The sequestration efficiency of the deep ocean:

Fast computations using transport matrices built from ACCESS-ESM1.5 archives

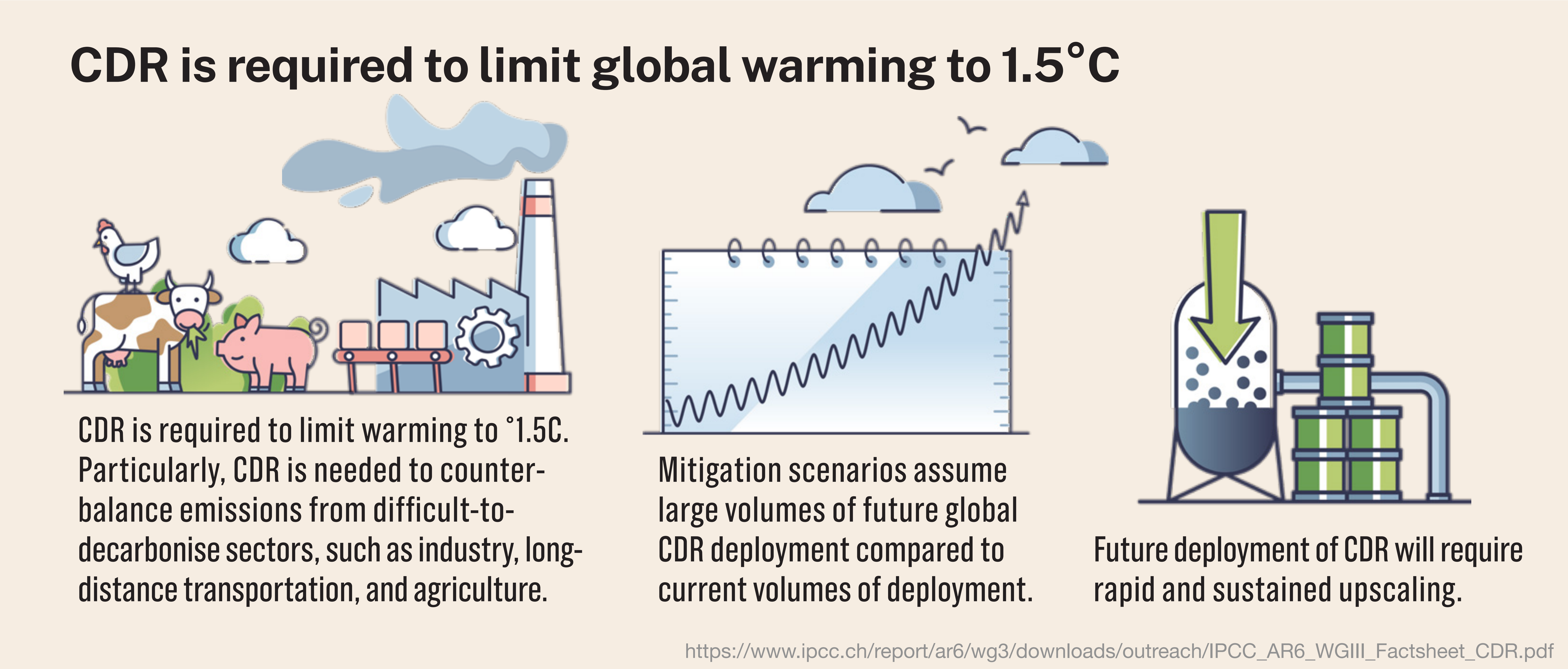
Benoît Pasquier, Richard J. Matear, Matthew A. Chamberlain, Tilo Ziehn, David K. Hutchinson, François W. Primeau, Yi Liu, and Ann Bardin

UNSW SYDNEY

CSIRO

UCI

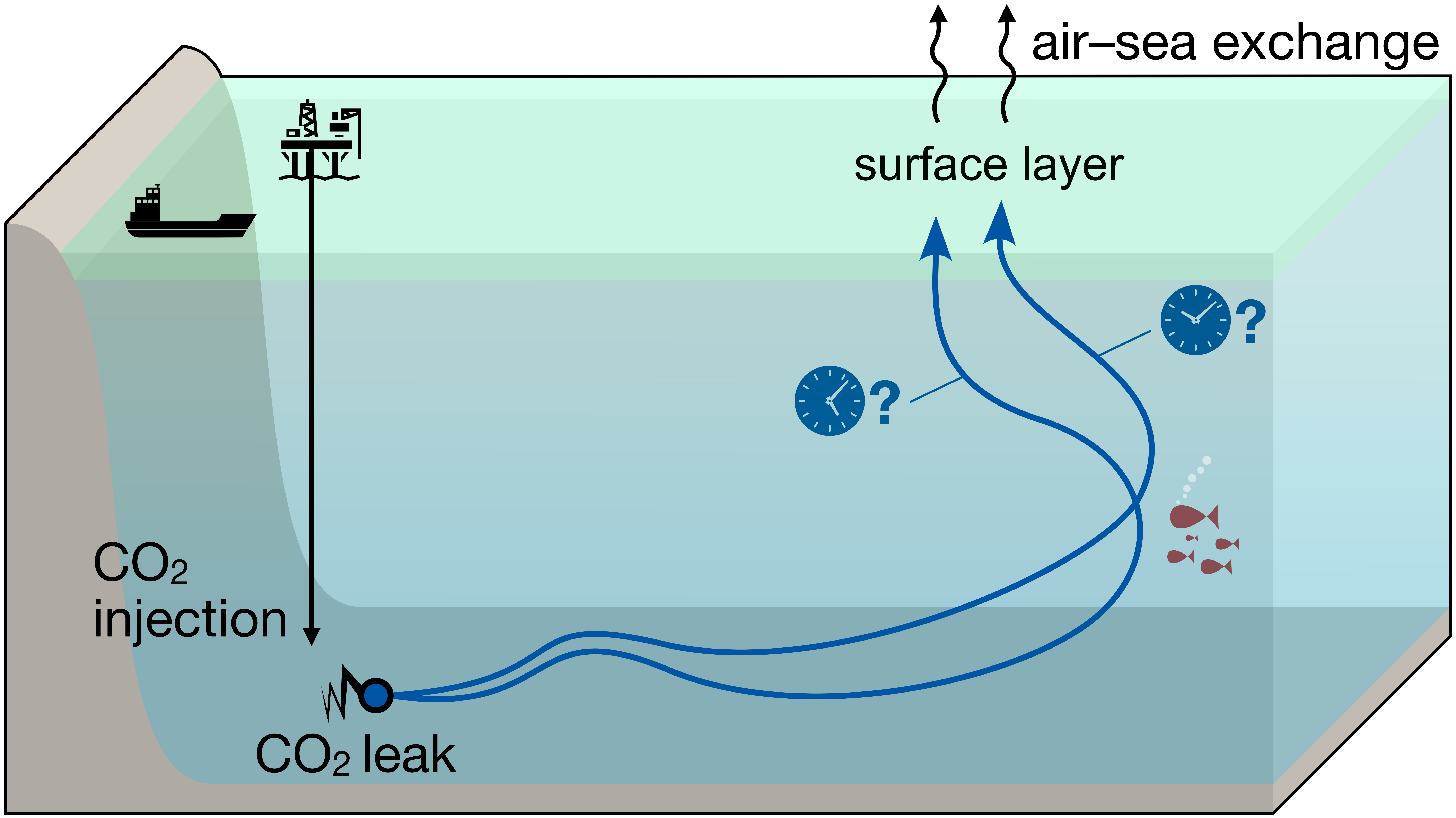
COSIMA WG meeting 2025



Ocean sediments, good candidate for CO_2 storage?

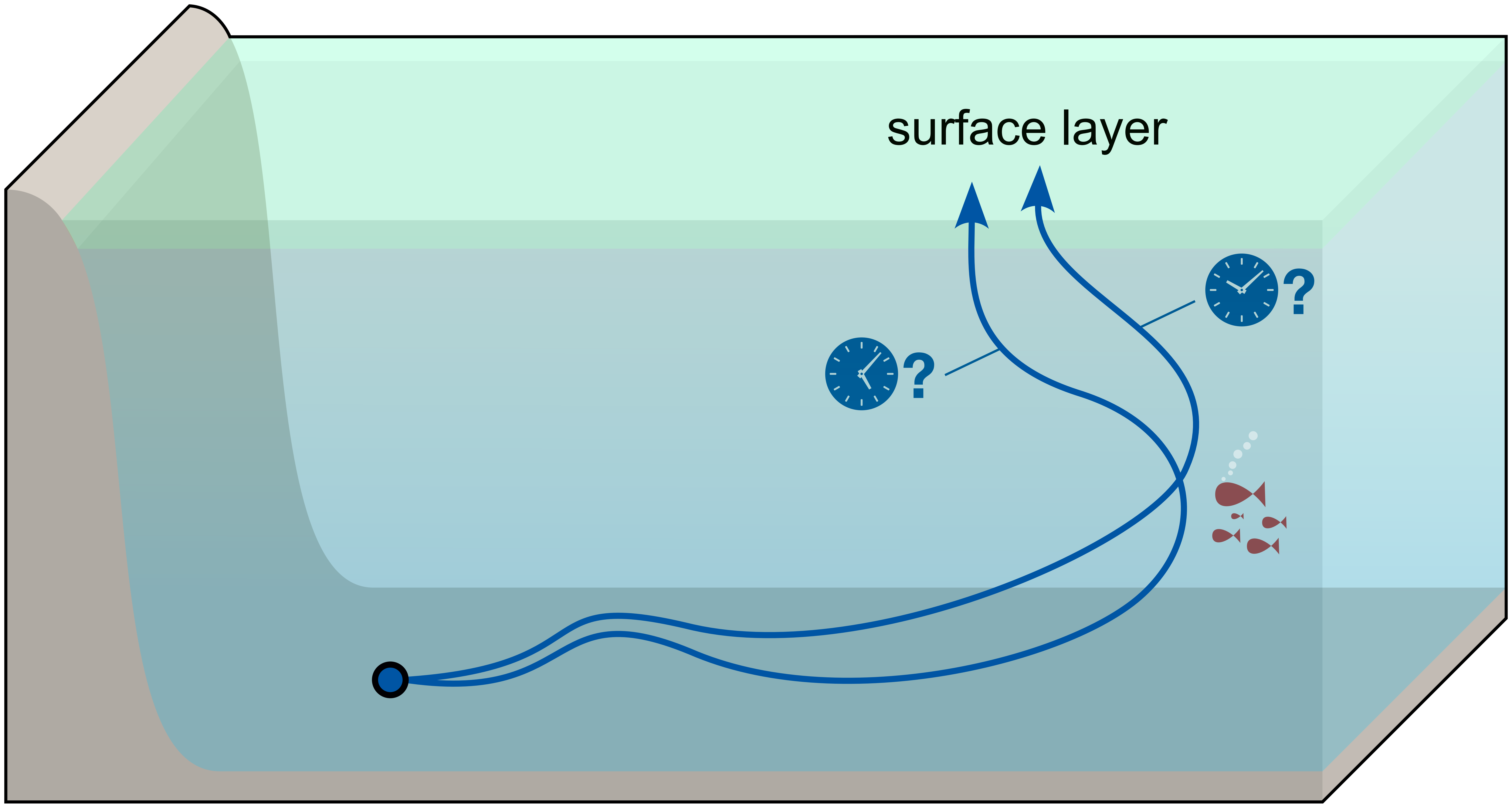
Large capacity + added sequestration from the ocean.

Q: How much added sequestration does the ocean provide?



air–sea exchange
surface layer
CO_2 injection
CO_2 leak
?
?

Q: How long does water take to make contact with the surface?



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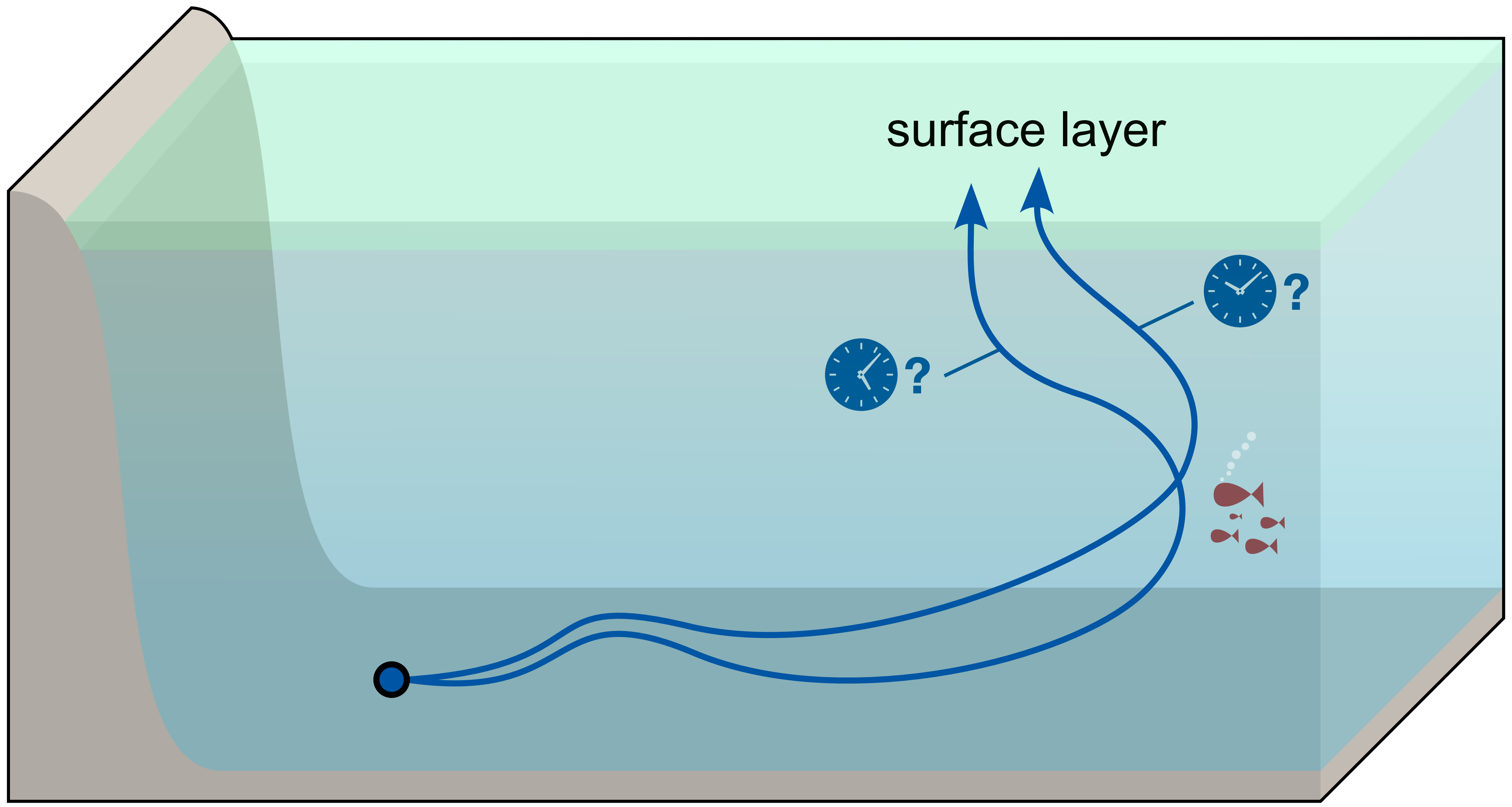

Naive solution: simulate dye, remove at surface and log times of removal.

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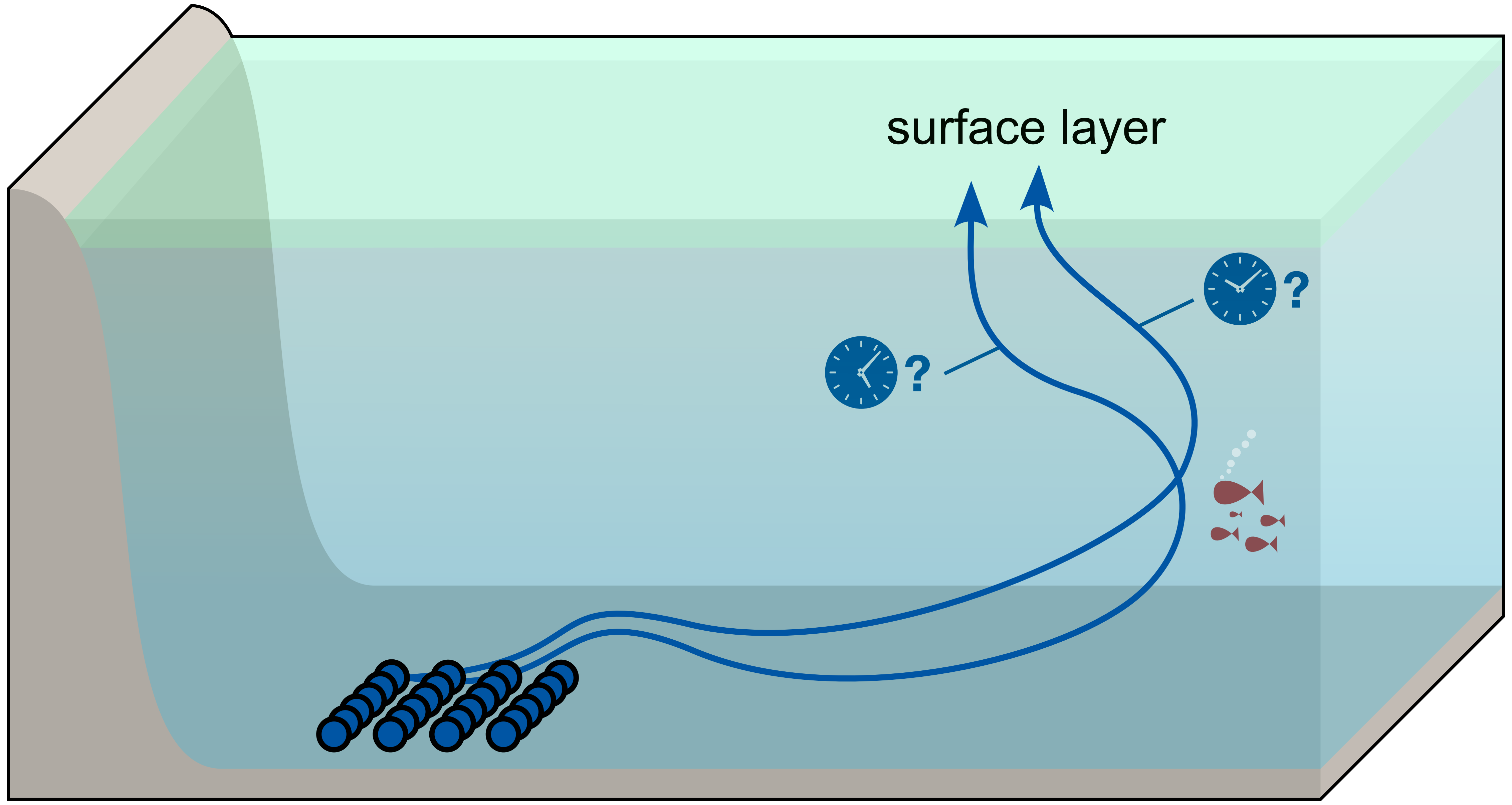

Naive solution: simulate dye, remove at surface and log times of removal.

Problems:
- long simulations (1000's of years)
- repeat for every location (~50'000 for 1°×1°)
- repeat for every injection time

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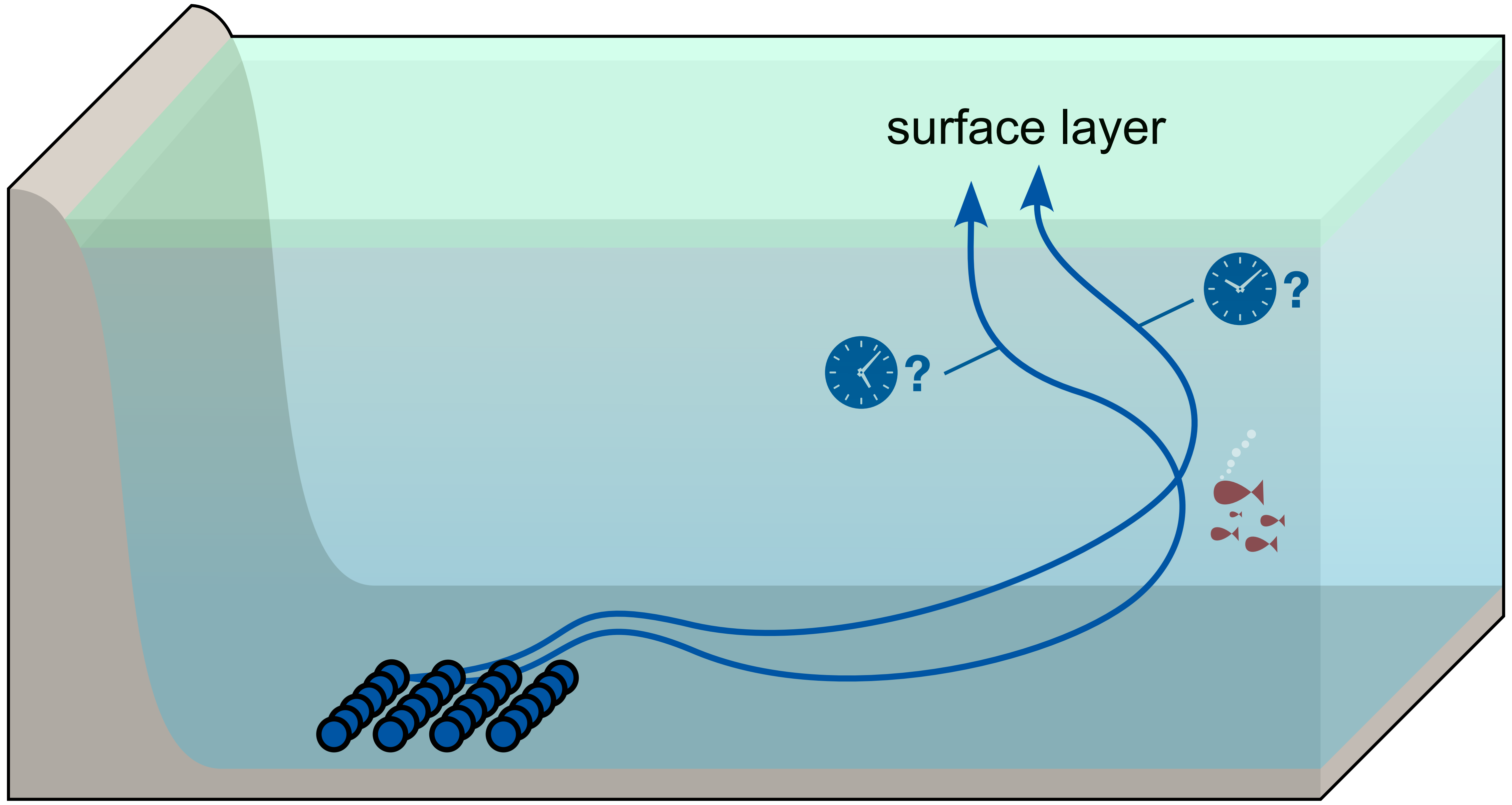

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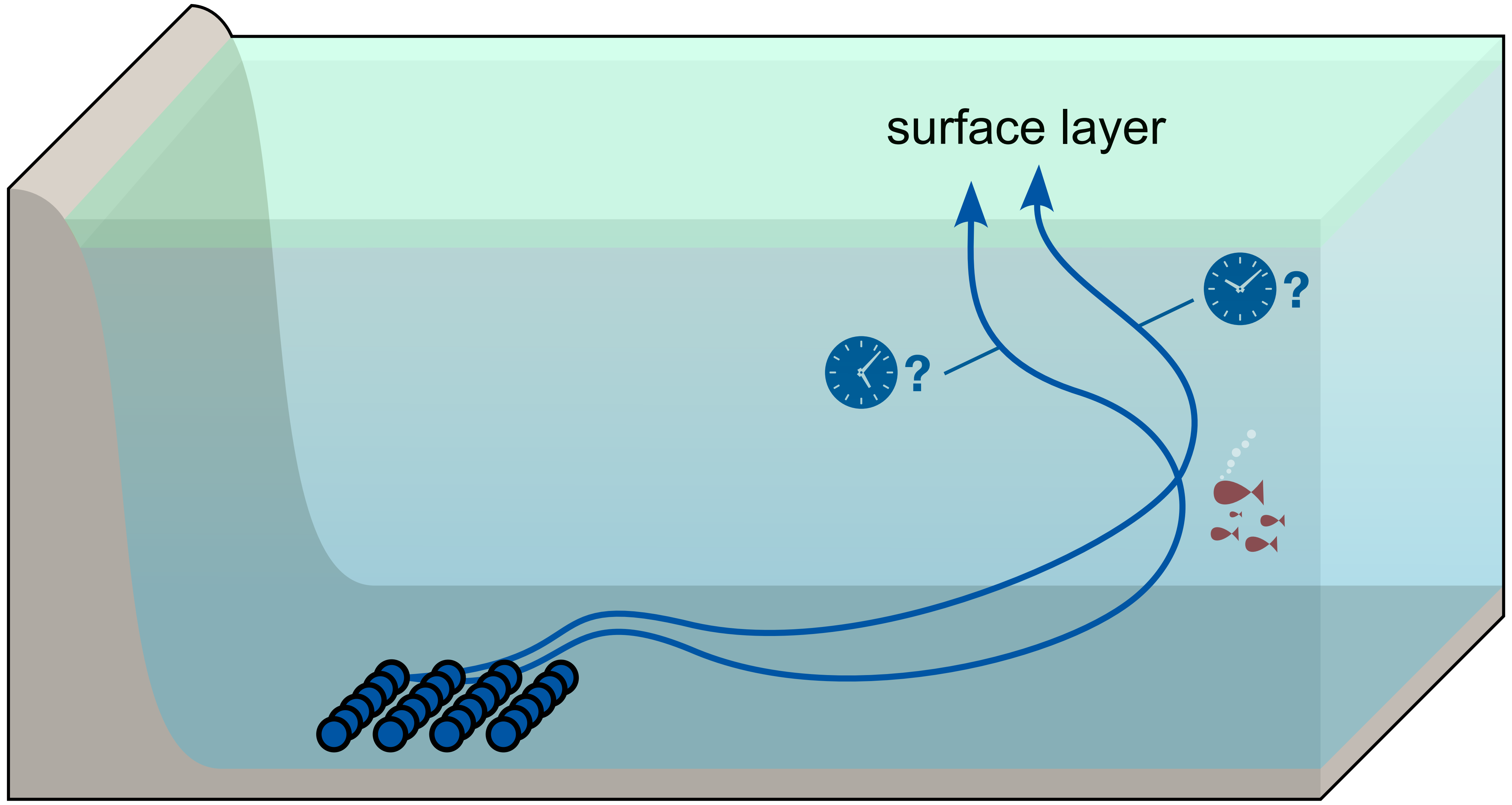

