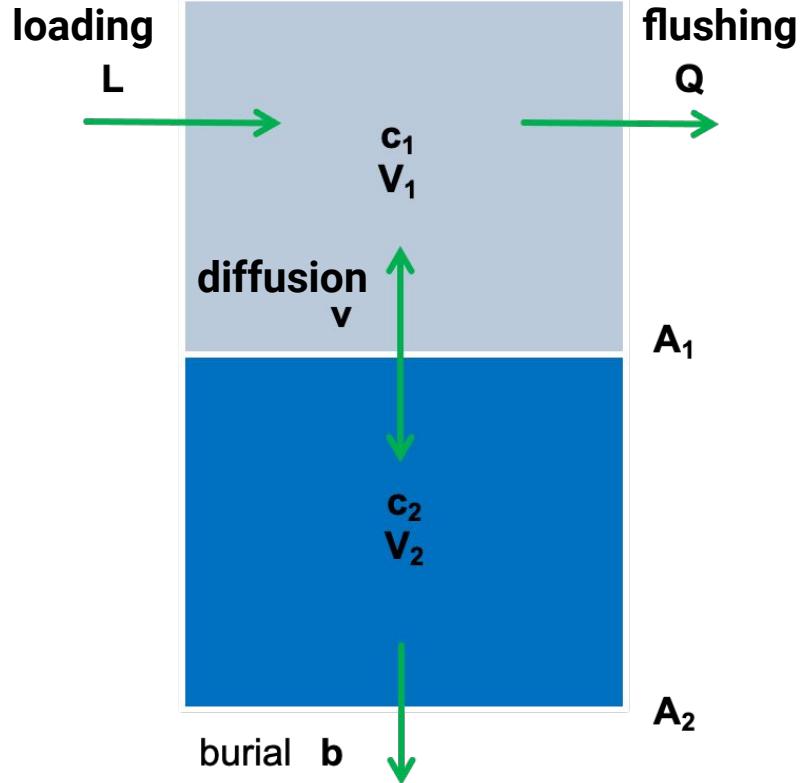


Step 3: add math

$$\frac{dc_1}{dt} = \frac{L - Qc_1 + vA_1(c_2 - c_1)}{V_1}$$

$$\frac{dc_2}{dt} = \frac{vA_1(c_1 - c_2) - bA_2c_2}{V_2}$$

Process-based modeling in a nutshell



Step 4: solve with numerics, e.g., Runge-Kutta

$$c_{i+1} = c_i + f(c_i, t_i) * \Delta t h = \Delta t$$

$$c_{i+1} = c_i + [\frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)]\Delta t$$

$$k_1 = f(t_i, c_i)$$

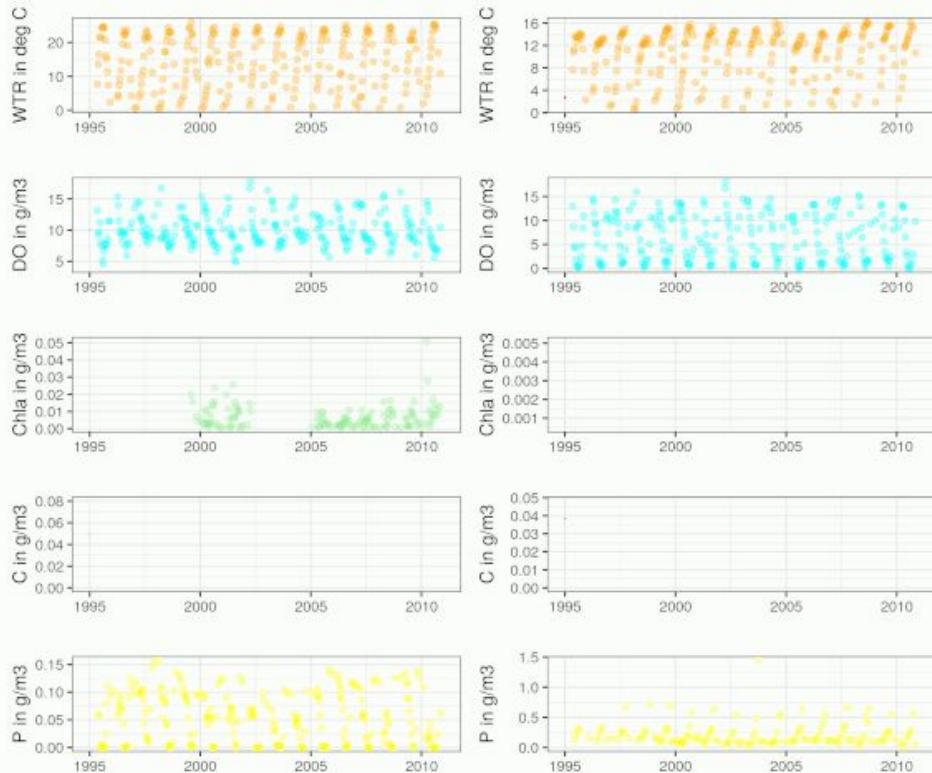
$$k_2 = f(t_i + \frac{1}{2}h, c_i + \frac{1}{2}hk_1)$$

$$k_3 = f(t_i + \frac{1}{2}h, c_i + \frac{1}{2}hk_2)$$

$$k_4 = f(t_i + h, c_i + hk_3)$$

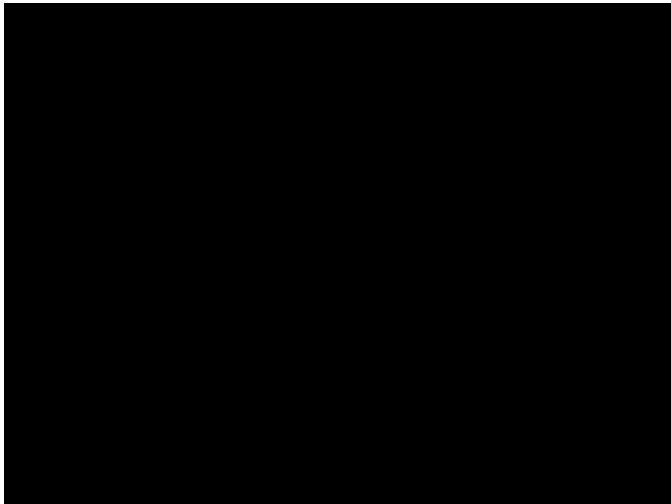
Process-based modeling in a nutshell

- results from simple 2-layer model:
 - replicates **physics well** (thermal dynamics, water temperature)
 - **sufficient replication of biogeochemical fluxes** (oxygen, nutrients, wait - negative P?)
 - **hard time capturing biology** (phytoplankton, food webs)



What are the laws?

- **Conservation of mass (continuity)**
 - source = sink (+ storage)
 - Mass cannot be created or destroyed



- **Conservation of momentum**
 - Velocity based on balances of forces (gravity, pressure, friction, earth-rotation)

State of the environment



$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = q_0$$
$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \nabla \mathbf{v} = -\frac{1}{p} \nabla p + g + \nu \Delta \mathbf{v}$$

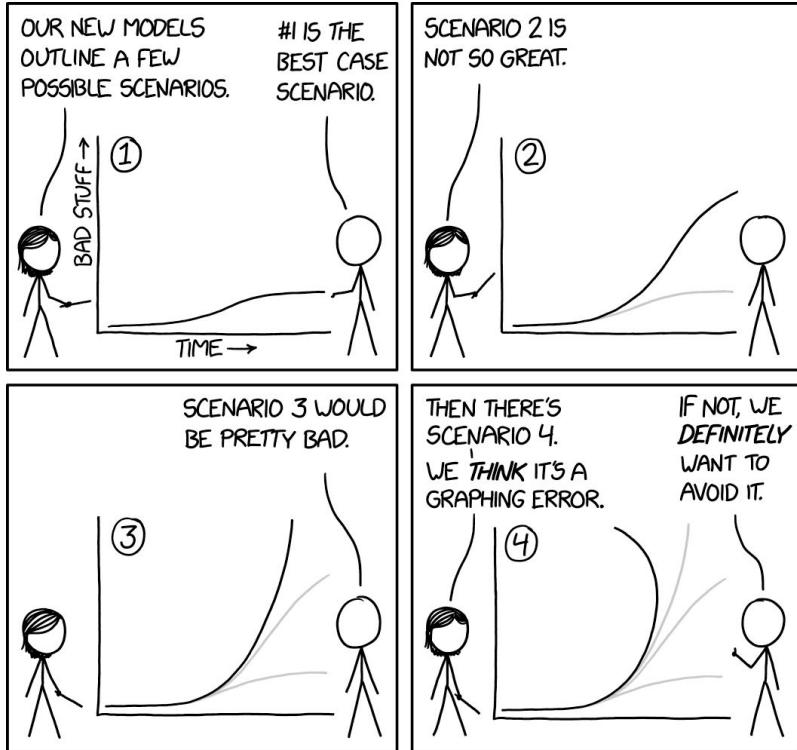


State of the system

Process-based modeling in a nutshell

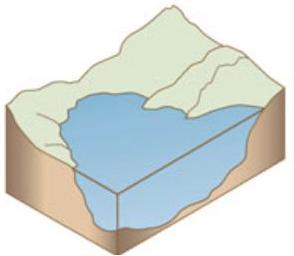
Why should you use a model?

- Explore ideas regarding ecological systems that may not be possible/feasible to field-test for
 - logistical, political, financial and/or physical reasons
- Formulating a model helps to better understand the system and can identify data needs → repetitive experiments
- test environmental constraints/thresholds
- “Your model is your hypothesis.” ([Kate](#))



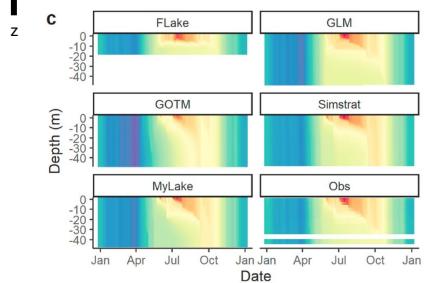
Model dimensions

zero-dimensional
0D: Box model



0D: Box model

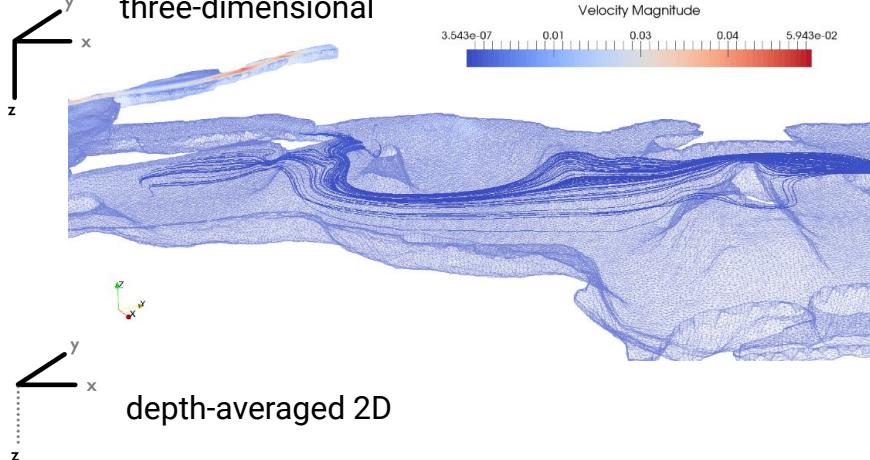
vertical 1D



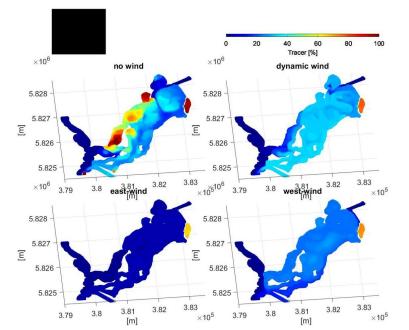
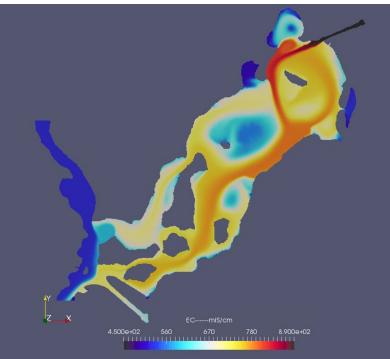
longitudinal-vertical 2D



three-dimensional

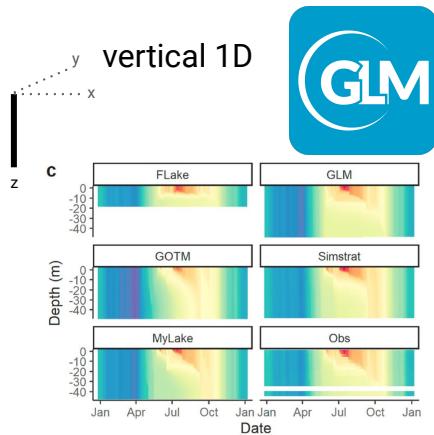
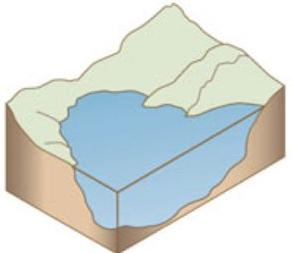


