Timescale methods for assessing biophysical interactions in aquatic ecosystems— an attempt at bringing

ORDER to the CHAOS

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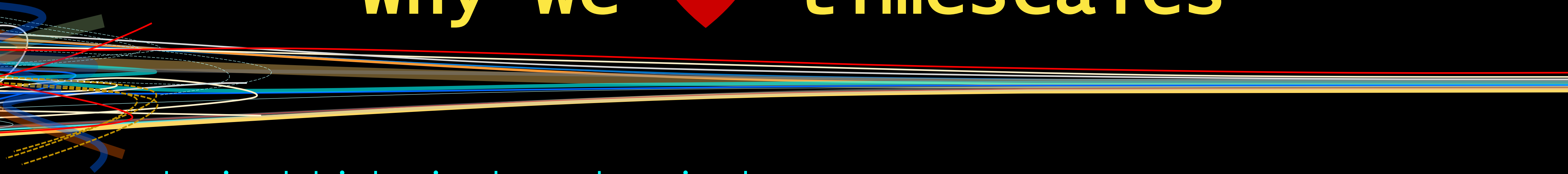
What are diagnostic timescales?

- Amount of time for a process to occur or complete
- Units of *time*
- An estimate
- Inverse of a rate
- Conveys info about speed of process
  - *Bigger* τ *= Slower process*
  - *Smaller* τ *= Faster process*

Lucas & Deleersnijder 2020, *Water*

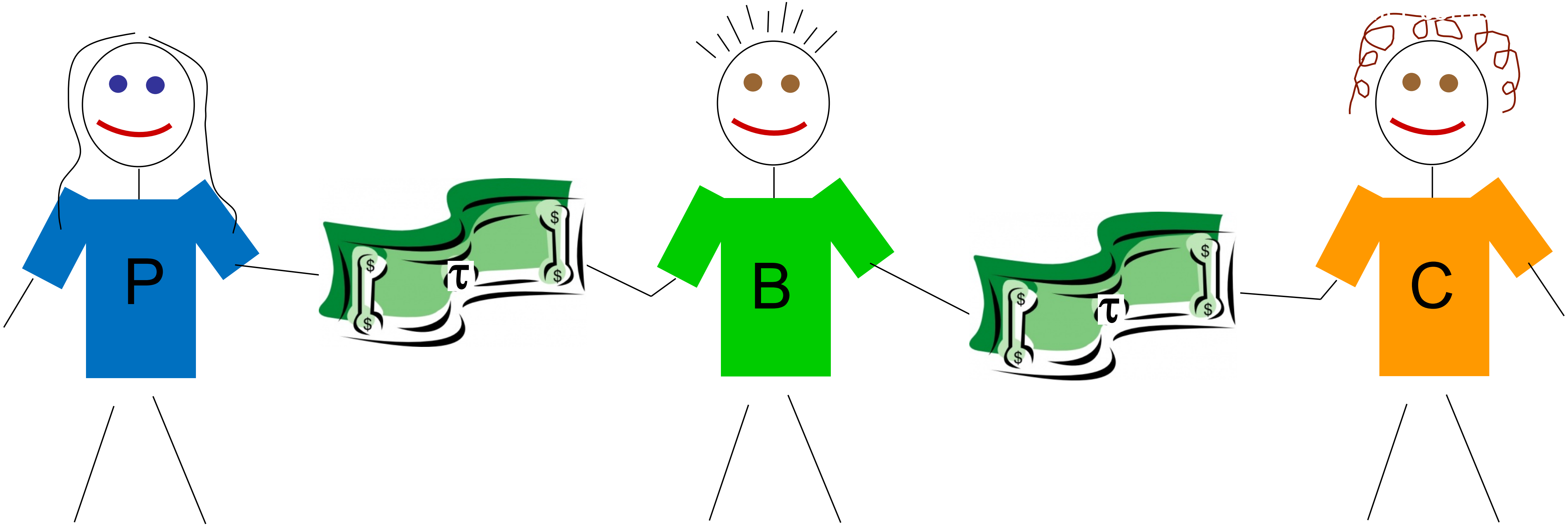
Why we ♥ timescales



- physical, biological, or chemical
- common currency

Lucas & Deleersnijder 2020, *Water*

Time scales provide a ***COMMON CURRENCY*** for integrating and comparing physics, biology, and chemistry