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Our Efficient solution is to use

Frozen Circulations e.g., 2030s climatology

Transport-Matrices

Adjoint Propagators inject at surface and time step backwards

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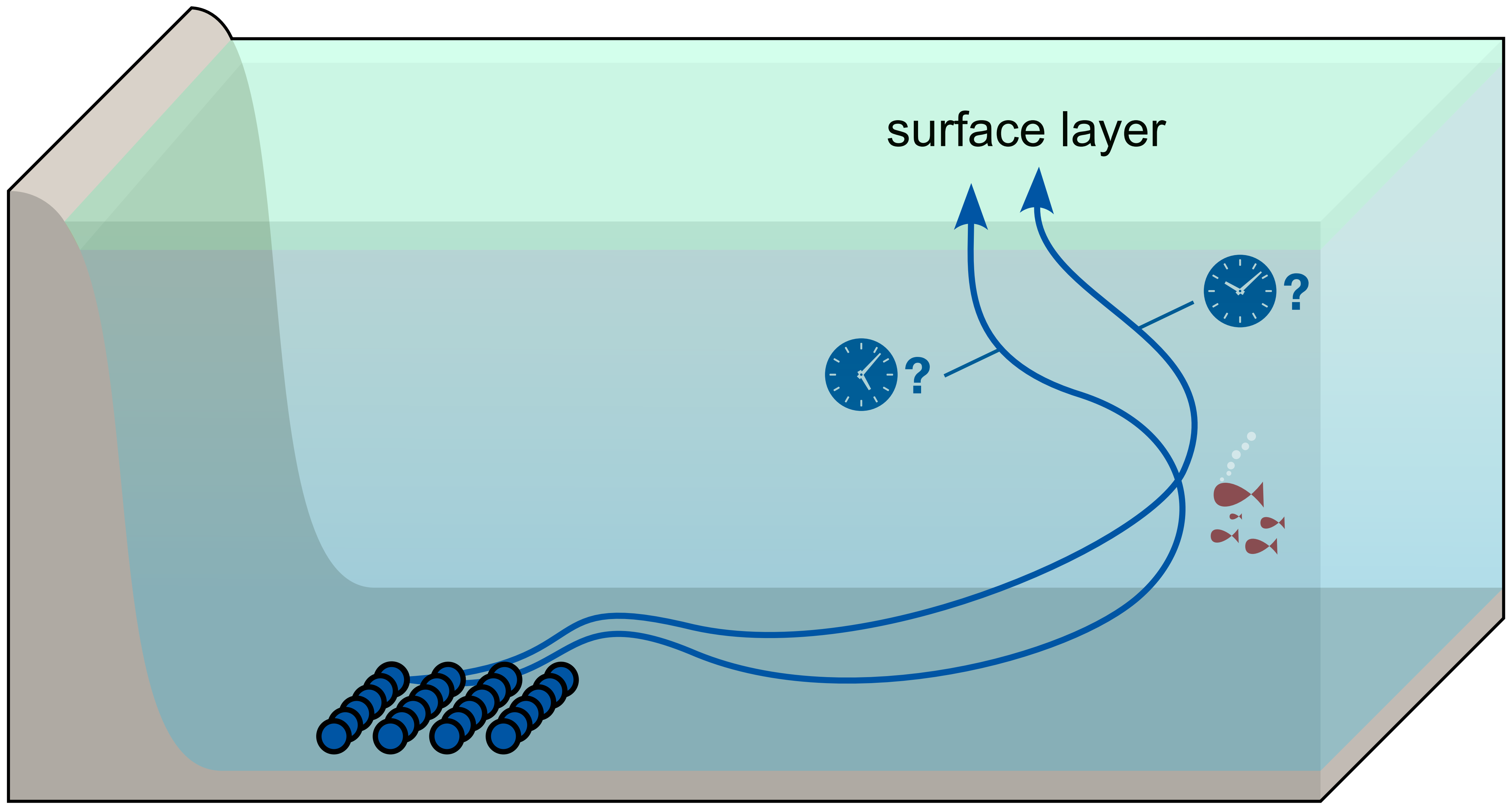

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☑ Beyond* 2100 (vs CMIP archives)
☑ Conceptually simpler than transient

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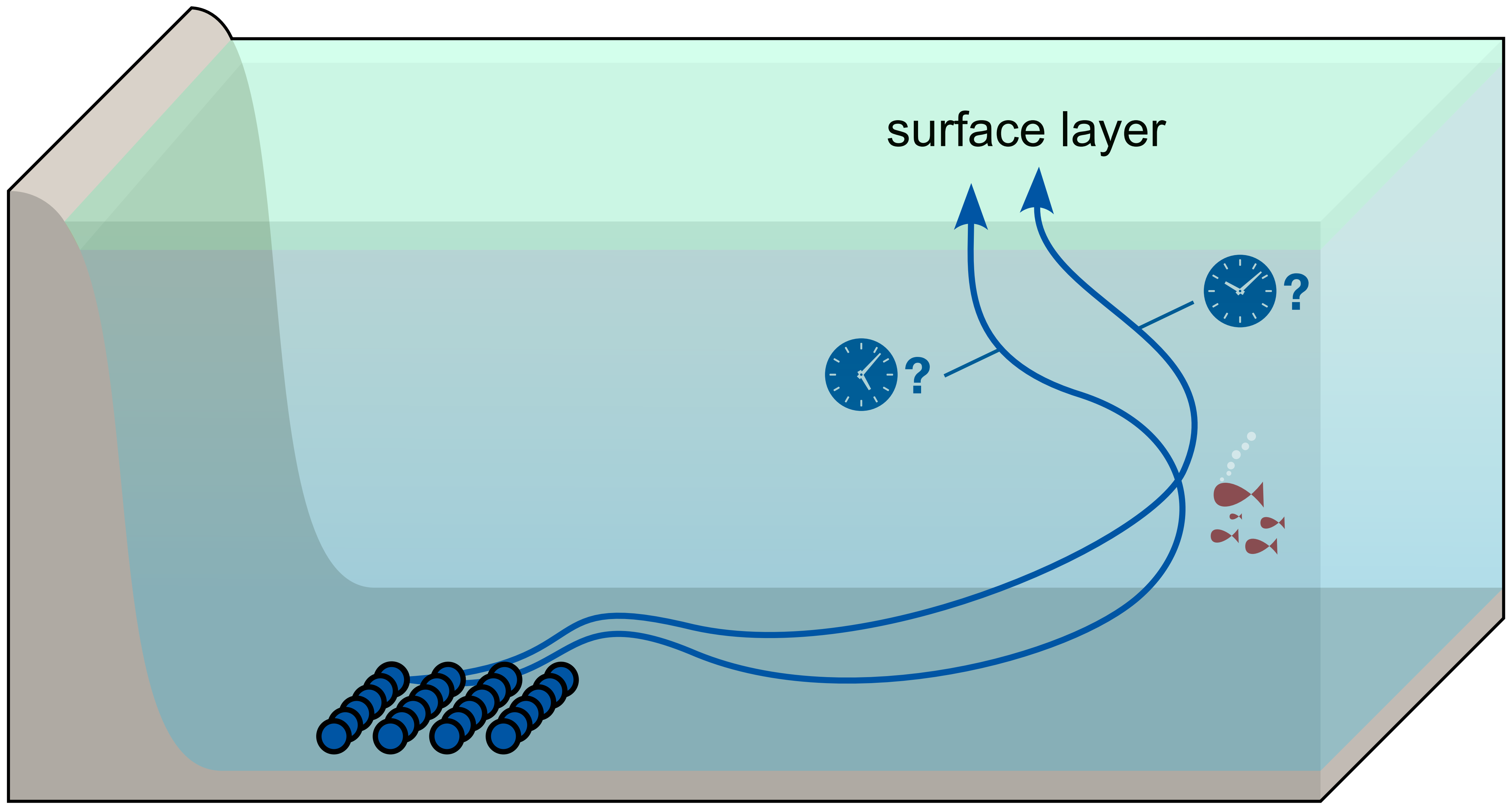

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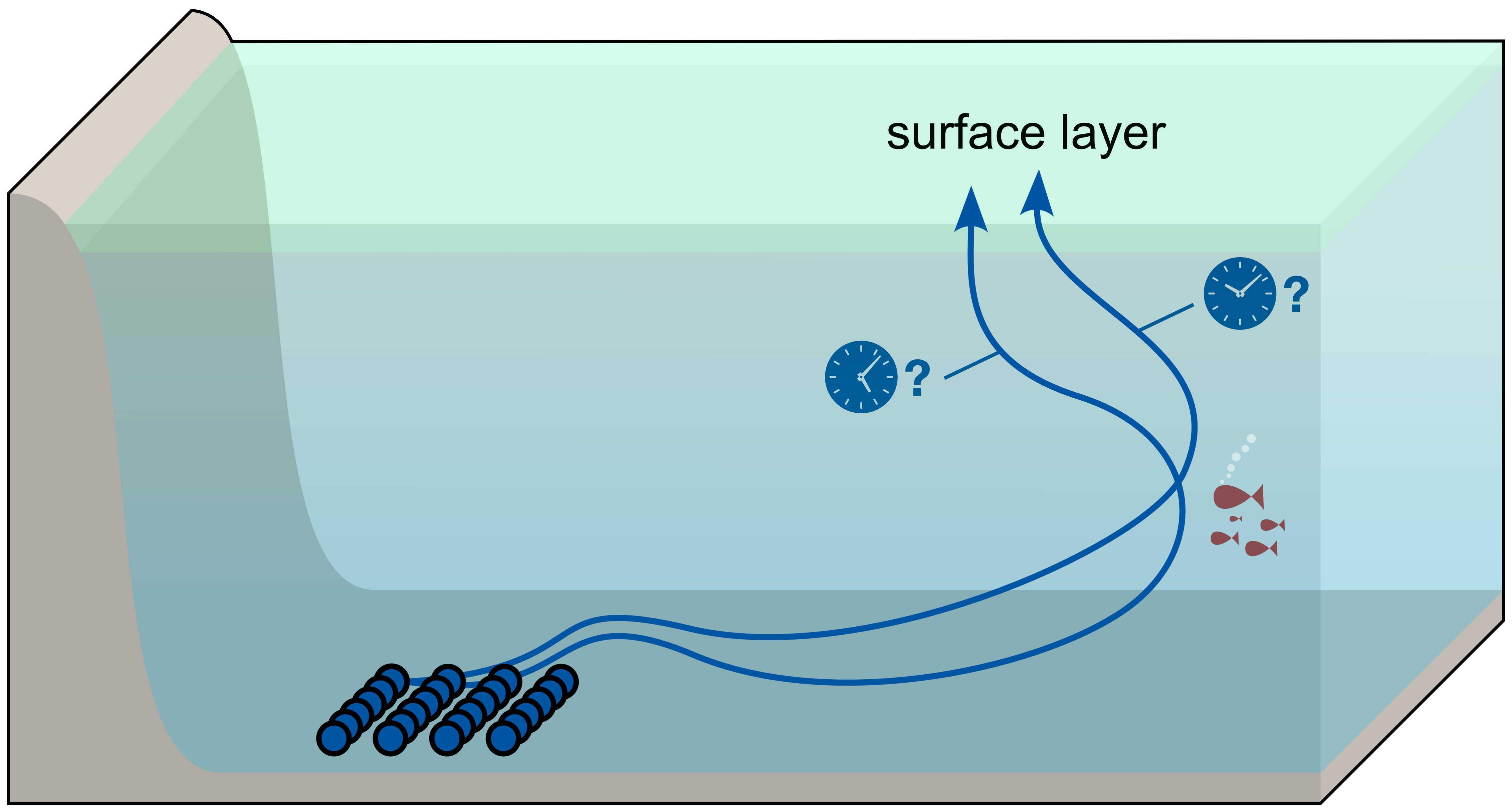

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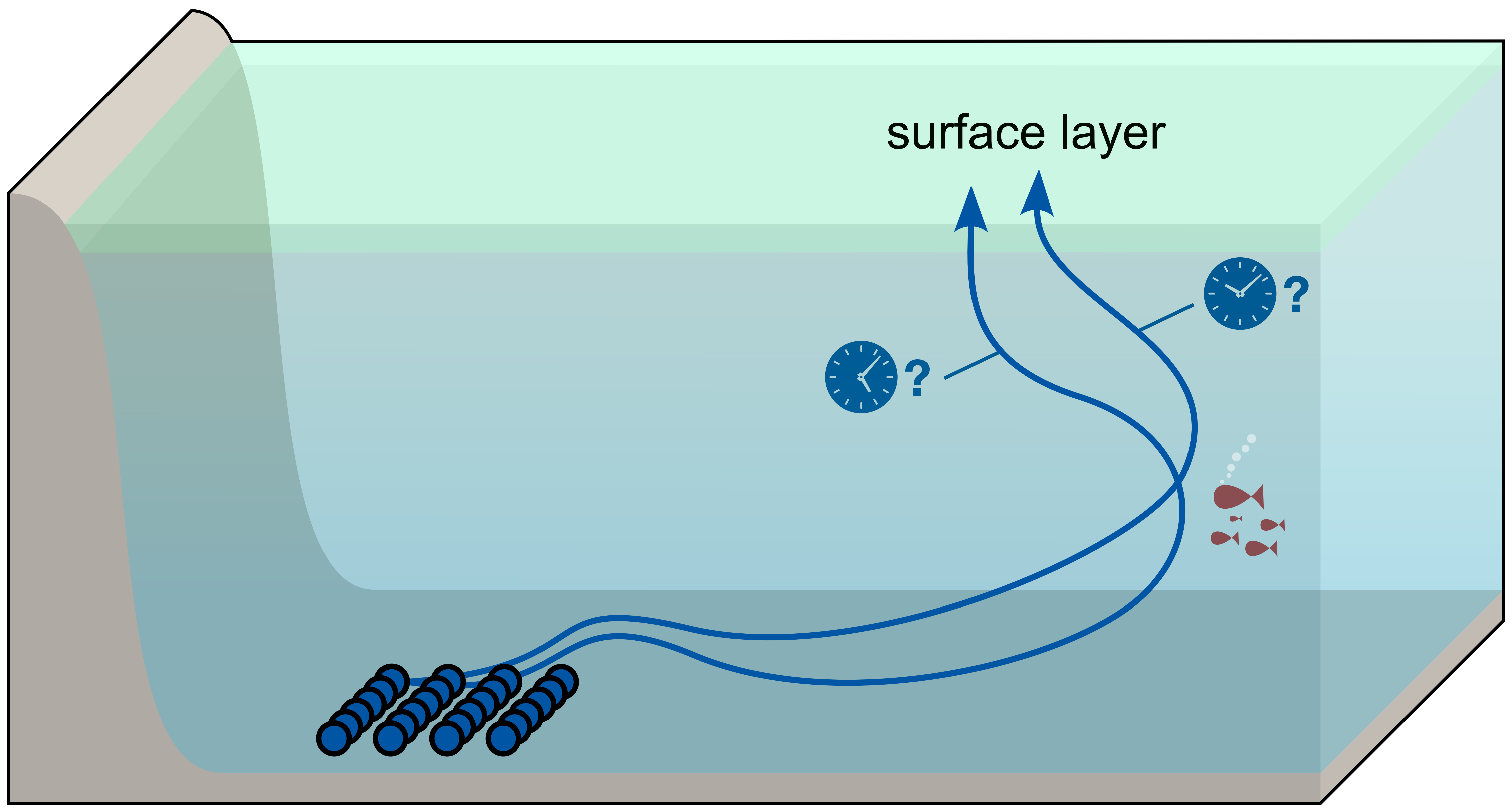

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Transport matrix

Tracer equation

tracer tendency

transport

sum of sources and sinks

$$\frac{\partial c}{\partial t} + \overbrace{\boldsymbol{u} \cdot \nabla c - \nabla \cdot \mathbf{K} \nabla c}^{\mathscr{T}\, c} = s$$

transport operator

$$\mathscr{T} \equiv \boldsymbol{u} \cdot \nabla - \nabla \cdot \mathbf{K} \nabla$$

advection
resolved + param.

diffusivity tensor

Transport matrix

3D field c $\longleftrightarrow$ column vector $\boldsymbol{c}$

Tracer equation

tracer tendency

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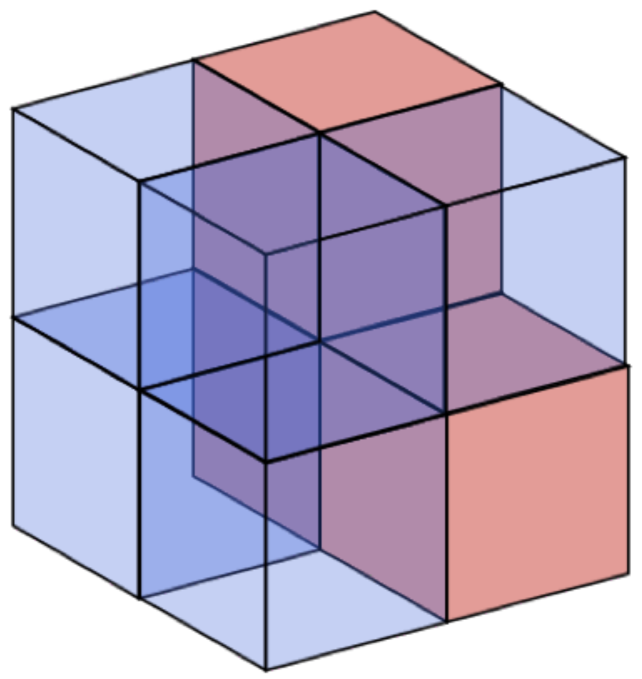
sum of sources and sinks

$$\underbrace{\frac{\partial c}{\partial t}}_{\text{tracer tendency}} + \overbrace{\boldsymbol{u}\cdot\nabla c - \nabla\cdot\mathbf{K}\nabla c}^{\mathscr{T} c} = s$$



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diffusivity tensor

linear operator $\mathscr{T}$ $\longleftrightarrow$ matrix $\mathbf{T}$

Matrix equation

$$\frac{\partial \boldsymbol{c}}{\partial t} + \mathbf{T}\,\boldsymbol{c} = \boldsymbol{s}$$

Transport matrix

3D field c $\longleftrightarrow$ column vector $\boldsymbol{c}$

Tracer equation

tracer tendency

transport $\mathscr{T}\,c$

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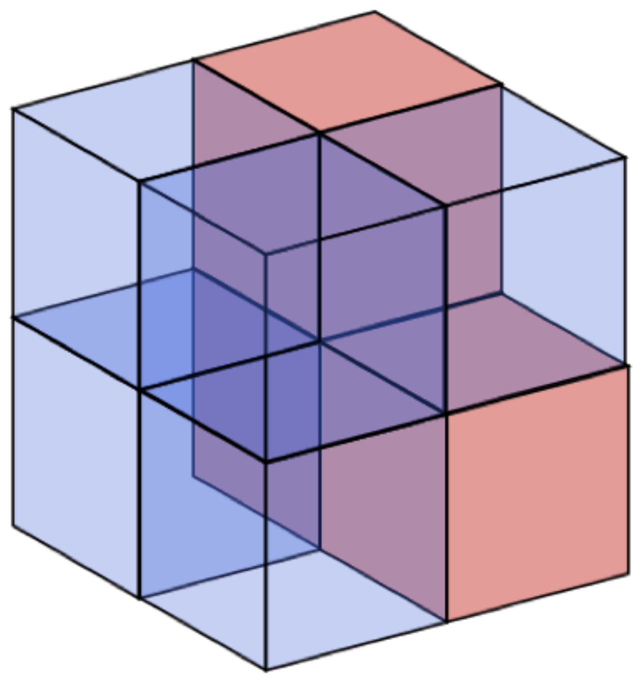

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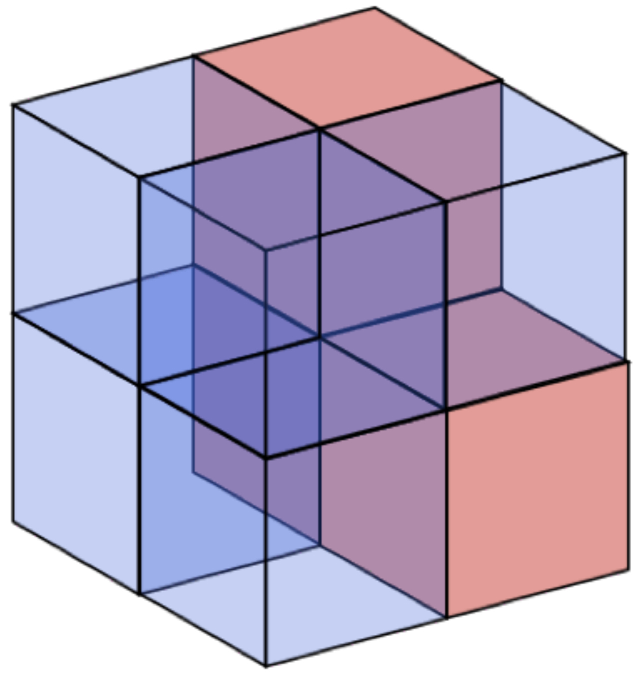

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from archives

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calibrated constants
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Chamberlain et al. (2019)

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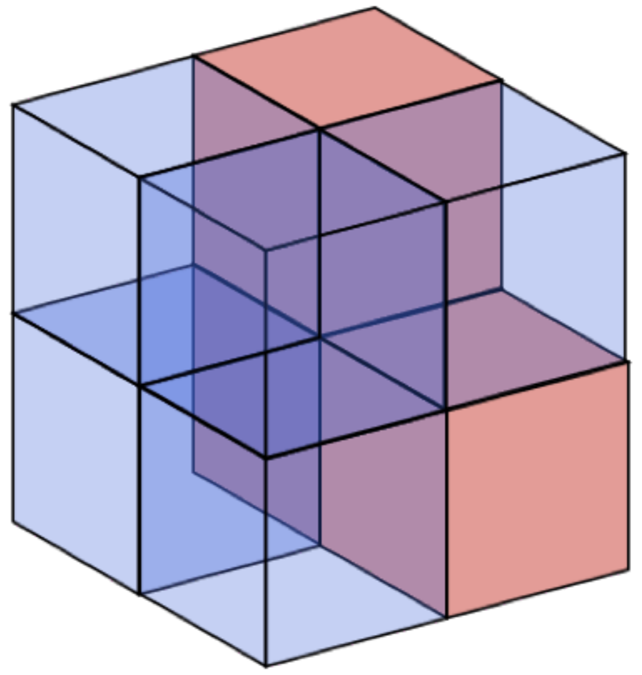