depth-averaged 2D

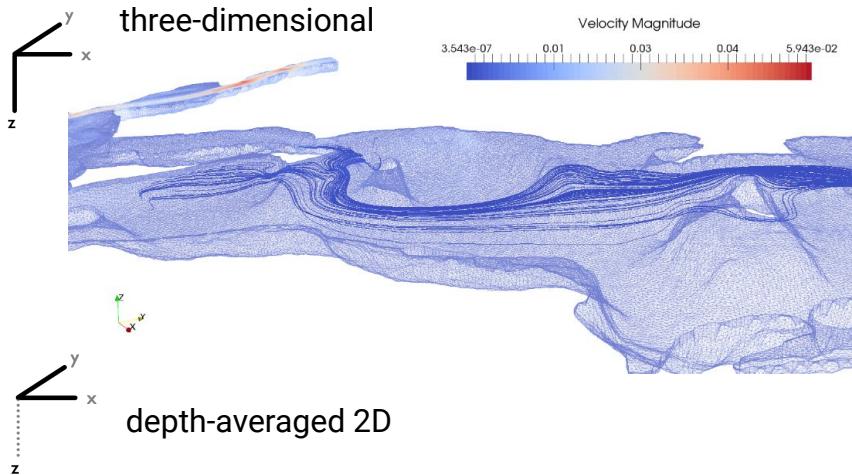


Model dimensions

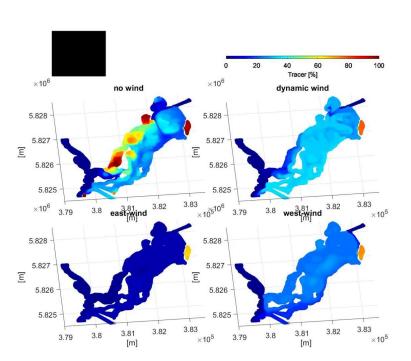
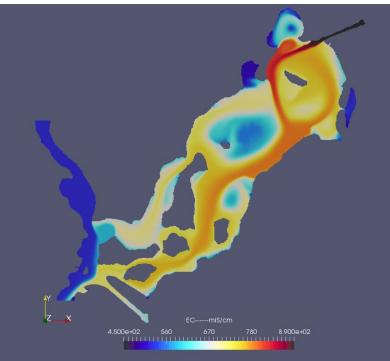
zero-dimensional
0D: Box model



longitudinal-vertical 2D



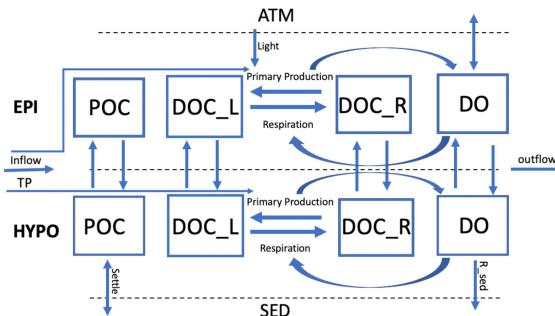
depth-averaged 2D



Learn from the expert: *Modeling of carbon dynamics in lake systems*

Austin Delany: Master of Science thesis at UW-Madison in the Paul Hanson team

- coded his own aquatic ecosystem model in R with feedbacks for organic carbon, light, oxygen, phosphorus and temperature dynamics

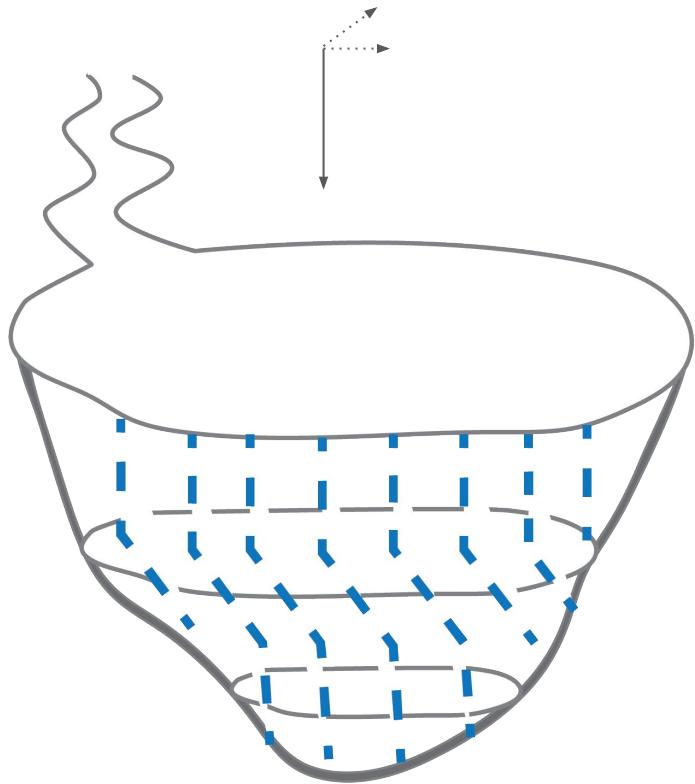


The General Lake Model (GLM)

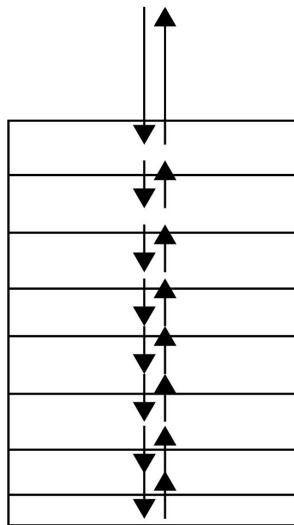
a: introduction



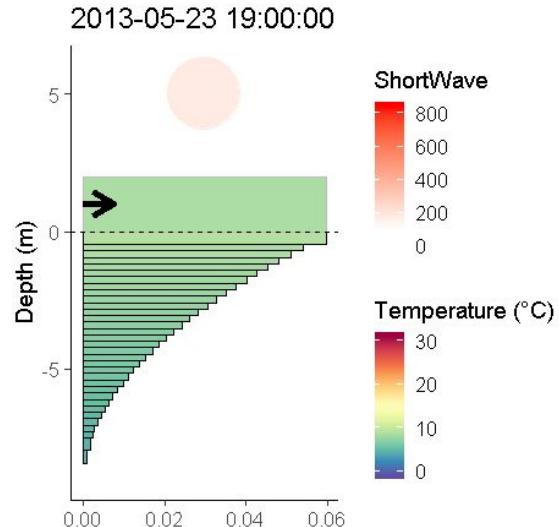
Process-based lake modeling



atmospheric exchange



- Vertical 1D model:
 - Horizontal homogeneity
 - No Coriolis force
- Layering over vertical axis
- Every layer = volume of lake
- **Focus on heat transport**



Process-based lake modeling

- reactive-diffusive transport equation for water temperature
 - turbulence-closure scheme to solve for momentum terms and diffusivities (e.g., k- ϵ in Simstrat)
- **GLM (General Lake Model):** energy-balance approach: potential ag. available kinetic energy → heat transport

$$\frac{\partial T}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left(A(v_t^i + v') \frac{\partial T}{\partial z} \right) + \frac{1}{\rho_0 c_p} \frac{\partial H_{sol}}{\partial z} + \frac{dA}{dz} \frac{H_{geo}}{A \rho_0 c_p}$$

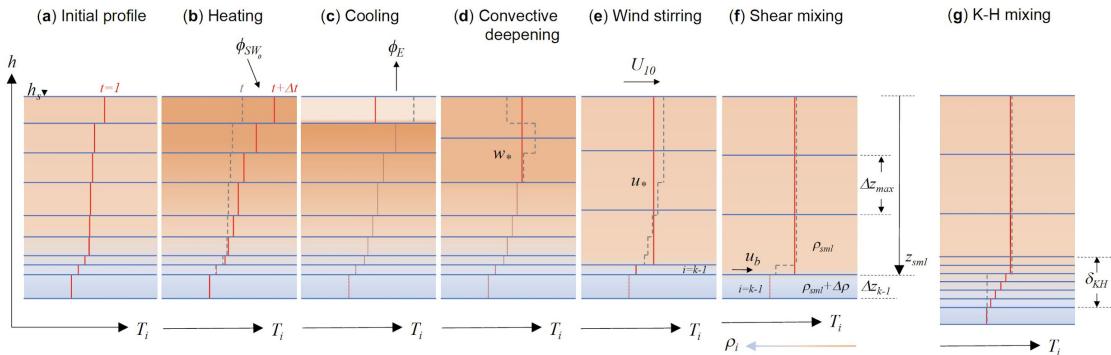
diffusive transport

atmospheric heating

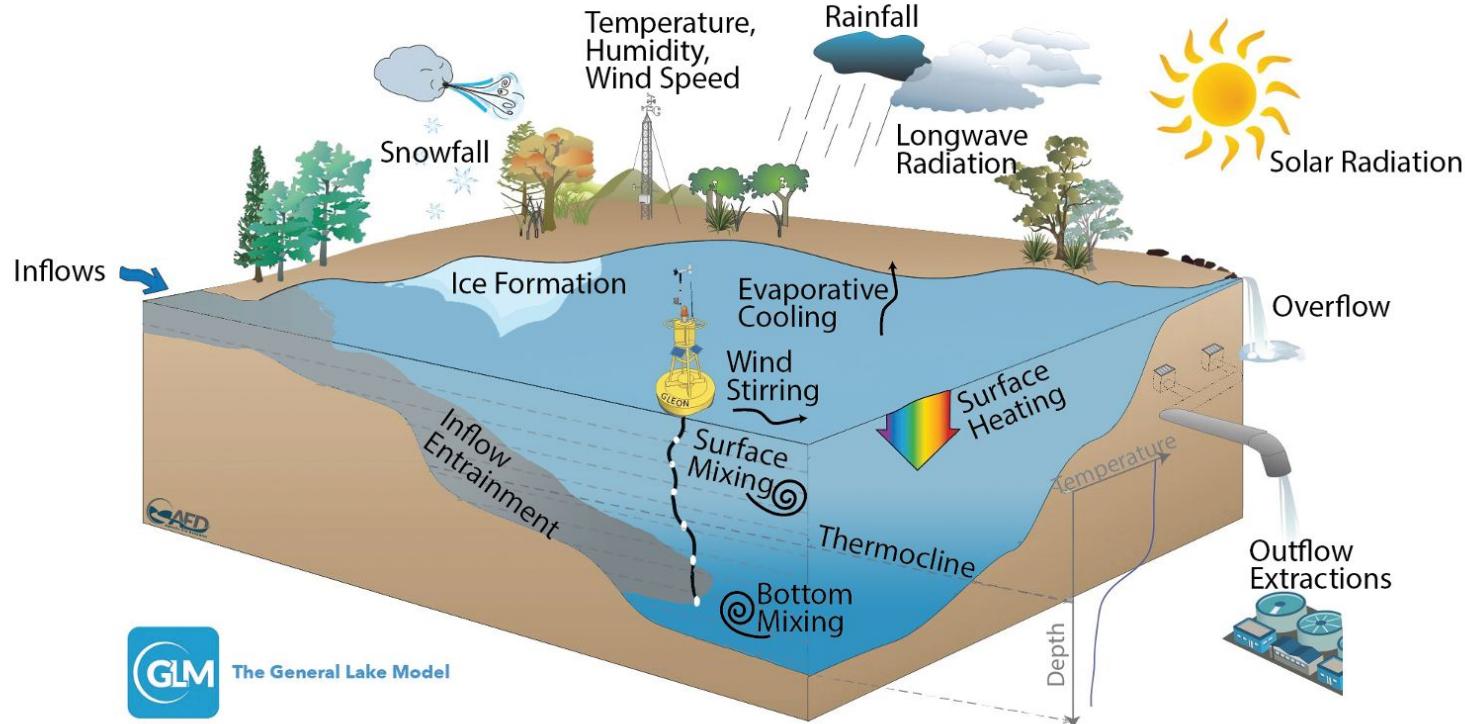
sediment heating

$$E_{TKE} = \underbrace{0.5C_K(w_*^3)\Delta t}_{\text{convection}} + \underbrace{0.5C_K(C_W w_*^3)\Delta t}_{\text{wind stirring}} + \underbrace{0.5C_S[U_b^2 + \frac{U_b^2}{6} \frac{d\xi}{dz_{SML}} + \frac{u_b \xi}{3} \frac{du_b}{dz_{SML}}]}_{\text{shear production, K-H production}} \Delta z_{k-1} \quad (5)$$

$$E_{PE} = \underbrace{[0.5C_T(w_*^3 + C_W U_*^3)^{2/3} + \frac{\Delta \rho}{\rho_0} g z_{SML}]}_{\text{acceleration}} + \underbrace{\frac{g \xi^2}{24 \rho_0} \frac{d(\Delta \rho)}{dz_{SML}} + \frac{g \xi \Delta \rho}{12 \rho_0} \frac{d\xi}{dz_{SML}}}_{\text{lifting}} \Delta z_{k-1} \quad (6)$$

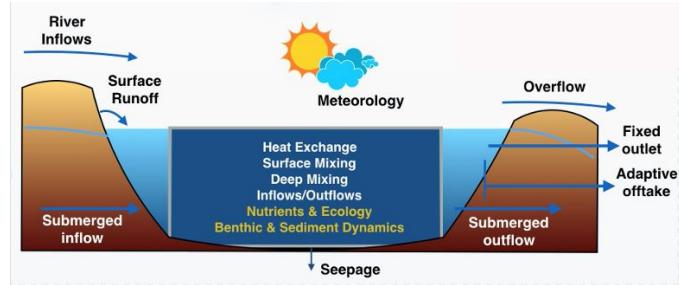


General Lake Model (GLM)



General Lake Model (GLM)

- GLM started as a GLEON project
- Developed by Matt Hipsey, Louise Bruce and Casper Boon at UWA
- Designed to operate with the Aquatic EcoDynamics Model Libraries (AED2) → water quality model
- Written in C and Fortran
- Freely available as open-source program:
<https://github.com/AquaticEcoDynamics/GLM>
- **Key features:** Lagrangian grid, energy balance approach, coupled with water quality module