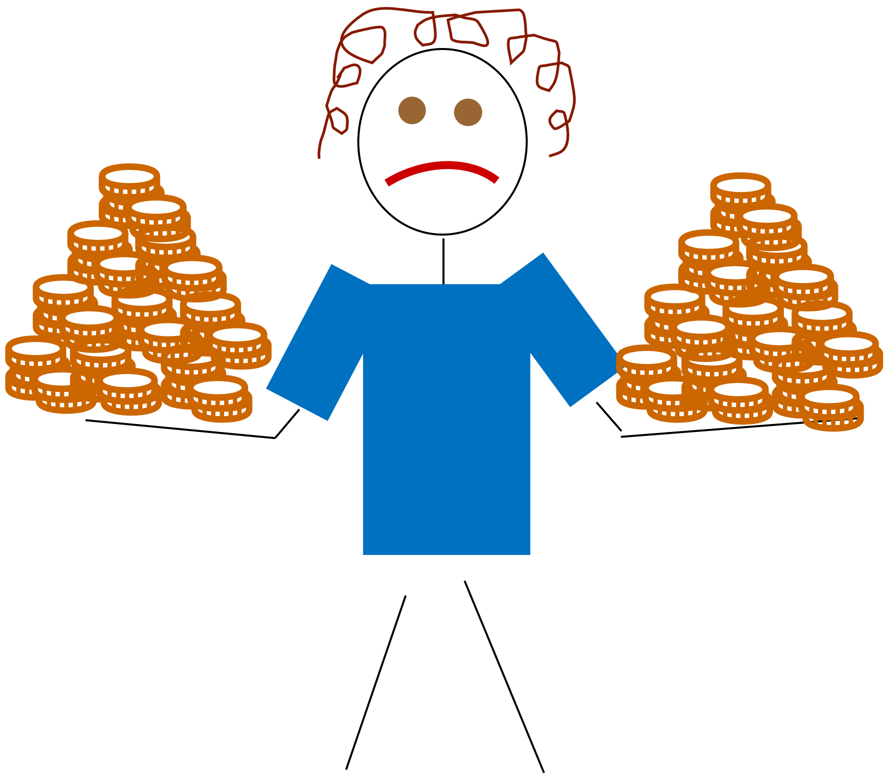
Lucas & Deleersnijder 2020, *Water*

why we ♥ timescales

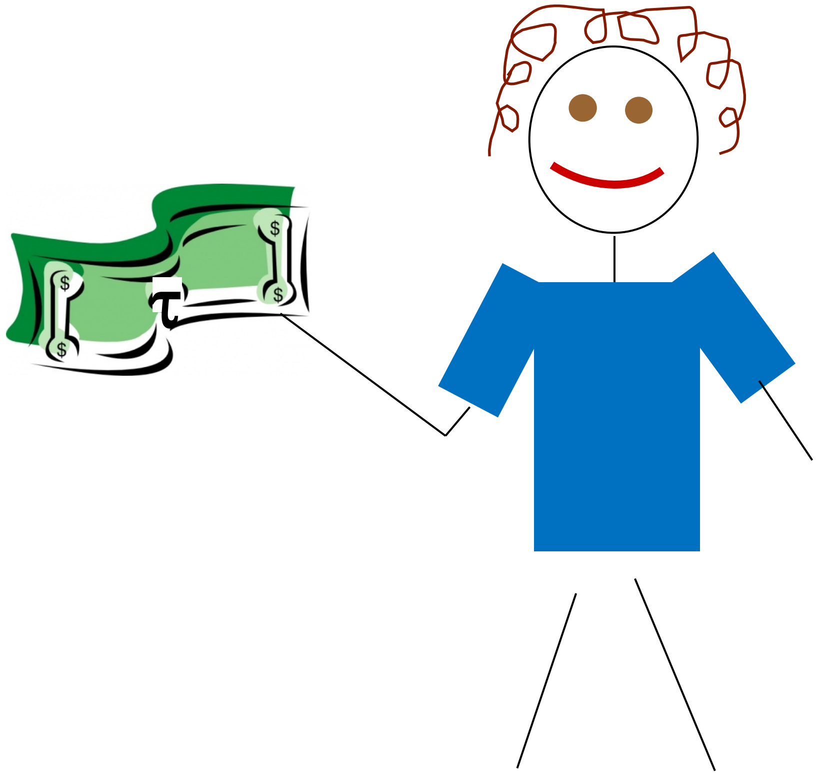
- physical, biological, or chemical
- common currency
- encapsulate complexity of real ecosystems

Lucas & Deleersnijder 2020, *Water*

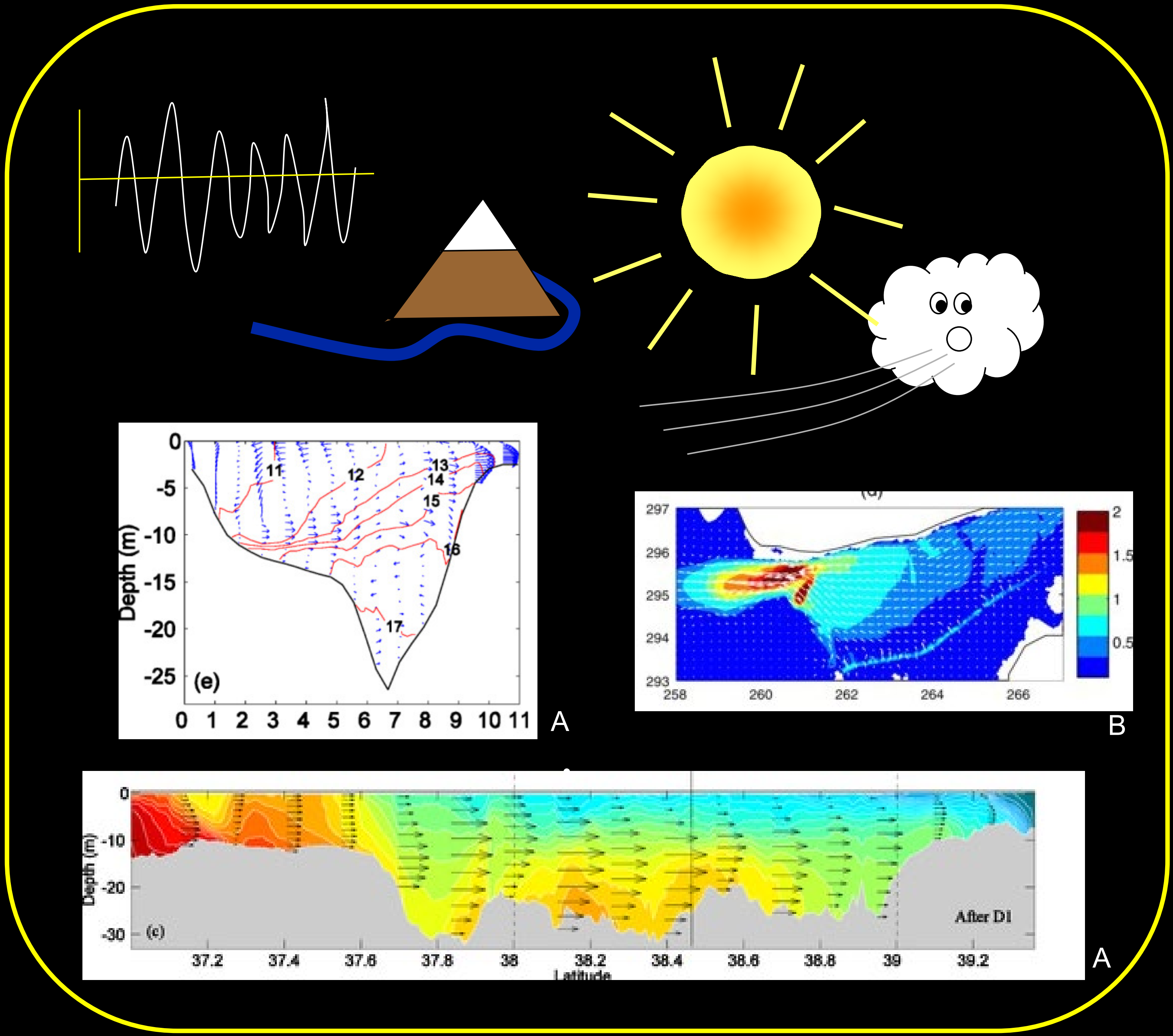
Timescales encapsulate complexity



OR



Lucas & Deleersnijder 2020, *Water*



“Flushing time”