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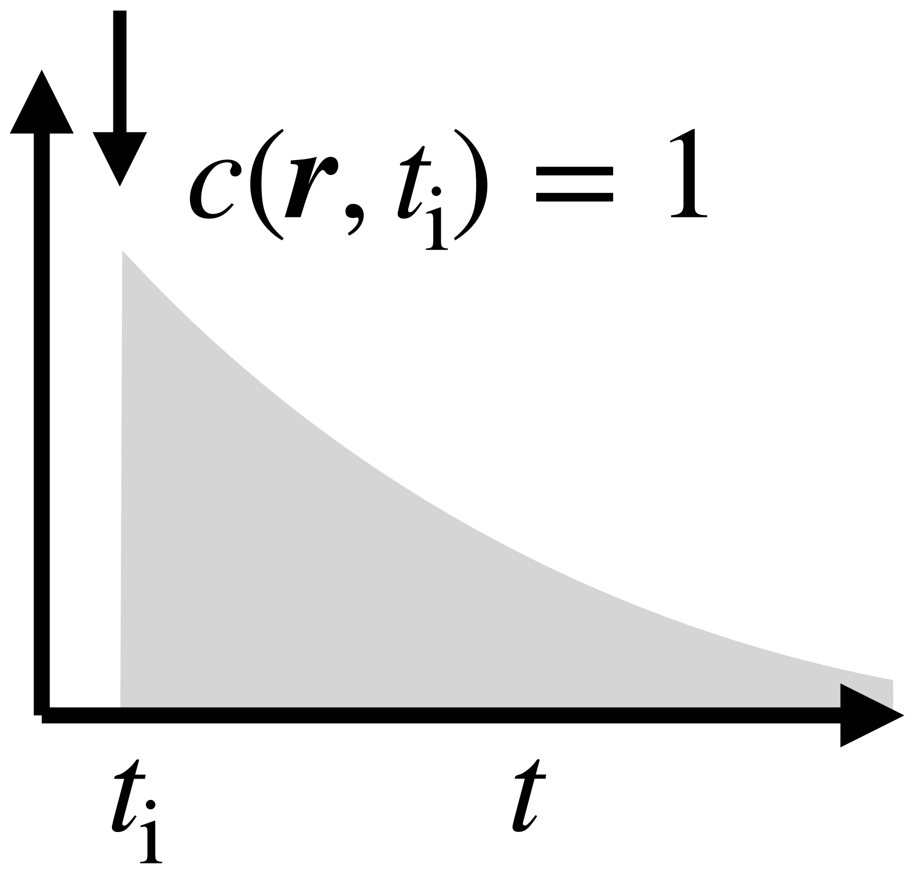
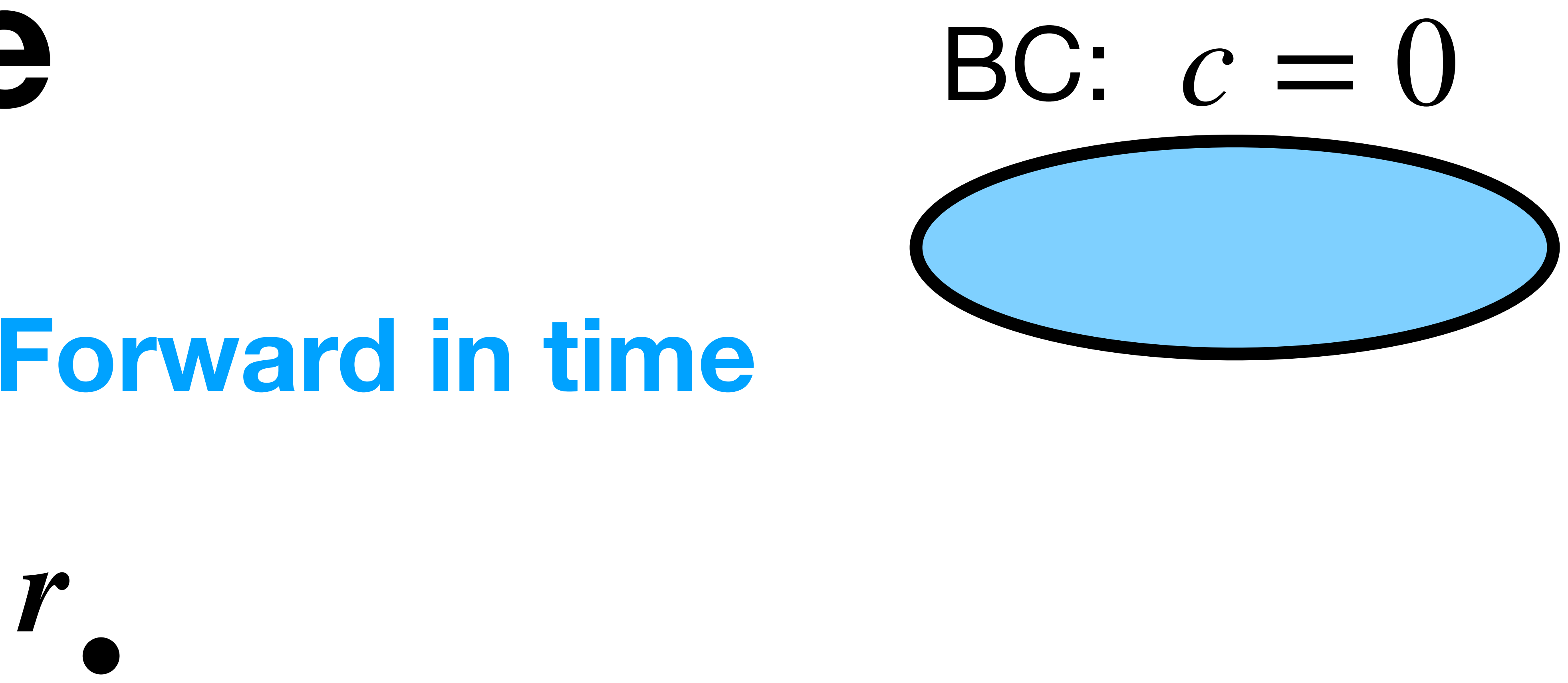
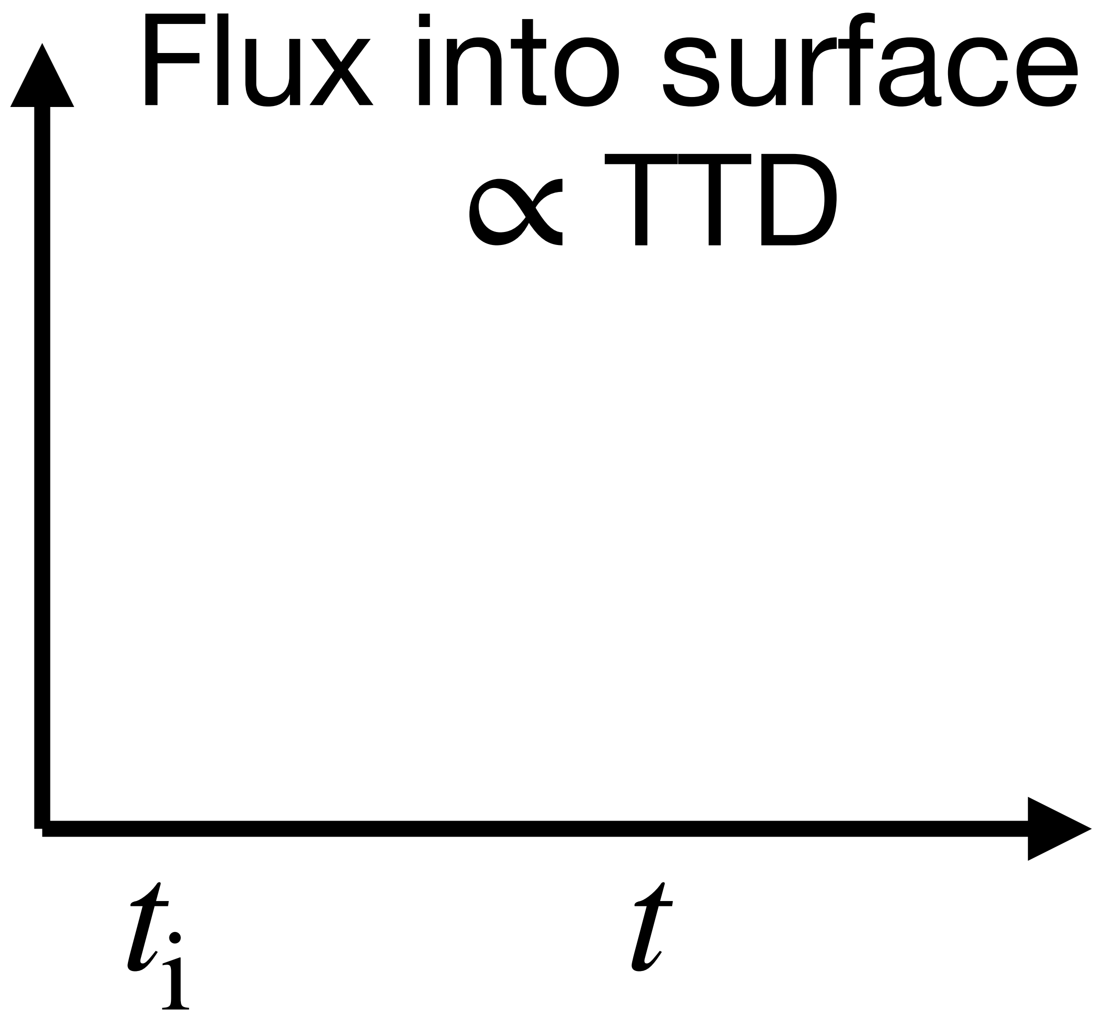
Classical Dye

Unit-mass injection:



Forward in time





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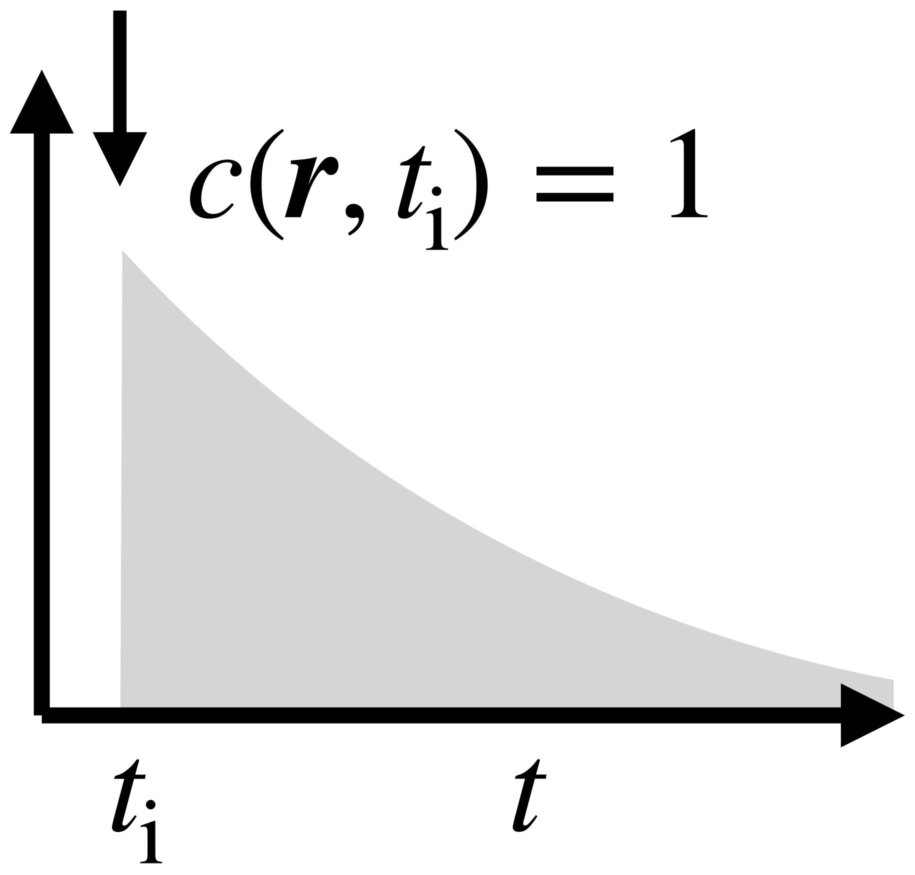

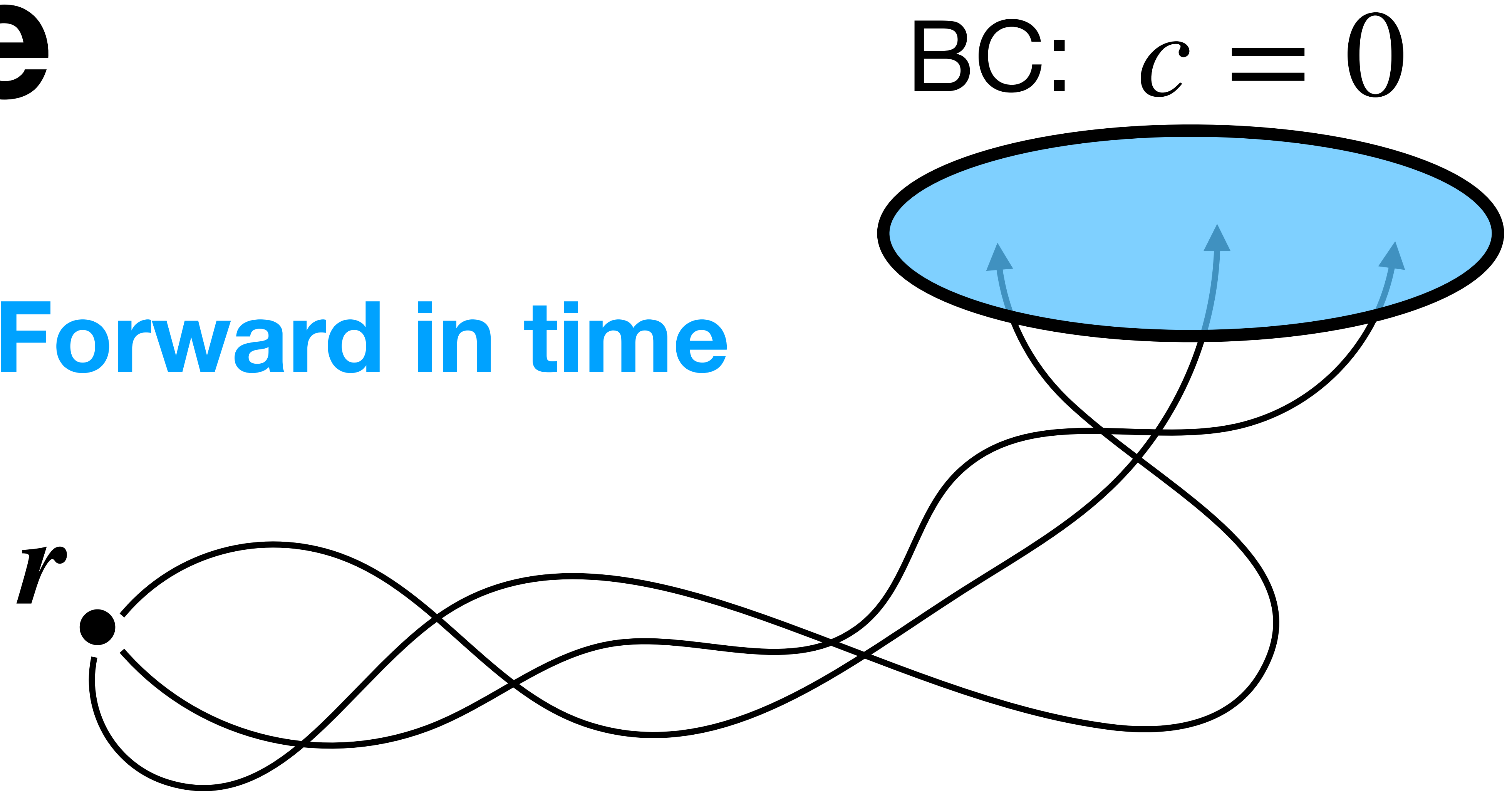

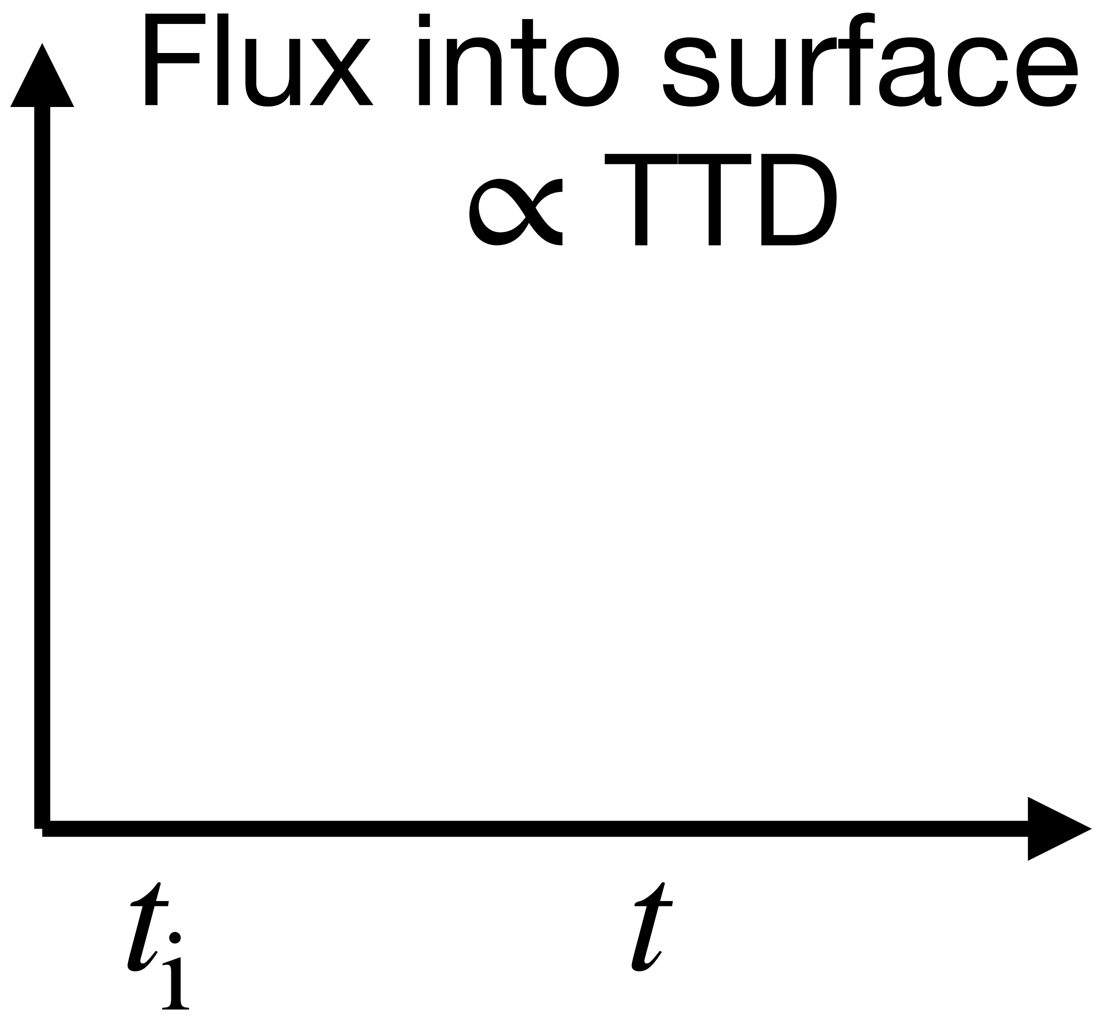

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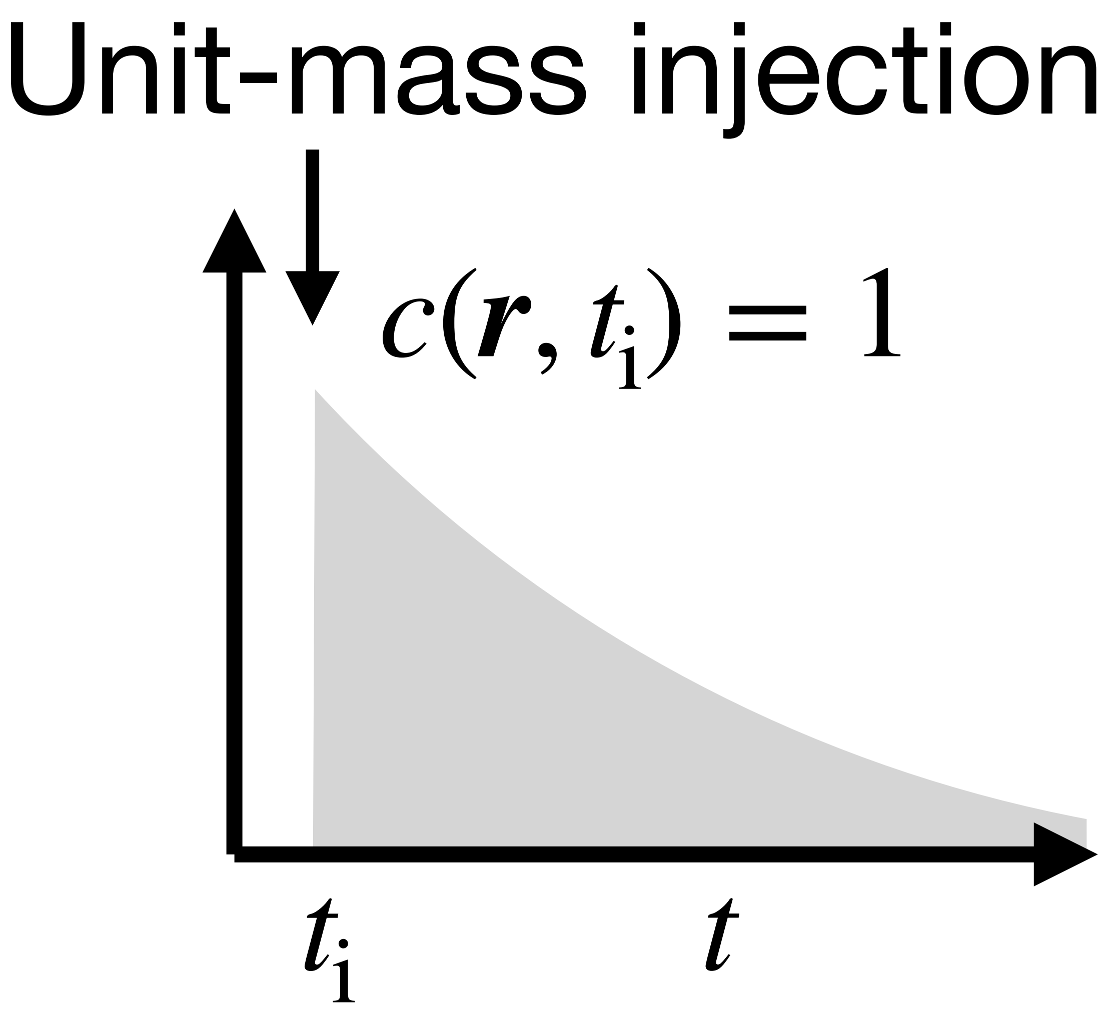

