Modeling the mixing of the ocean floor:

An intriguing link between crustaceans and xerox machines

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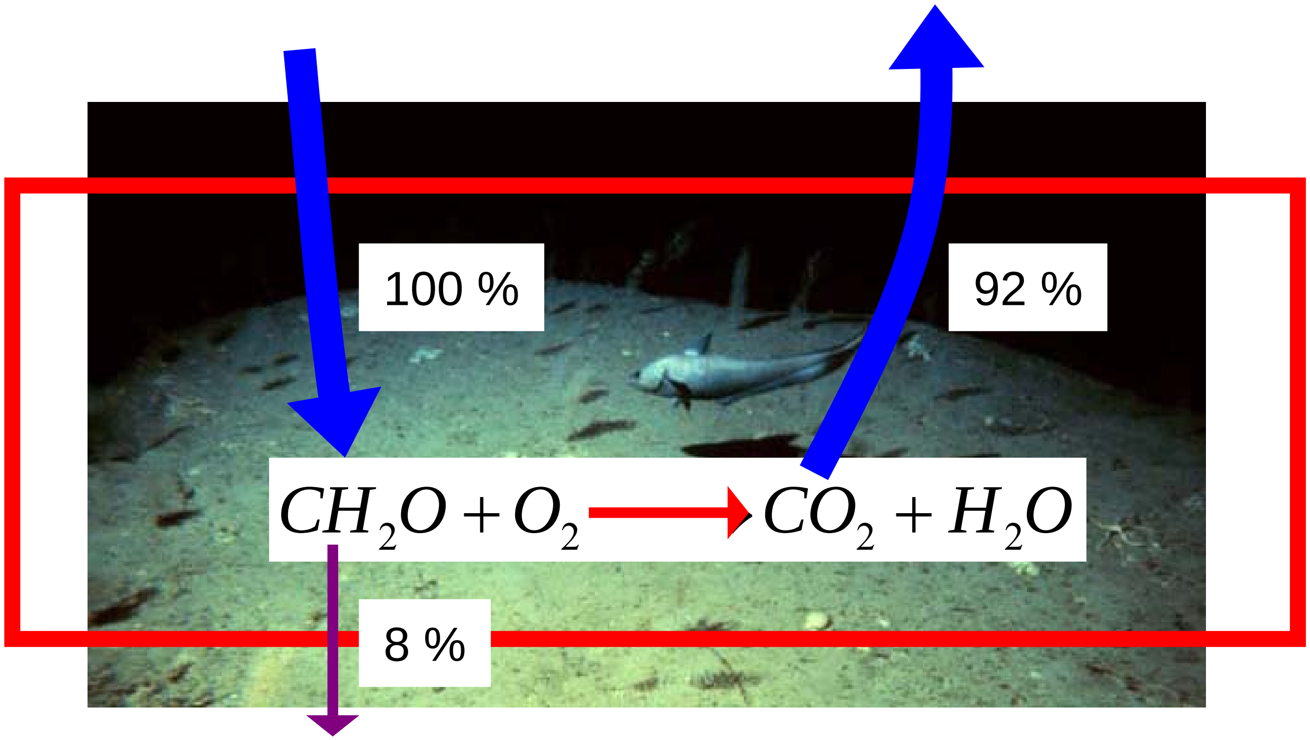
Why should we study mixing within the ocean floor?

Modern ocean floor = efficient biochemical reactor

Flux of
Organic carbon (CH_2O)
from water column

Return CO_2
water column



Sequestration
into deeper sediments
(CH_2O)

How much carbon stays and how much goes?

What controls the recycling efficiency?

How does this efficiency vary between environments?

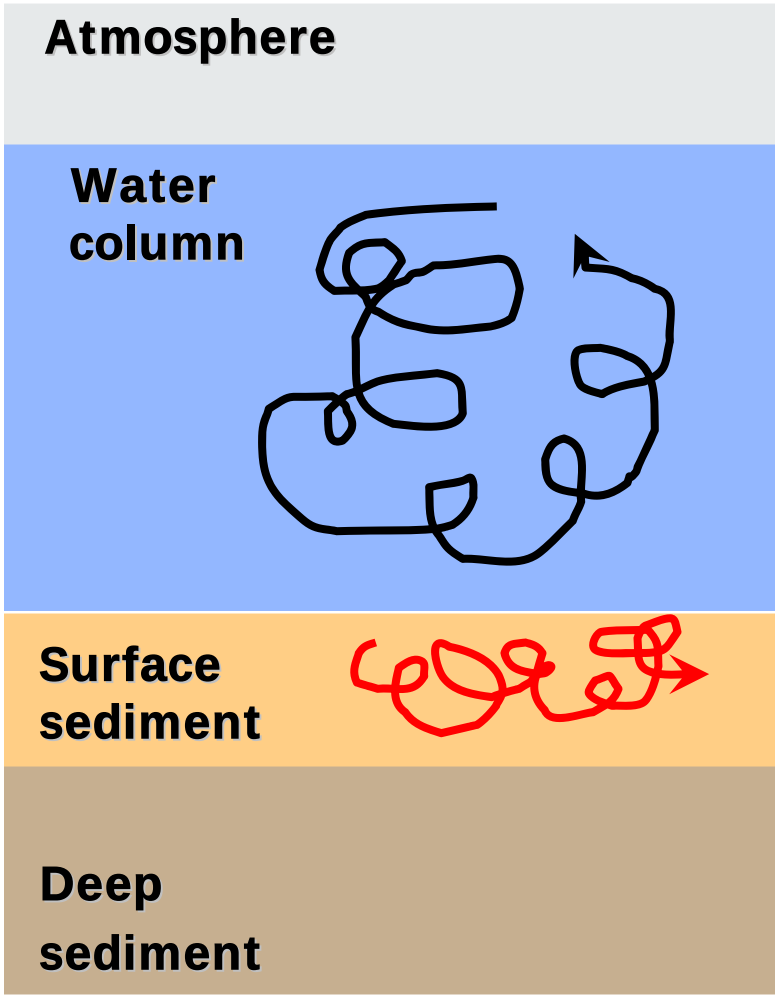
Biogeochemical models of the ocean floor

General balance statement for a the chemical compound:

$$\frac{\partial C}{\partial t} = \underbrace{\text{Transport}} + \text{Reaction}$$

We need a good mathematical description for the mixing activity in the ocean floor...