A: Xie and Li 2018, JGR-Oceans
B: Robins et al. 2011, J. Coast Cons

why we ♥ timescales

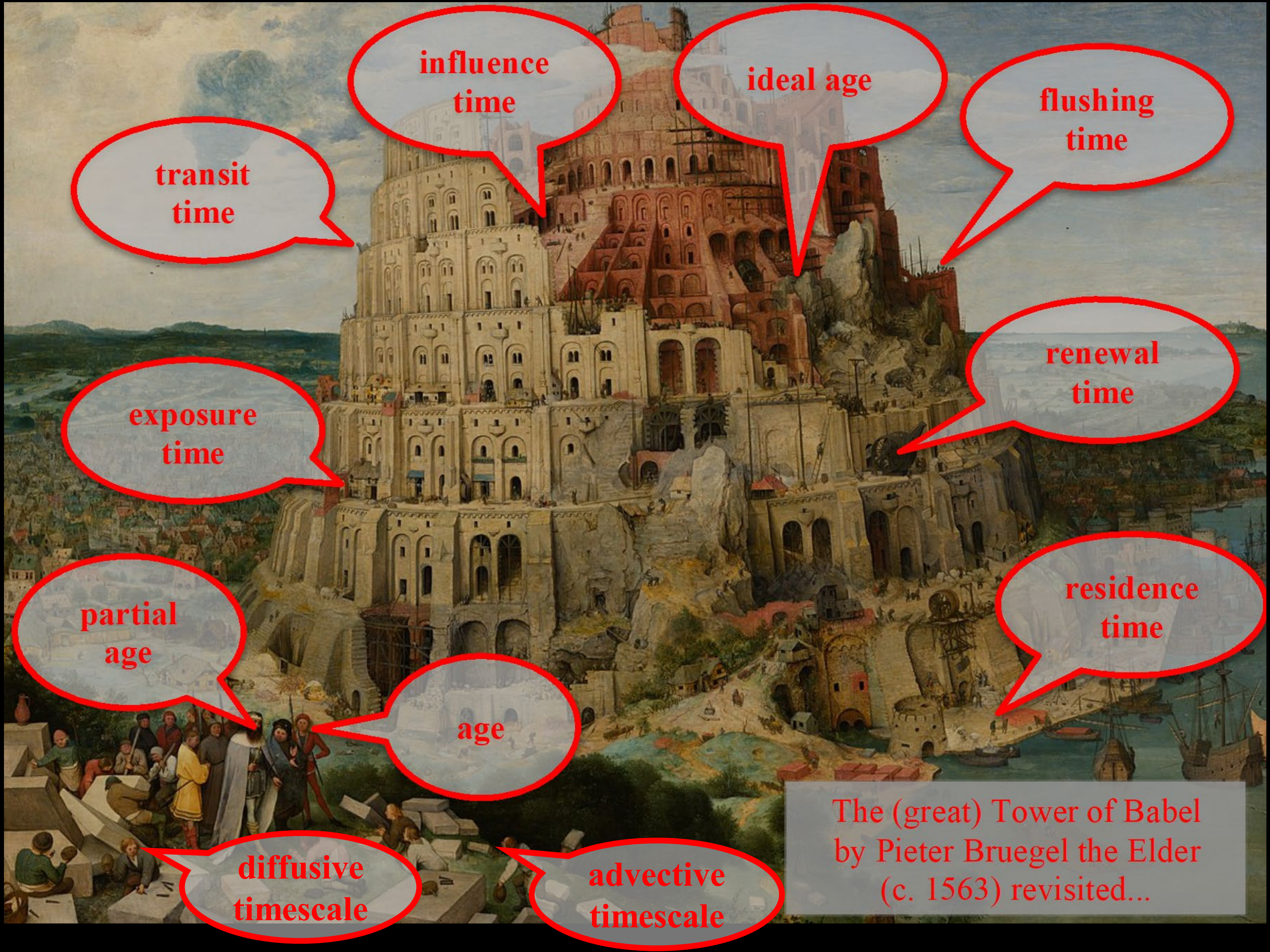
- physical, biological, or chemical
- common currency
- encapsulate complexity of real ecosystems
- distill large datasets / extract essence
- more meaningful than primitive variables
- paint graspable picture of system function
- variable process richness ("holism")
- foundation for simple models

Deleersnijder, Mouchet, Delhez 2018
Lucas & Deleersnijder 2020, *Water*

Transport timescales

… and the timescale "Tower of Babel"