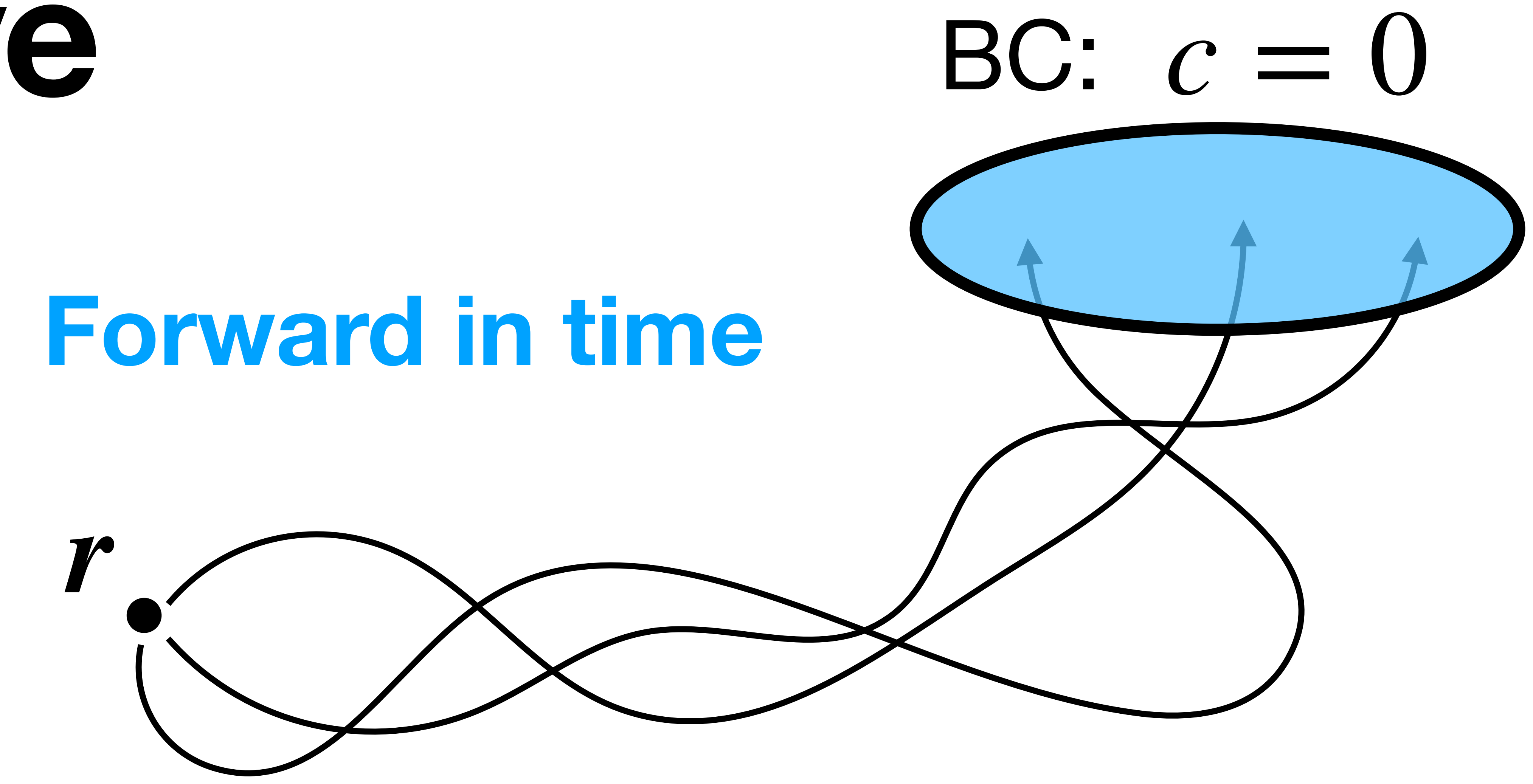

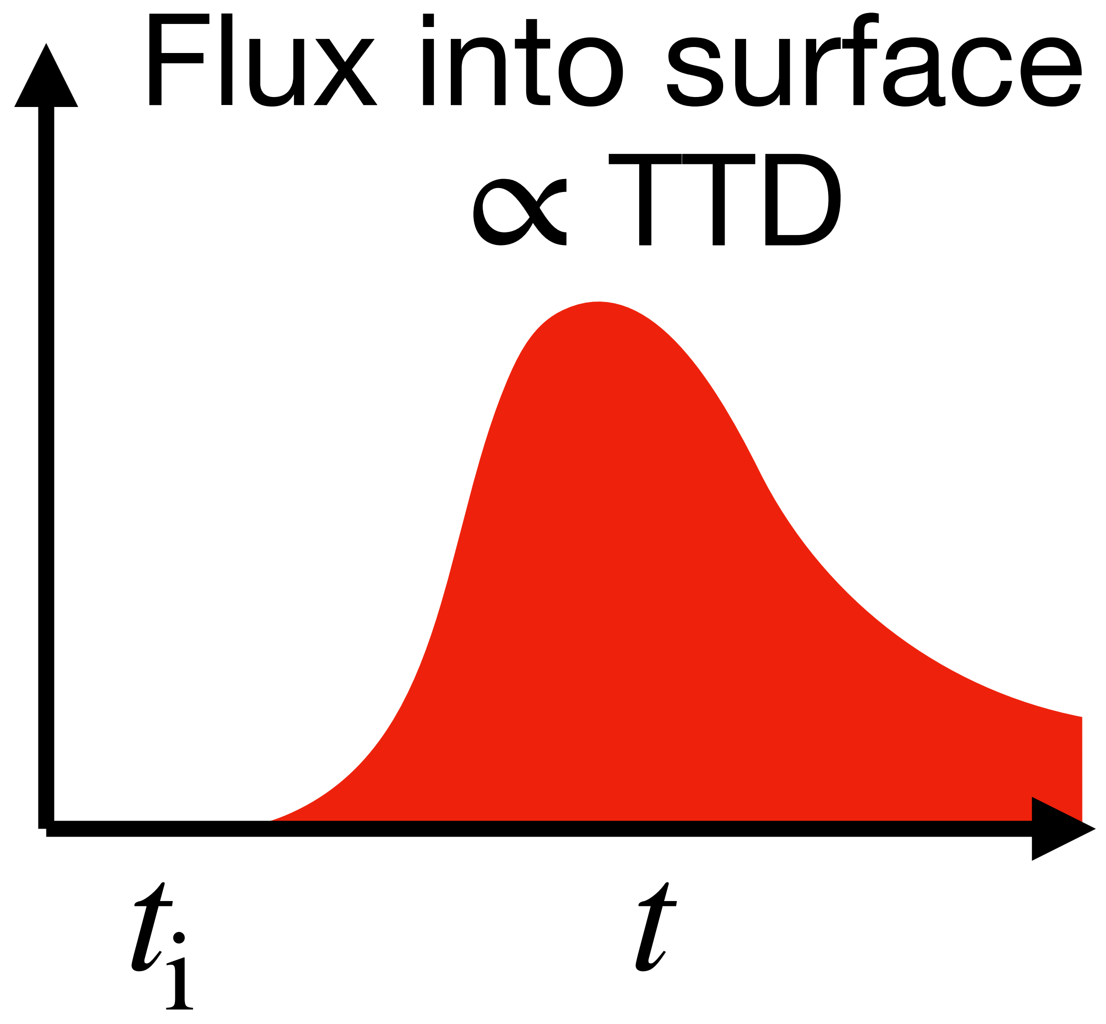

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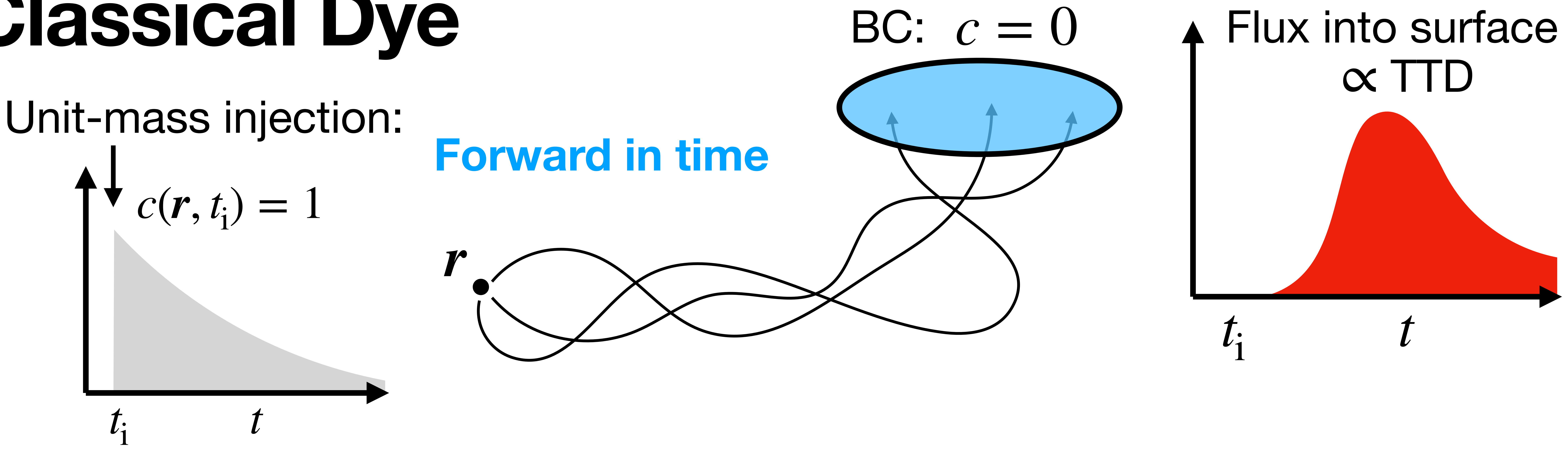
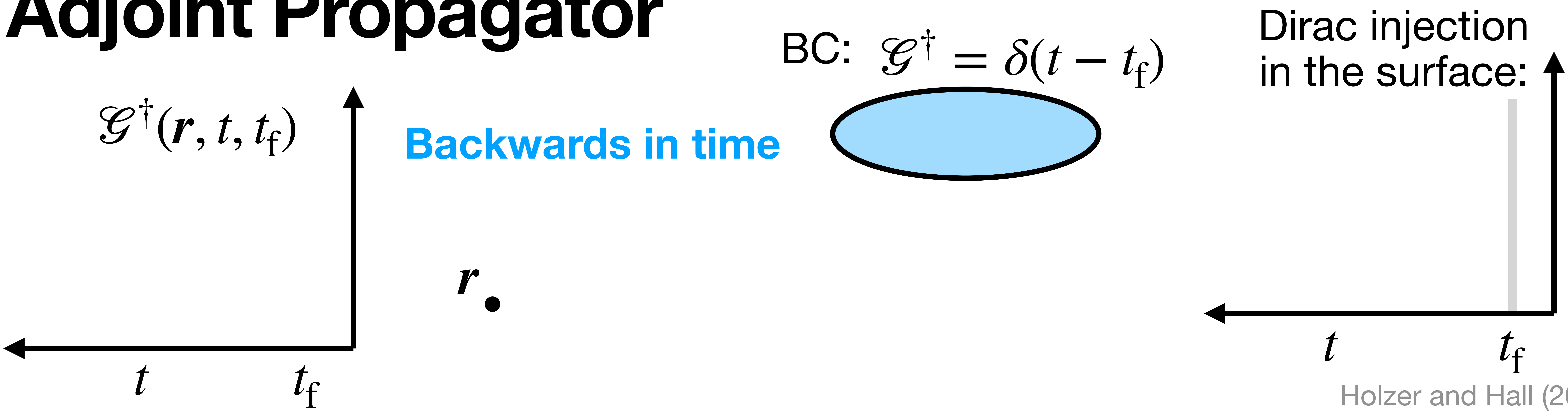
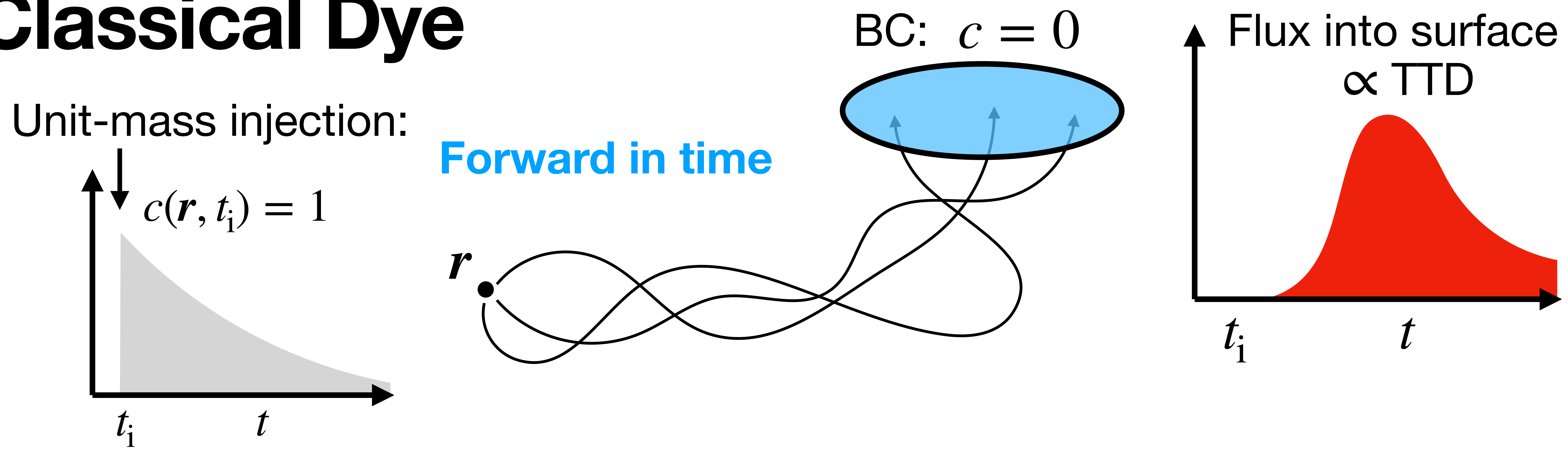


Adjoint Propagator



Holzer and Hall (2000)

Classical Dye



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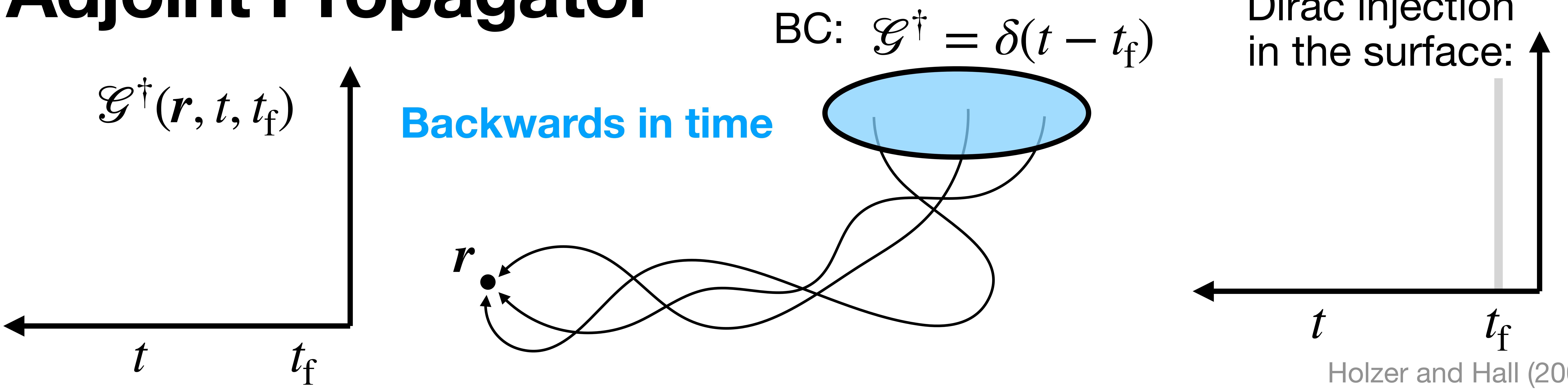

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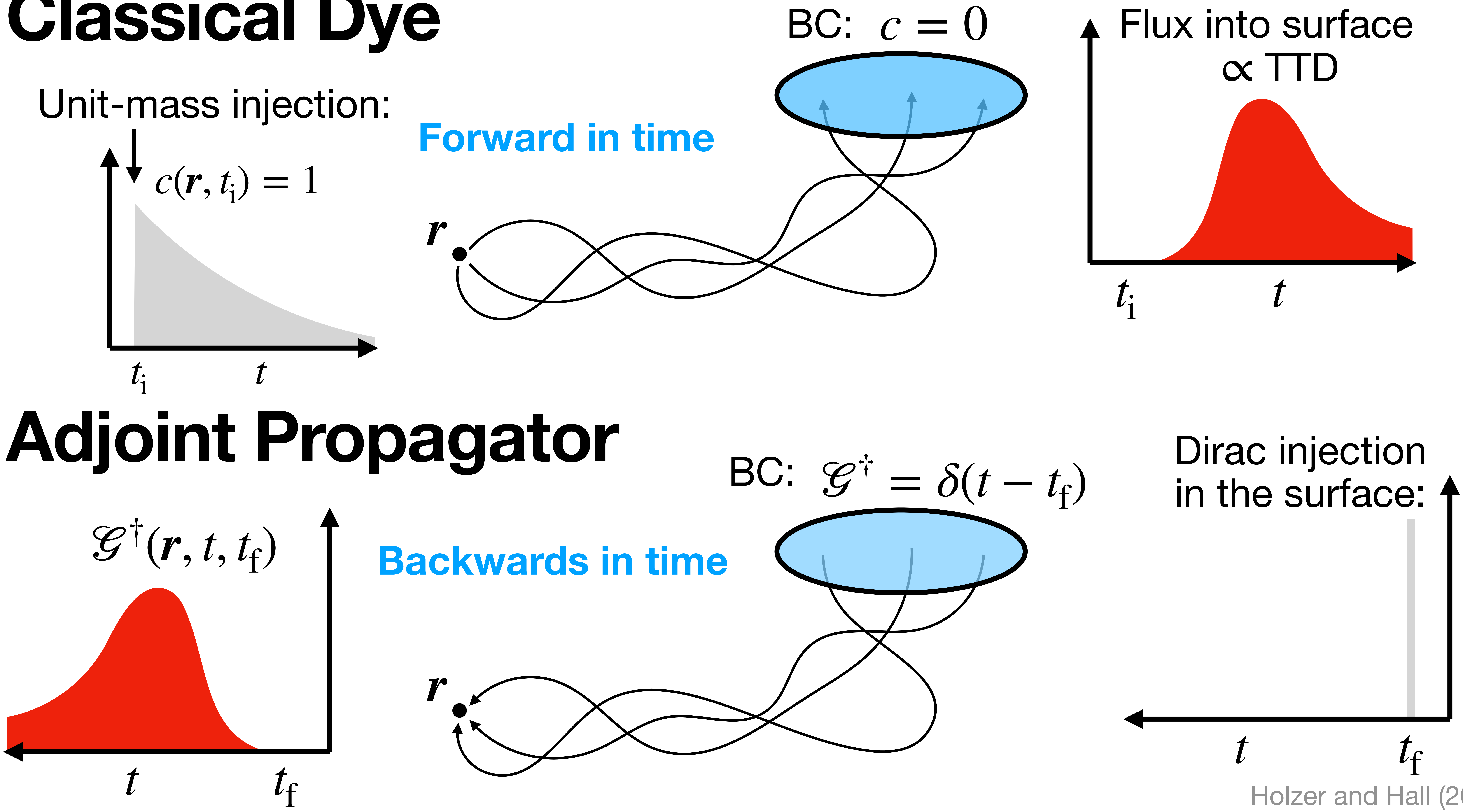

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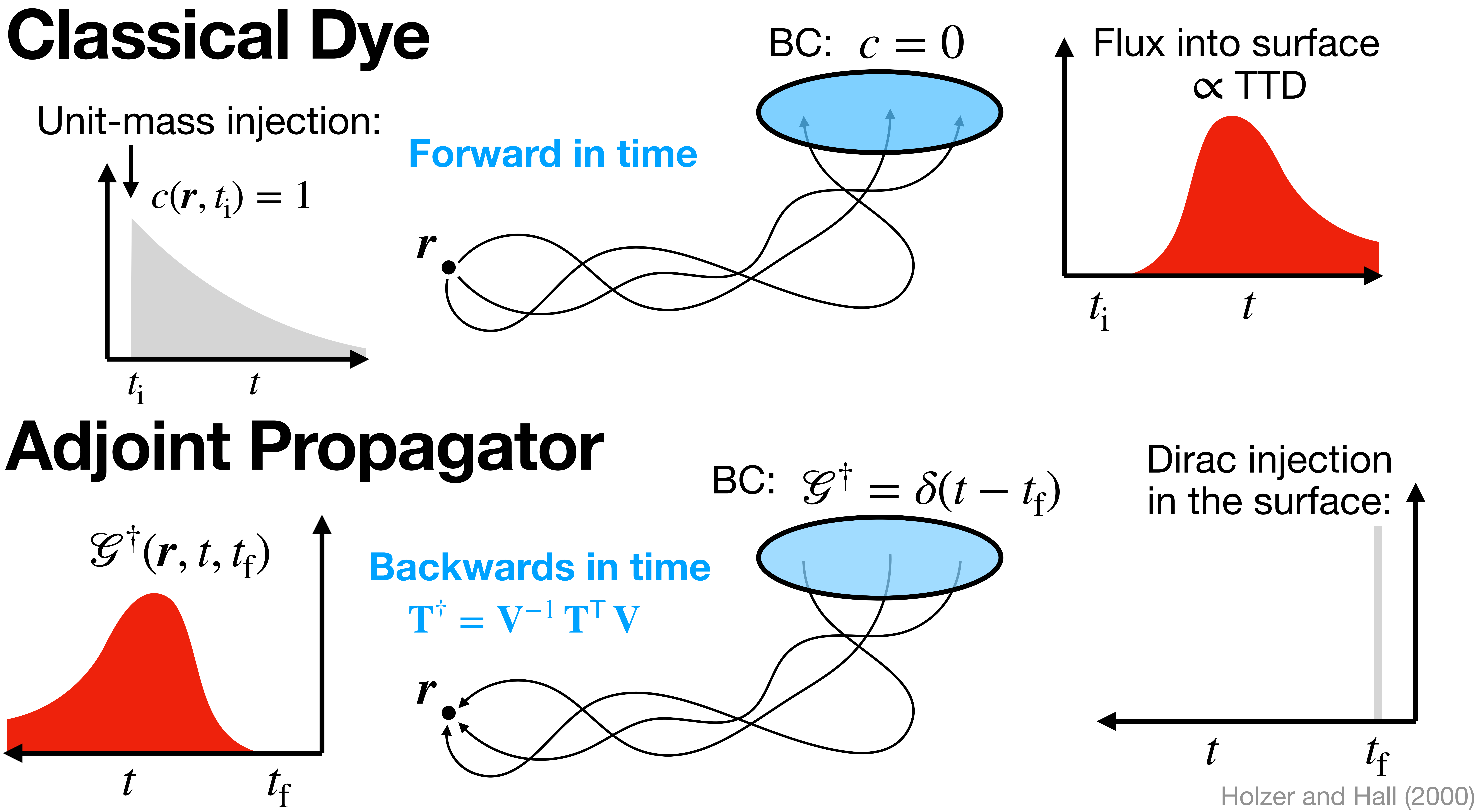

Classical Dye
Unit-mass injection:
$c(\boldsymbol{r}, t_\mathrm{i}) = 1$
t_i
t
Forward in time
$\boldsymbol{r}$
BC: $c = 0$
Flux into surface
∝ TTD
t_i
t
Adjoint Propagator
$\mathscr{G}^\dagger(\boldsymbol{r}, t, t_\mathrm{f})$
t
t_f
Backwards in time
$\mathbf{T}^\dagger = \mathbf{V}^{-1}\,\mathbf{T}^\intercal\,\mathbf{V}$
$\boldsymbol{r}$
BC: $\mathscr{G}^\dagger = \delta(t - t_\mathrm{f})$
Dirac injection
in the surface:
t
t_f
Holzer and Hall (2000)

Framework

ACCESS-ESM1.5
CMIP6 archives

+ CSIRO archives

Framework

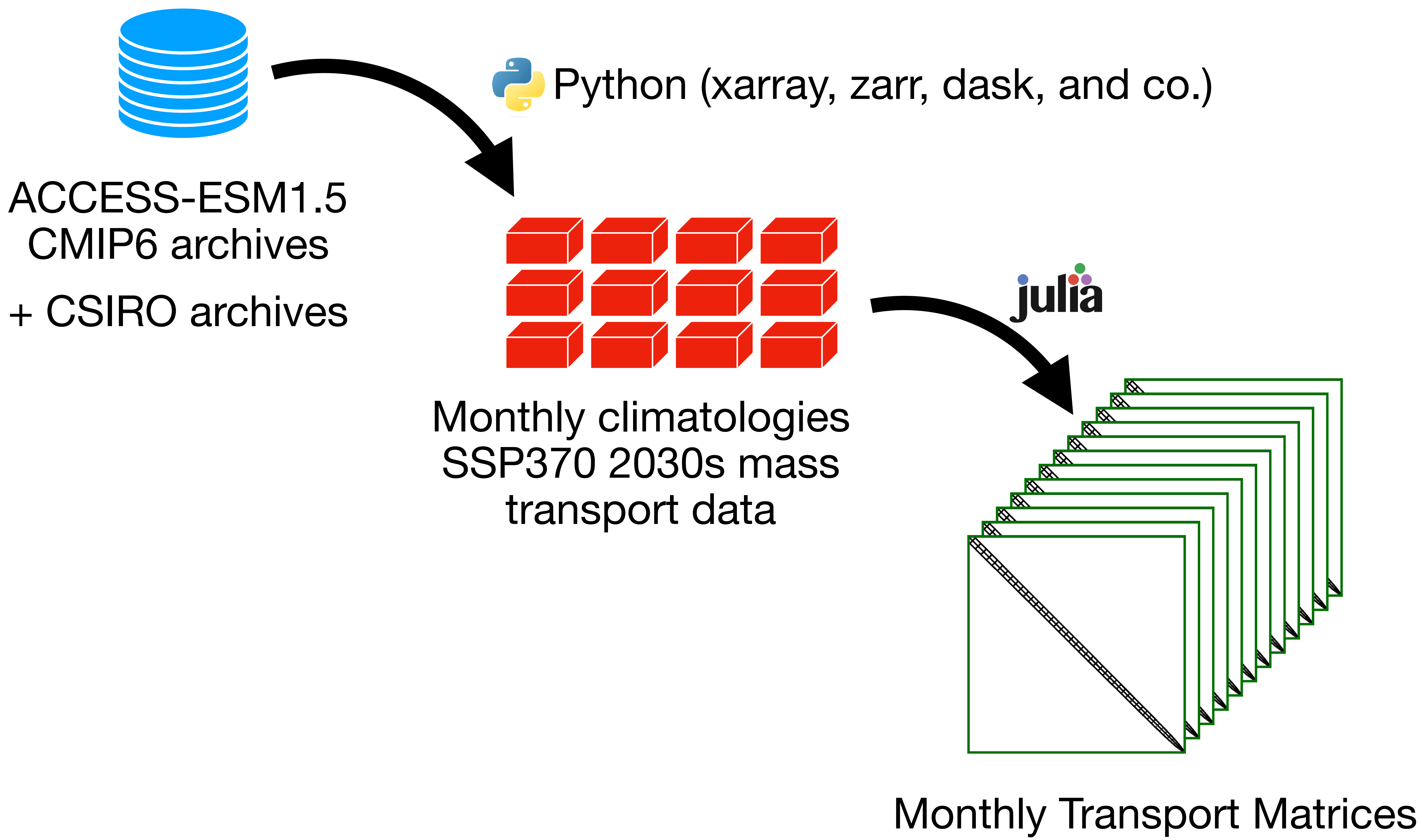
Python (xarray, zarr, dask, and co.)