Mixing in the ocean and ocean floor

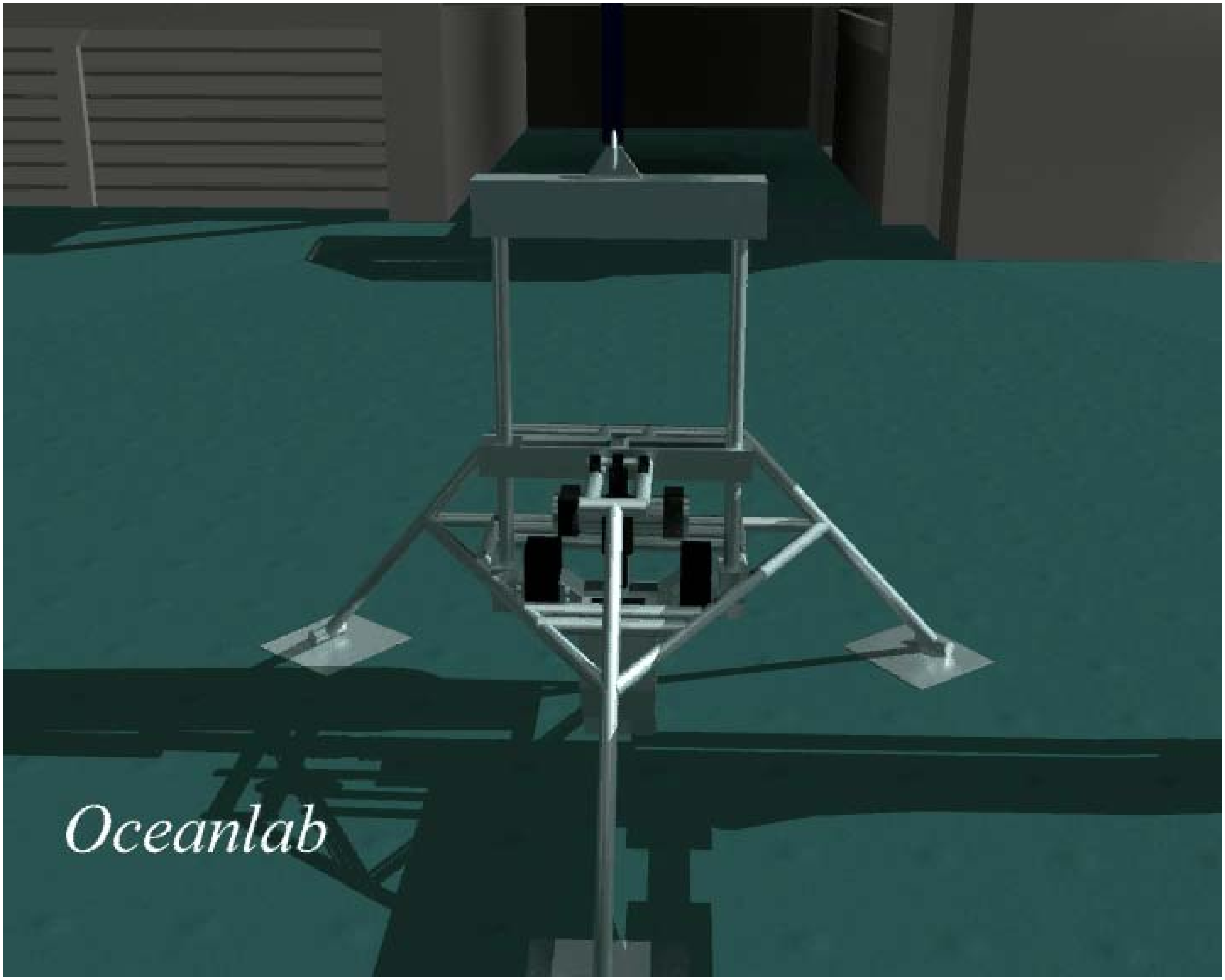


Mixing is induced by turbulence (physics)

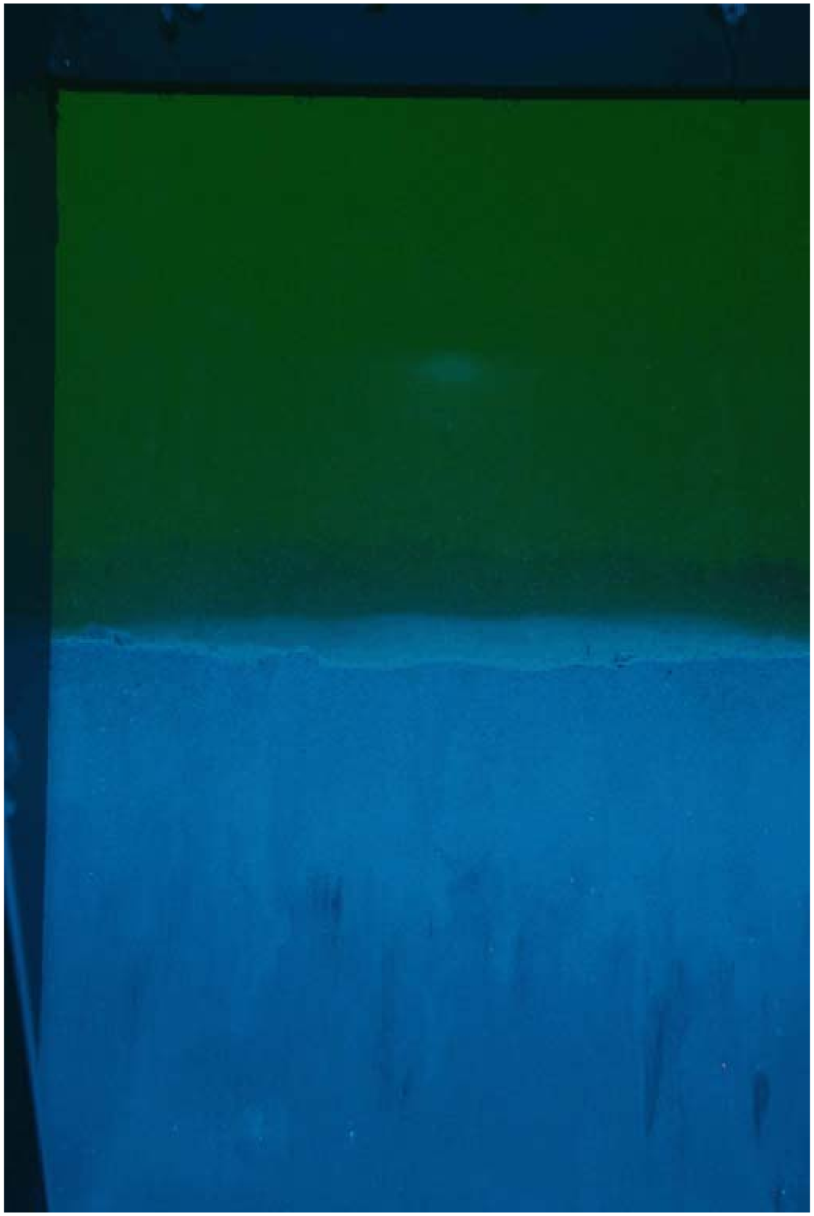
Mixing is induced by bioturbation (biology)