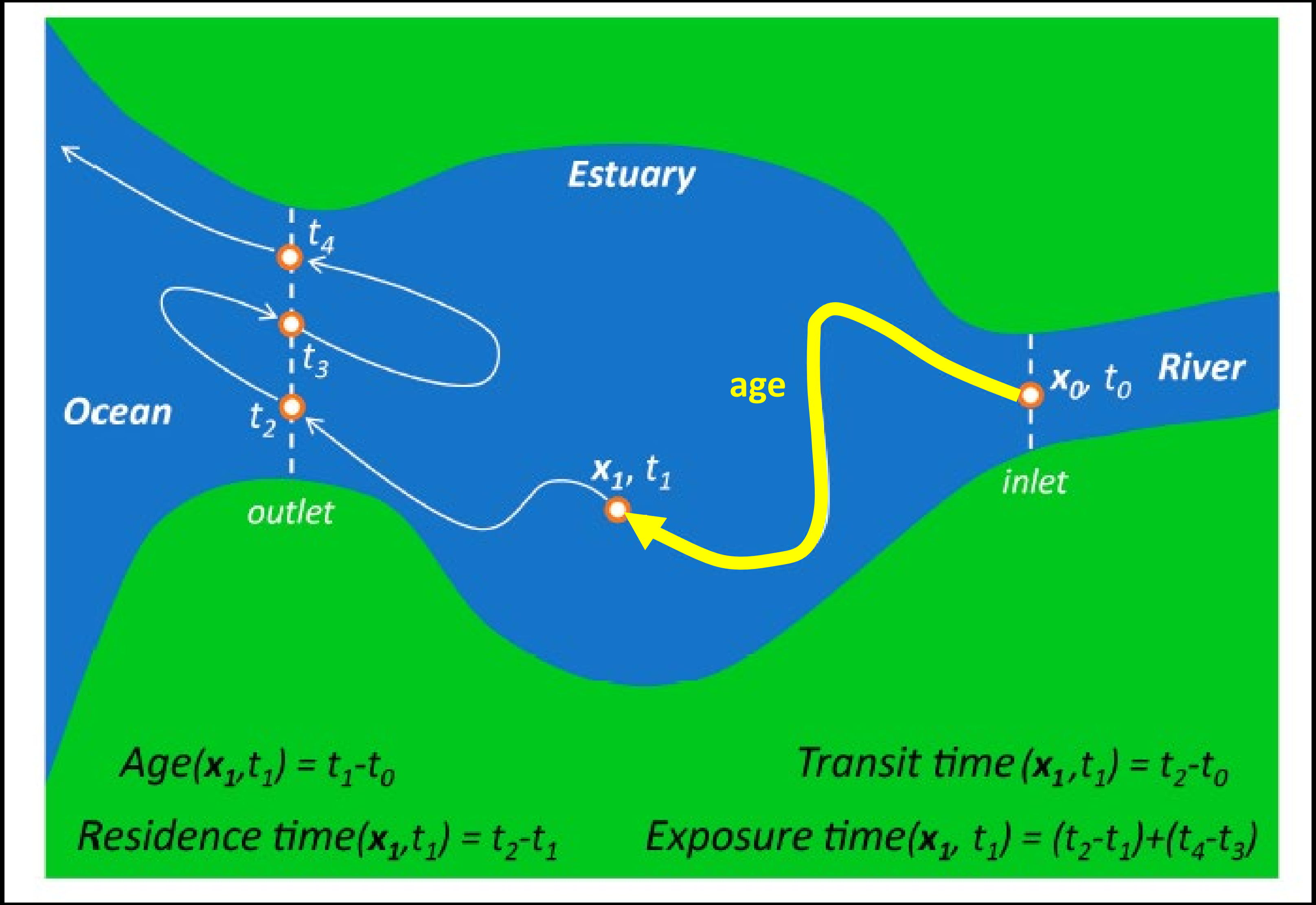
- Viero & Defina, 2016



Adapted from Deleersnijder, Mouchet, Delhez 2018

Precise definitions

age = time since entering

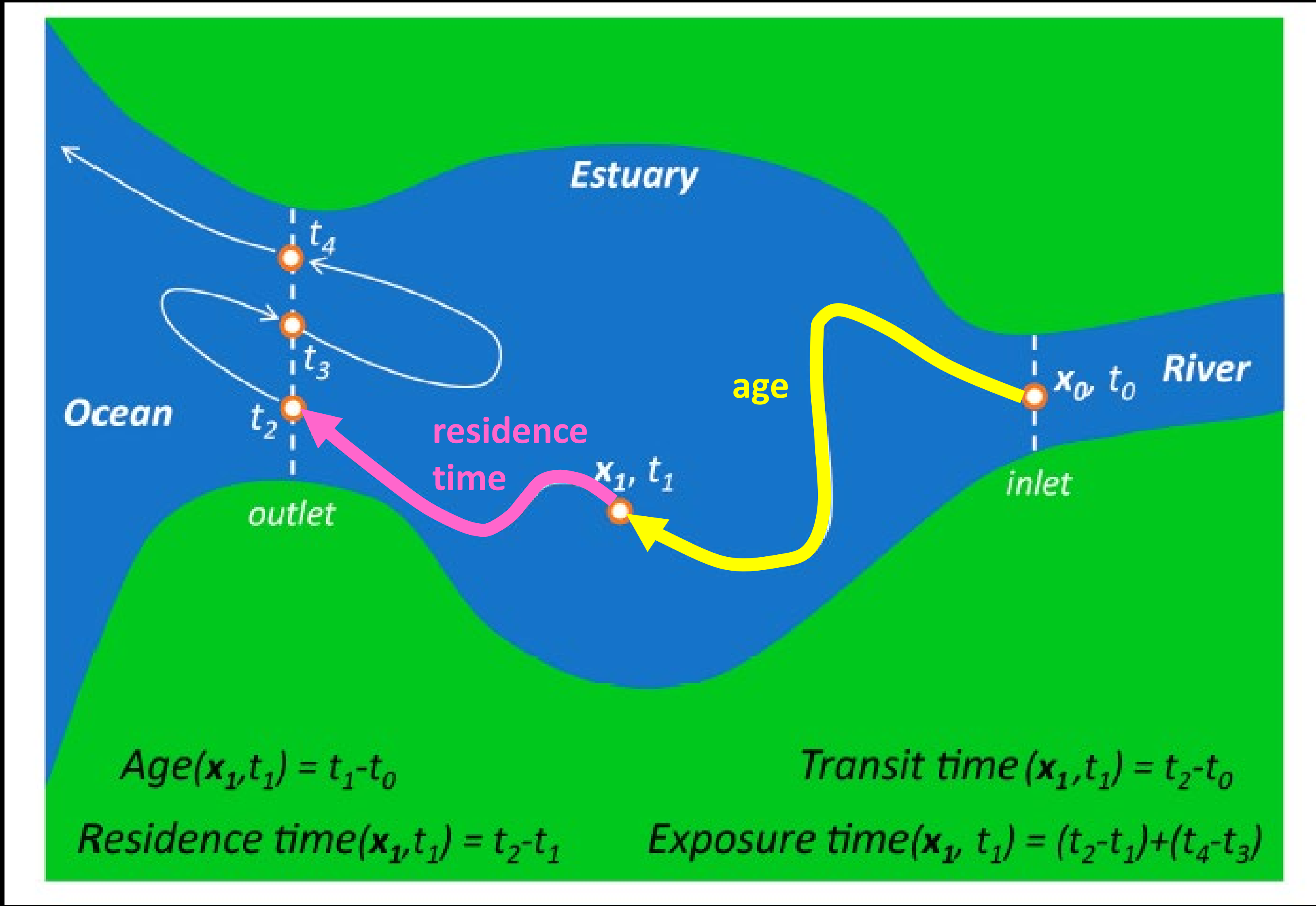


Lucas & Deleersnijder 2020, inspired by countless others

Precise definitions

age = time since entering

residence time = time until leaving for first time



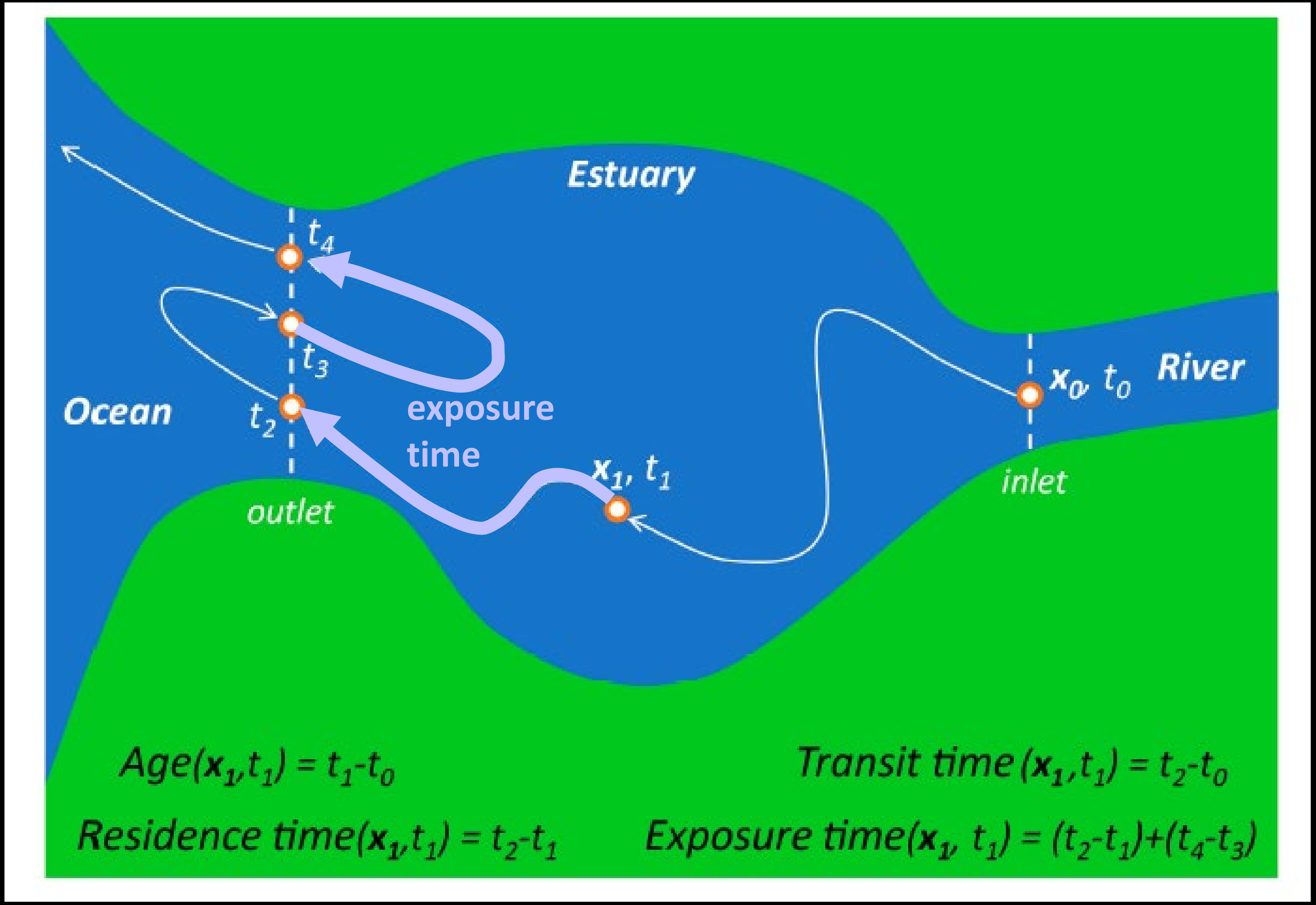
Lucas & Deleersnijder 2020, inspired by countless others