ACCESS-ESM1.5
CMIP6 archives

+ CSIRO archives

Monthly climatologies
SSP370 2030s mass
transport data

Framework



Chamberlain et al. (2019)

https://github.com/TMIP-code/OceanTransportMatrixBuilder.jl

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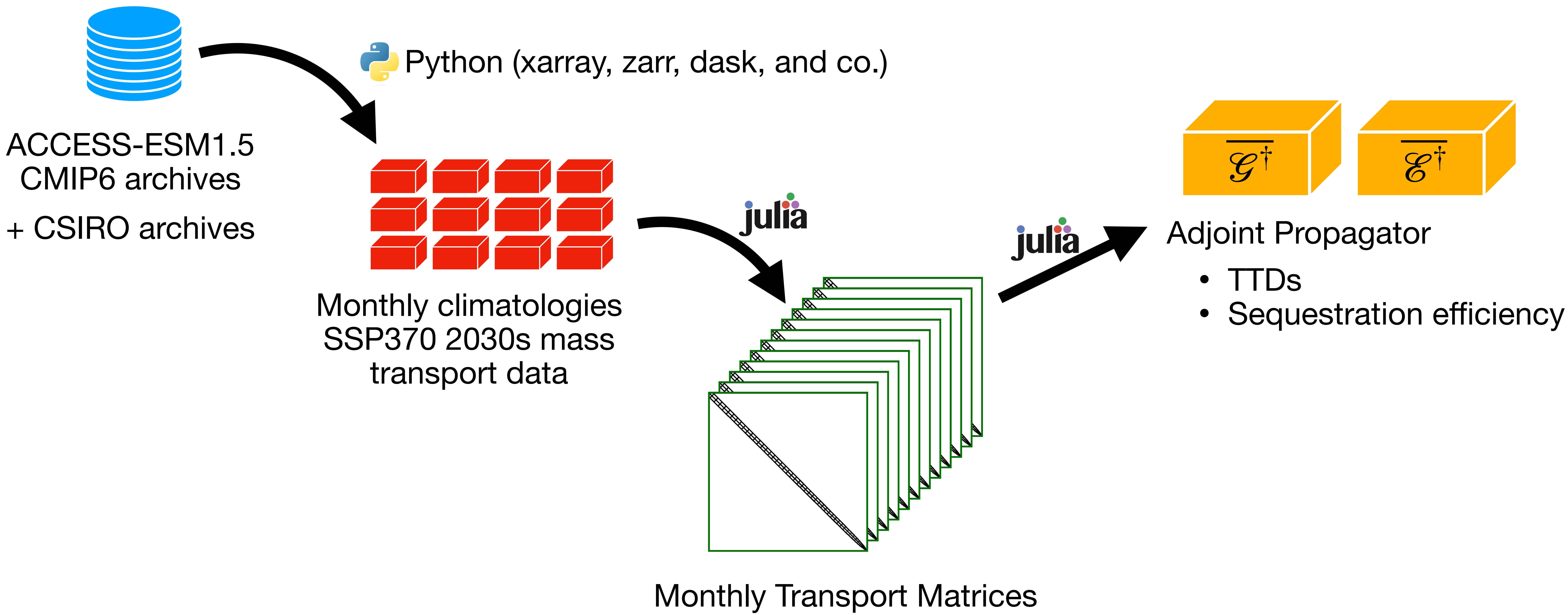

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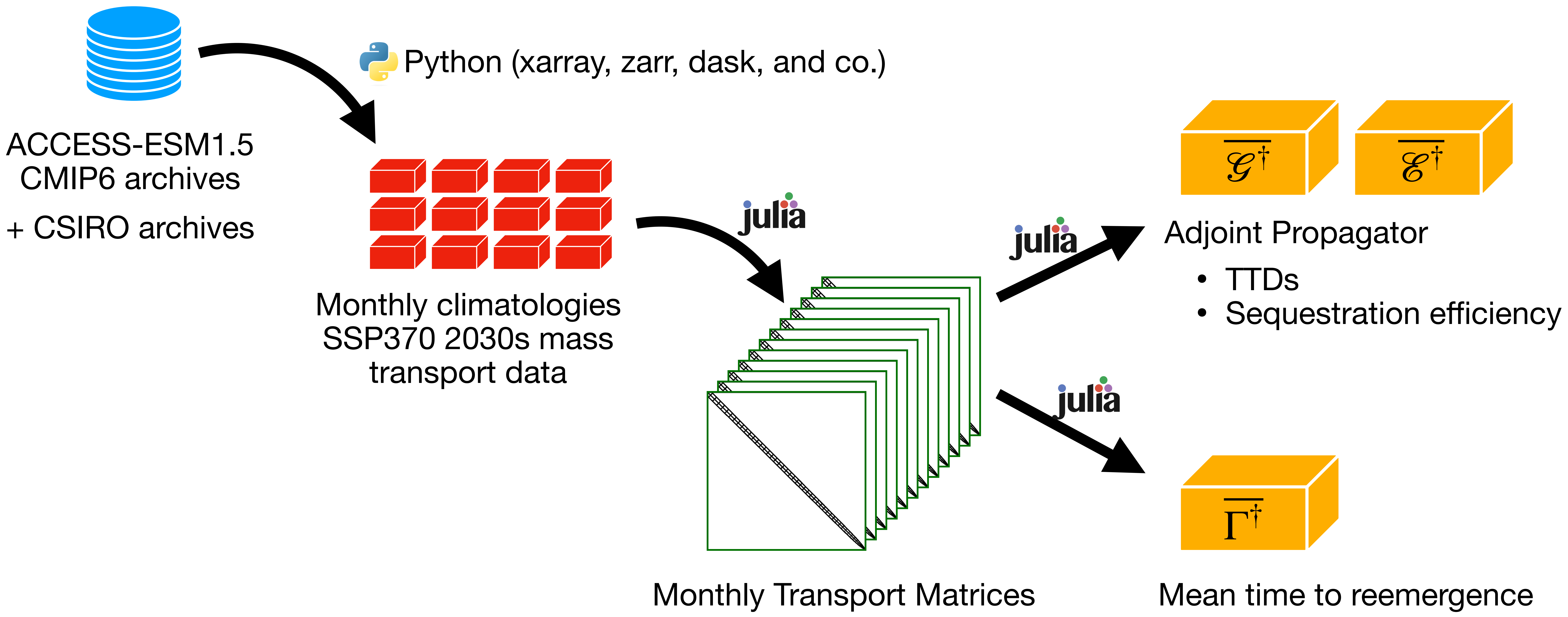

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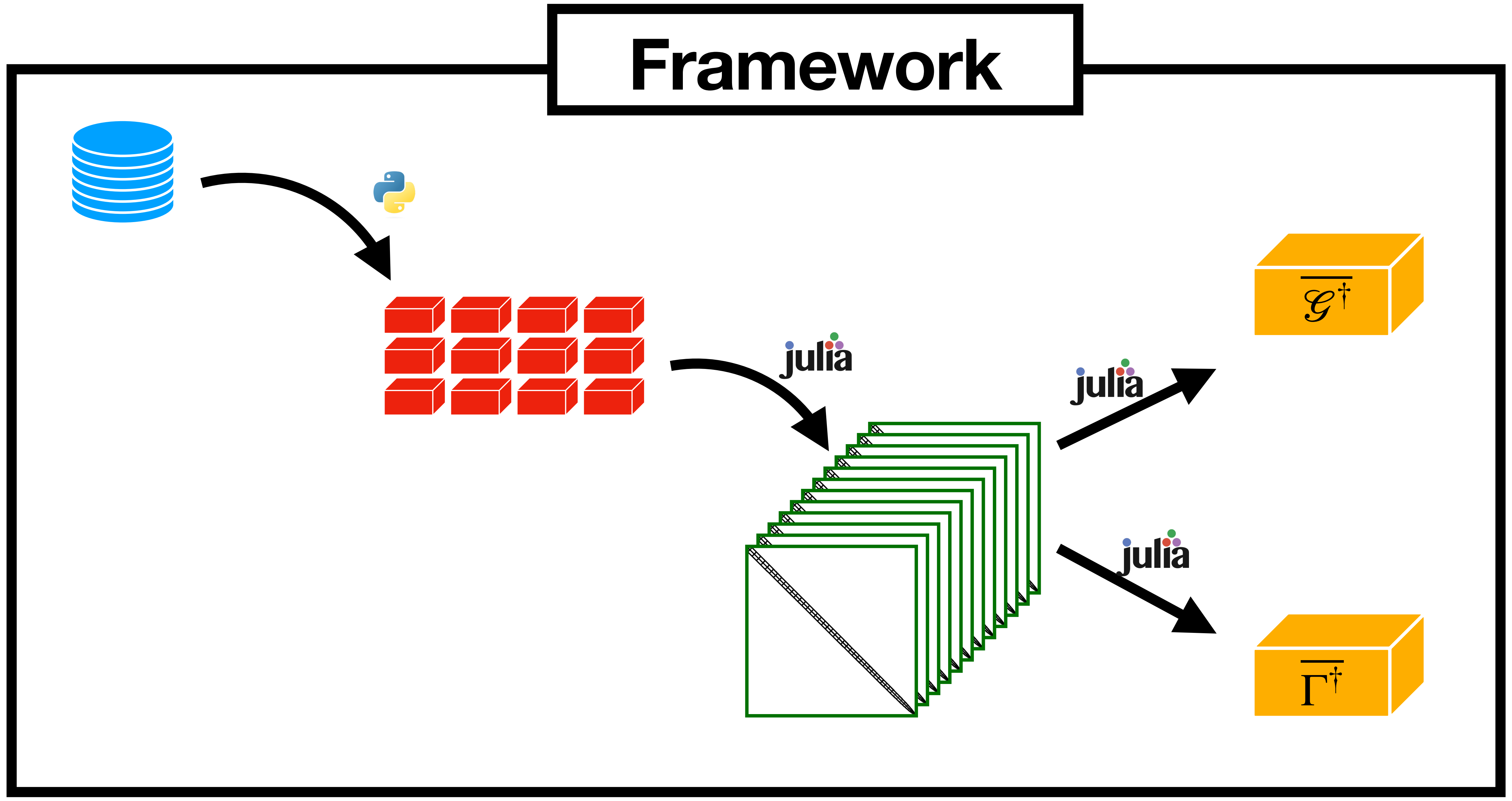
For Climate variability



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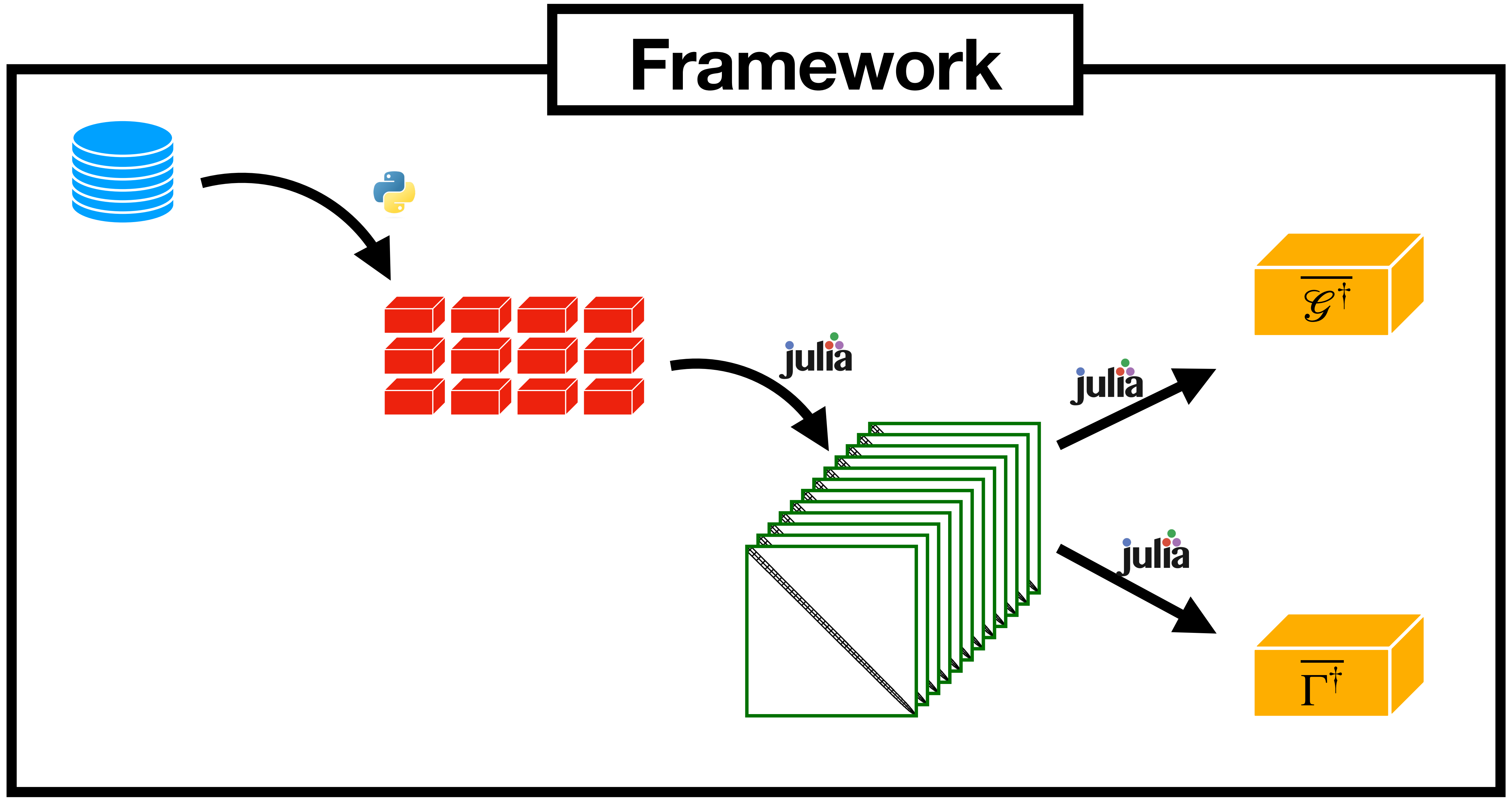

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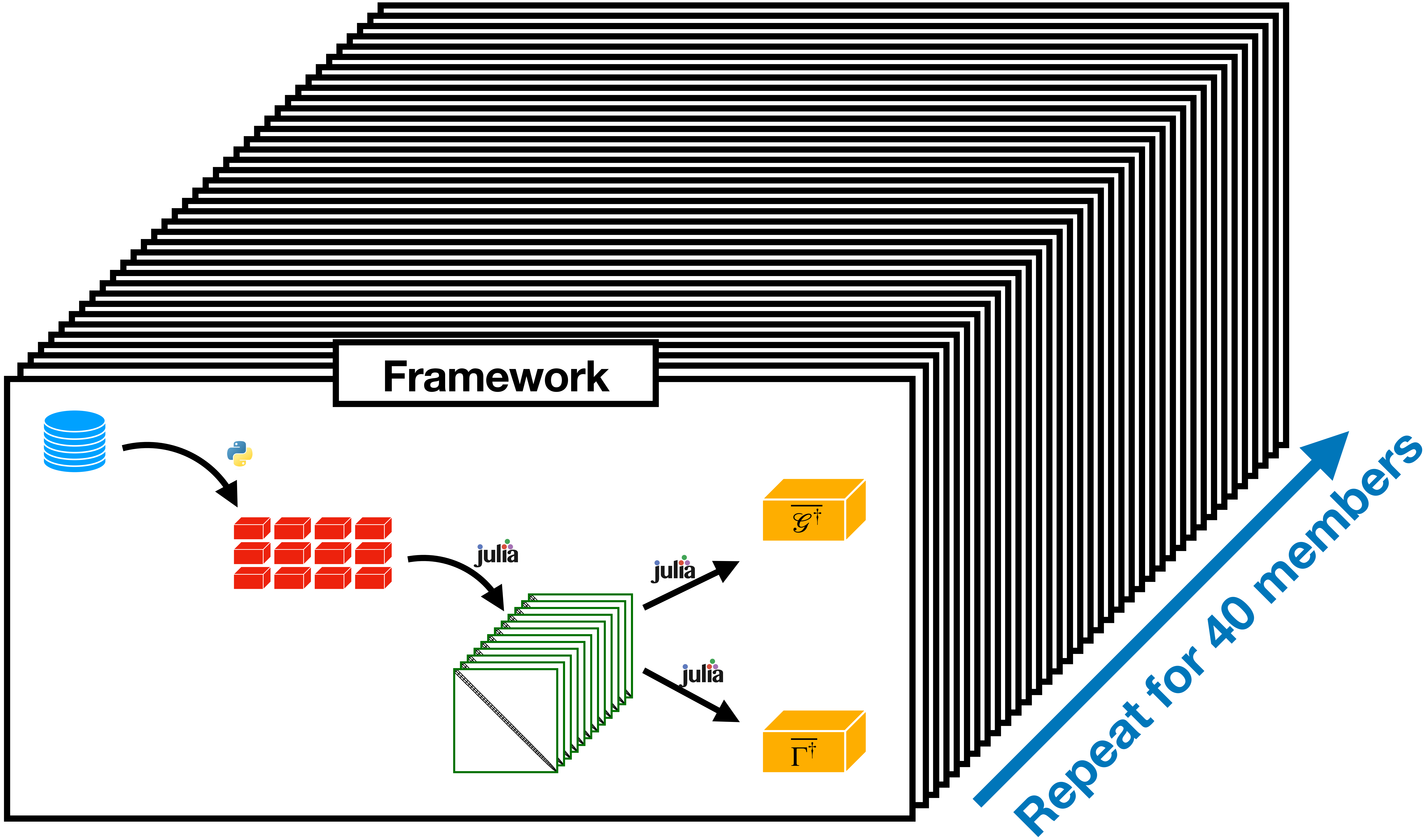
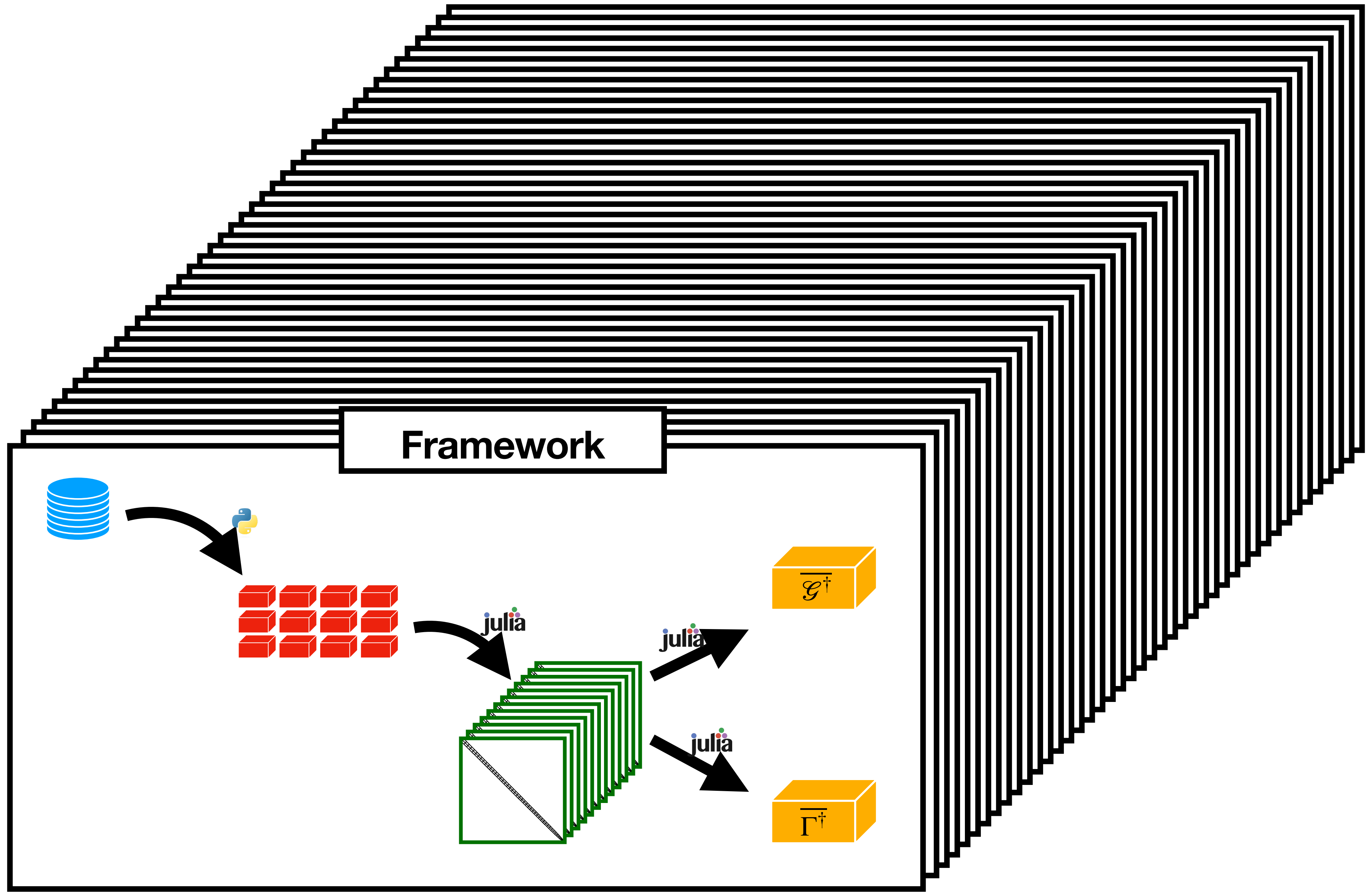


For Climate change effect

SSP370 2030s



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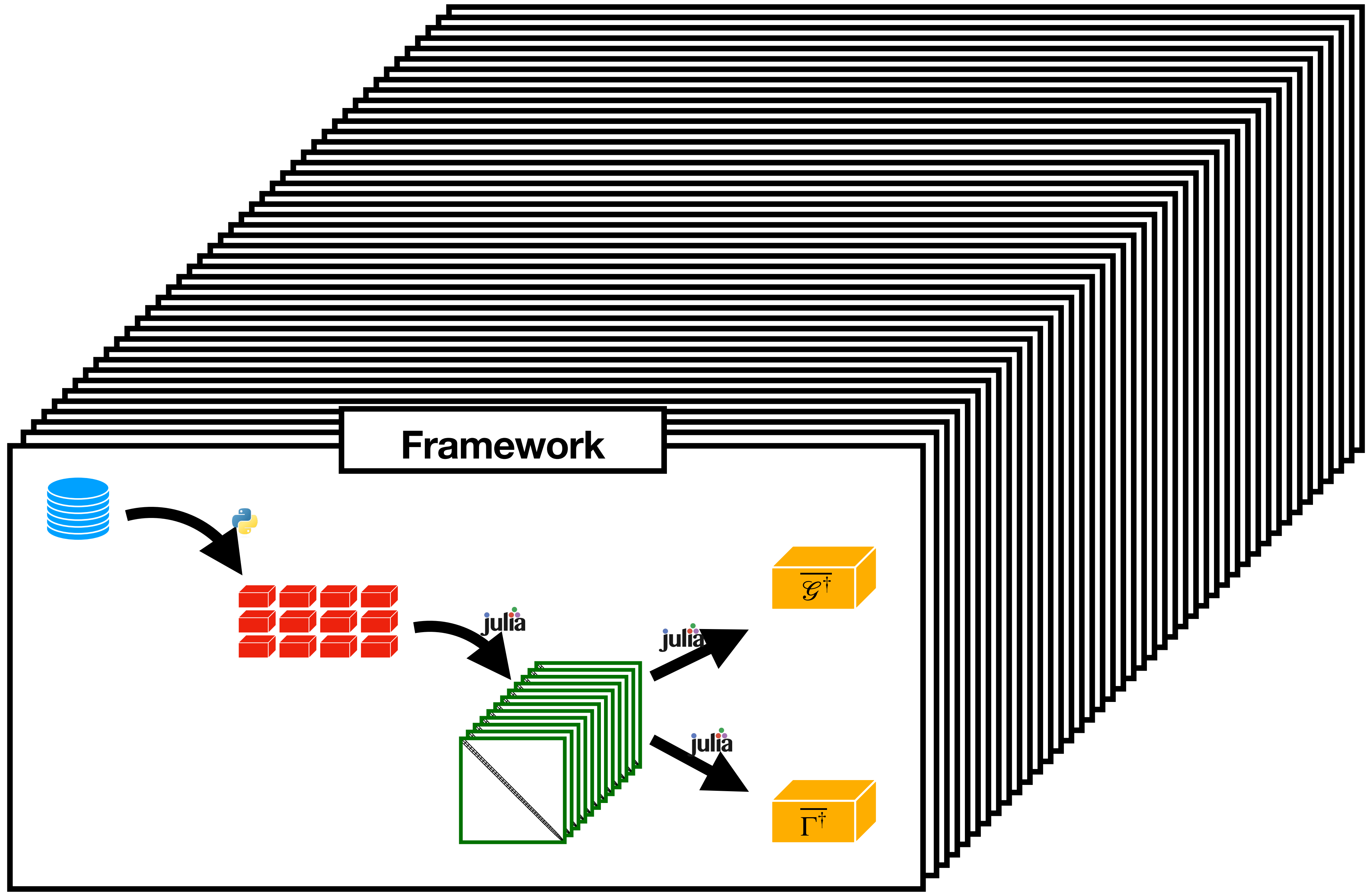