How do we measure the mixing intensity within the ocean floor?

Vizualization of mixing: Sediment Imaging Profiling



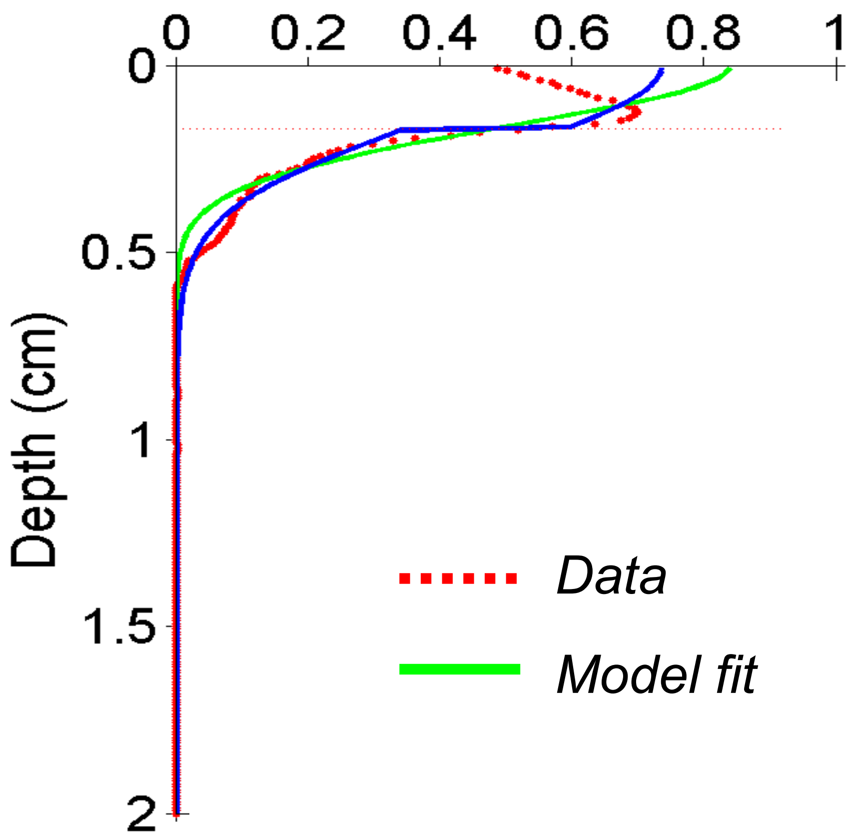
Pulse tracer addition experiments



- Sediment Profiling Image (SPI)
- Gullmarsfjord (Sweden) – 28 m depth – 48 hour cycle
- Spider Crab (*Hyas araneus*)

Solan et al. (2004)

Classical modelling approach: diffusion



Diffusion model

$$\frac{\partial C}{\partial t} = D_b \frac{\partial^2 C}{\partial x^2} - \lambda C$$

Step 1: tracer addition
(inert or with known tracer half life λ)

Step 2: Measure tracer depth profile at specific time t

Step 3: Model fitting provides best value for mixing intensity D_b

Current situation

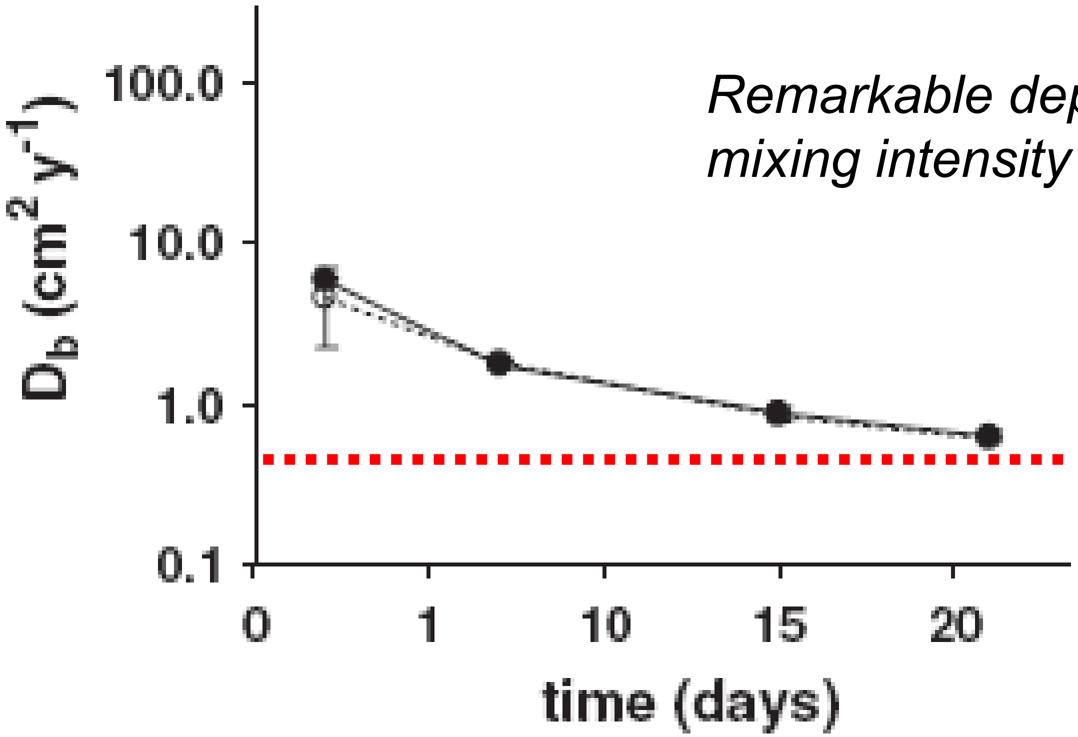
- Inverse modeling based on diffusion model has been widely applied over the last 25 years
- Current global database contains about ~ 950 values of the biodiffusion coefficient Db

