Sub-grid model for convective mixing (DRSDTCON)

OPM Summit 2025

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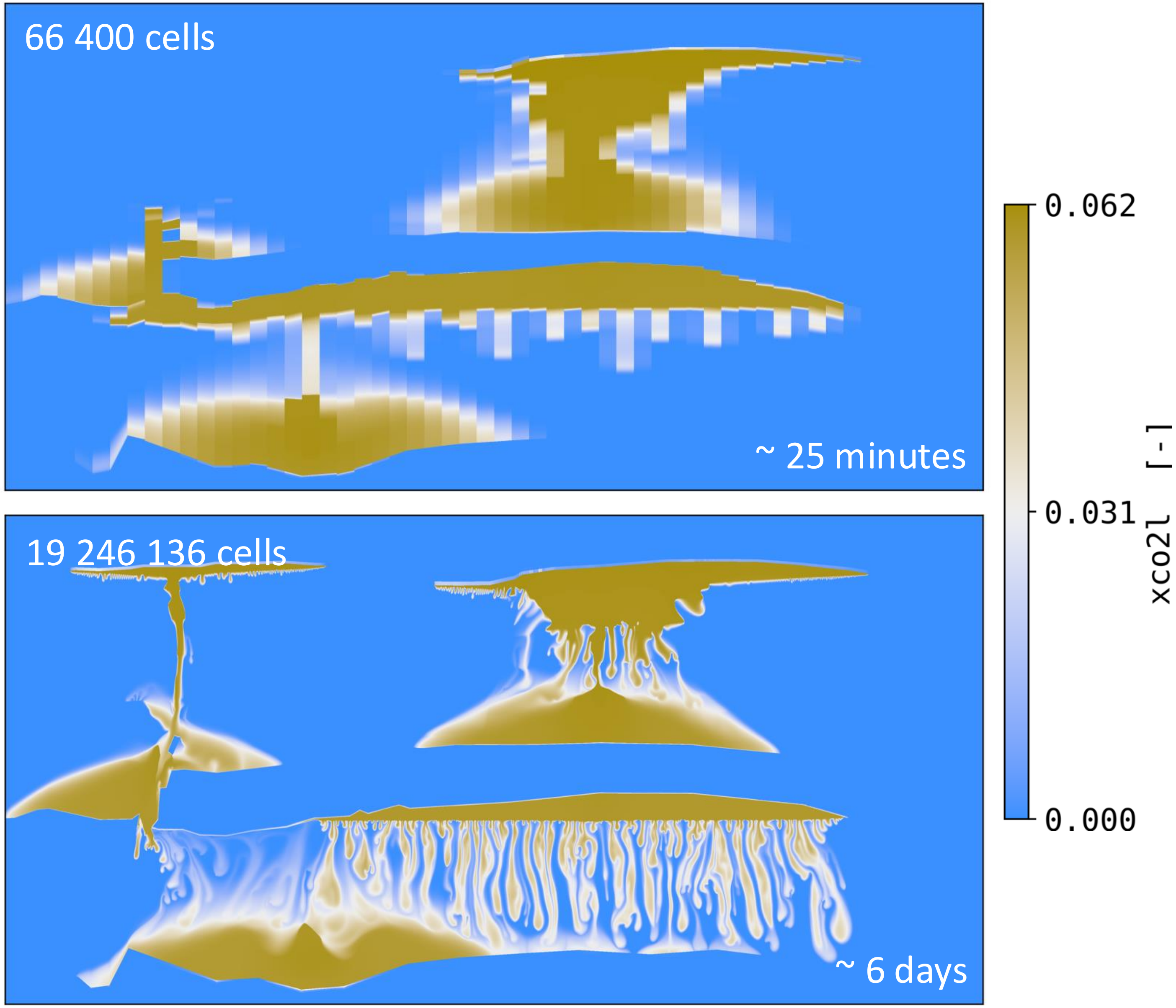
Background

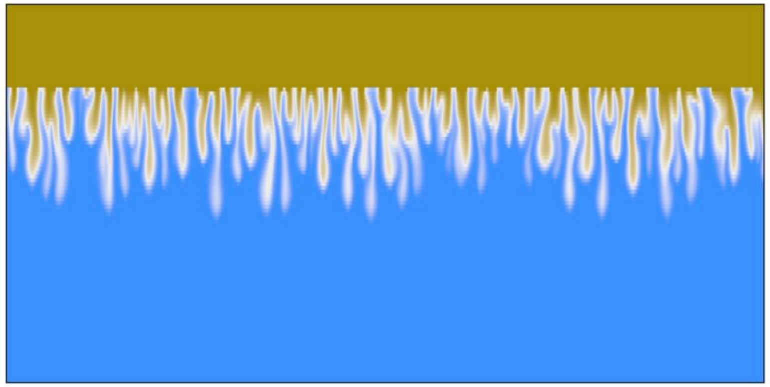
How to resolve the impact of small cm-scale physics for decadal timescales when your simulator only realistically handles 1-100m grid cells ?