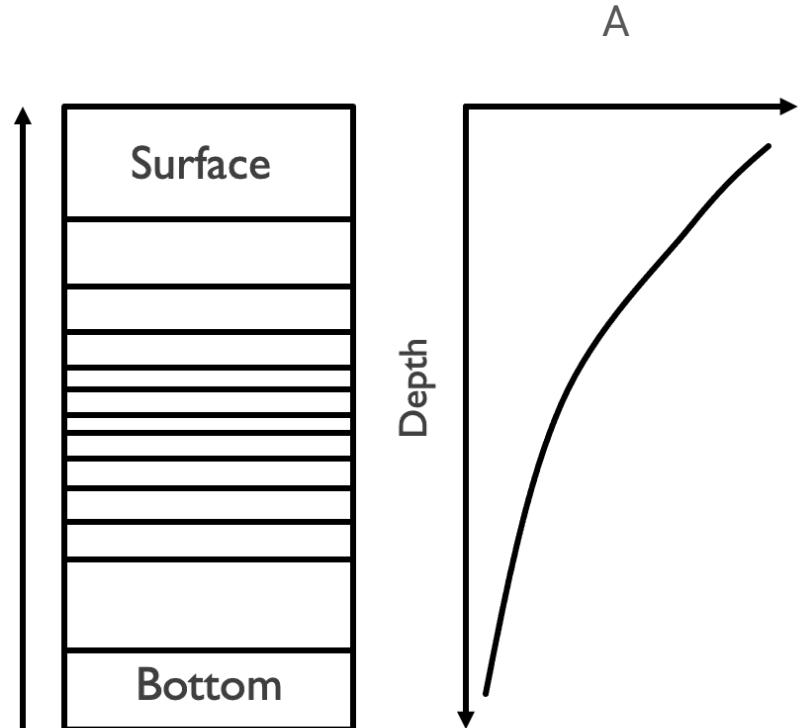
The General Lake Model (GLM)

b: hydrodynamics



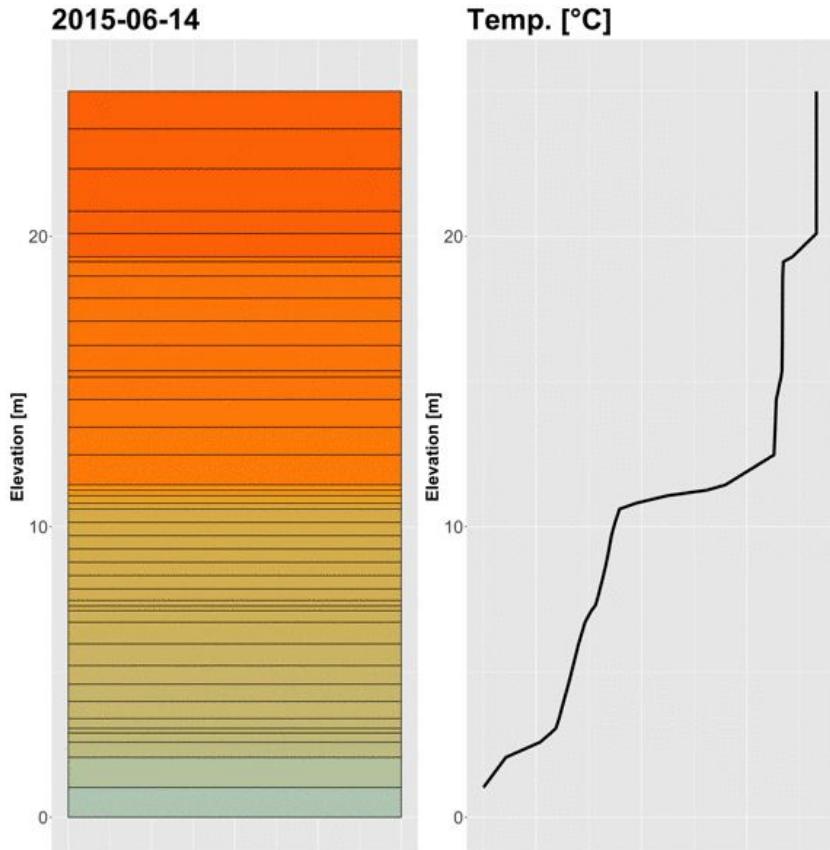
Grid

- Each vertical layer (= control volume) adapts its thickness due to flows, mixing and mass fluxes
→ flexible Lagrangian structure
- Each layer has 'unique' density
- When there's enough energy to overcome density gradient → layers merge
- Layer's volume changes depending on hypsography



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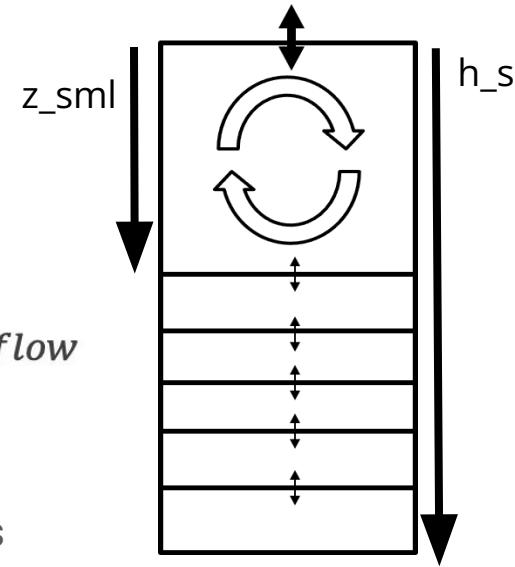
Water balance

- Net water flux over total lake (solved by integration over time):

$$\frac{dV_s}{dt} = A_s \frac{dh_s}{dt} + \sum_I^N Q_{inf,I} - \sum_I^N Q_{out,I} - Q_{seepage} - Q_{overflow}$$

Surface layer height

- Code solves first for surface flux changes, then for all other fluxes



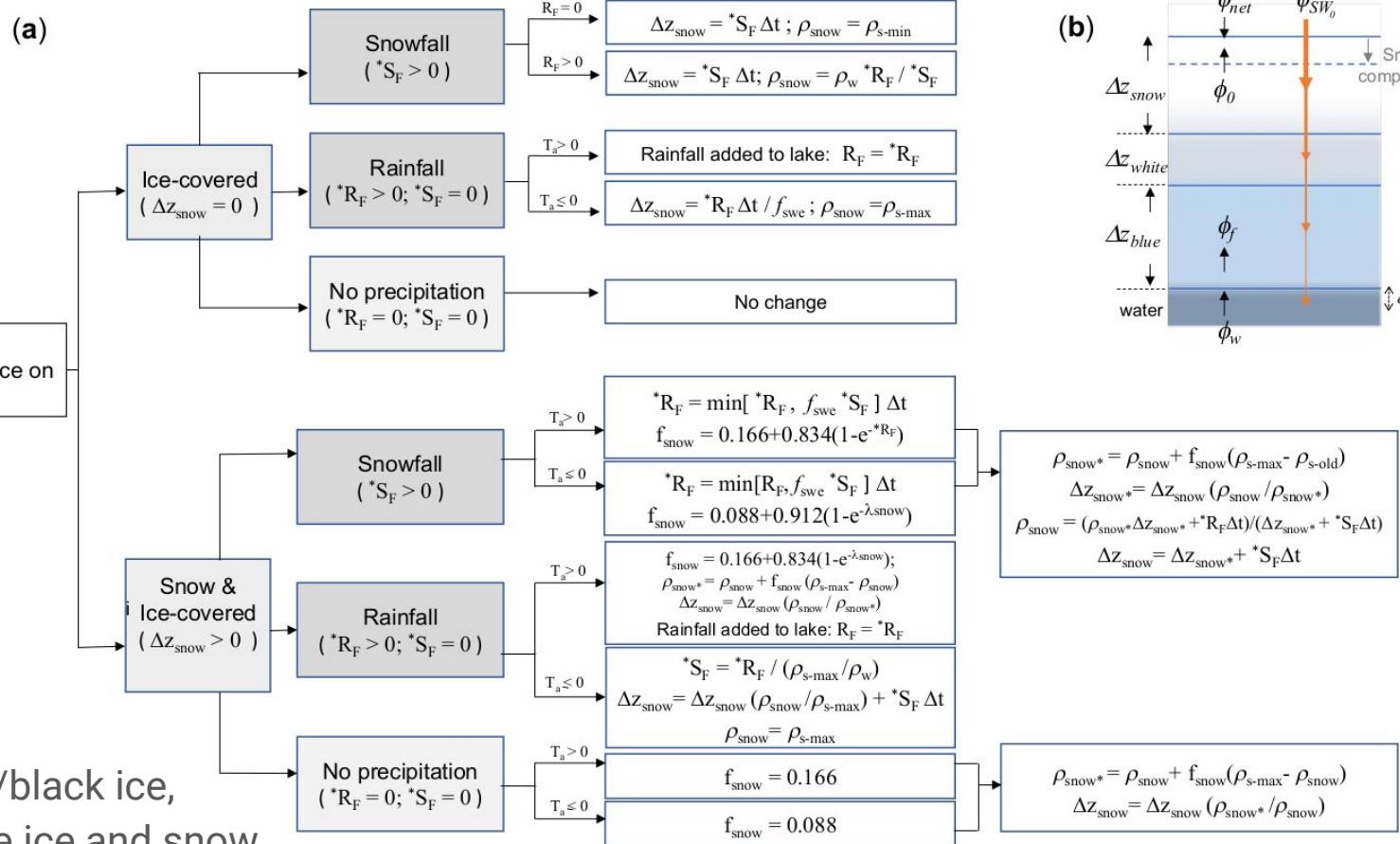
Mass balance of surface layer = precipitation + snowfall + run-off – evaporation - ice