Precise definitions

age = time since entering

residence time = time until leaving for first time

exposure time = time until leaving for good



Lucas & Deleersnijder 2020, inspired by countless others

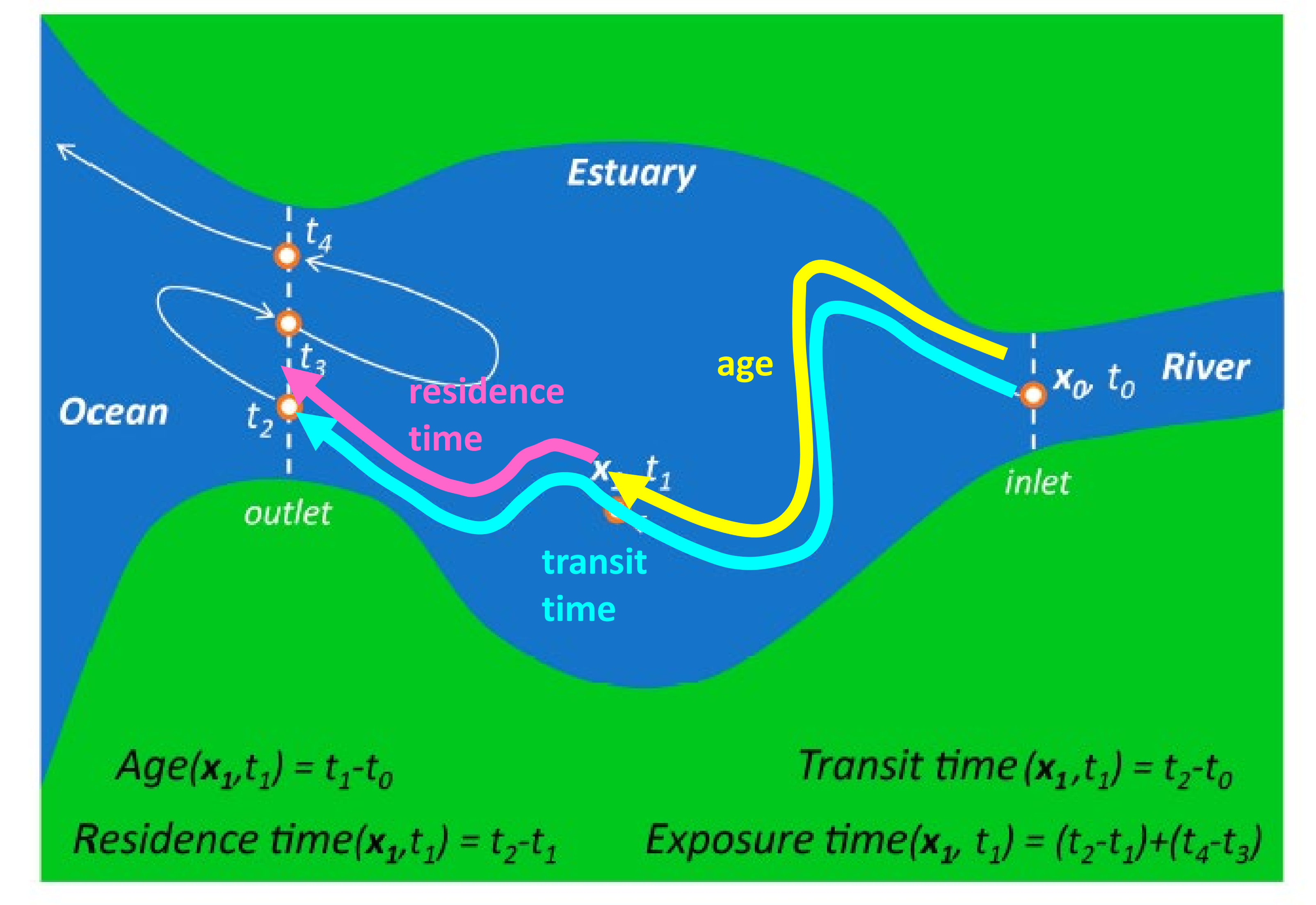
Precise definitions

age = time since entering

residence time = time until leaving for first time

exposure time = time until leaving for good

transit time = total time from entrance to exit (age+residence time)