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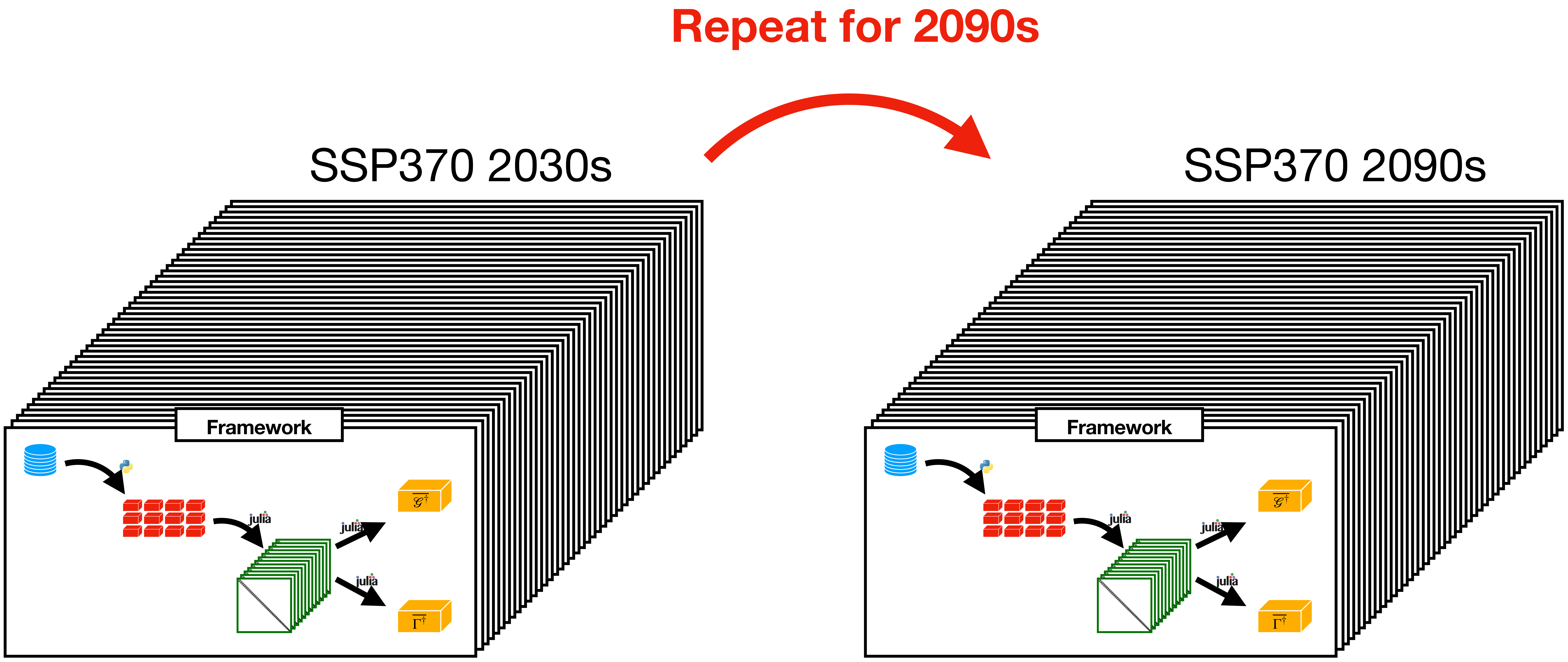

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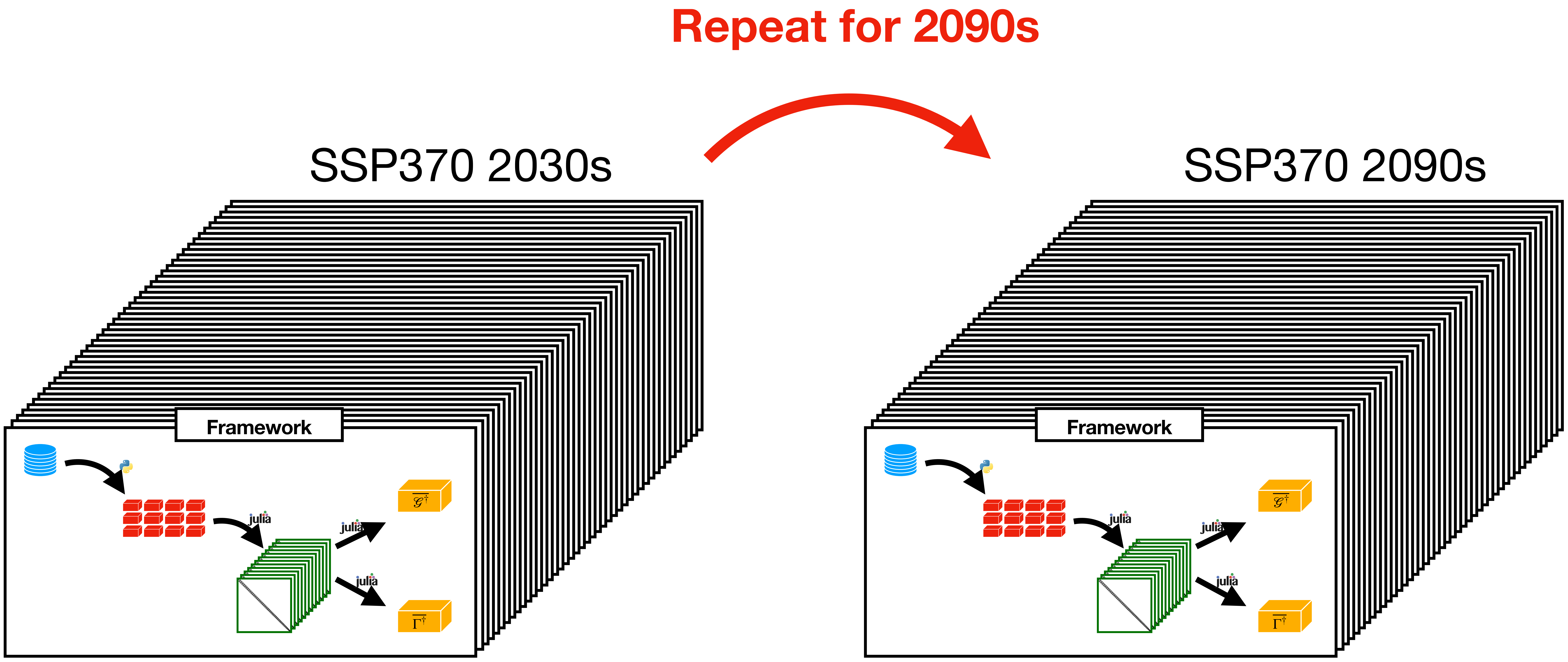
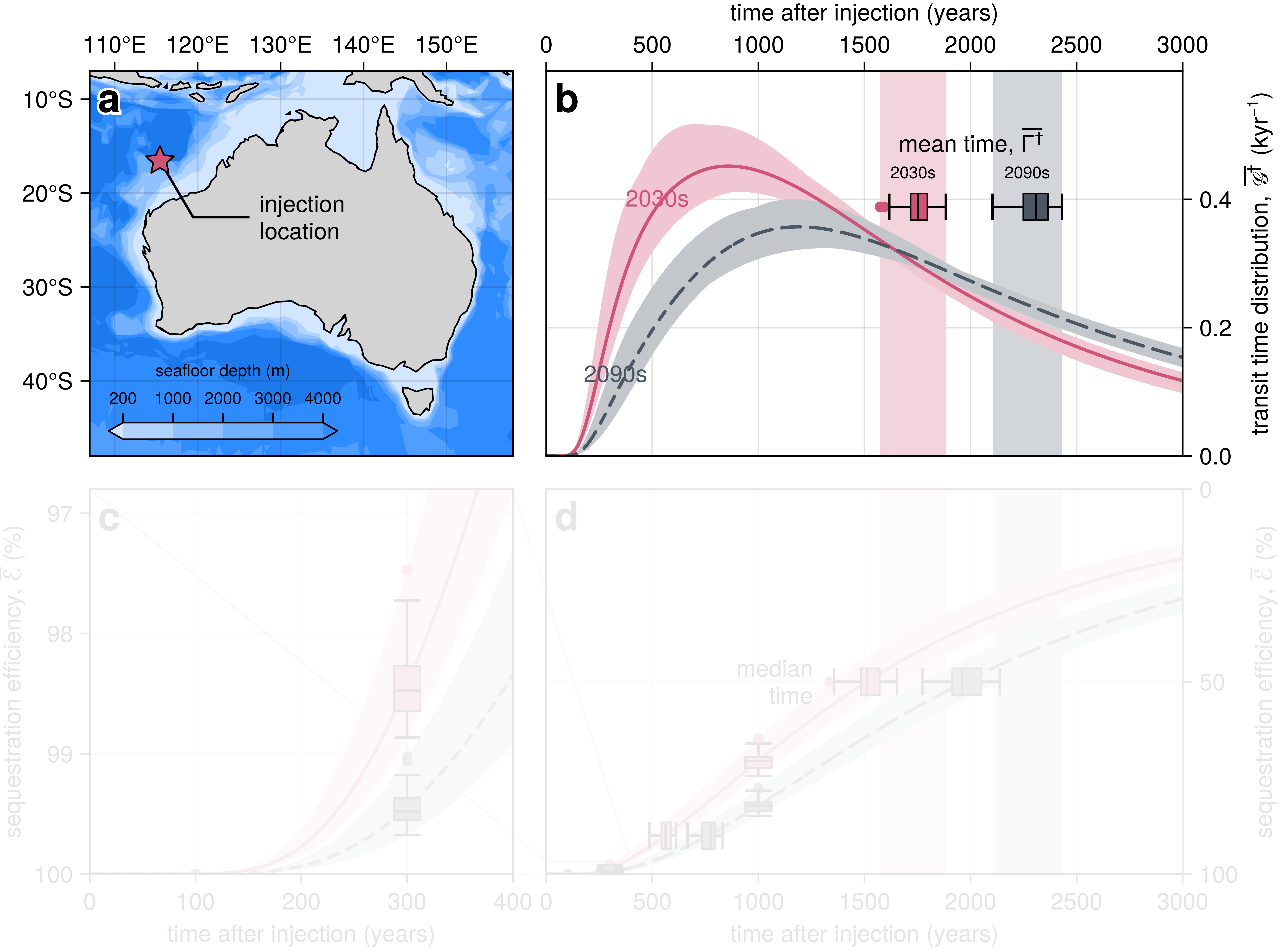
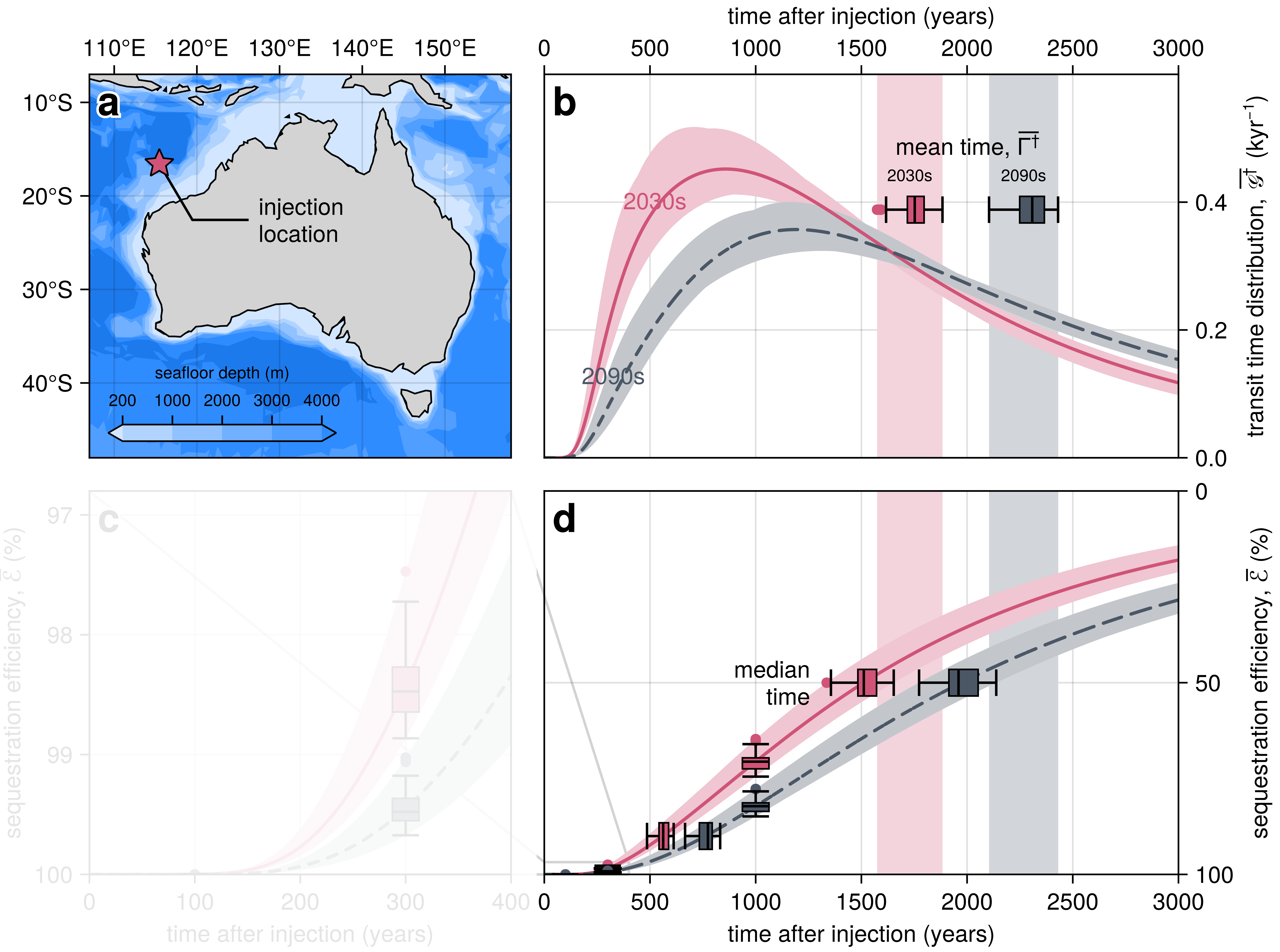


Run on Gadi… Thanks NCI!



Seafloor to Surface Transit-Time Distribution (TTD)

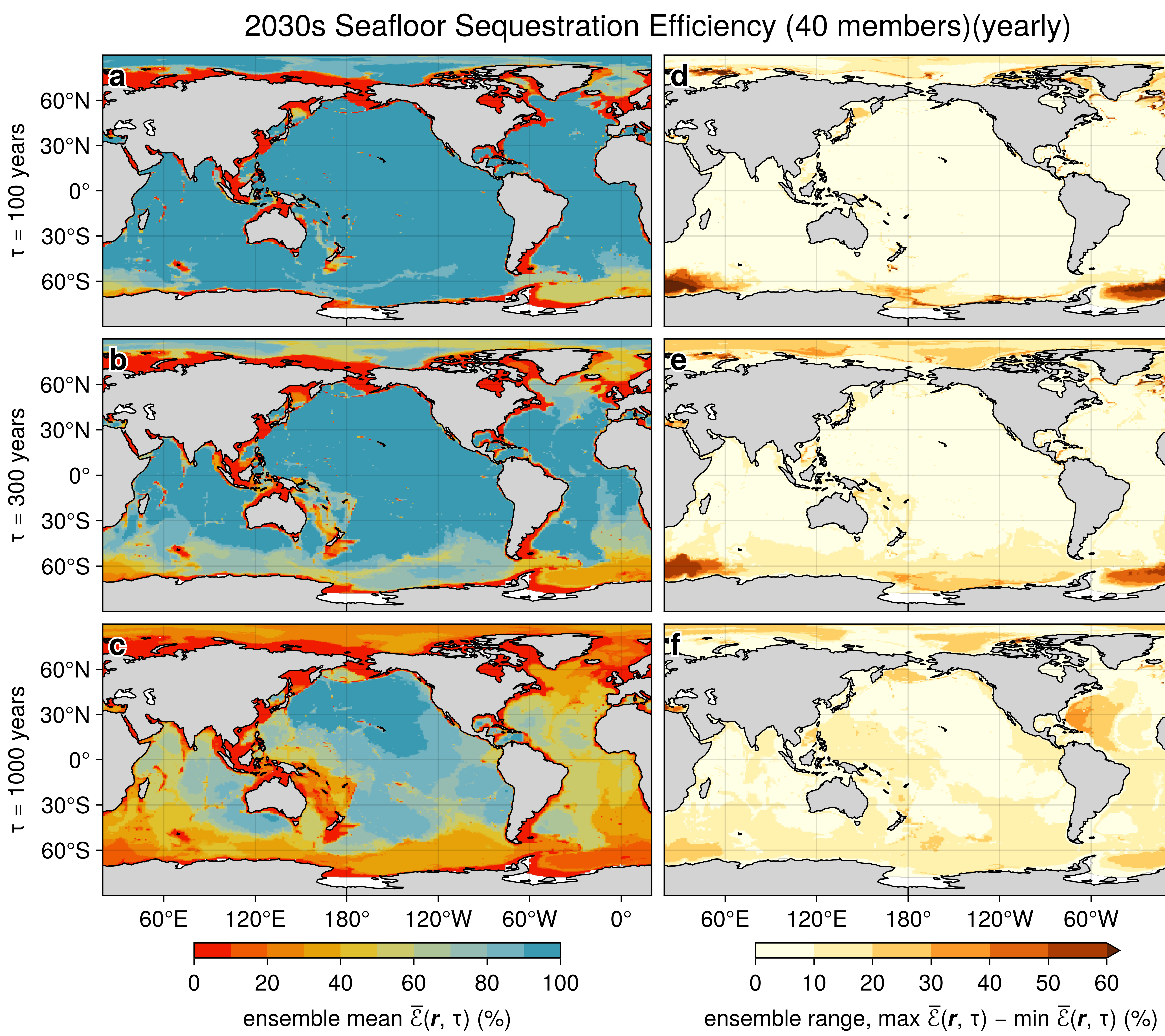


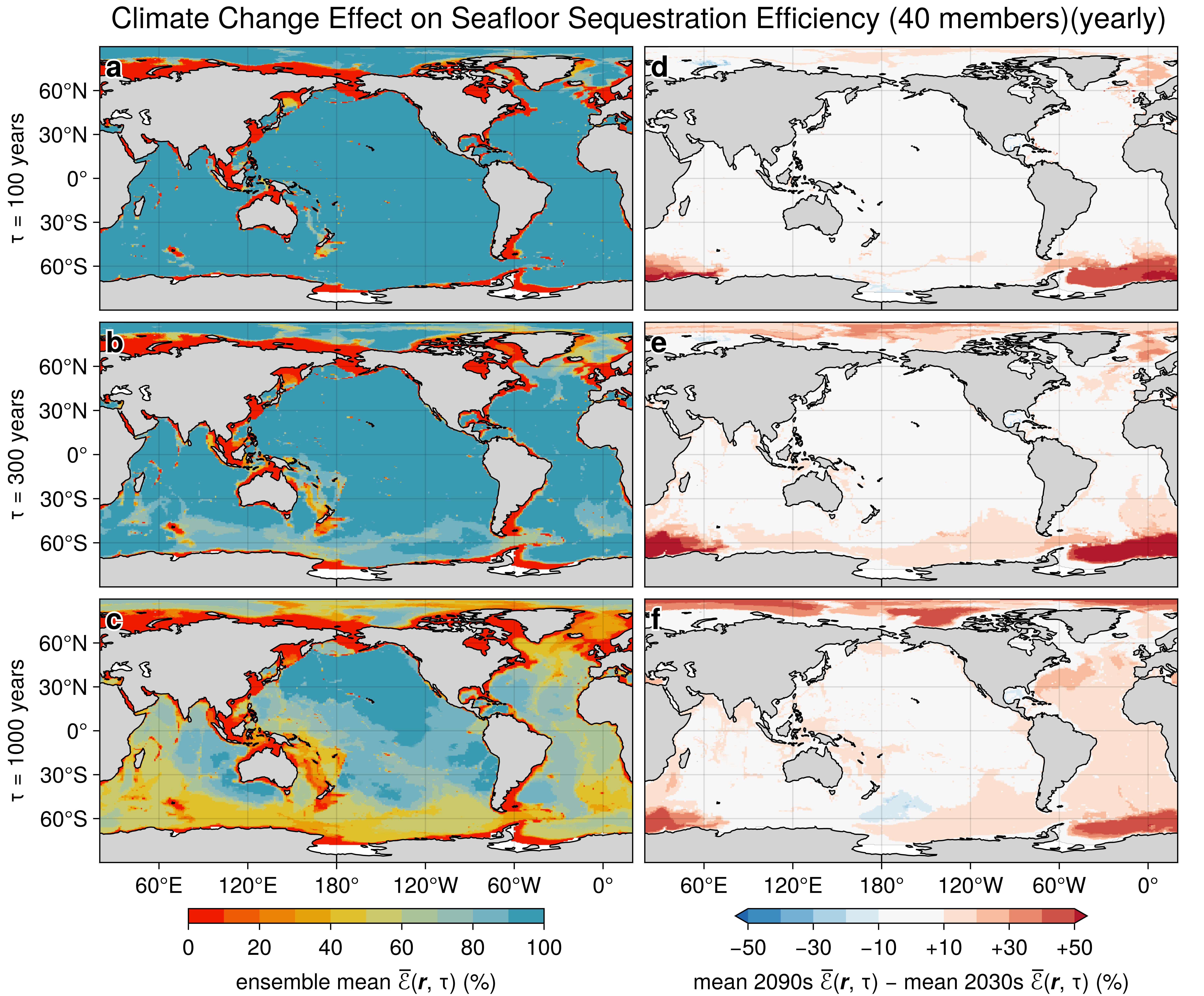
Seafloor to Surface Transit-Time Distribution (TTD)