$$\frac{dh_s}{dt} = P + S + \frac{Q_R}{A_S} - E - \frac{d\Delta z_{ice}}{dt}$$

- Mixing only affects thickness of surface layer (z_{sml}) not its height

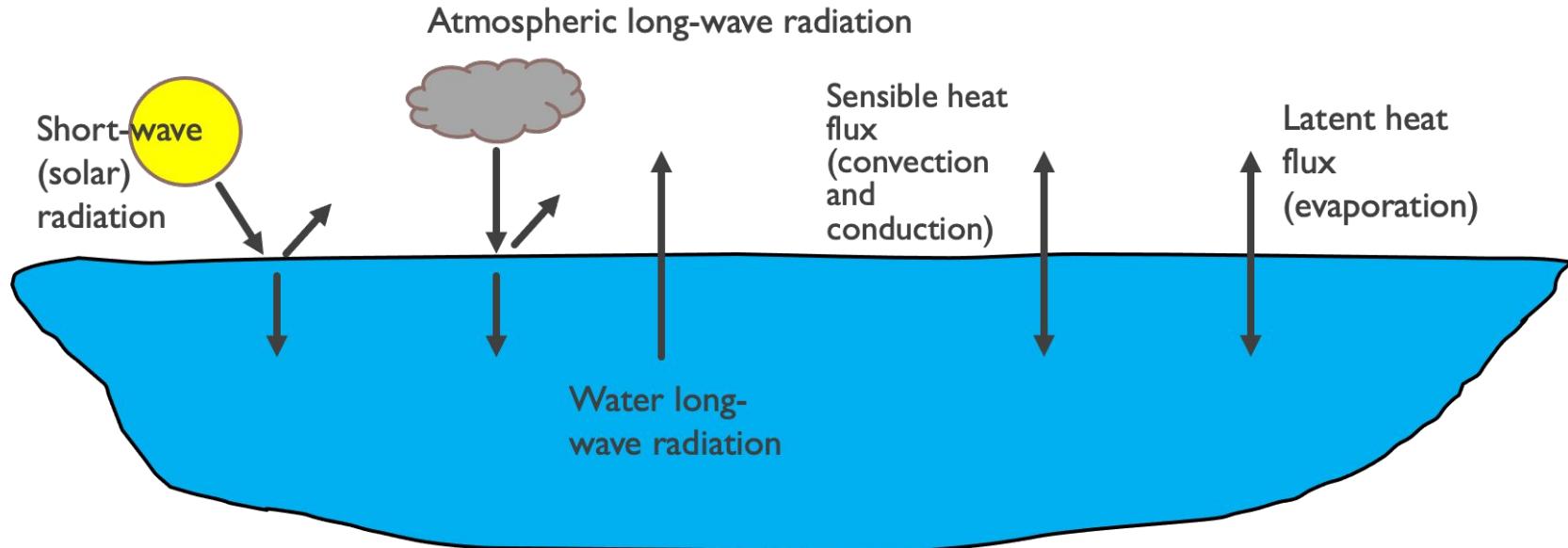
Snow and ice dynamics

blue/black ice,
white ice and snow



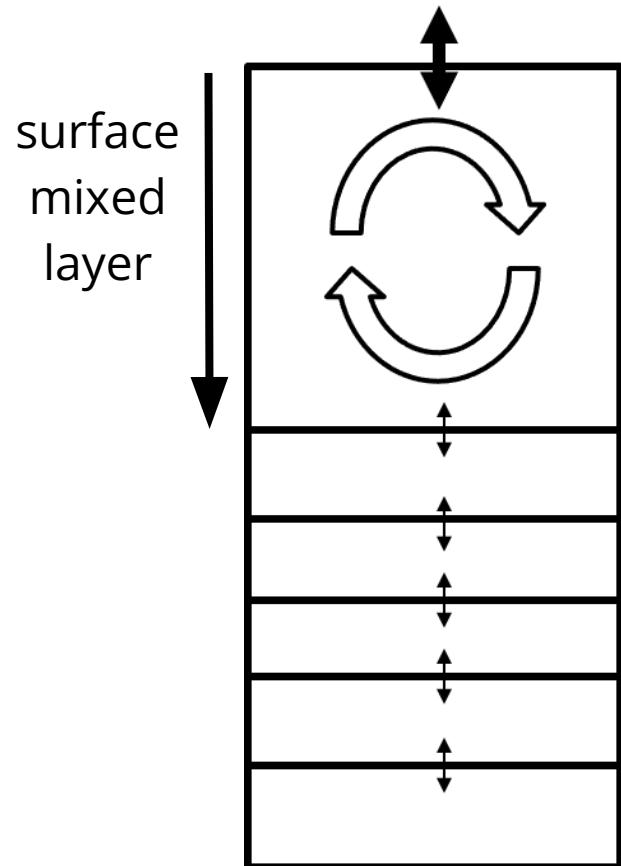
Surface energy balance

$$\rho C_p z_s \frac{dT_s}{dt} = J_{SW} + J_{LW,in} - J_{LW,out} - J_E + J_H$$

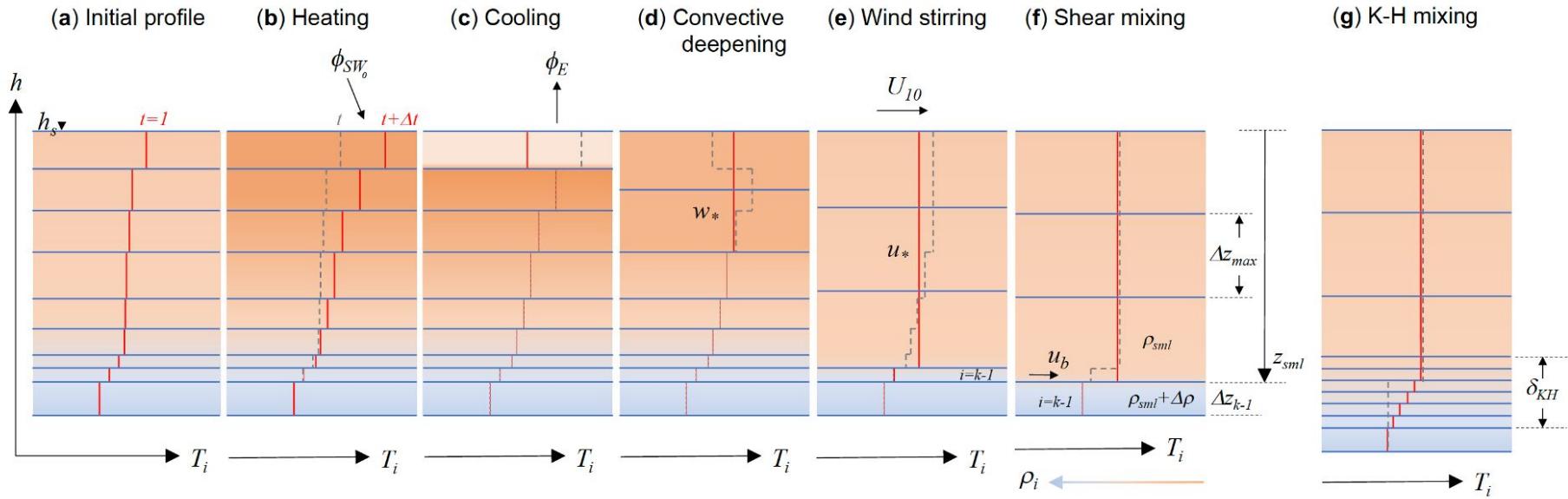


Mixing I

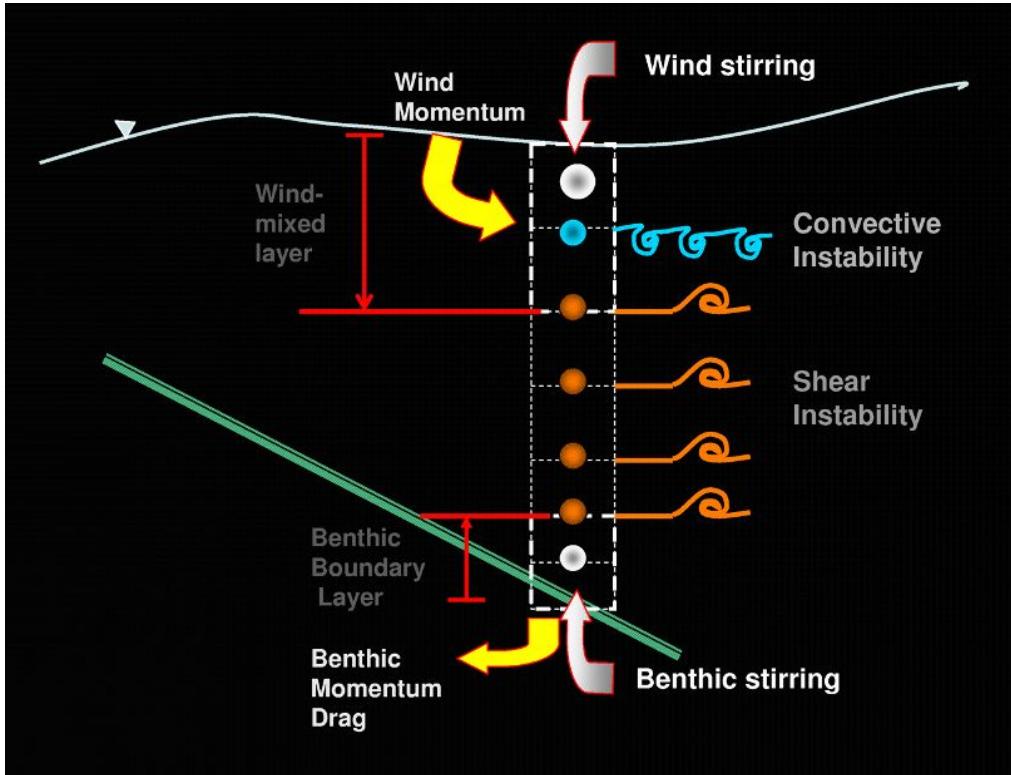
- Surface layer: energy balance approach
 - Energy balance determines thickness of surface mixed layer
 - Below surface mixed layer, turbulent diffusion approach is used
- Here, mixing depends on difference between potential energy and available kinetic energy
- Kinetic energy = convective overturn, wind stirring and shear production/Kelvin-Helmholtz billowings



Mixing II



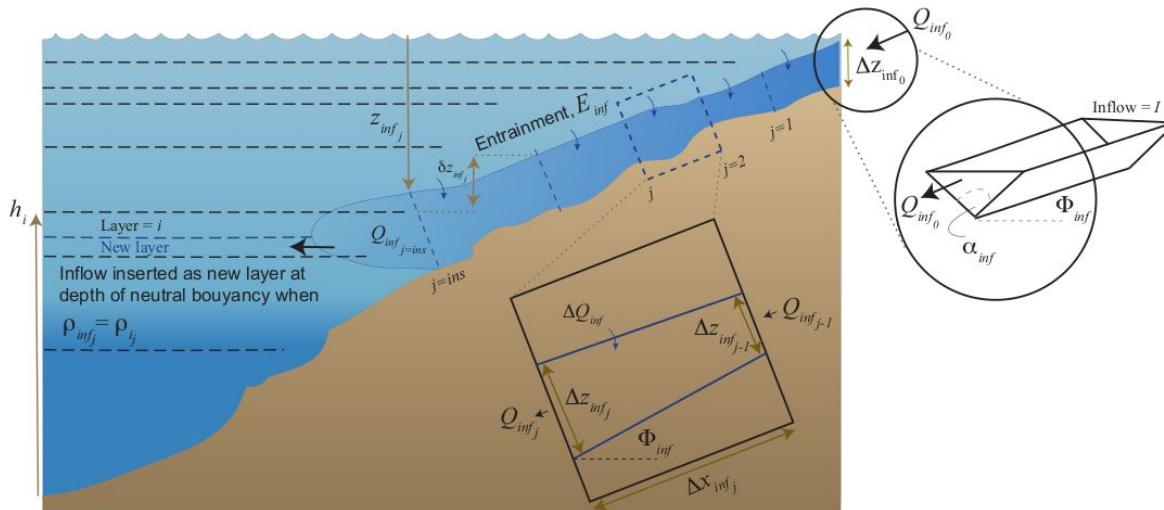
Mixing III



Kelvin-Helmholtz instabilities

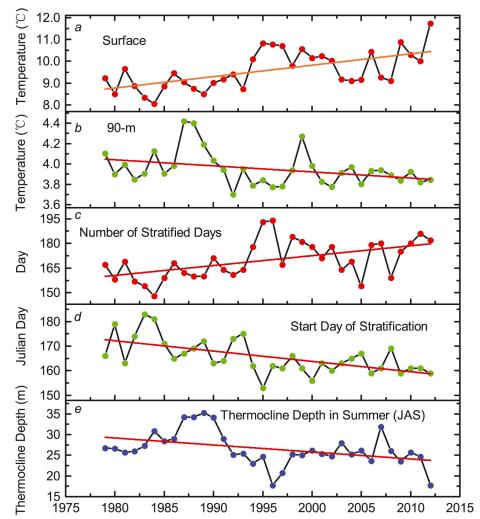
Inflow and outflow dynamics

- inflows can be riparian run-off, river inflows (either buoyant or plunge) or submerged inflow (groundwater)
- outflows can be depth-specific withdrawal (reservoirs), adaptive offtake (reservoirs), groundwater seepage or river outflow; everything else = overflow

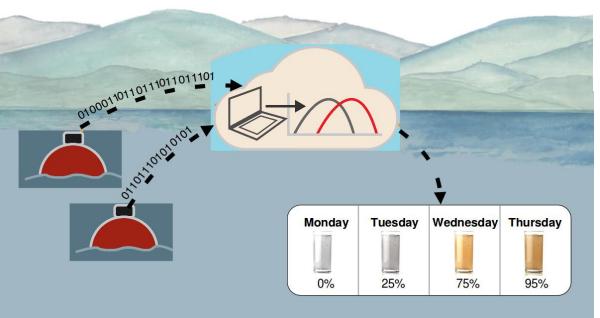
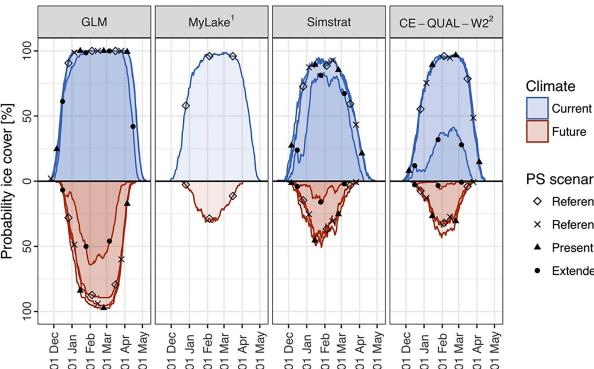


Example applications

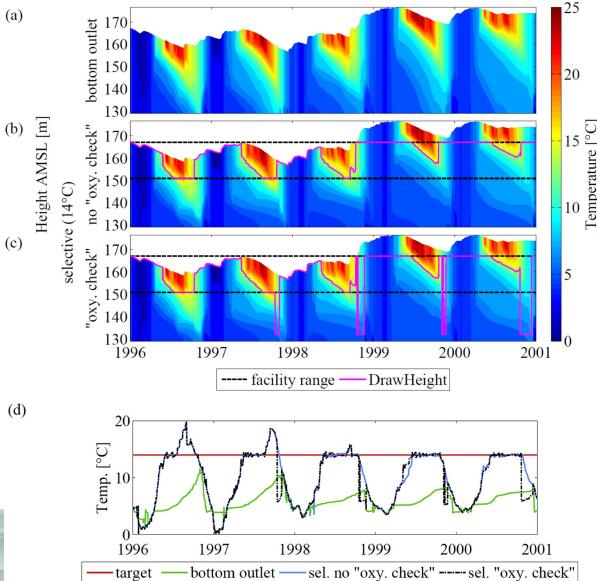
Climate change effects on lakes¹



Future ice cover shifts²



Optimal withdrawal depth in reservoirs⁴



Smart ecological forecasting (FLARE)³

¹Huang et al. 2017; ²Kobler et al. 2019; ³Figueiredo, Thomas, Carey & Weathers; ⁴Weber et al. 2017

Learn from the expert: *Climate change impact on Brazilian reservoirs*

Carolina C. Barbosa, M.C. Calijuri, A.C. Alves dos Santos, R. Ladwig, L.F.A de Oliveira, and A.C. Sarmento: Future projections of water level and thermal regime changes of a multipurpose subtropical reservoir (Sao Paulo, Brazil), Science of the Total Environment 770, 144741 (2021)