Lucas & Deleersnijder 2020, inspired by countless others

Precise definitions

PAST

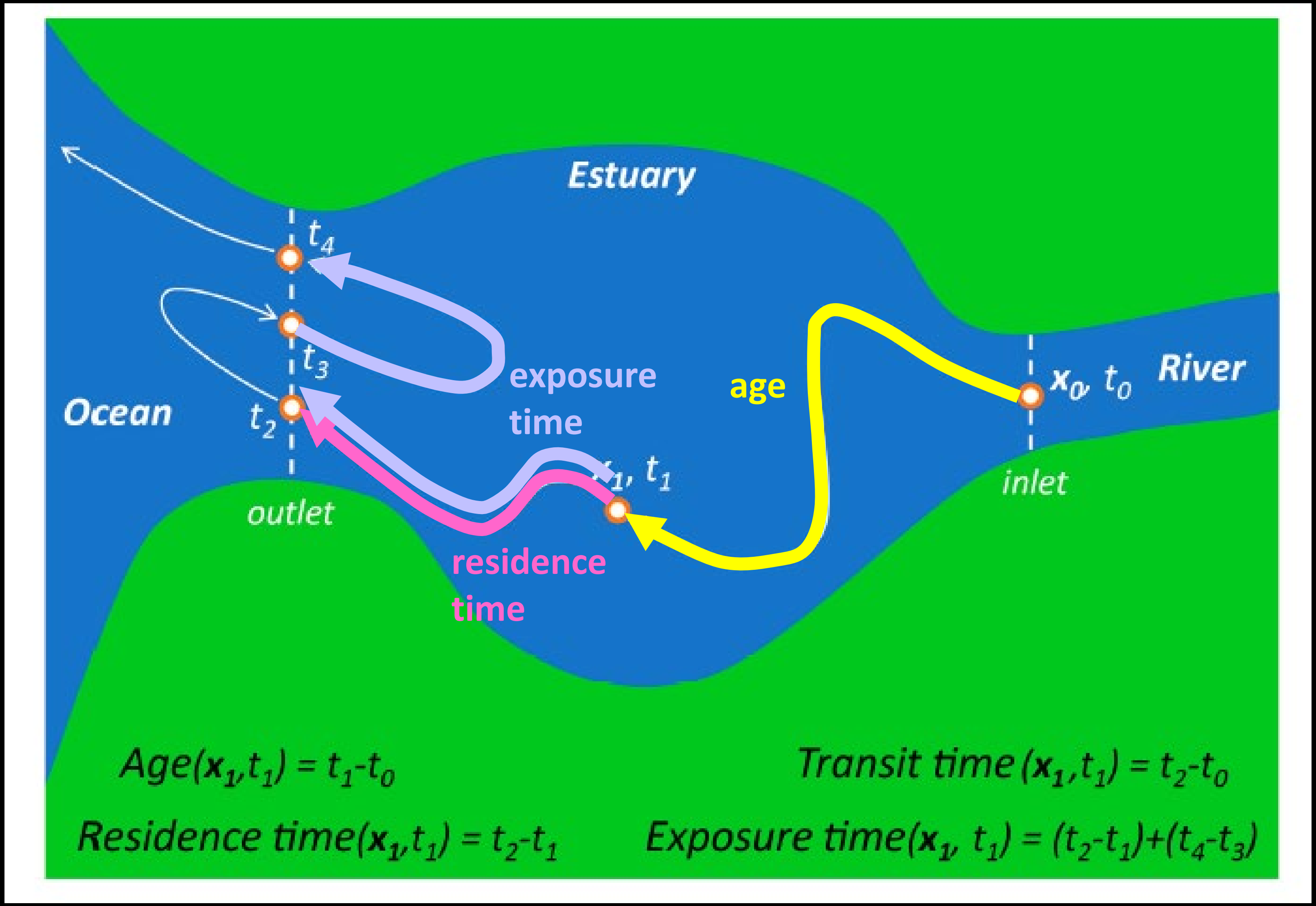
FUTURE

age = time since entering

residence time = time until leaving for first time

exposure time = time until leaving for good

transit time = total time from entrance to exit (age+residence time)



Lucas & Deleersnijder 2020, inspired by countless others

Transport timescales

Adapted from Deleersnijder, Mouchet, Delhez 2018

Example: Dissolved oxygen dynamics in Chesapeake Bay

The full 3D time-dependent advection-diffusion-reaction equation for DO:

$$\underbrace{\frac{\partial c}{\partial t}}_{\text{time-dependence}} + \underbrace{\frac{\partial}{\partial x}(Uc) + \frac{\partial}{\partial y}(Vc) + \frac{\partial}{\partial z}(Wc)}_{\text{advection}} = \underbrace{\frac{\partial}{\partial x}\left(K_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right)}_{\text{diffusion/dispersion}} + \underbrace{PROD - CONS}_{\text{reaction terms}}$$

c = dissolved oxygen concentration

Shen et al. 2013

Example: Dissolved oxygen dynamics in Chesapeake Bay

$$\cancel{\frac{\partial c}{\partial t}} + \frac{\partial}{\partial x}(Uc) + \cancel{\frac{\partial}{\partial y}(Vc) + \frac{\partial}{\partial z}(Wc)} = \cancel{\frac{\partial}{\partial x}\left(K_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right)} + \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) + \underbrace{PROD - CONS}$$

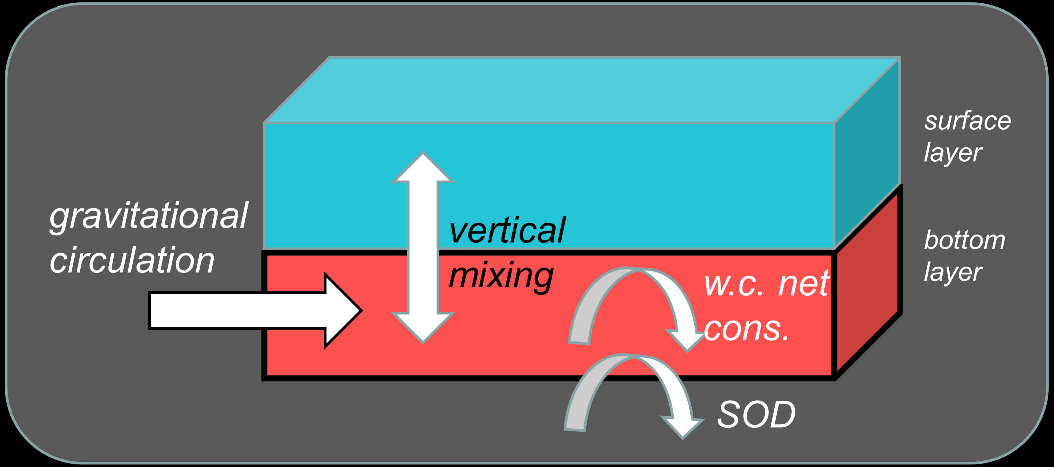
steady state

streamwise advection (gravitational circulation)

vertical mixing & stratification

Net consumption (sediment + water column)

Reduce full equation to most salient processes



Shen et al. 2013

Example: Dissolved oxygen dynamics in Chesapeake Bay

$$\cancel{\frac{\partial c}{\partial t}} + \frac{\partial}{\partial x}(Uc) + \cancel{\frac{\partial}{\partial y}(Vc) + \frac{\partial}{\partial z}(Wc)} = \cancel{\frac{\partial}{\partial x}\left(K_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right)} + \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) + \underbrace{PROD - CONS}$$