The Sequestration Efficiency

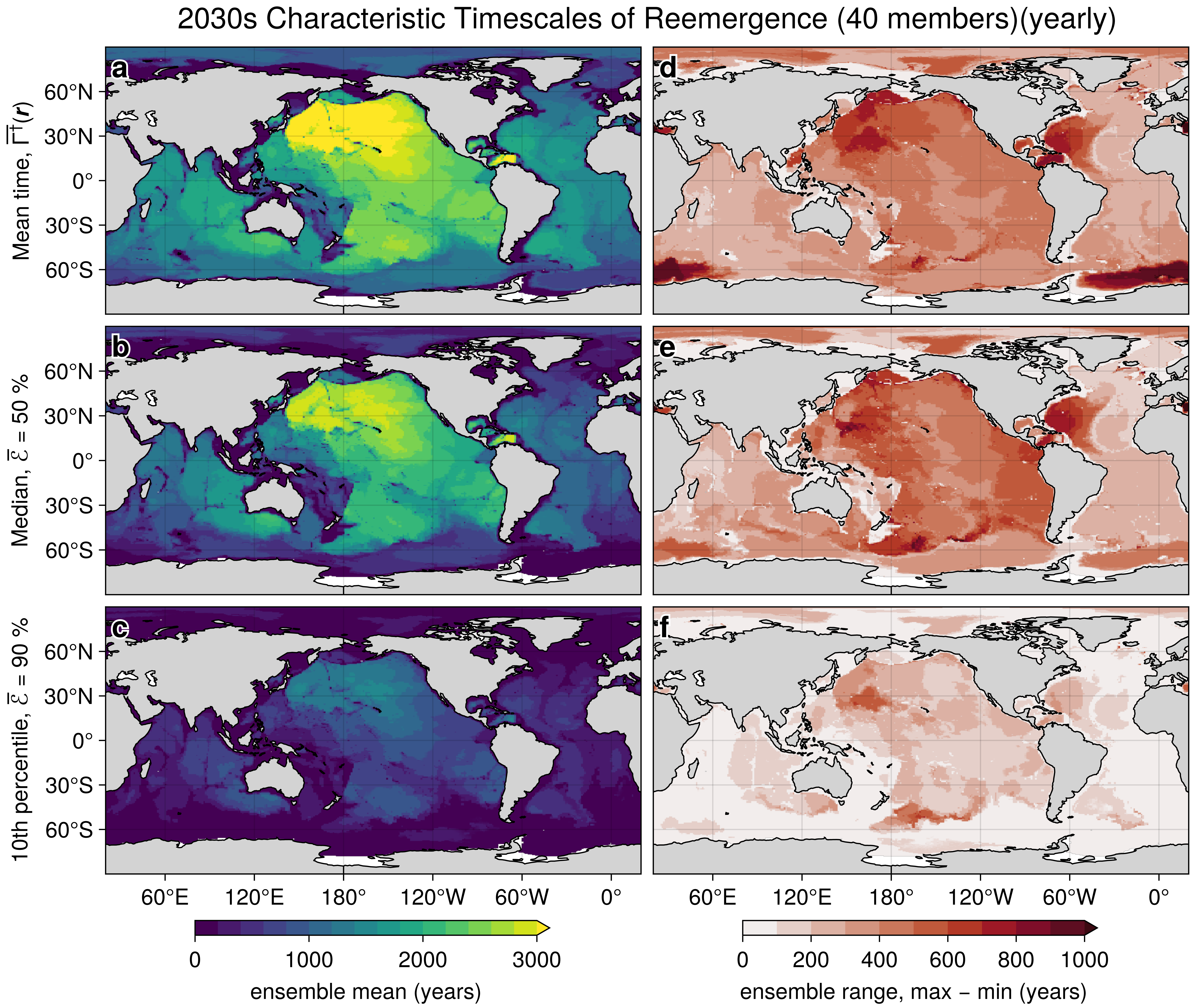
=

Complement of the CDF of the TTD

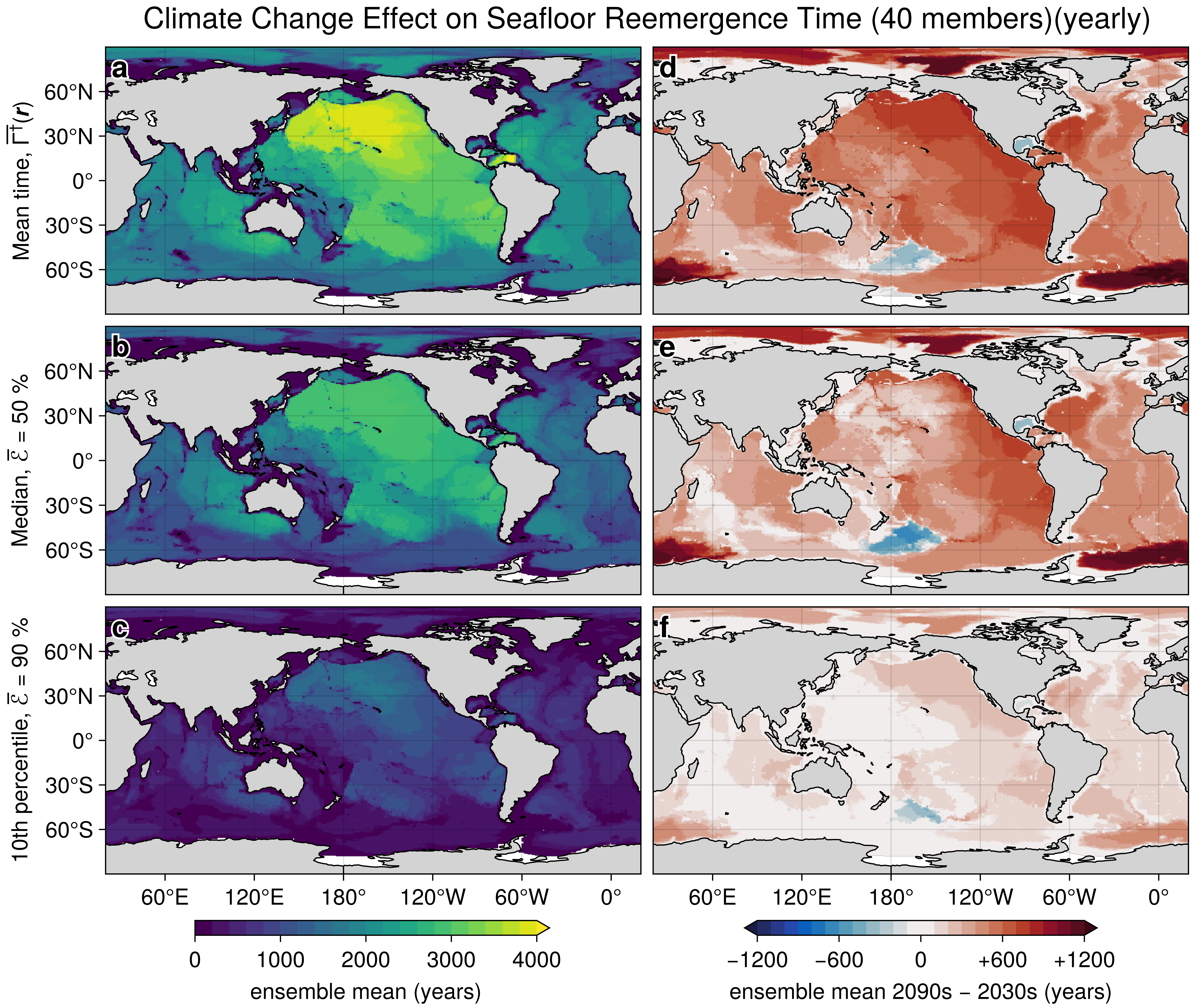

2030s Seafloor Sequestration Efficiency (40 members)(yearly)
a
b
c
d
e
f
τ = 100 years
τ = 300 years
τ = 1000 years
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°
0
20
40
60
80
100
ensemble mean $\overline{\mathcal{E}}(\boldsymbol{r}, \tau)$ (%)
0
10
20
30
40
50
60
ensemble range, max $\overline{\mathcal{E}}(\boldsymbol{r}, \tau)$ – min $\overline{\mathcal{E}}(\boldsymbol{r}, \tau)$ (%)



Climate Change Effect on Seafloor Sequestration Efficiency (40 members)(yearly)
τ = 100 years
τ = 300 years
τ = 1000 years
a
b
c
d
e
f
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°
0
20
40
60
80
100
ensemble mean $\overline{\mathcal{E}}(\boldsymbol{r}, \tau)$ (%)
−50
−30
−10
+10
+30
+50
mean 2090s $\overline{\mathcal{E}}(\boldsymbol{r}, \tau)$ − mean 2030s $\overline{\mathcal{E}}(\boldsymbol{r}, \tau)$ (%)



2030s Characteristic Timescales of Reemergence (40 members)(yearly)
Mean time, $\overline{\Gamma}^{\dagger}(\boldsymbol{r})$
Median, $\overline{\mathcal{E}}$ = 50 %
10th percentile, $\overline{\mathcal{E}}$ = 90 %
a
b
c
d
e
f
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°
0
1000
2000
3000
ensemble mean (years)
0
200
400
600
800
1000
ensemble range, max − min (years)



Climate Change Effect on Seafloor Reemergence Time (40 members)(yearly)
a
b
c
d
e
f
Mean time, $\overline{\Gamma}^{\dagger}(\boldsymbol{r})$
Median, $\overline{\mathcal{E}}$ = 50 %
10th percentile, $\overline{\mathcal{E}}$ = 90 %
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°
0
1000
2000
3000
4000
ensemble mean (years)
−1200
−600
0
+600
+1200
ensemble mean 2090s − 2030s (years)

Conclusions

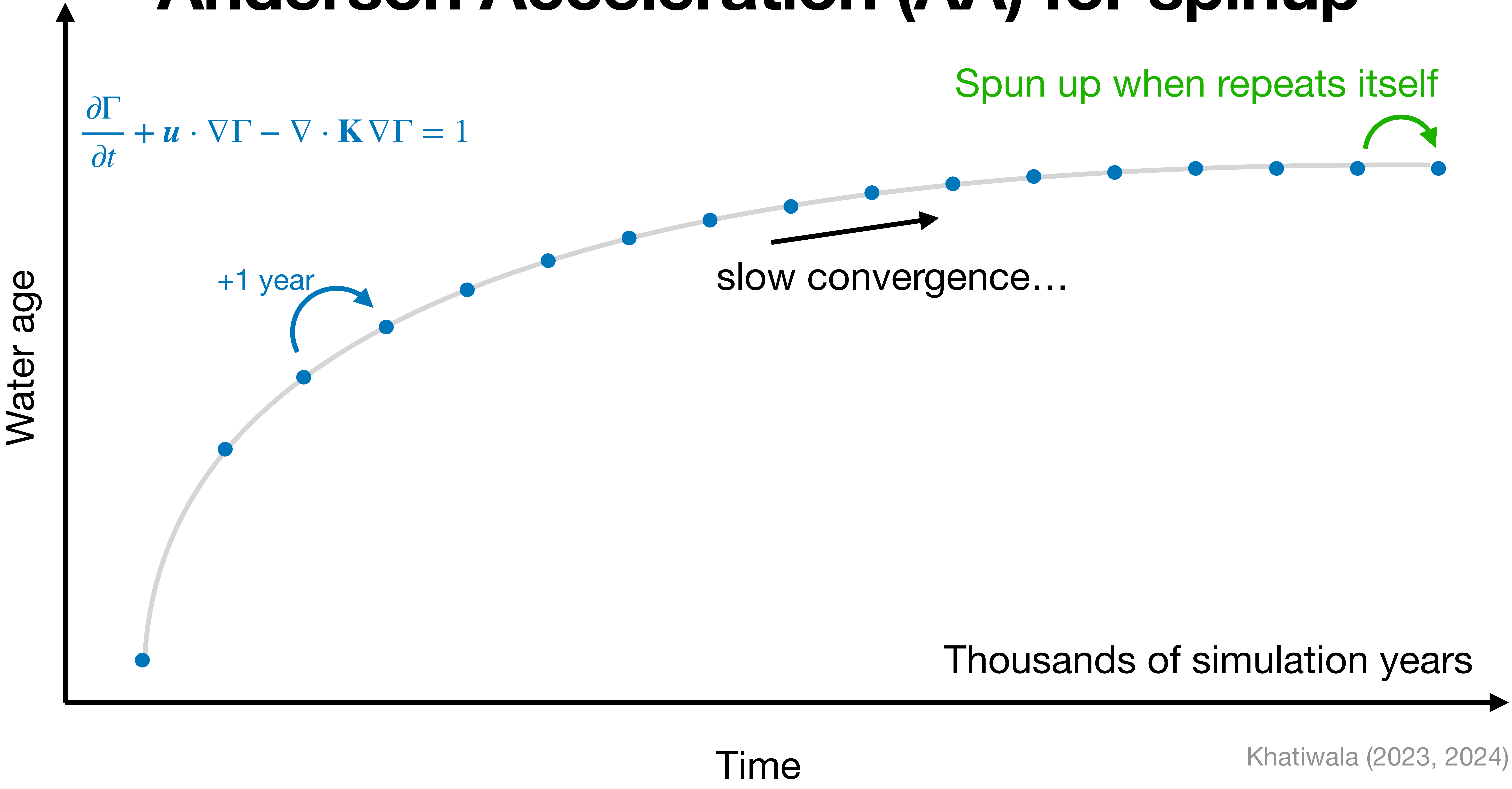
- continental shelf sequestration <100 years
- **abyssal plain sequestration** ~1000 years
  and more when **isolated from conveyor belt** (e.g., North Pacific)
- **Climate variability** ~20%
  but **huge (~100%)** when members “bifurcate” (e.g., Weddell Sea)
- **Climate warming** (mostly) slows circulation,
  lengthens transit by ~30%
  but **by up to ~100%** if deep connections shut down (e.g., Weddell Sea)

What's next?

TMIP
Transport Matrix
Intercomparison
Project
https://github.com/TMIP-code

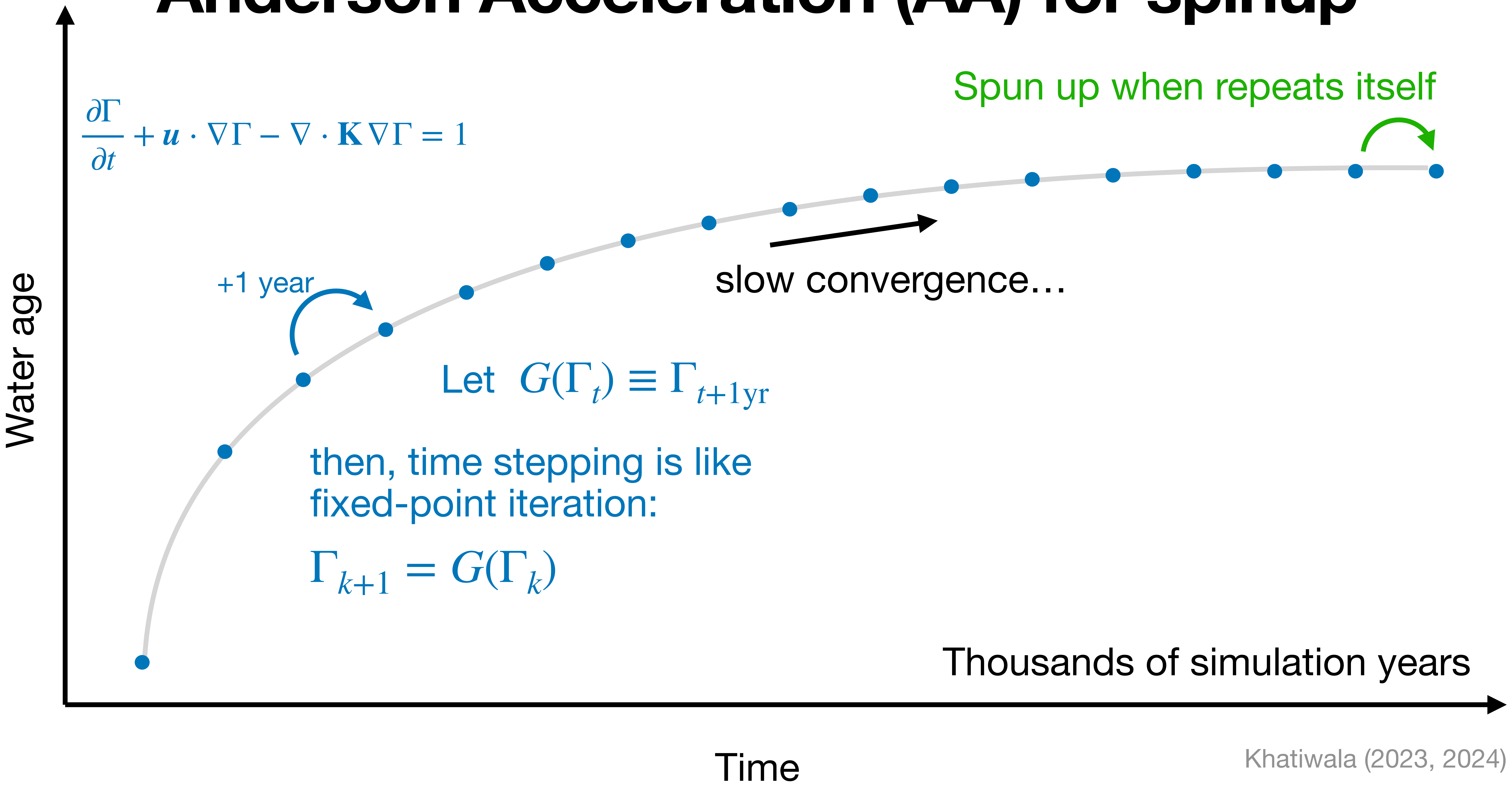
- Specific to ACCESS-ESM1.5! **Redo for more models**
- **other mCDR techniques**
- **deoxygenation / carbon pump** explored with ACCESS1.3 in Pasquier et al. (2024a, 2024b)
- **deep-sea mining impacts**
- **characterise ocean transport in general** in CMIP models (age, ventilation tracers, paleo tracers, time to reemergence, upstream exposure time, …)
- **Passive tracer spinup** (Newton–Krylov + TM faster than AA!)
- **Parameter optimisation** (Wombat BGC?) with ACCESS1.3 PCO2 model in Pasquier et al. (2023)
- **<your_idea>** or **<your_funded_project>?**

Anderson Acceleration (AA) for spinup



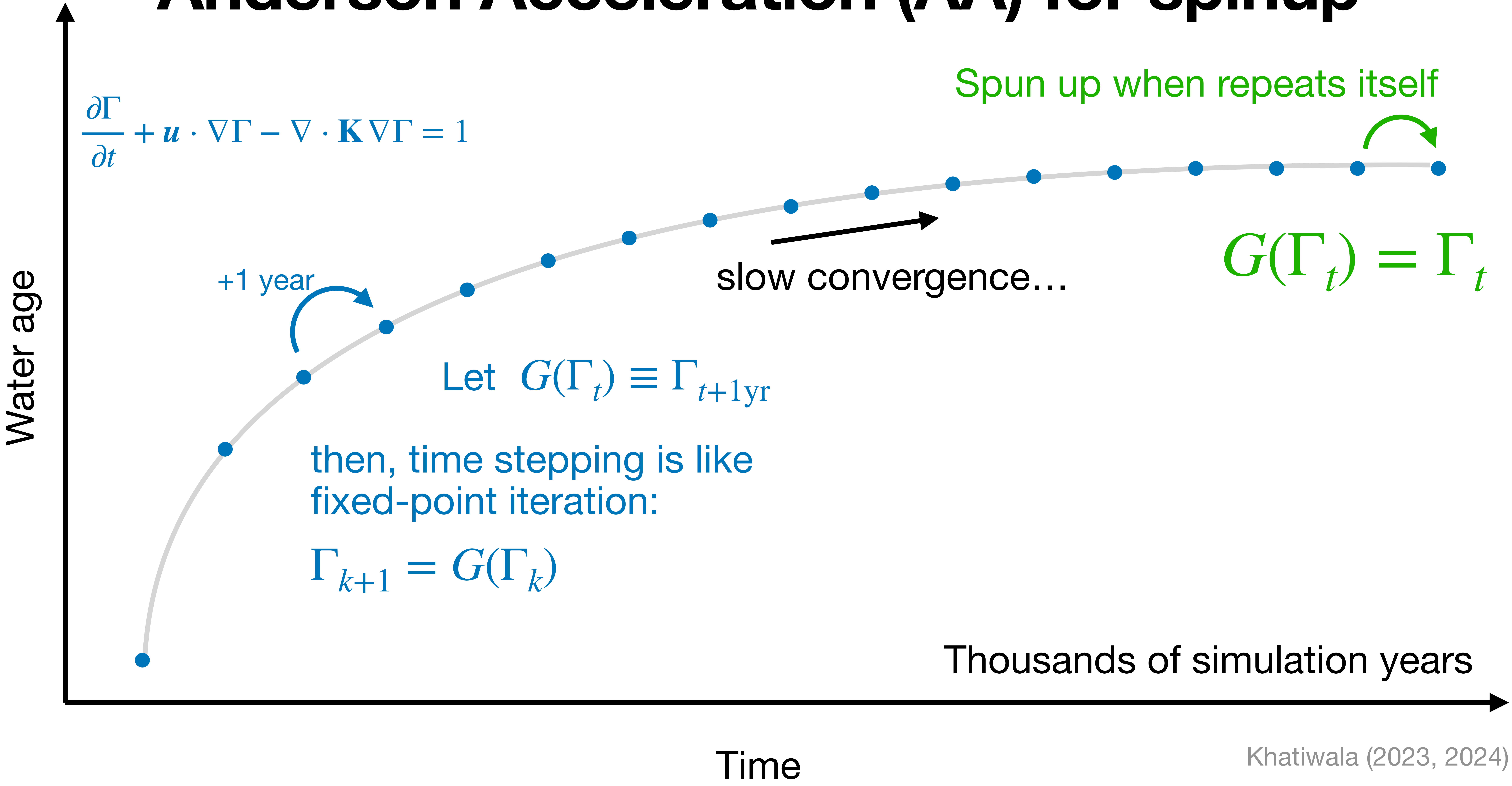
Khatiwala (2023, 2024)

Anderson Acceleration (AA) for spinup



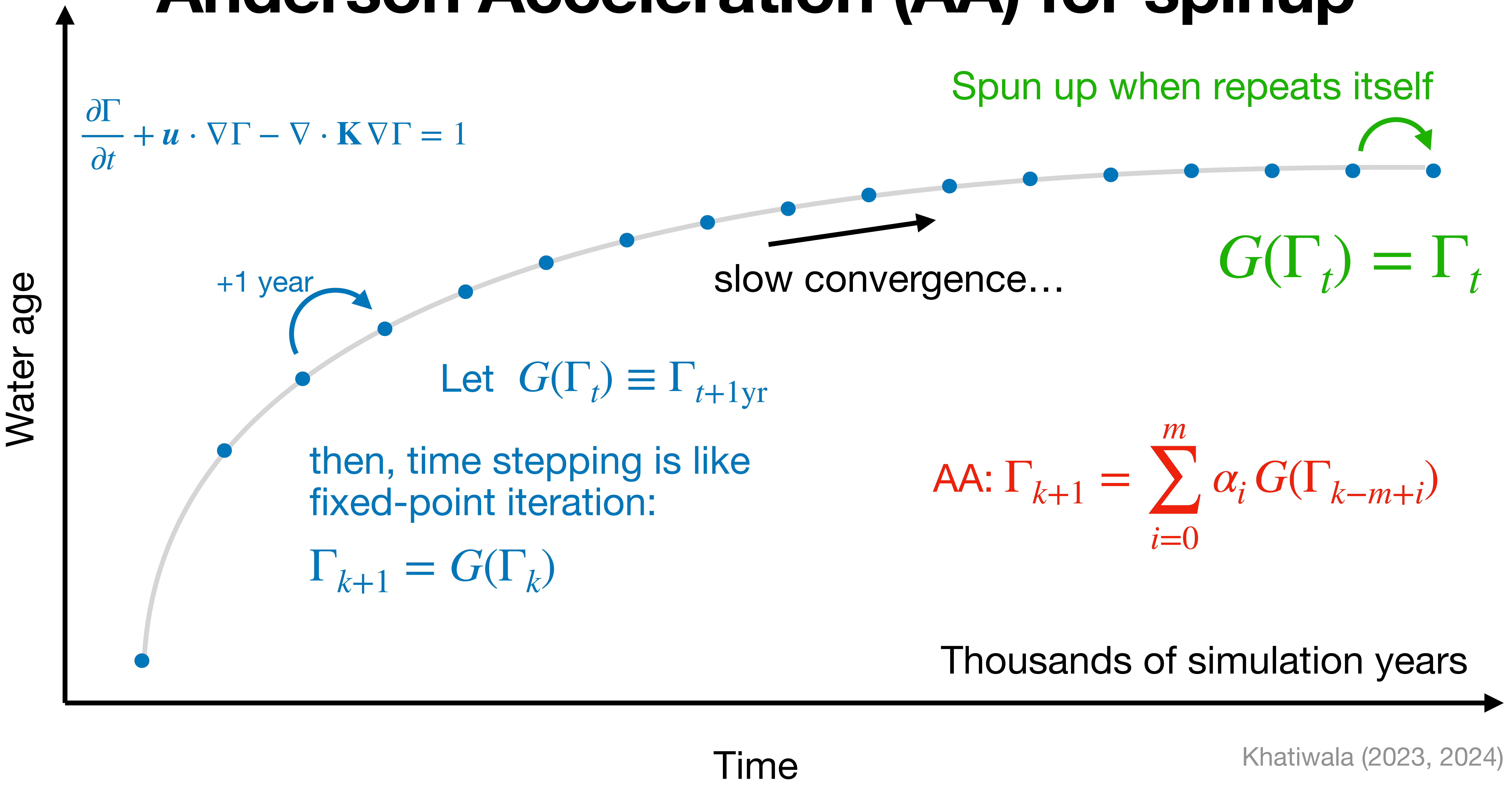
Khatiwala (2023, 2024)