… but nagging problems on closer inspection

Problems with bio-diffusion analogy

<u>Problem 1</u>: **The result of the experiment depends on the patience of the experimenter**

Mixing intensity

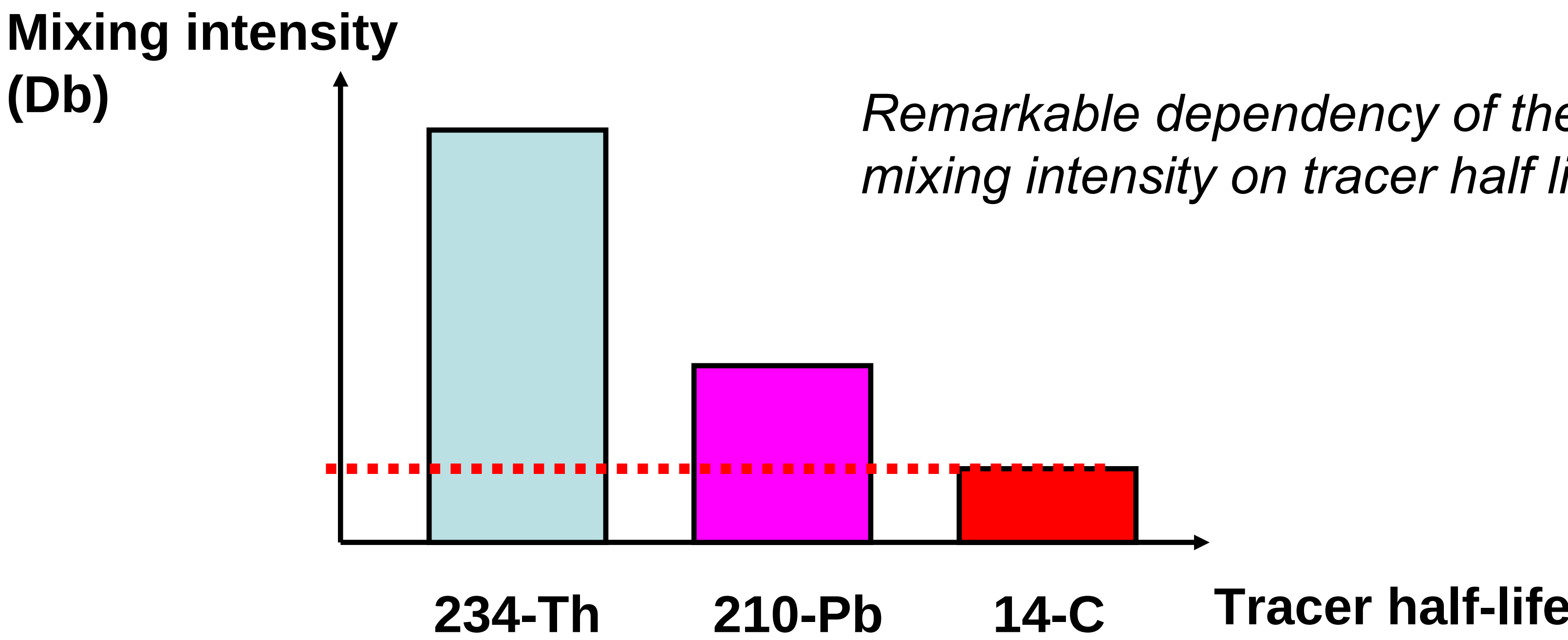


Remarkable dependency of the mixing intensity on time

Fernandes et al. (Marine Chemistry, 2006)

Problems with bio-diffusion analogy

<u>Problem 2</u>: **The result of the experiment depends on the particular tracer that is chosen**



Remarkable dependency of the mixing intensity on tracer half life

Questions

1. What causes this “strange behavior” of the diffusion model?
2. Can we trust the mixing intensities that have been measured in the past?

Challenges

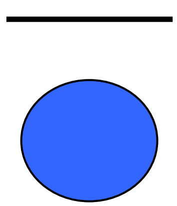
1. We need to examine the mechanistic foundations of mixing in the ocean floor.
2. We need to explicitly constrain under what conditions we can use a diffusive model for mixing

Modeling tool 1:
Stochastic models
– Random walk analysis

The connection to photocopying machines

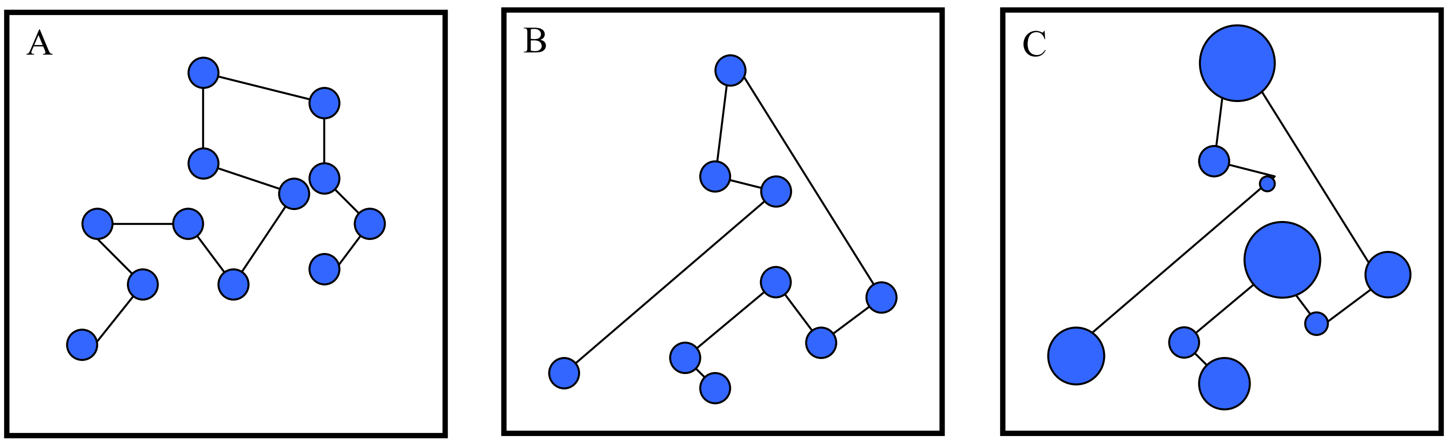
- Early 70’s at Xerox Park: investigations in the transport of charges in amorphous semi-conductors
- Classical diffusion did not a good job in describing the behaviour of charges and holes
- Statistical physicists came up with something new: a generalization of the random walk, termed the **continuous time random walk**