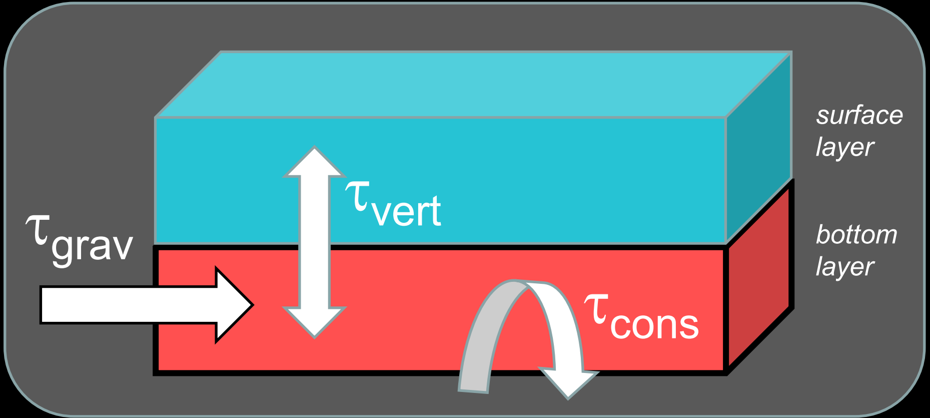
steady state

streamwise advection (gravitational circulation) → τ_{grav}

vertical mixing & stratification → τ_{vert}

Net consumption (sediment + water column) → τ_{cons}

Define timescales for major processes



Shen et al. 2013

Example: Dissolved oxygen dynamics in Chesapeake Bay

$$\cancel{\frac{\partial c}{\partial t}} + \frac{\partial}{\partial x}(Uc) + \cancel{\frac{\partial}{\partial y}(Vc)} + \cancel{\frac{\partial}{\partial z}(Wc)} = \cancel{\frac{\partial}{\partial x}\left(K_x \frac{\partial c}{\partial x}\right)} + \cancel{\frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right)} + \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) + \underbrace{PROD - CONS}$$

steady state

streamwise advection (gravitational circulation) → τ_{grav}

vertical mixing & stratification → τ_{vert}

<u>Net</u> consumption (sediment + water column) → τ_{cons}

Define dimensionless timescale ratios

$$\tau^*_{grav} = \frac{\tau_{grav}}{\tau_{vert}} \qquad \tau^*_{cons} = \frac{\tau_{cons}}{\tau_{vert}}$$

Shen et al. 2013

Example: Dissolved oxygen dynamics in Chesapeake Bay

Define: $$c^*_{bot} = \frac{c_{bot}}{c_{surf}}$$

…*after some more* ***simplifying assumptions***,

substituting timescales *into reduced PDE,*

and a little algebraic ***rearrangement***:

$$\boxed{c^*_{bot} = 1 - \frac{1}{\tau^*_{cons}}\left(1 - e^{-\tau^*_{grav}}\right)}$$

Super-simple, process-based model of bottom DO !

f(2 params)

Shen et al. 2013

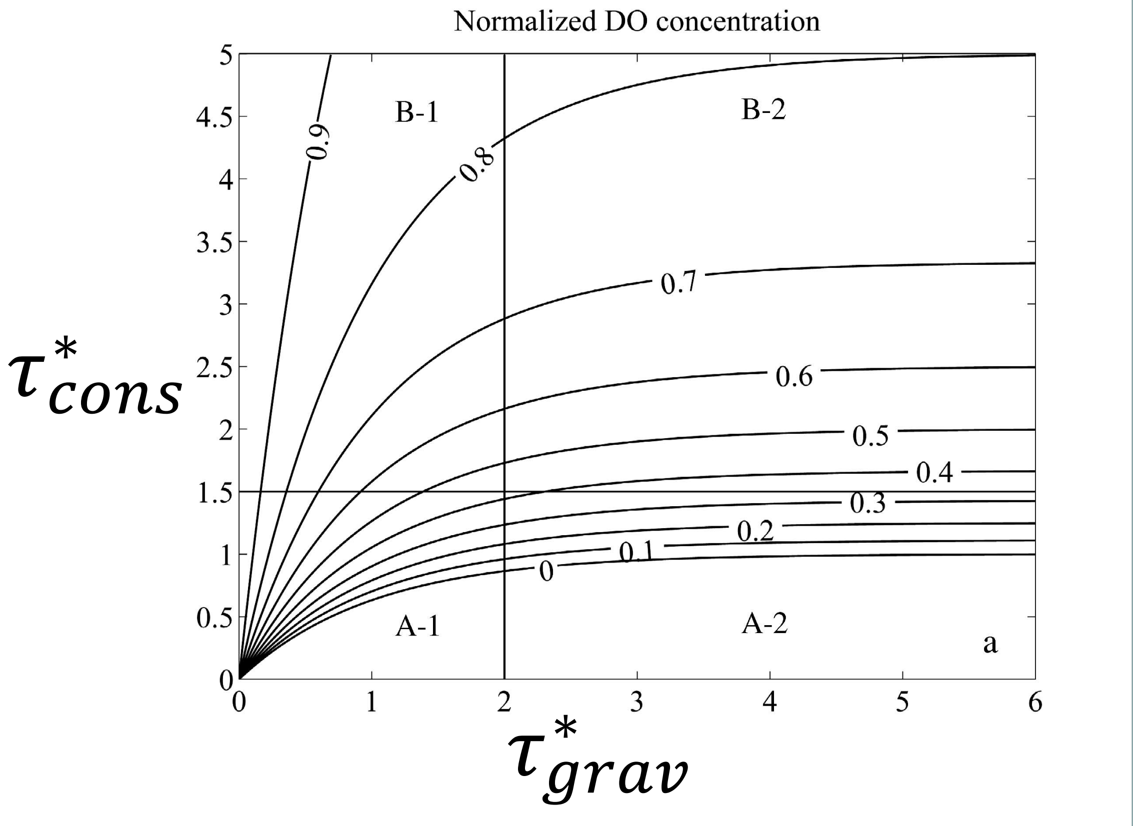
Example: Dissolved oxygen dynamics in Chesapeake Bay

$$c^*_{bot} = 1 - \frac{1}{\tau^*_{cons}}\left(1 - e^{-\tau^*_{grav}}\right)$$

f(2 params)

where $c^*_{bot} = \dfrac{c_{bot}}{c_{surf}}$

Contours of normalized bottom DO concentration



Hurray! We can plot it!