- GLM to project water level changes in reservoir → threat of dead storage



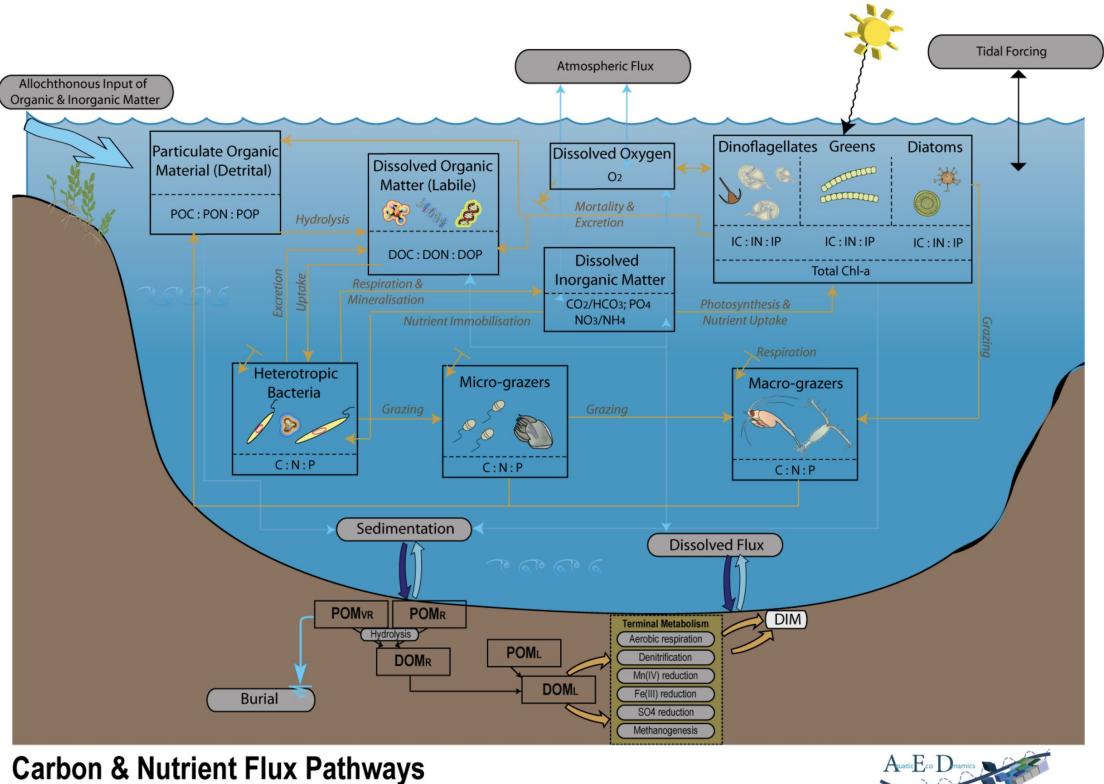
The General Lake Model (GLM)

c: water quality



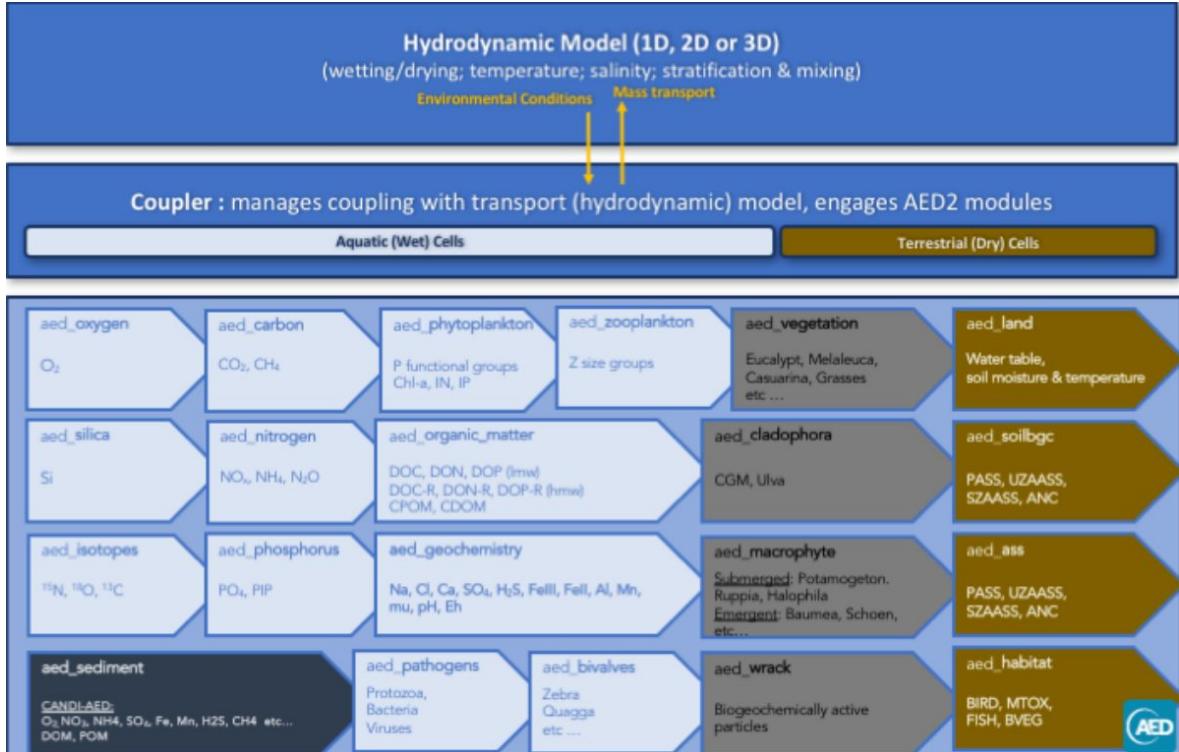
AED2: water quality model

- Coupled to GLM
- Conceptualize your individual ecosystem:
 - Oxygen, nutrients, phytoplankton
 - Sediment biogeochemistry
 - Benthic communities
- “manual”:
<https://aquaticecodynamics.cs.github.io/aed-science/index.html>



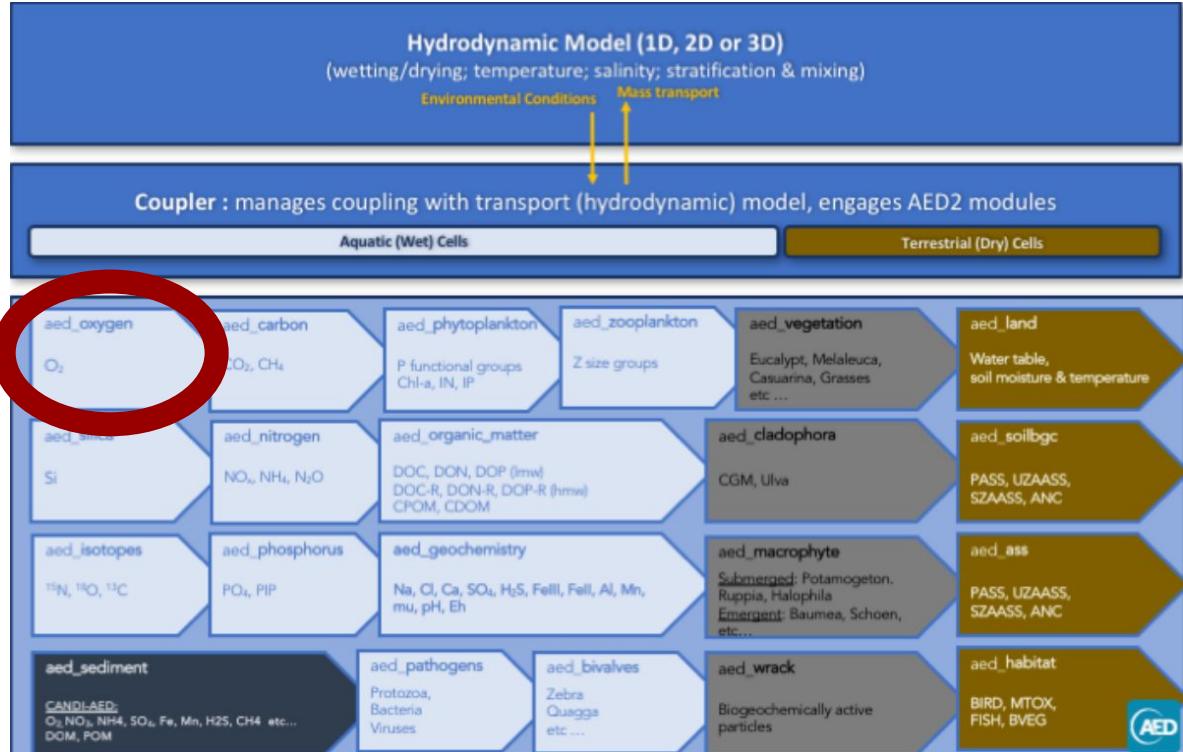
AED2: modularised structure

- Interacts with GLM (two-way coupling)
- Array of modules are available
- Hierarchy of dependencies between modules, e.g., nitrogen reactions can depend on availability of oxygen



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- Array of modules are available
- Hierarchy of dependencies between modules, e.g., nitrogen reactions can depend on availability of oxygen

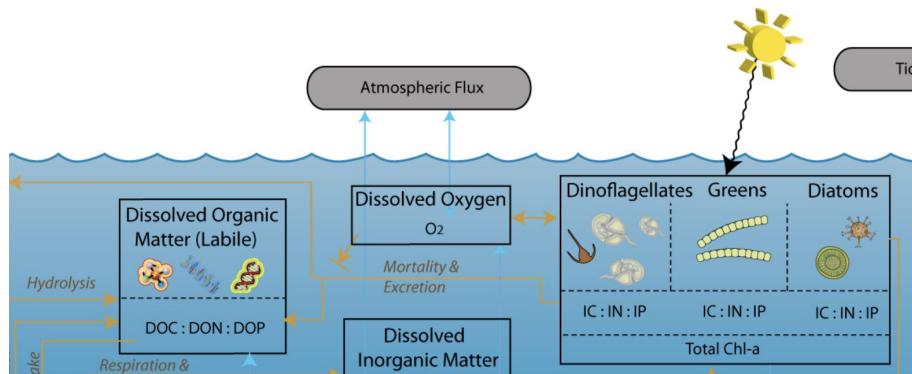
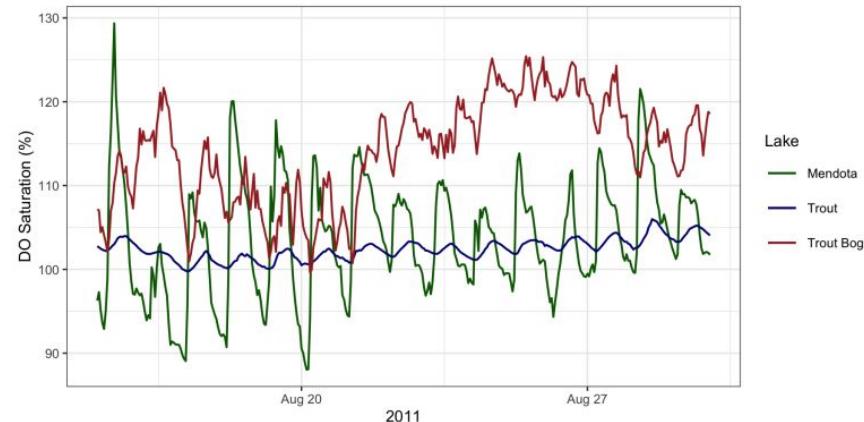


AED2: dissolved oxygen

atmospheric exchange sediment oxygen demand

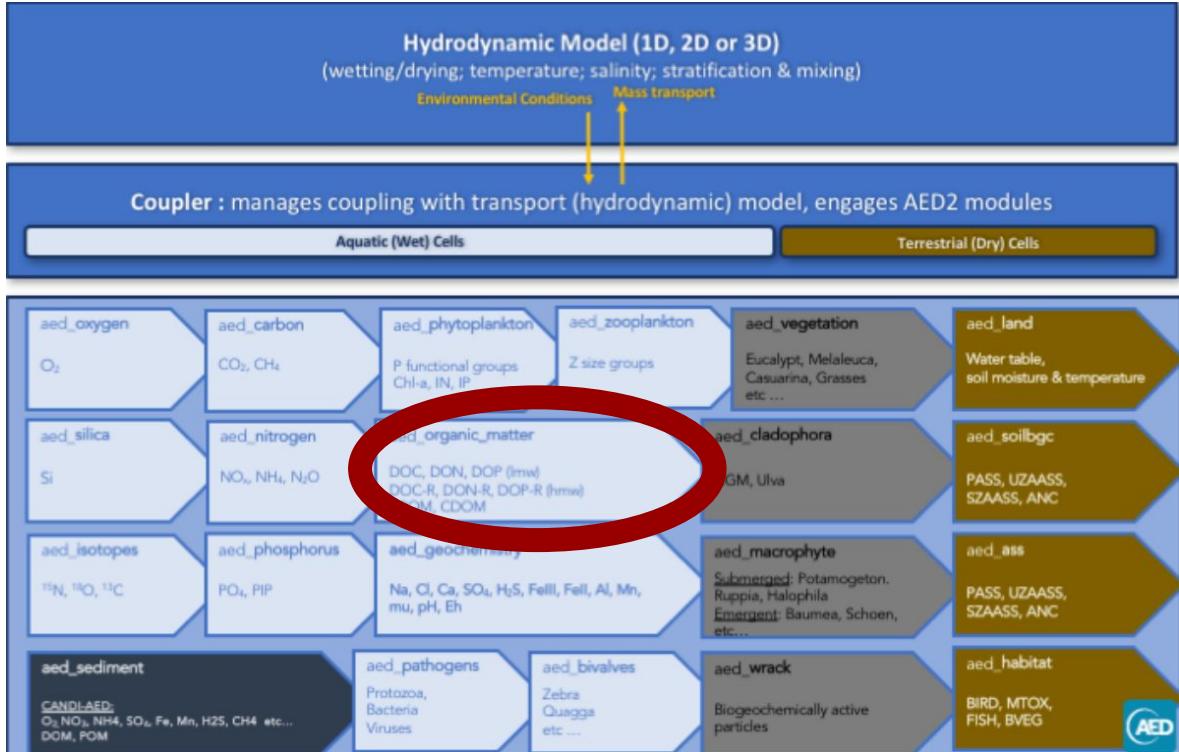
$$F_{[DO]}^{total} = k_{O_2} ([DO]_{air} - [DO]_{water}) + S_{SOD} f_{SOD}^T(T) f_{SOD}^{DO}(DO) + F_{mineralisation} + F_{nitrification} + F_{photosynthesis} + F_{respiration}$$

- Fast moving pool (minutes to days)
- Solved over vertical axis
- Plus advection and diffusion
- Photosynthesis/respiration = phytoplankton, zooplankton, seagrass, bivalves