Different types of random walks



Length of the line denotes how far a particle jumps

Radius of the circle denotes how long a particle waits

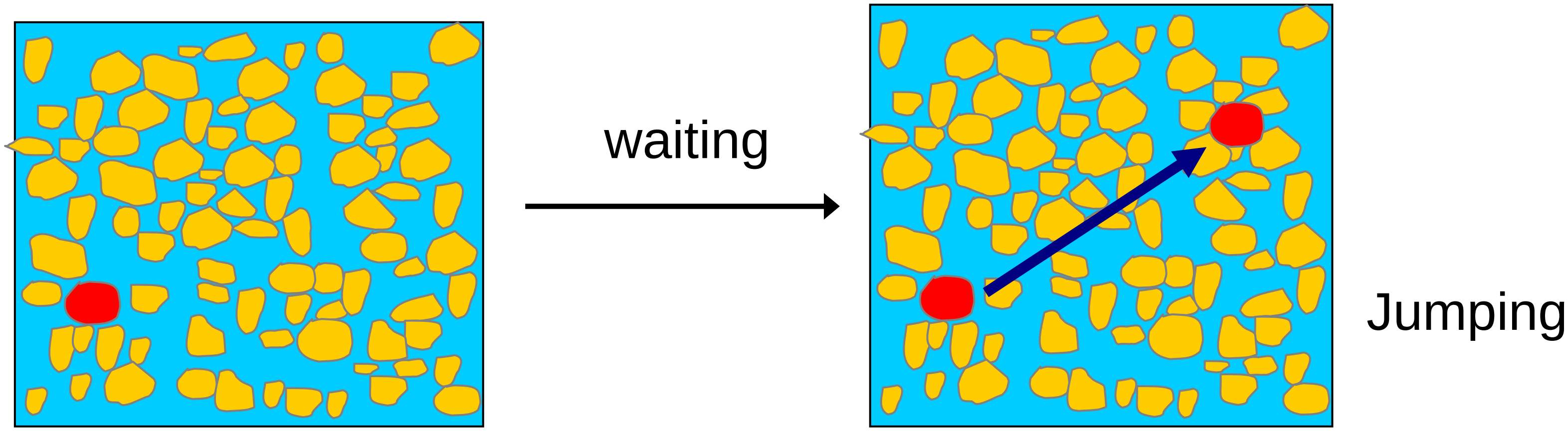


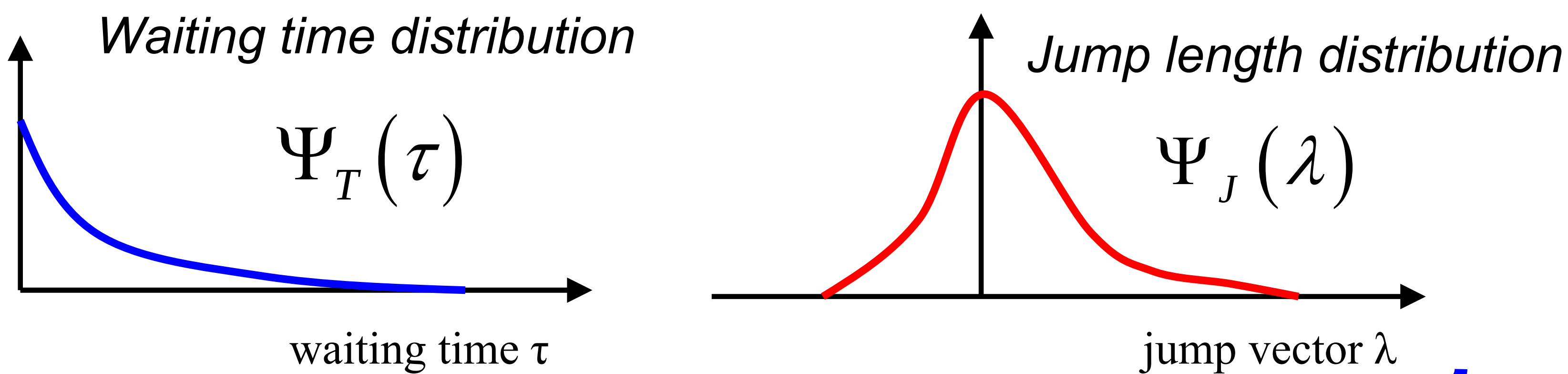
Classical random walk

Levy walk

Continuous time random walk

Translation to biological mixing activity





Mixing fingerprint of a bioturbating community

Meysman et al. (GCA, 2008)