Shen et al. 2013

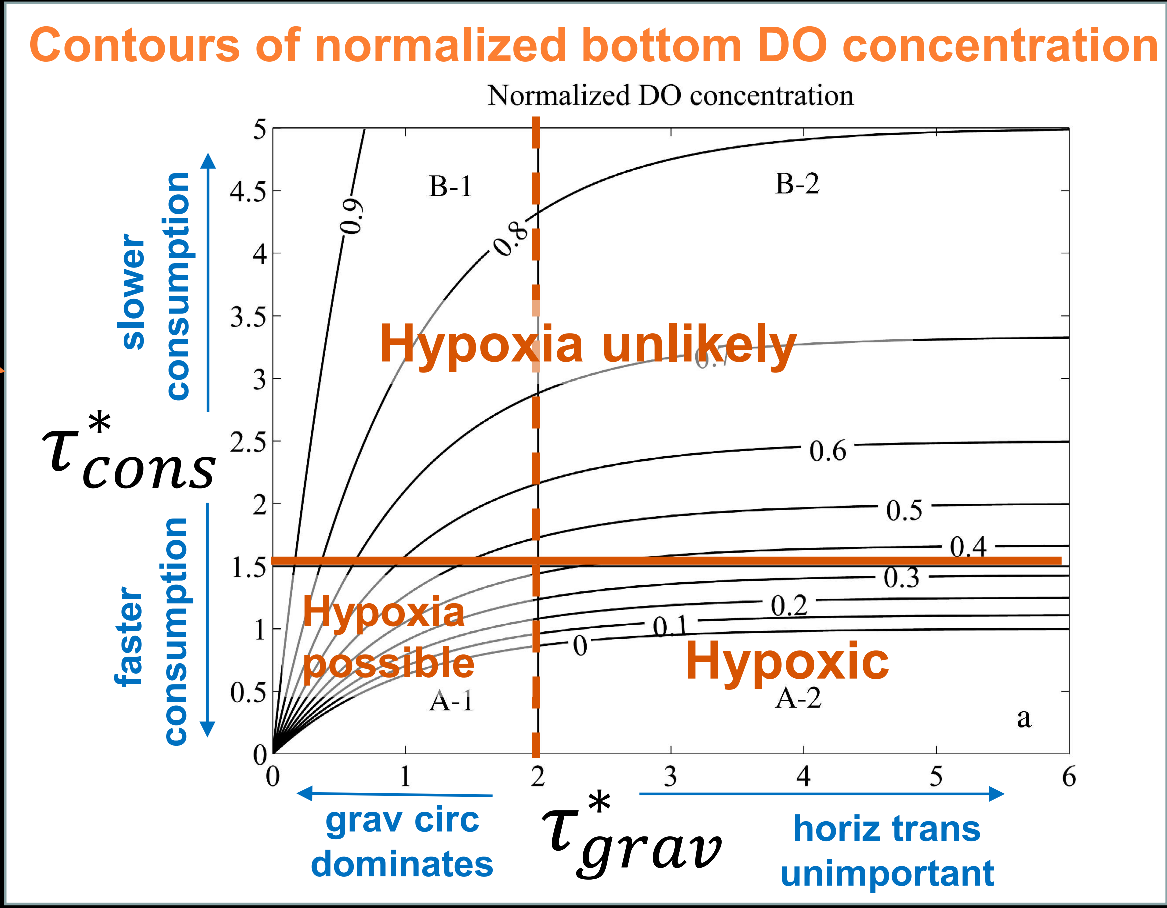
Example: Dissolved oxygen dynamics in Chesapeake Bay

$$\boxed{c^*_{bot} = 1 - \frac{1}{\tau^*_{cons}}\left(1 - e^{-\tau^*_{grav}}\right)}$$

f(2 params)

where $$c^*_{bot} = \frac{c_{bot}}{c_{surf}}$$

$$\tau^*_{grav} = \frac{\tau_{grav}}{\tau_{vert}} \qquad \tau^*_{cons} = \frac{\tau_{cons}}{\tau_{vert}}$$



Shen et al. 2013

Example: Dissolved oxygen dynamics in Chesapeake Bay

$$c^*_{bot} = 1 - \frac{1}{\tau^*_{cons}}\left(1 - e^{-\tau^*_{grav}}\right)$$

The simple model works pretty danged well!

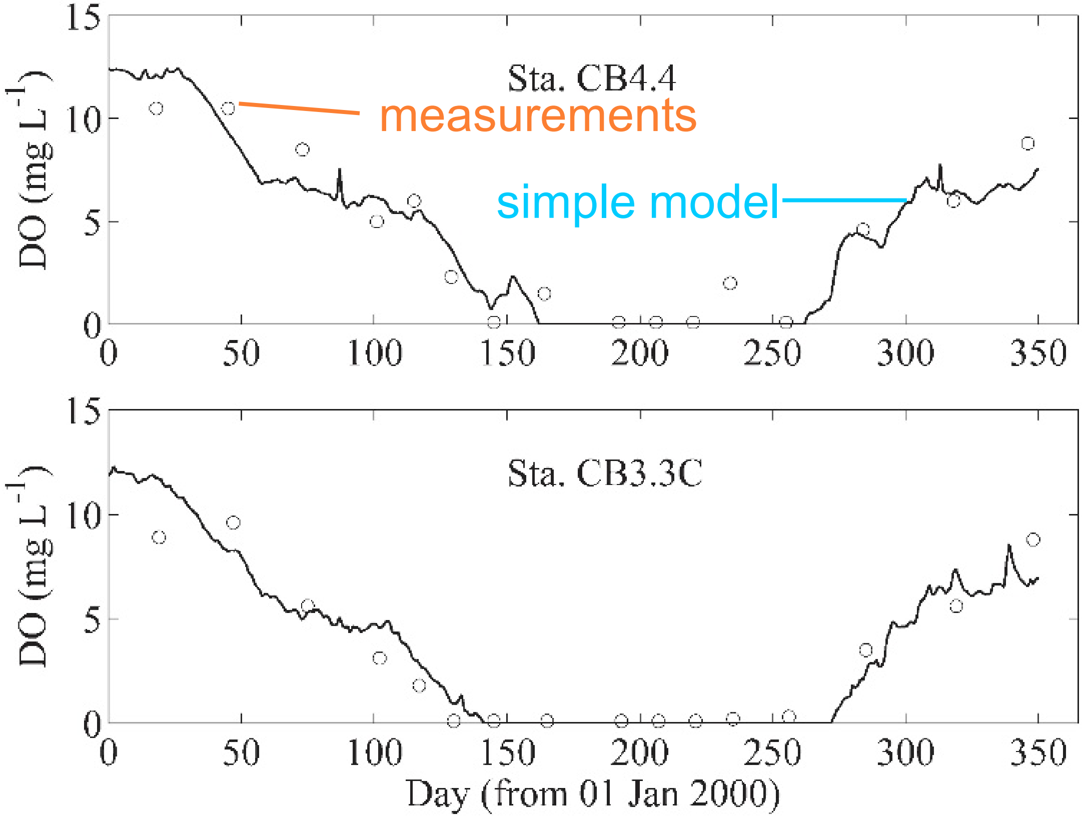


Fig. 7. Comparisons of conceptual model results and observations at Sta. CB4.4 and CB3.3C, respectively, in 2000 (lines are model results, circles are observations).

Shen et al. 2013

Take home

Timescales can

- Represent **ANY** kind of **PROCESS**
- **COMMON CURRENCY**
- **REDUCE** complex problems to **ESSENTIAL** parts
- develop intuition for **HOW SYSTEM WORKS**, more **MEANINGFUL** than primitive variables
- Basis of **SIMPLE** but effective **MODELS**

> **"To avoid misunderstandings and even erroneous conclusions it is important to introduce precise definitions and to use [timescales] with care."**
>
> ***-Bolin & Rodhe 1973***

Interested in learning more?

water

Review

Timescale Methods for Simplifying, Understanding and Modeling Biophysical and Water Quality Processes in Coastal Aquatic Ecosystems: A Review

Lisa V. Lucas [1,*] and Eric Deleersnijder [2]

Water **2020**, *12*, 2717; doi:10.3390/w12102717