CO_2 dissolved in brine
SPE 11B, 500years after injection started:

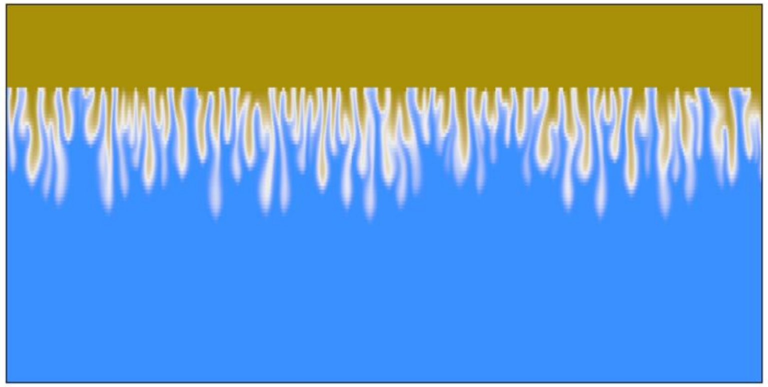


Convective mixing

- CO_2 dissolution increases brine density by 2-5%
- Density instability triggers convection and enhances dissolution

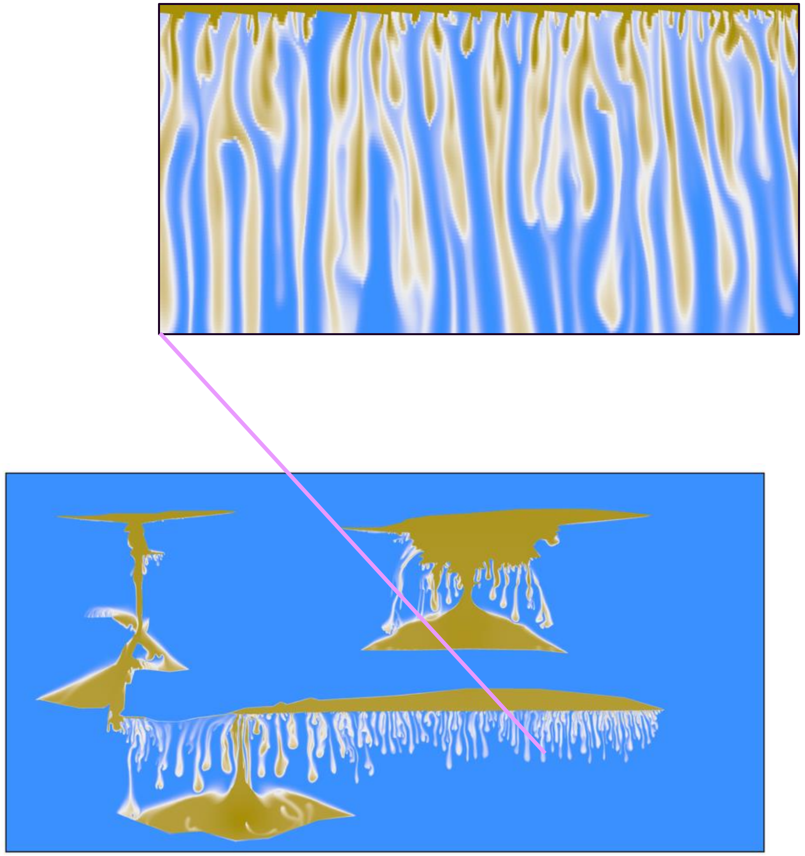


10m
x
1m



1000m
x

~10000m
x
~1000m



Small-scale convection
impacts
large-scale
trapping efficiency
over decadal timescales

Resolving fine-scale fingers is
not realistic (e.g. SPE 11c)

DRSDTCON – CO2 Convective Dissolution Parameter (χ)

purpose and background

dimensionless parameter (χ) that controls convective dissolution of CO_2 into in situ brine within a grid cell [Sandve et. al. (2021)], based on an assumption of vertical equilibrium

```
OIL
GAS
CO2STORE
DISGAS


DRSDTCON
- - χ
0.04 /
```

Dissolution rate kg/m²/s [Elenius et. al. (2014)], in black-oil framework:

$$F = \boxed{\chi} \frac{R_{s,\text{sat}} K_z \Delta\rho g}{\mu_o D_z S_o \phi}$$