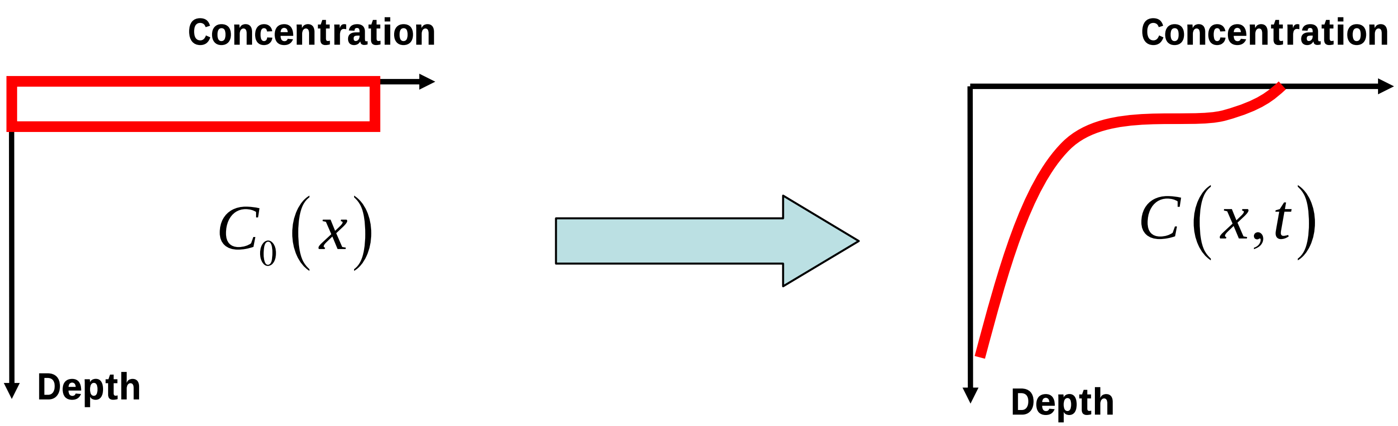
CTRW model of bioturbation

Model equation :

$$C(x,t) = C_0(x)\left[1 - \int_0^t \phi(t')\,dt'\right] + \int_0^t \int_{\mathbb{R}^n} \phi(t-t')\,\vartheta(x',x)\,C(x',t')\,dx'dt'$$

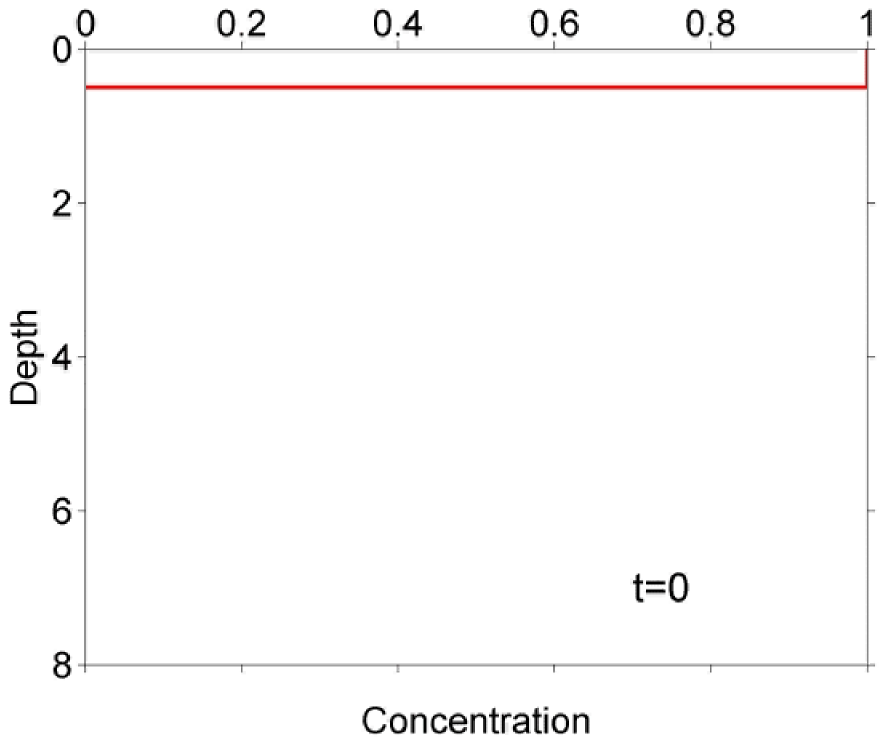
Model solution: combined Laplace and Fourier Transform

Initial condition (0) **Final condition (t)**



Meysman et al. (Aq. Biol., 2008)

Continuous time random walk: analysis



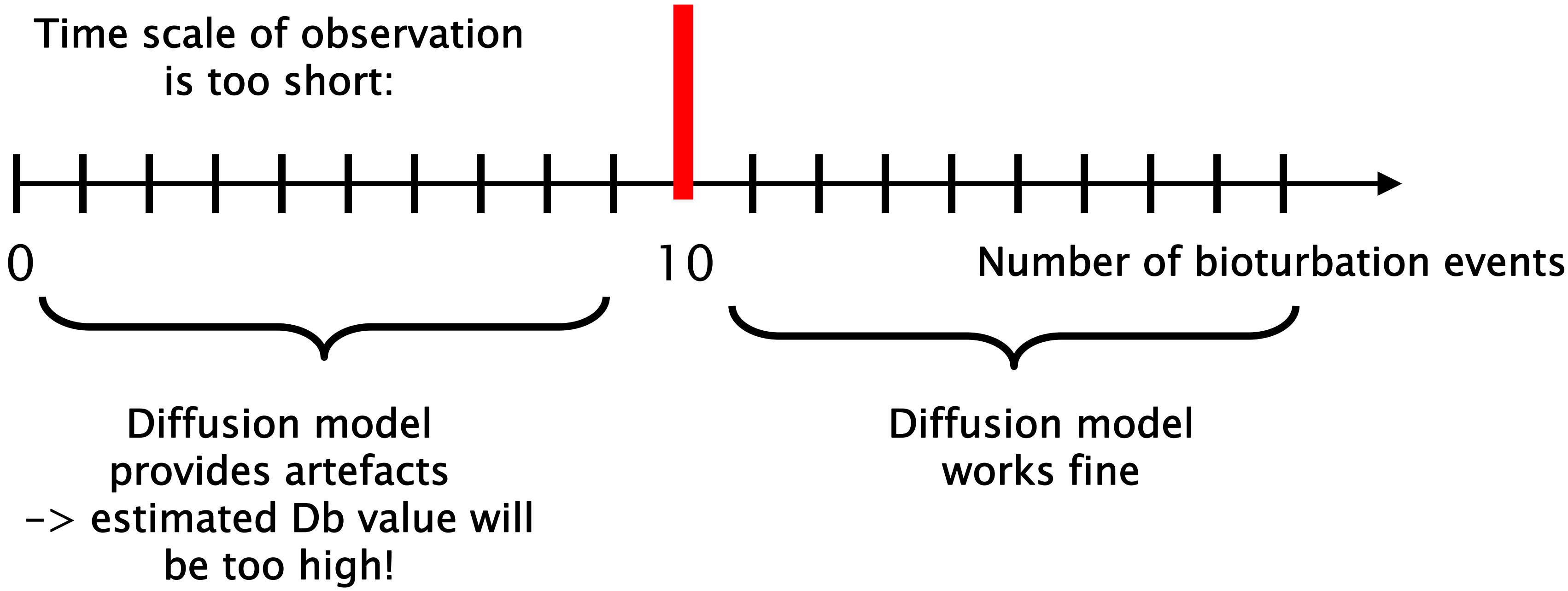
Inert tracer pulse [3mm]

Depth = cm
Time = scaled by the average waiting time

Biodiffusion
CTRW model

After 10 time units (bioturbation events) no difference between biodiffusion model and non-local !