AED2: modularised structure

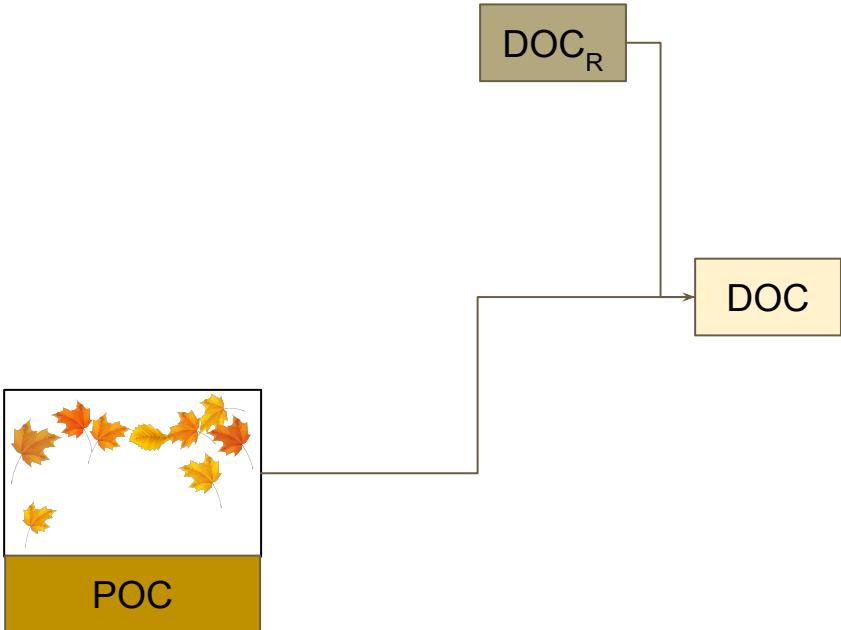
- Interacts with GLM (two-way coupling)
- Array of modules are available
- Hierarchy of dependencies between modules, e.g., nitrogen reactions can depend on availability of oxygen



AED2: dissolved organic carbon - concept

Three pools:

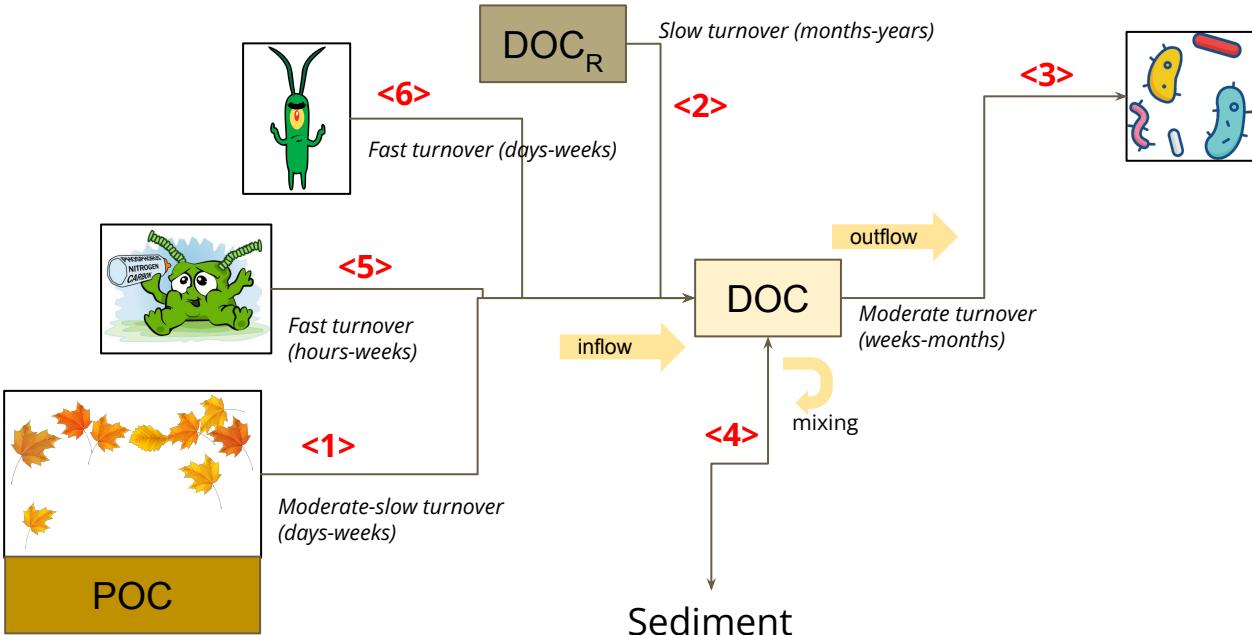
- Labile dissolved OC (**DOC**): fast turnover
- Refractory dissolved OC (**DOCr**): resistant to decomposition
- particulate OC (**POC**)



AED2: dissolved organic carbon - concept

$$\frac{dDOC}{dt} = (1 - f_{ref})f_{decom}^{POC} + (1 - f_{photo})f_{photo}^{DOCR} - f_{miner}^{DOC} \pm f_{sed}^{DOC} + \sum_a N_{PHY} f_{excr}^{PHY-C_a} + \sum_z N_{ZOO} f_{excr}^z$$

<1> <2> <3> <4> <5> <6>



- Boxes are variables (states) you can observe
- In the model, C exists only in the boxes
- Arrows are fluxes, transformations, processes you generally cannot observe directly
- Fluxes determine how the boxes change through time
- Fluxes have equations with parameters
- Recalcitrant means the arrow is slow, labile fast
- Fitting a model requires changing parameter values so that boxes match observations, given boundary conditions
- All of these processes happen in all layers

AED2: dissolved organic carbon - equations

$$\frac{dDOC}{dt} = (1 - f_{ref})f_{decom}^{POC} + (1 - f_{photo})f_{photo}^{DOCR} - f_{miner}^{DOC} \pm f_{sed}^{DOC} + \sum_a^{N_{PHY}} f_{excr}^{PHY,C_a} + \sum_z^{N_{ZOO}} f_{excr}^z$$

- = + decomposition from particulate detritus (POC)
- + phototransformation of chromophoric DOM (DOC-R)
- mineralisation by bacteria
- ± sediment flux
- excretion by phytoplankton groups
- excretion by zooplankton groups

$$\frac{dDOC_R}{dt} = f_{ref}f_{decom}^{POC} - f_{miner}^{DOCR} - f_{photo}^{DOCR} \pm f_{sed}^{DOCR}$$

- = + accumulation during particulate detritus (POC) mineralisation
- slow mineralisation by bacteria
- photolysis of chromophoric DOM (DOC-R)
- ± sediment flux

$$\frac{dPOC}{dt} = f_{bdown}^{CPOM} - f_{decom}^{POC} - f_{sett}^{POC} + \sum_a^{N_{PHY}} f_{mort}^{PHY,C_i} + \sum_z^{N_{ZOO}} [(1 - k_{assim}^z)f_{assim}^z + (1 - k_{fse}^z)f_{fse}^z + f_{mort}^z]$$

- = + breakdown of CPOM
- decomposition to DOC
- ± sedimentation
- + mortality from phytoplankton groups
- + messy feeding, faecal pellet release and mortality from zooplankton groups

$$\frac{dCPOM}{dt} = -f_{bdown}^{CPOM} - f_{sett}^{CPOM}$$

- = - breakdown of CPOM
- ± sedimentation

Aerobic mineralization of DOC

$f(O_2)$ = scales from 0-1 based on $[O_2]$

$f(T)$ = scales from ~0.2-2.0 based on T

$$f_{miner}^{VAR} = R_{miner}^{VAR} \frac{[O_2]}{K_{miner} + [O_2]} (\theta_{miner})^{T-20} [VAR] \quad (15)$$

$$+ f_{denit}^{NO_3} \chi_{denit}^{VAR} \quad (16)$$

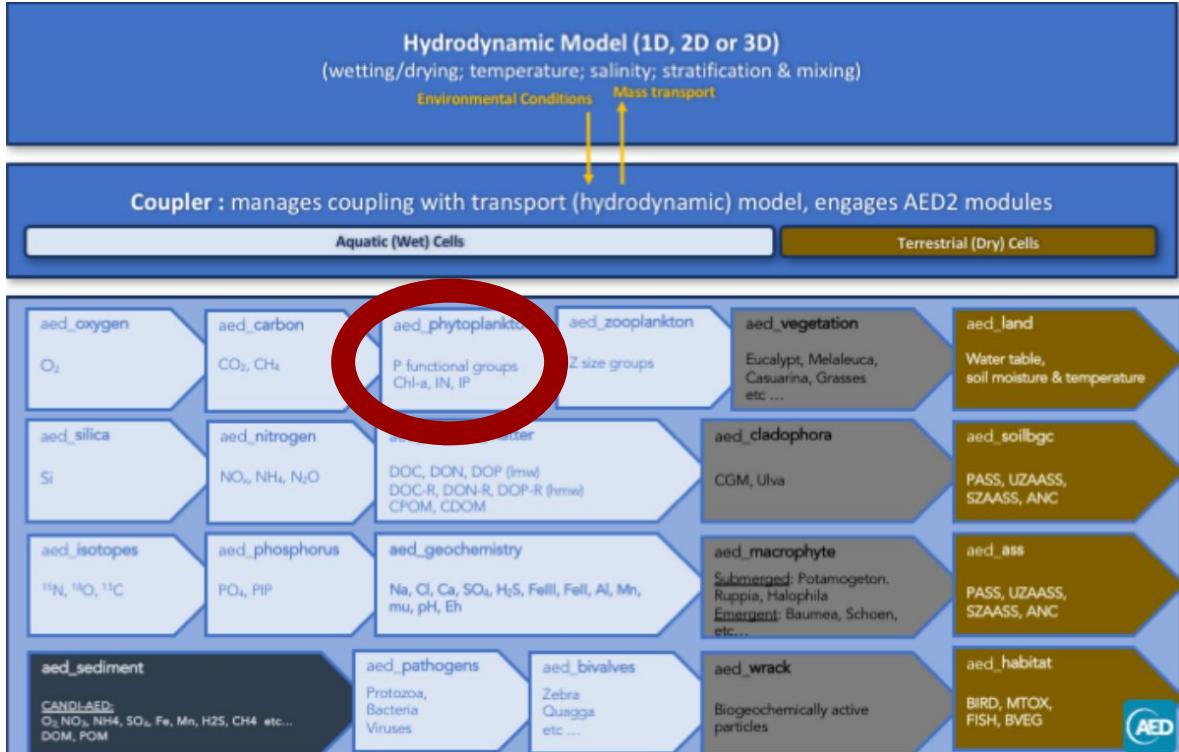
Anaerobic mineralization of DOM



RDOC, minimum-maximum rate of aerobic mineralization of labile DOC @20C ($0.01\text{-}0.10\text{ d}^{-1}$)

AED2: modularised structure

- Interacts with GLM (two-way coupling)
- Array of modules are available
- Hierarchy of dependencies between modules, e.g., nitrogen reactions can depend on availability of oxygen



AED2: phytoplankton

- functional group modeling of phytoplankton groups
- you can define all parameters yourself → domain knowledge
 - database:
https://aed.see.uwa.edu.au/research/models/AED/aed2_dbase/db_edit.php
- you can also set up zooplankton dynamics (grazing and feeding)

Carbon

$$\frac{d(PHY_{C_a})}{dt} = +f_{uptake}^{PHY_{C_a}} - f_{excr}^{PHY_{C_a}} - f_{mort}^{PHY_{C_a}} - f_{resp}^{PHY_{C_a}} - f_{sett}^{PHY_{C_a}} - \sum_z^{N_{ZOO}} (f_{assim}^z p_a^z)$$

number of species

aed2.nml

```
&aed2_phytoplankton
num_phytos = 2
the_phytos = 1, 2
settling = 3, 3
p_excretion_target_variable = 'OGM_dop'
n_excretion_target_variable = 'OGM_don'
c_excretion_target_variable = 'OGM_doc'
si_excretion_target_variable = ''
p_mortality_target_variable = 'OGM_pop'
n_mortality_target_variable = 'OGM_pon'
c_mortality_target_variable = 'OGM_poc'
si_mortality_target_variable = ''
p1_uptake_target_variable = 'PHS_frp'
n1_uptake_target_variable = 'NIT_nit'
n2_uptake_target_variable = 'NIT_amm'
si_uptake_target_variable = 'SIL_rsi'
do_uptake_target_variable = 'OXY_oxy'
c_uptake_target_variable = 'CAR_dic'
dbase = 'aed2/aed2_phyto_pars.nml'
extra_diag = .true.
min_rho = 900
max_rho = 1200
```

all interactions

cyanobacteria and diatoms

aed2_phyto_pars.nml

```
&phyto_data
pd%p_name = 'cyano', 'diatom'
pd%p_initial = 10, 8.4
pd%p0 = 0.03, 0.03
pd%w_p = 0, -0.05
pd%Xcc = 50,50
pd%R_growth = 5.2, 5.8 !1.2, 2.8
pd%fT_Method = 1, 1
pd%theta_growth = 1.08, 1.08
pd%T_std = 20, 15
pd%T_opt = 28, 20
pd%T_max = 35, 32
pd%lightModel = 0, 0
pd%I_K = 25, 10
pd%I_S = 100, 100
pd%KePHY = 0.005, 0.001
pd%f_pr = 0.005, 0.002
pd%R_resp = 0.08, 0.12
pd%theta_resp = 1.05, 1.07
pd%k_fres = 0.6, 0.6
pd%k_fdom = 0.05, 0.05
pd%salTol = 0, 0
pd%S_bep = 2, 2
pd%S_maxsp = 35, 35
pd%S_opt = 1, 1
```

parameter file

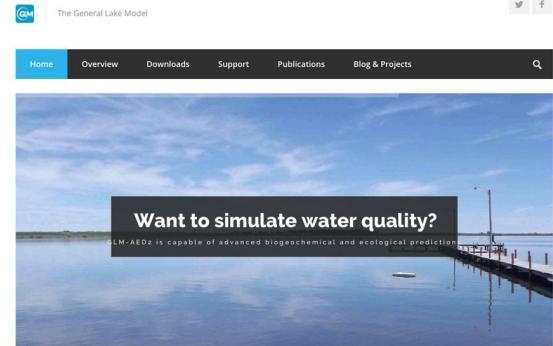
The General Lake Model (GLM)

d: run the model



Setting up GLM

- Installing GLM:
 - Download software package via AED GLM website:
http://aed.see.uwa.edu.au/research/models/GLM/latest_release.html (precompiled binaries)
 - Source code and compilation instructions are available, accessible via the GitHub repository -
<https://github.com/AquaticEcoDynamics/GLM>
 - GLM3r in R
devtools::install_github("GLEON/GLM3r")



The screenshot shows the 'Downloads' section of the GLM website. It includes three circular icons: 'Science Basis' (describing GLM as a 1-dimensional lake water balance and stratification model), 'Suitability' (noting its suitability for various lake types from ponds to Great Lakes), and 'Open Access' (mentioning it's an open-source project). Below these are sections for 'Latest Release' (GLM V3.0, 2019 release), 'Download Model', and 'Source Code'.