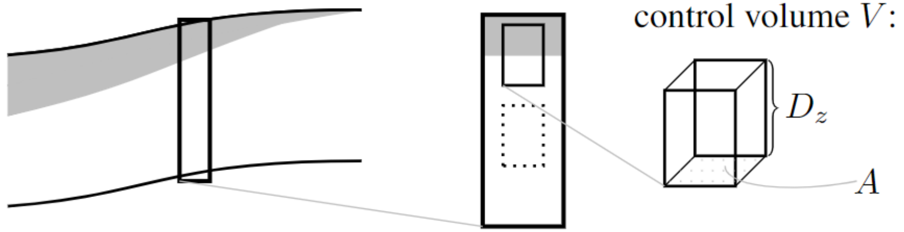
Sandve, T.H., et al. Convective dissolution in field-scale CO2 storage simulations using the OPM flow simulator. In: TCCS–11, 2021

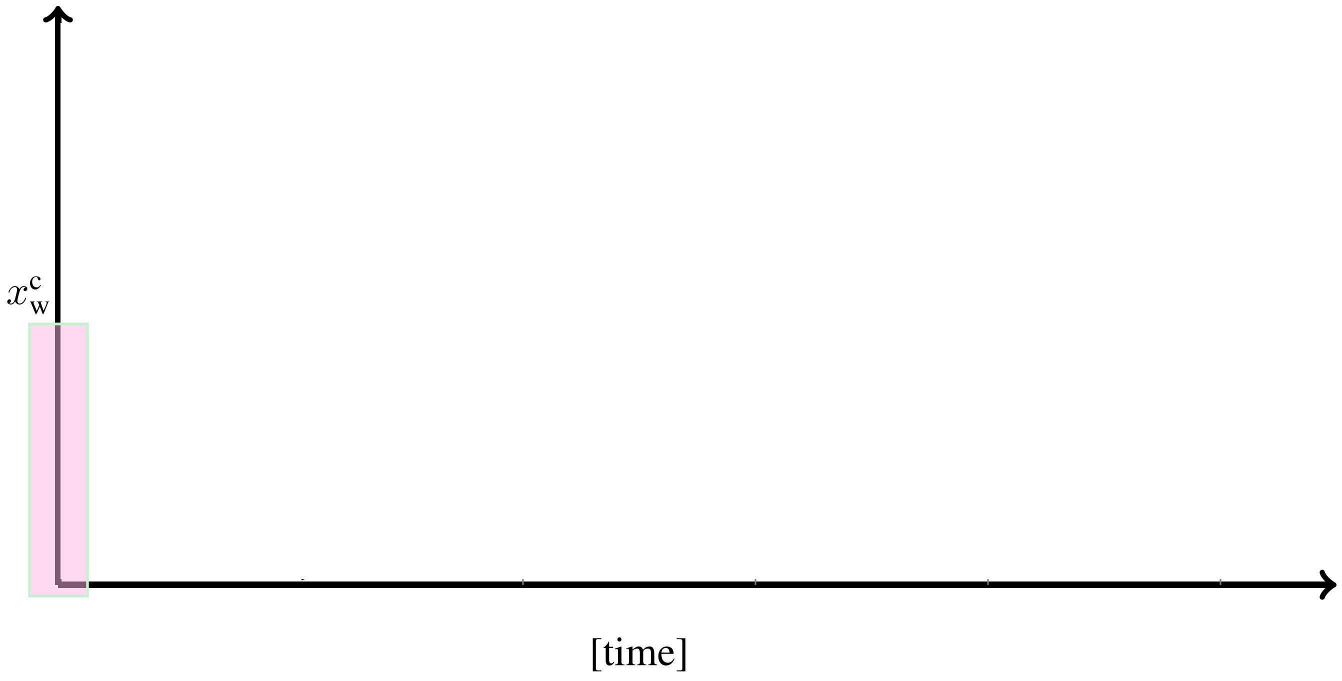
Elenius, M. T., et al. Convective mixing influenced by the capillary transition zone. Computational Geosciences, 18(3-4), 417-431, 2014