Prediction by CTRW

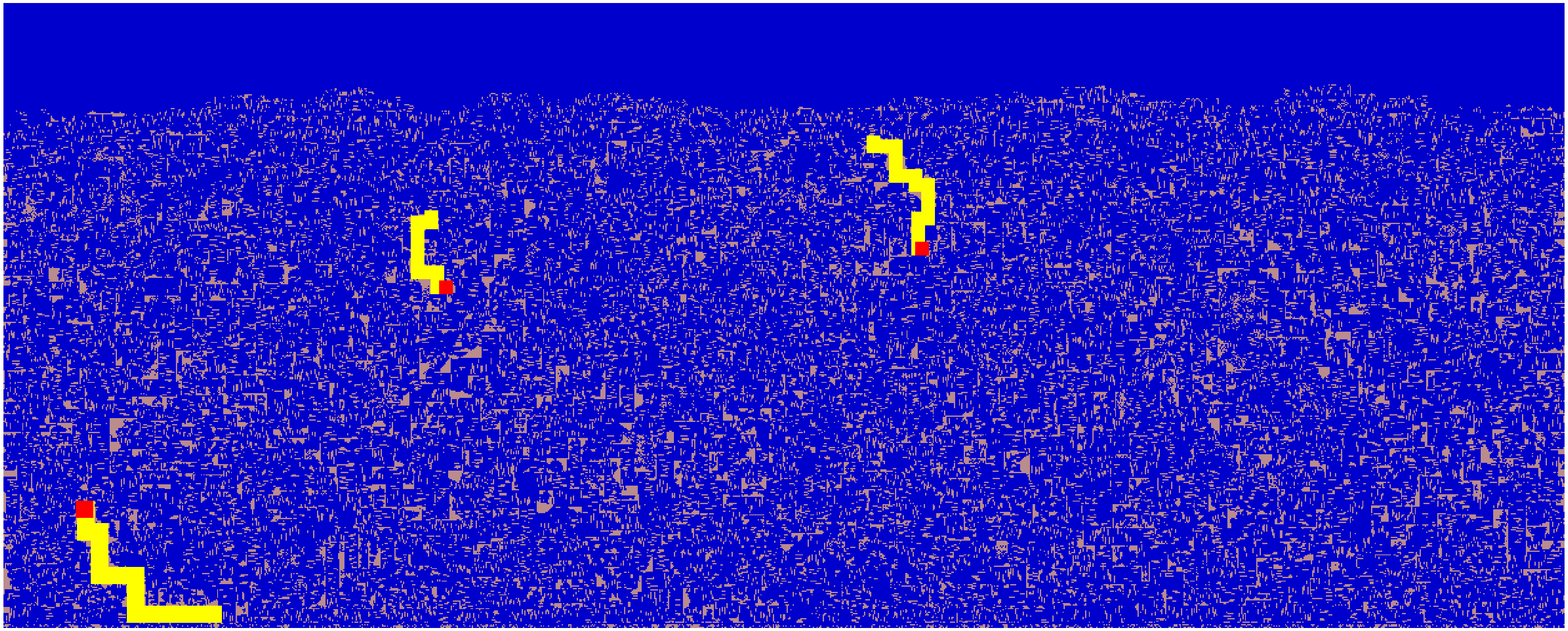


Can we check these predictions of random walk theory?

Modeling tool 2:
Lattice Automaton Simulations

Lattice Automaton Bioturbation Simulations

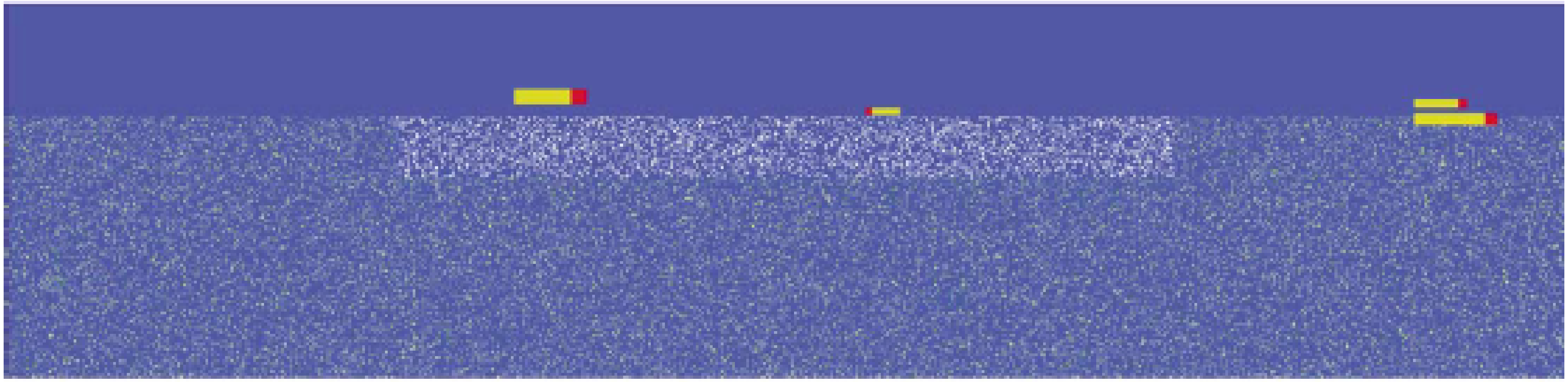
- Real experiments with live organisms are difficult
- Impossibility of particle tracking in sediment matrix
- Solution: create your own sediment!