Anderson Acceleration (AA) for spinup



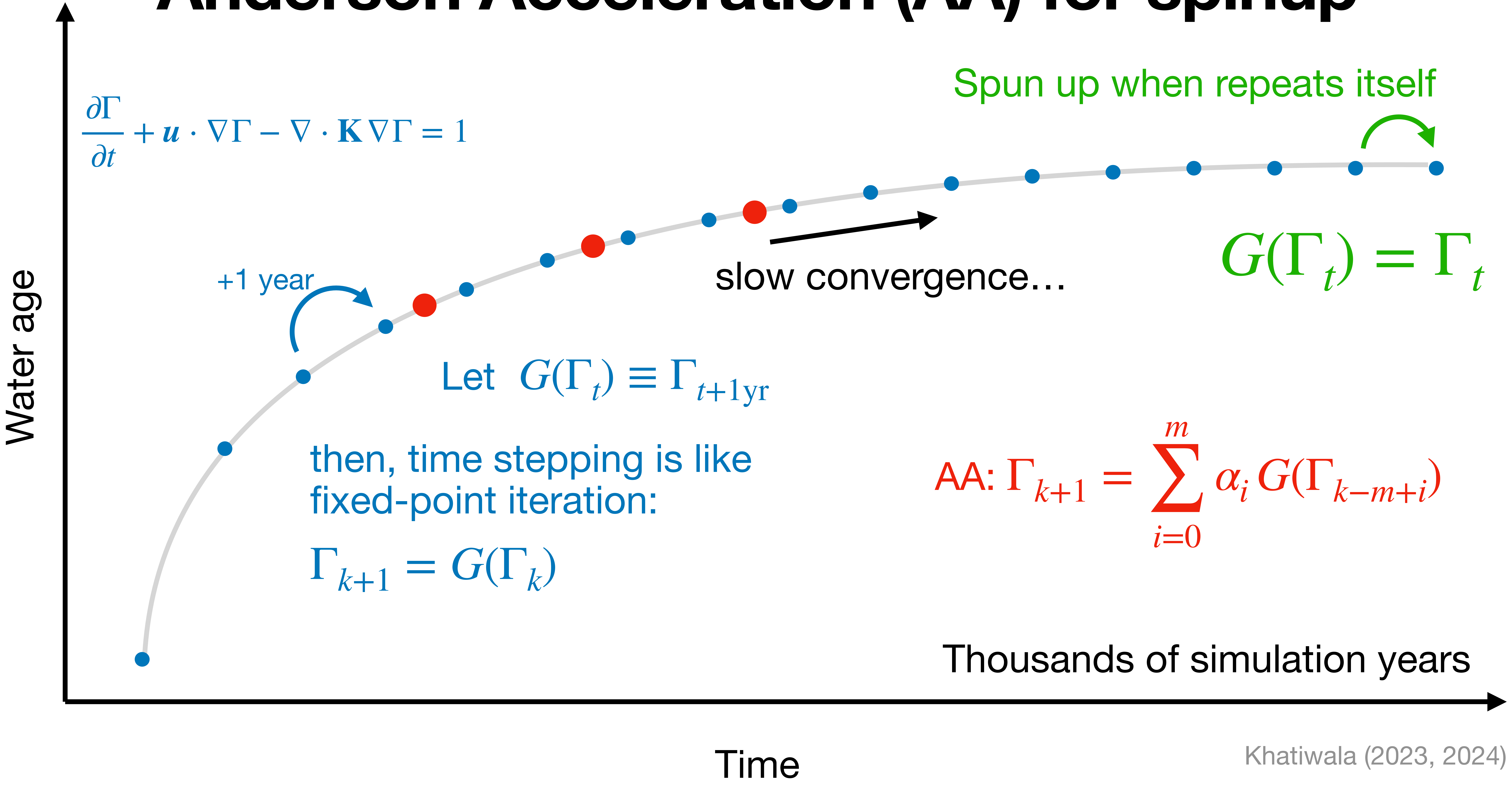
Khatiwala (2023, 2024)

Anderson Acceleration (AA) for spinup



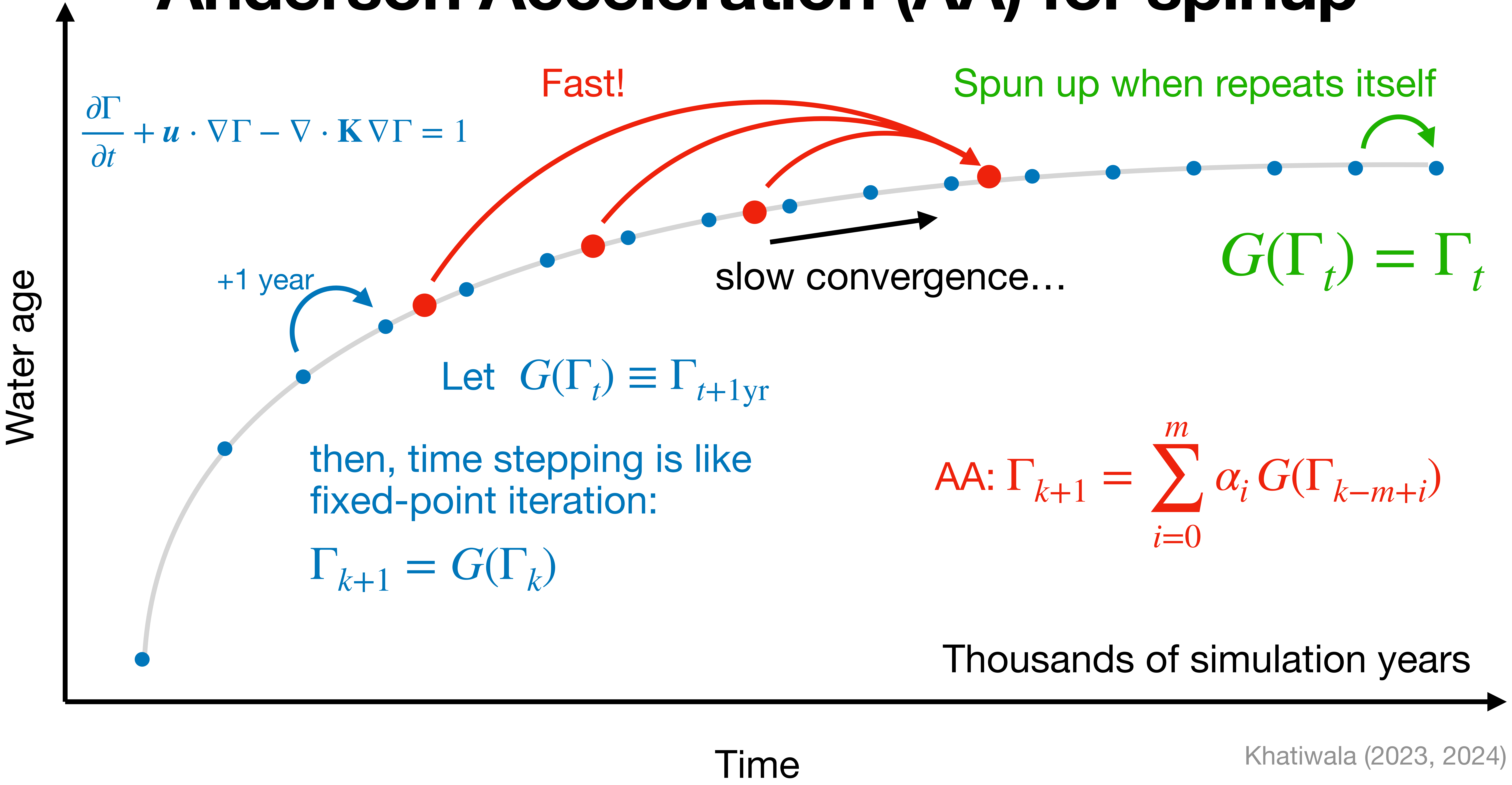
Khatiwala (2023, 2024)

Anderson Acceleration (AA) for spinup

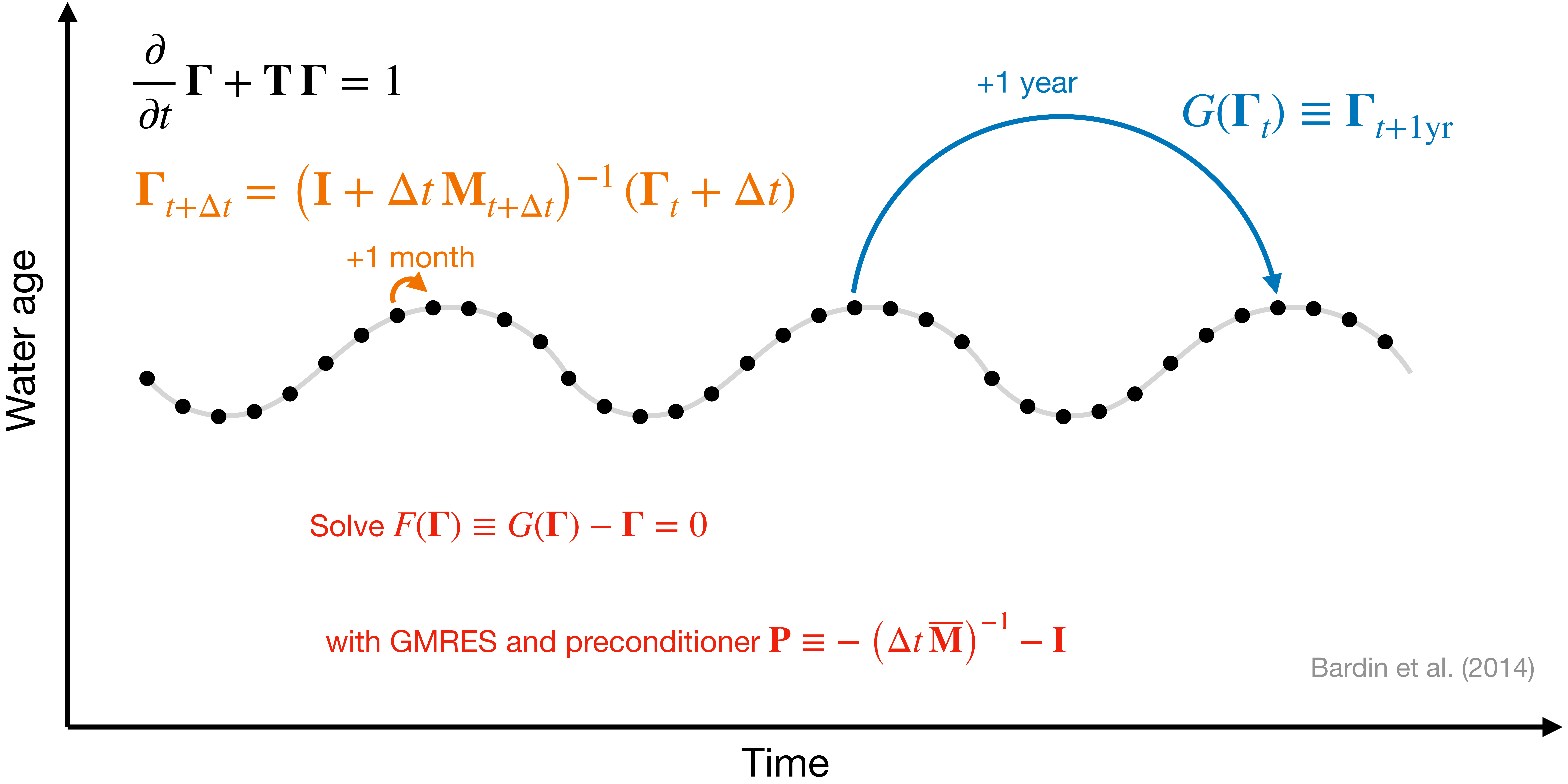


Khatiwala (2023, 2024)

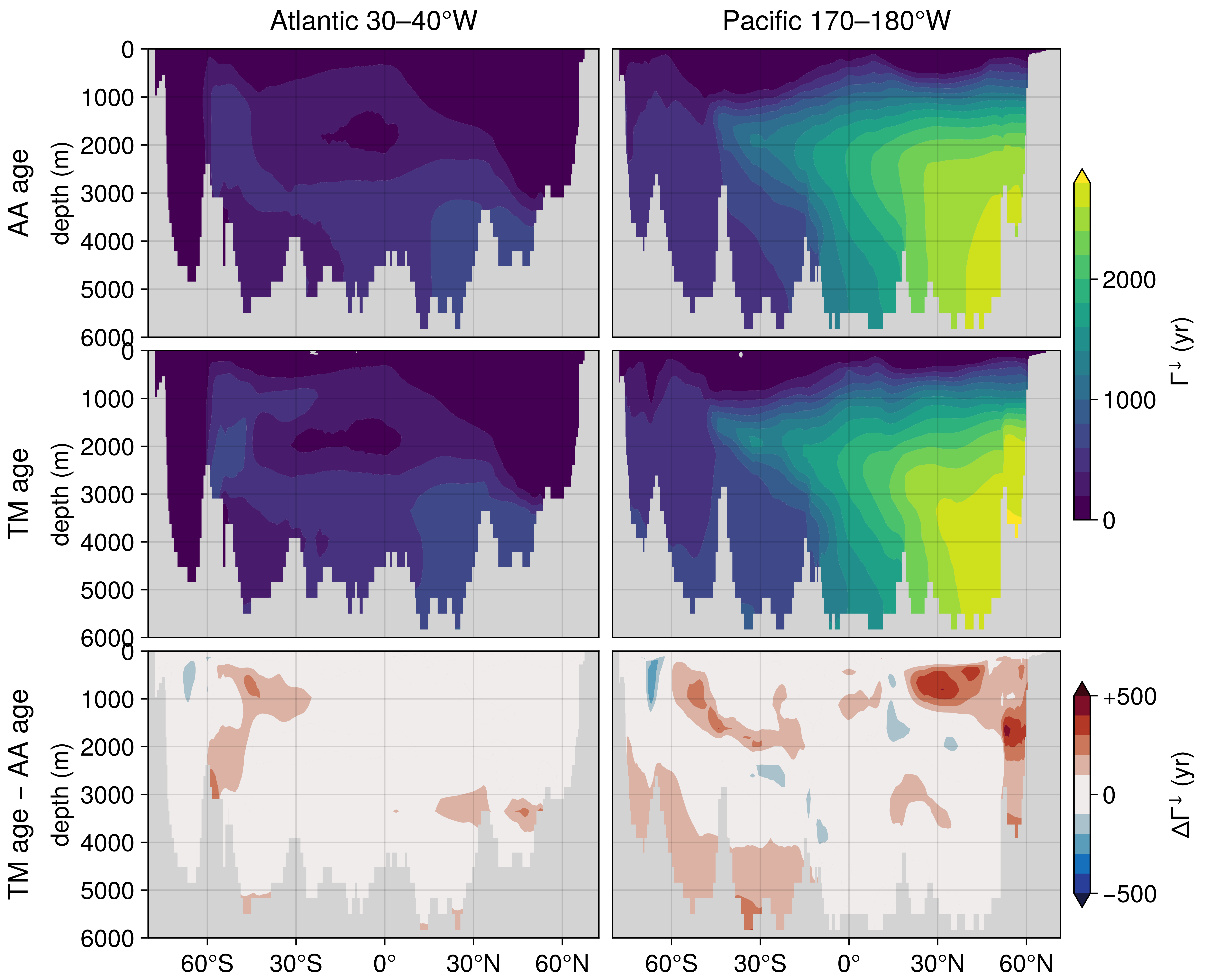
Anderson Acceleration (AA) for spinup



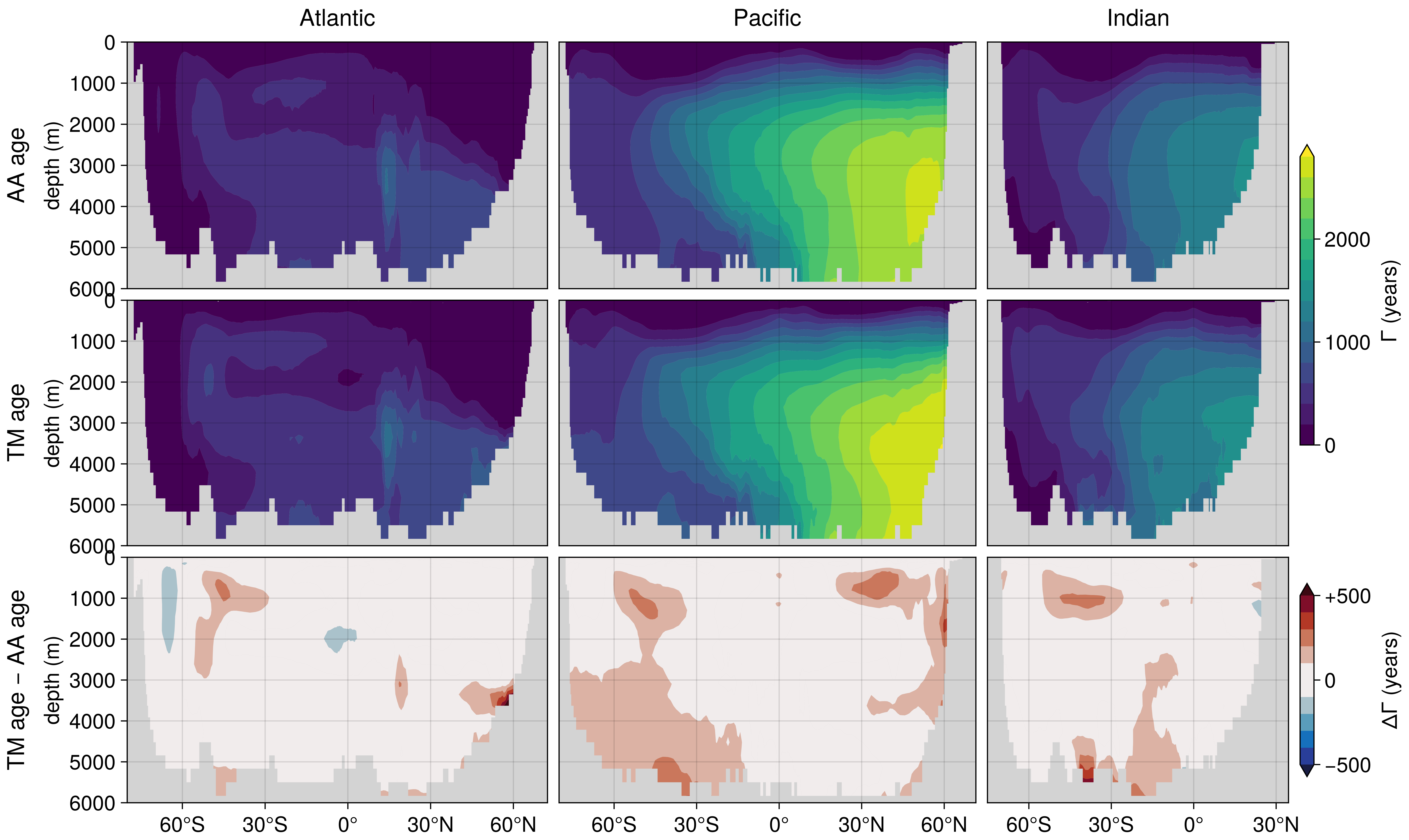
Newton Krylov for mean water age



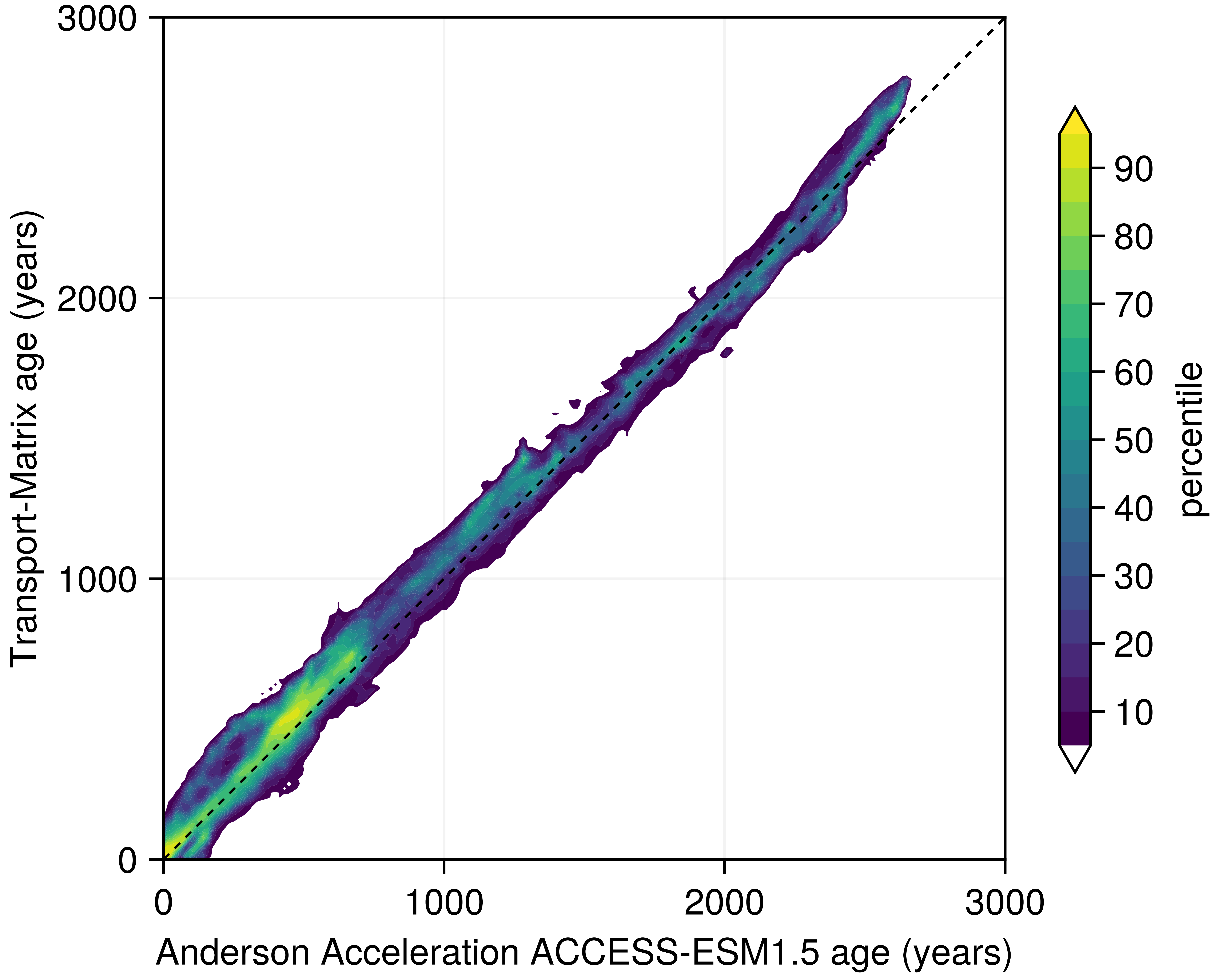
TM vs AA age: Zonal Slices



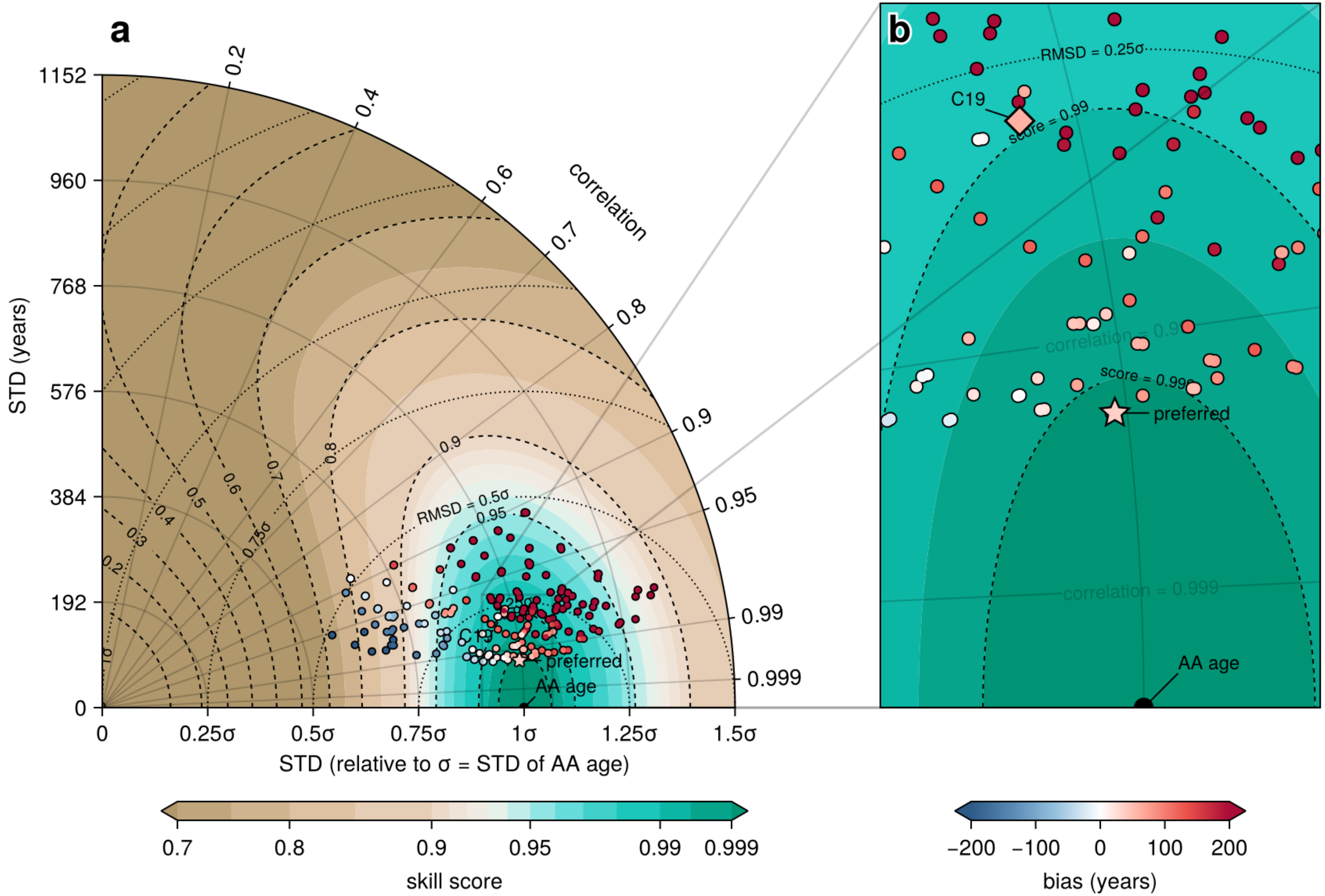
TM vs AA age: Zonal Averages



TM vs AA age: Joint PDF



TM vs AA age: Successful Calibration



Newton Krylov for mean time to reemergence