Setting up GLM

- Main file: glm3.nml
- Ordered into blocks
 - Begin with: &
 - End with: /
- Includes model setup and relative paths to water quality and driver data
- GLM executable needs the setup file

```
1 !-----  
2 ! general model setup  
3 !-----  
4 &glm_setup  
5   sim_name = 'Mendota'  
6   max_layers = 75  
7   min_layer_vol = 0.1  
8   min_layer_thick = 0.15  
9   max_layer_thick = 1.5  
10  density_model = 1  
11 /  
12 &mixing  
13   surface_mixing = 1  
14   coef_mix_conv = 0.2  
15   coef_wind_stir = 0.23  
16   coef_mix_shear = 0.3  
17   coef_mix_turb = 0.51  
18   coef_mix_KH = 0.3  
19   coef_mix_hyp = 0.4689587  
20   deep_mixing = 2  
21   diff = 0  
22 /  
23 &light  
24   light_mode = 0  
25   n_bands = 4  
26   light_extc = 1, 0.5, 2, 4  
27   energy_frac = 0.51, 0.45, 0.035, 0.005  
28   Benthic_Imin = 10  
29   Kw = 0.4315141  
30 /  
31 !-----  
32 ! water quality setup  
33 ! if this block is read, water quality functionality will be enabled  
34 !-----
```

Setting up GLM

- Define the &morphometry
 - Area-depth relationship (&H and &A)
- Define what you want to simulate
 - State variables (temperature, salinity, etc.)
 - Grid resolution and time step (&glm_setup, &time)
- Define external environment
 - Boundary conditions (inflows, meteorology, outflows) (&meteorology, &inflows, &outflows)
- Provide an initial condition (&init_profiles)
- Start your simulation

glm3.nml file

&glm_setup:	General simulation info
&wq_setup:	Water quality
&time:	Time control
&morphometry:	Lake morphometric information
&output:	Output file details
&init_profiles:	Initial vertical profiles
&meteorology:	Surface forcing and meeorology
&inflows:	Information about inflowing rivers
&outflows:	Information about outflows
&light:	Information about light climate

Setting up GLM

- Boundary conditions: data that drive the model
- At minimum, GLM needs meteorological data (hourly or daily) in CSV-format

```
Date,ShortWave,LongWave,AirTemp,RelHum,WindSpeed,Rain,Snow  
2009-01-01 00:00:00,0,191.50999,-15.609991,88.86569,2.9134343,0,0  
2009-01-01 01:00:00,0,217.56,-14.750006,88.178638,3.5679266,0,0  
2009-01-01 02:00:00,0,217.56,-14.15,88.305945,3.9796608,0,0  
2009-01-01 03:00:00,0,217.57001,-13.560004,88.286784,4.3862171,0,0  
2009-01-01 04:00:00,0,230.42999,-12.959998,88.028059,4.8016873,0,0  
2009-01-01 05:00:00,0,230.42999,-12.449988,87.745015,5.3791169,0,0  
2009-01-01 06:00:00,0,230.42999,-11.929999,87.288882,5.9664732,0,0  
2009-01-01 07:00:00,0,246.75,-11.41001,86.734669,6.5488395,0,0  
2009-01-01 08:00:00,0,246.75999,-10.620001,86.510658,6.995177,0,0  
2009-01-01 09:00:00,50.312,246.75999,-9.8200134,85.935506,7.4708298,0,0  
2009-01-01 10:00:00,168.256,253.35001,-9.0199951,85.14882,7.9805386,0,0  
2009-01-01 11:00:00,255.60001,253.35001,-7.8599915,85.236462,8.1806115,0,0  
2009-01-01 12:00:00,325.892,253.35001,-6.6900085,84.658597,8.4221193,0,0  
2009-01-01 13:00:00,349.651,265.15002,-5.5300049,83.680197,8.6924564,0,0  
2009-01-01 14:00:00,318.17099,265.14999,-4.9799866,84.281007,8.1392691,0,0  
2009-01-01 15:00:00,264.33701,265.14999,-4.4299988,84.709775,7.6592037,0,0  
2009-01-01 16:00:00,153.472,271.73001,-3.880011,84.970459,7.2817926,0,0  
2009-01-01 17:00:00,51.591999,271.73001,-4.1399902,86.532806,6.6806363,0,0
```

Time, FLOW, TEMP, SALT
2009-01-01 00:00:00,3.560861,-0.526716,0
2009-01-02 00:00:00,6.162997,-0.585426,0
2009-01-03 00:00:00,3.826635,-0.639793,0
2009-01-04 00:00:00,5.397271,-0.696168,0
2009-01-05 00:00:00,5.417987,-0.742644,0
2009-01-06 00:00:00,3.886593,-0.784772,0
2009-01-07 00:00:00,5.806259,-0.821455,0
2009-01-08 00:00:00,5.65432,-0.85336,0
2009-01-09 00:00:00,4.725836,-0.873803,0
2009-01-10 00:00:00,5.821722,-0.906718,0
2009-01-11 00:00:00,5.724123,-0.926215,0
2009-01-12 00:00:00,5.495776,-0.936452,0
2009-01-13 00:00:00,5.473368,-0.947798,0
2009-01-14 00:00:00,5.513825,-0.955154,0

- And flow data (inflow and/or outflow, hourly or daily) in CSV-format

Setting up GLM: buildyourownmodel/

Your first steps:

- (1) Download meteorological data of your site: *radiation, wind speed, air temperature, rainfall, relative humidity*
- (2) use toy glm3.nml file in workshop material to
 - (a) insert lake hypsography
 - (b) relative path to meteorological driver data file (CSV)
- (3) run lake model in R, see 'run_GLMmodel.R'

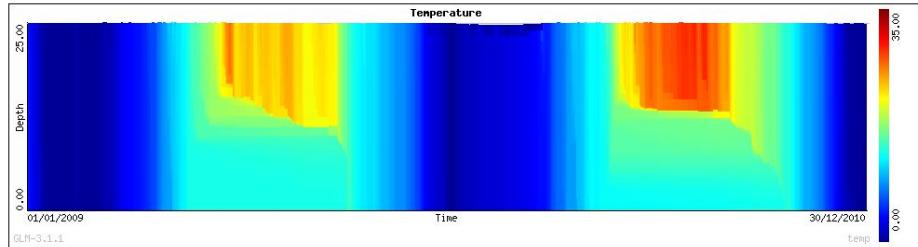
Let's switch



Setting up GLM: buildyourownmodel/

Your first steps:

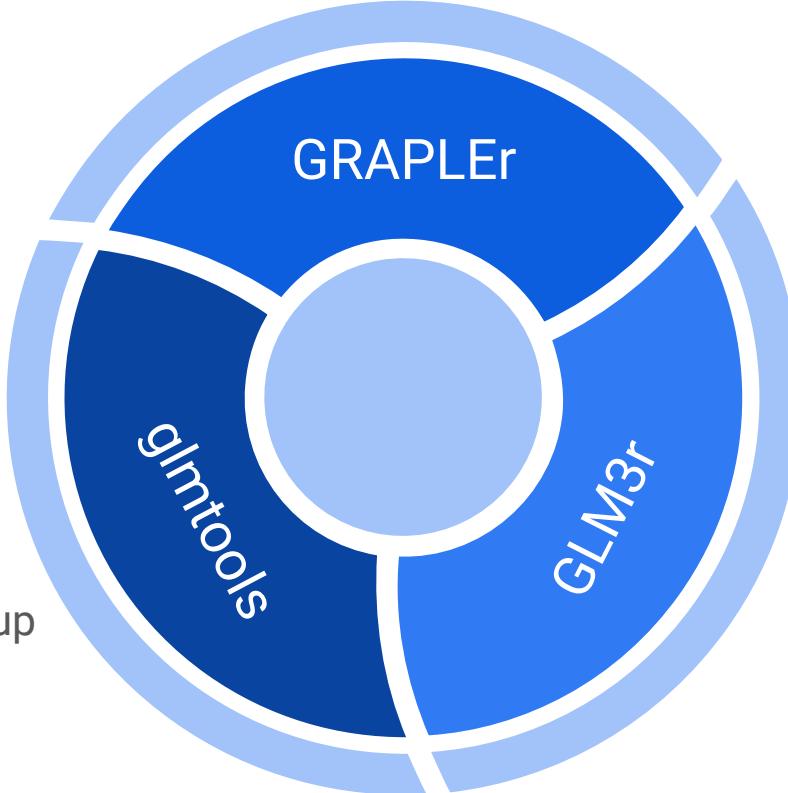
- (1) Download meteorological data of your site: *radiation, wind speed, air temperature, rainfall, relative humidity*
- (2) use toy glm3.nml file in workshop material to
 - (a) insert lake hypsography
 - (b) relative path to meteorological driver data file (CSV)
- (3) run lake model in R, see 'run_GLMmodel.R'



What you get:

- (1) output.nc - all output variables
- (2) lake.csv - daily diagnostics
- (3) abovesediment*.csv - output at specific depths
- (4) heatmap plot - temperature output

GLM in R



- Distributed computing system
- Run multiple GLM simulations

- Changing model setup
- Visualizing results
- Physical derivatives
- Calibration

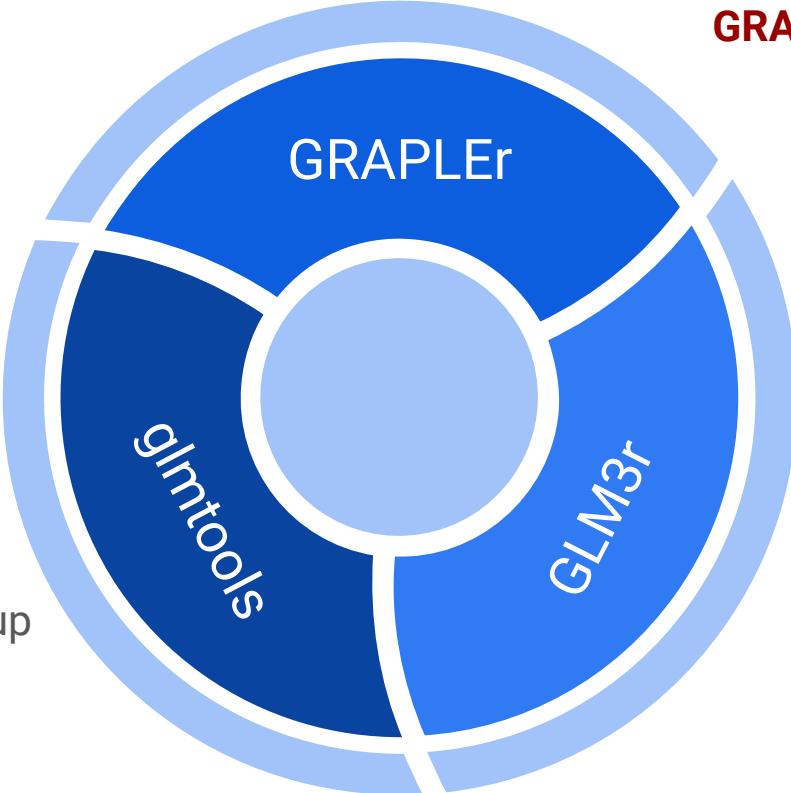
- Run GLM in R

GLM in R



USGS-R/glmtools

- Changing model setup
- Visualizing results
- Physical derivatives
- Calibration



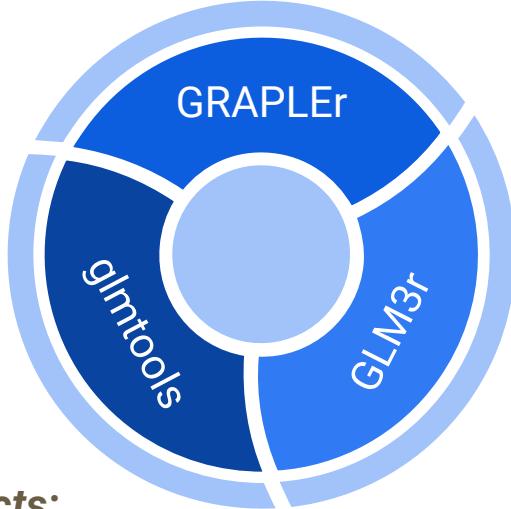
- Distributed computing system
- Run multiple GLM simulations