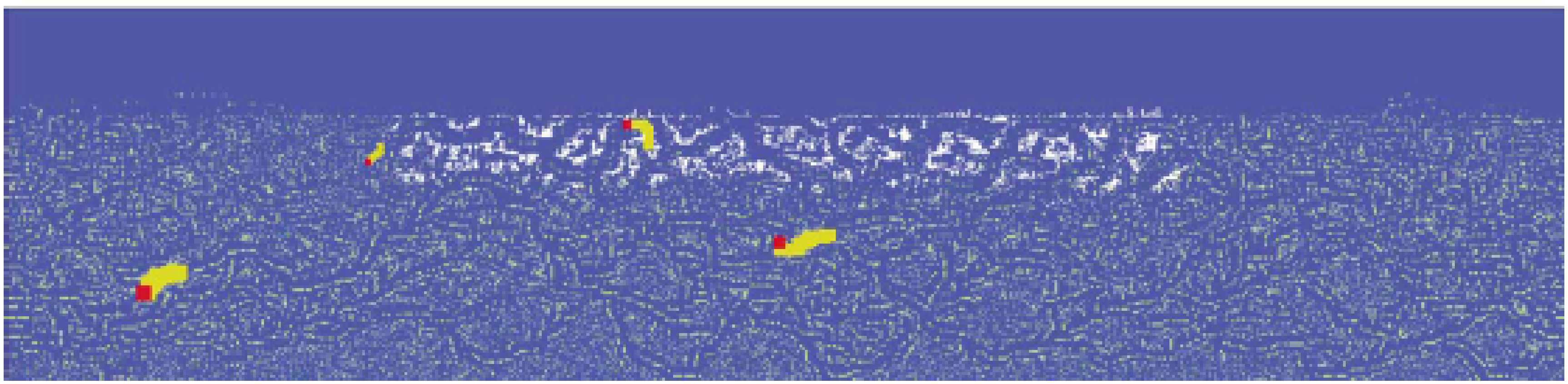
Choi et al. (2002)

Virtual tracer addition experiments

Time = 0 days



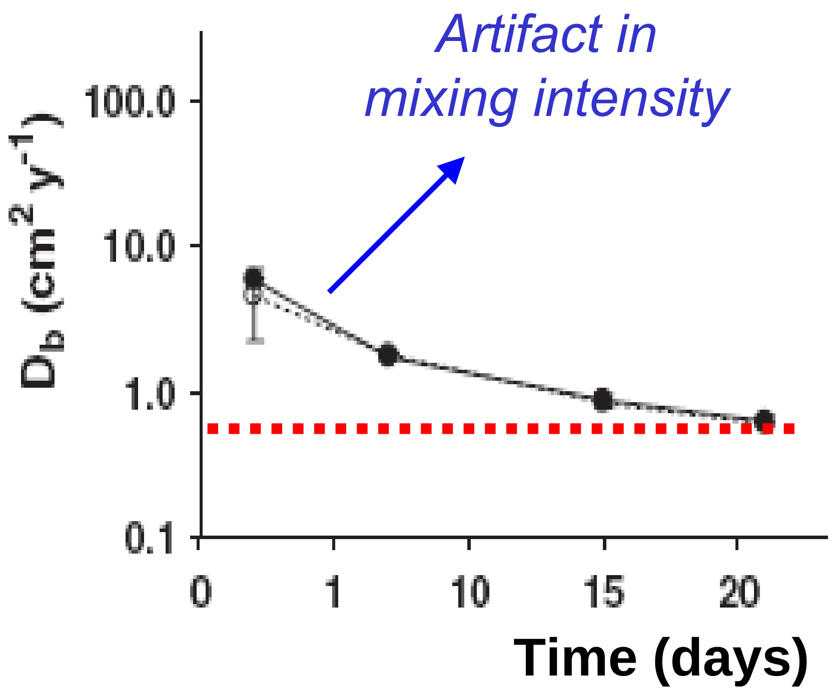
Time = 100 days



Choi et al. (2002)

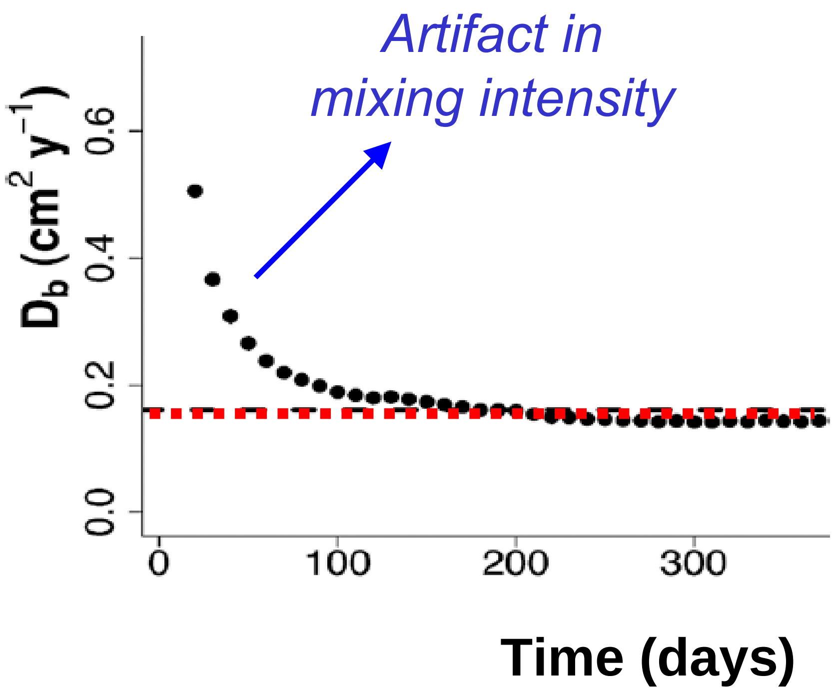
Comparison real and virtual data

Real data



Fernandes et al. (MarChe, 2006)

Virtual LABS data



Reed et al. (JMR, 2007)

Conclusions: modeling mixing in the ocean floor

- Modeling helps us to understand when and why are experimental produce artefacts
- Random walk analysis: provides deeper understanding of mixing processes.
- Lattice Automaton Simulations: Virtual data creation allows to check hypotheses that can not be checked otherwise

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