GRAPLE/GRAPLEr

GLEON/GLM3r

- Run GLM in R

GLM in R



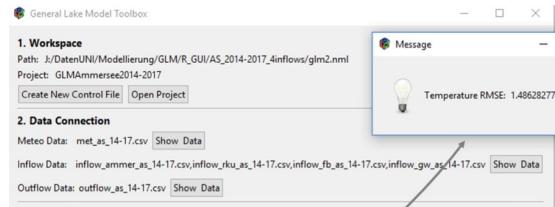
More awesome R-related GLM projects:

[Macrosystems EDDIE](#): classroom modules to teach macrosystems ecology

[LakeEnsemblR](#): R-package to run lake ensembles

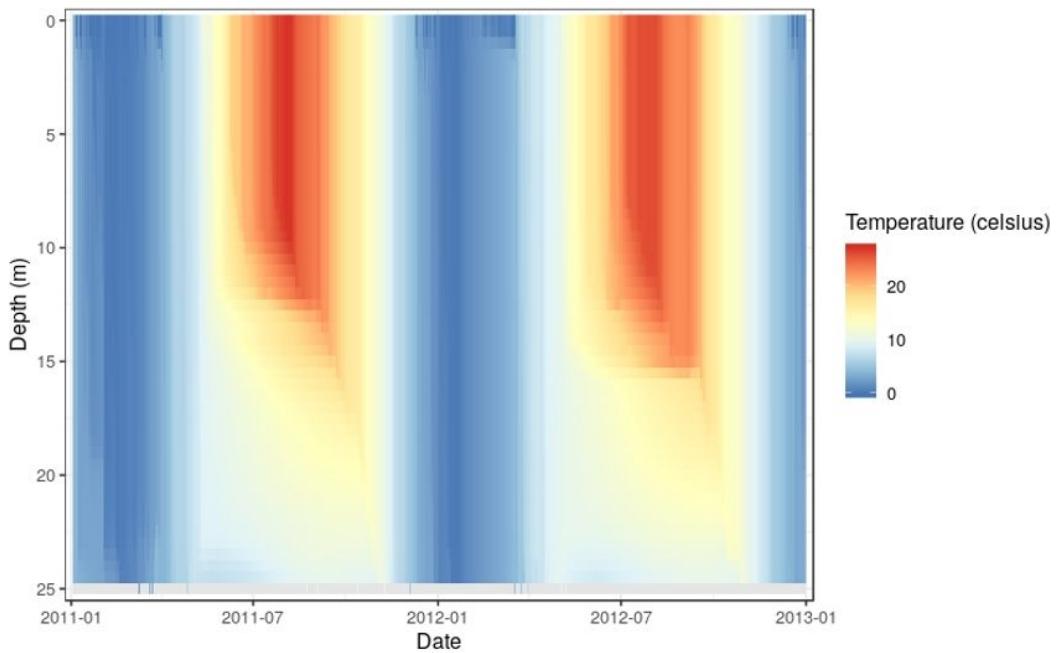
[glmGUI](#): GUI and toolbox to run GLM

[Columbus4Limnology](#): Run GLM online in the cloud (release soon)



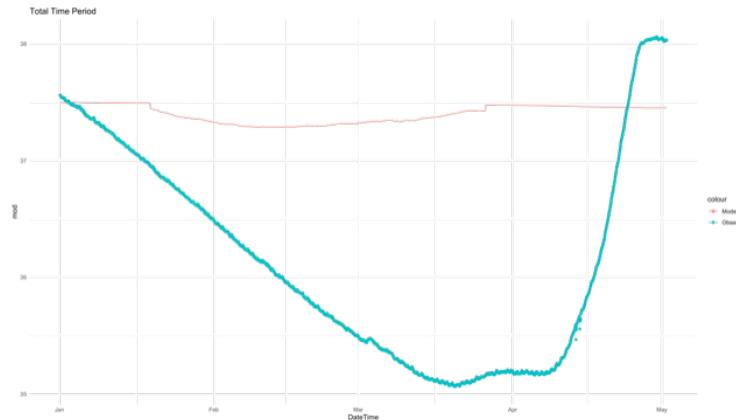
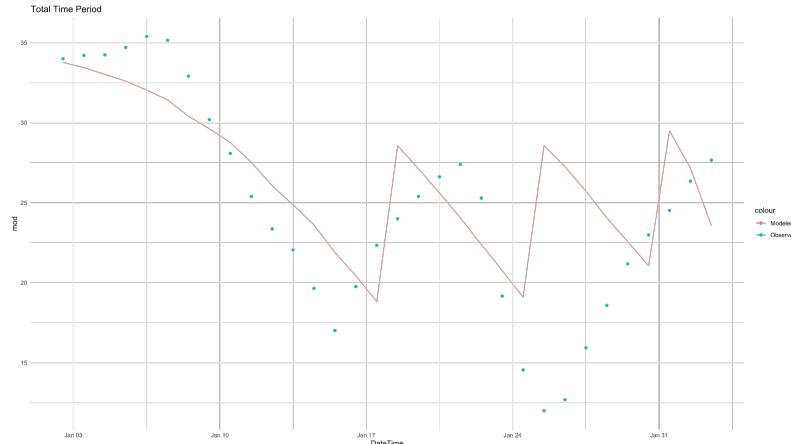
glmtools

- Either from github or GRAN
- Offers lots of functionalities:
 - Manipulate model setup
 - Retrieve output data
 - Compare observed to simulated data
 - Visualize results
 - Calibration functions
- 'ggplot_overhaul' branch includes up-to-date version with experimental features (e.g., water quality calibration)



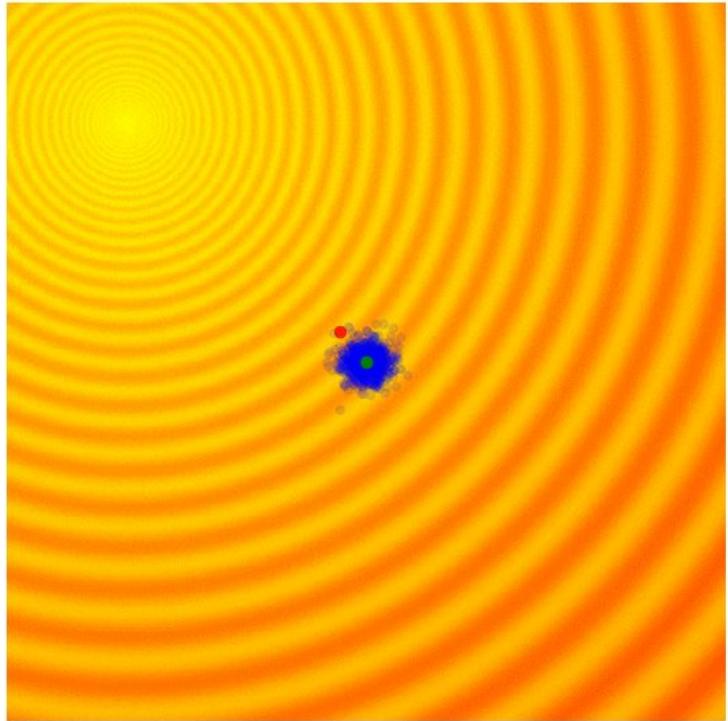
glmtools

- experimental version available at
https://github.com/robertladwig/glmtools/tree/ggplot_overhaul
- small bug fixes
- calibration functions for water level (reservoir management, closing water balance, ...)
 - can reveal missing inflows or outflows
 - can identify missing ice formation



glmtools: calibration

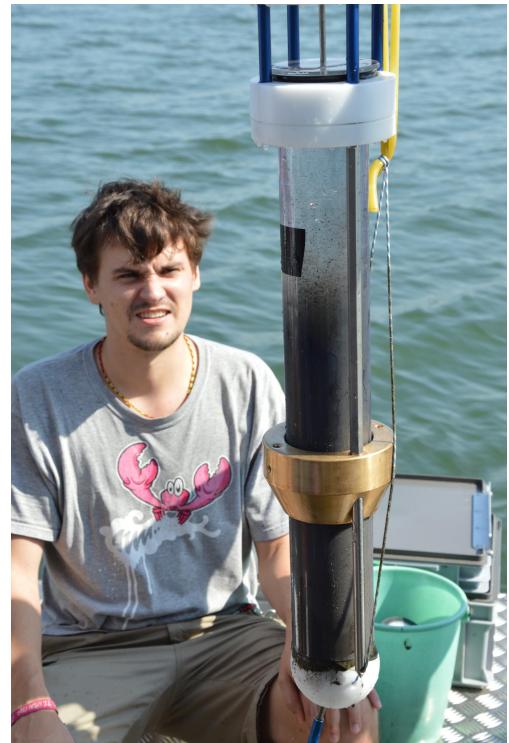
- a) CMA-ES: derivative-free optimization, which adaptively changes the search path for every generation (modifying normal distribution and covariance matrix), covers wide search space, converges fast but needs more computational time ($\sim O(N^2)$)
- b) Nelder-Mead method: derivative-free optimization, direct search method



Learn from the expert: *Ensemble modeling of lake phenology changes*

Johannes Feldbauer, T.N. Moore, J. Mesman, R. Ladwig, T. Berendonk, H. Zündorf, and T. Petzoldt: Ensemble of models show coherent response of a reservoir's stratification and ice cover to climate warming, *submitted to Aquatic Sciences*

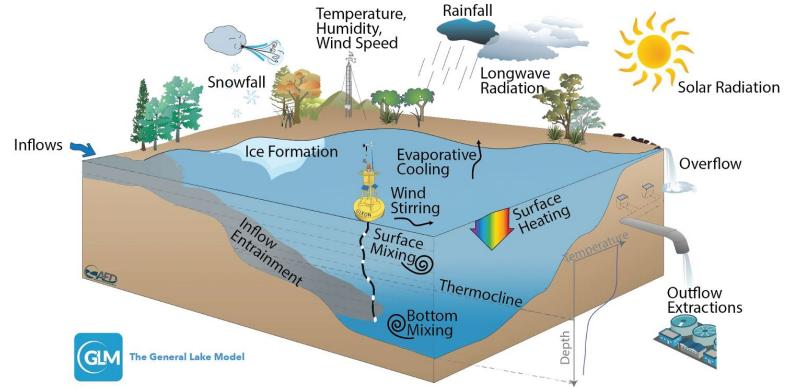
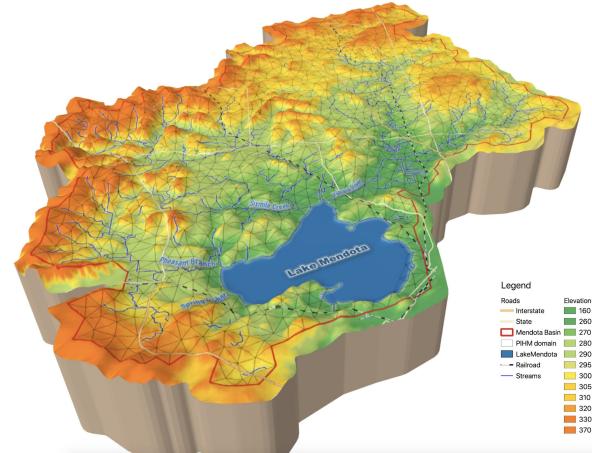
- application of LakeEnsemblR running FLake, GLM, GOTM, Simstrat and MyLake on a German reservoir



Hands-on exercises

Lake Mendota in Wisconsin, USA

- Lake Mendota: eutrophic, 25 m max. depth, residence time ~ 4-5 years
- 70 % agricultural and 25 % urban watershed
- dimictic: strong summer stratification with cyanobacteria bloom, ice formation during winter



Lake Mendota in Wisconsin, USA



Example 5a: Team *Physics* (climate change impact on lake ice)

Example 1: reading the configuration file into R

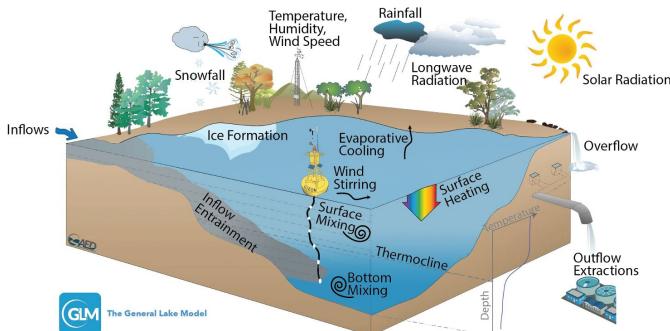
Example 2: model output processing and visualizations

Example 3: calibrating water temperature parameters

Example 4: calibrating dissolved oxygen parameters

Example 5b: Team *Biology* (nutrients driving algae blooms)

(bonus) Example 6: check your phytoplankton dynamics



Let's switch





Important links

GLM homepage: <https://aed.see.uwa.edu.au/research/models/glm/>

GLM manual: <https://gmd.copernicus.org/articles/12/473/2019/>

AED2 homepage: <https://aed.see.uwa.edu.au/research/models/aed/index.html>

AED2 ‘manual’: <https://aquaticecodynamics.github.io/aed-science/index.html>

Github: <https://github.com/AquaticEcoDynamics>

Slack: https://join.slack.com/t/general-lake-model/shared_invite/zt-a7pyrxhj-oe4dYm6oLQfk1r_ZGLFTwQ





Wrapping up

Questions, issues, problems & feedback?

Thank you for joining!

Have fun lake modeling!

Join the GLM Slack for help and support:

https://join.slack.com/t/general-lake-model/shared_invite/zt-a7pyrxhj-oe4dYm6oLQfk1r_ZGLFTwQ



rladwig2@wisc.edu



@hydrobert

Interested in lake modeling? Join our
working group meetings this week
<https://gleon.org/research/working-groups/ecosystem-modeling>