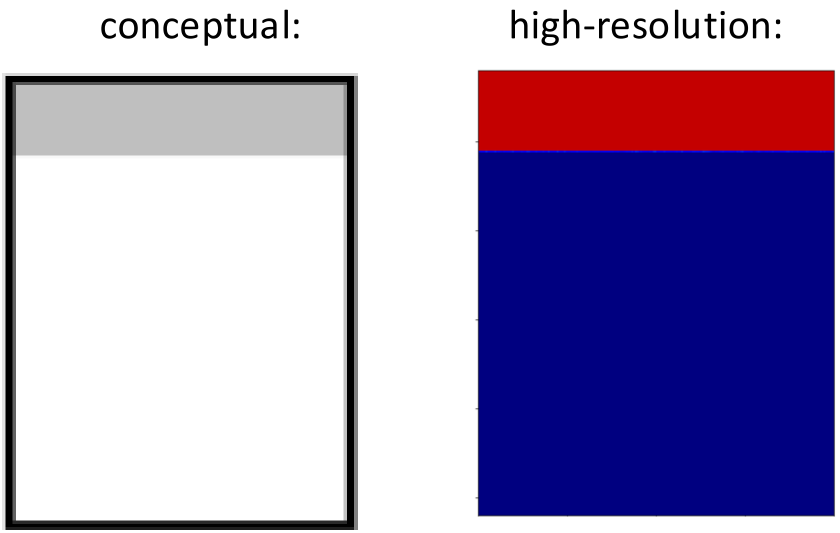
Sub-grid model

Conceptual model:

1. **Initial instantaneous dissolution if both phases coexist**





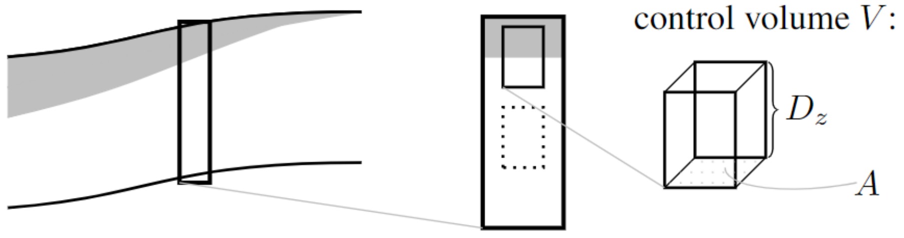


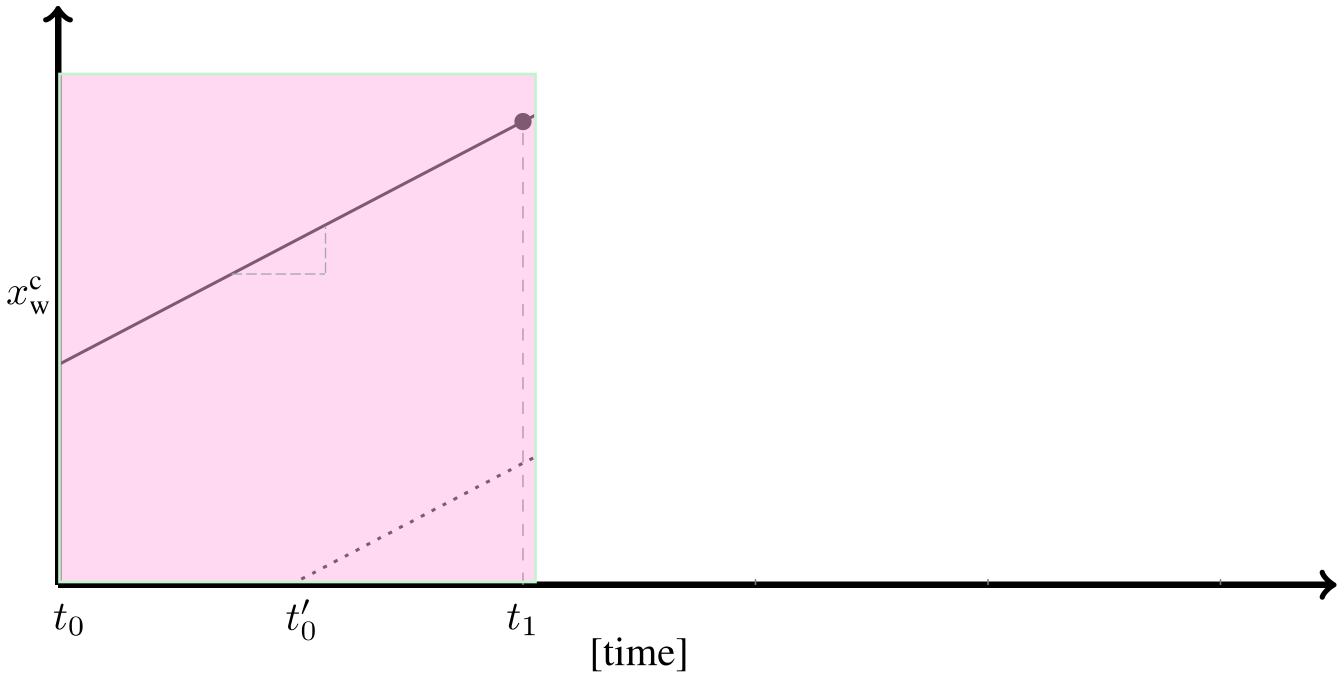
Mykkeltvedt, T.S., et al. New Sub-grid Model for Convective Mixing in Field-Scale Storage Simulation.Transp Porous Med 152, 9, 2025

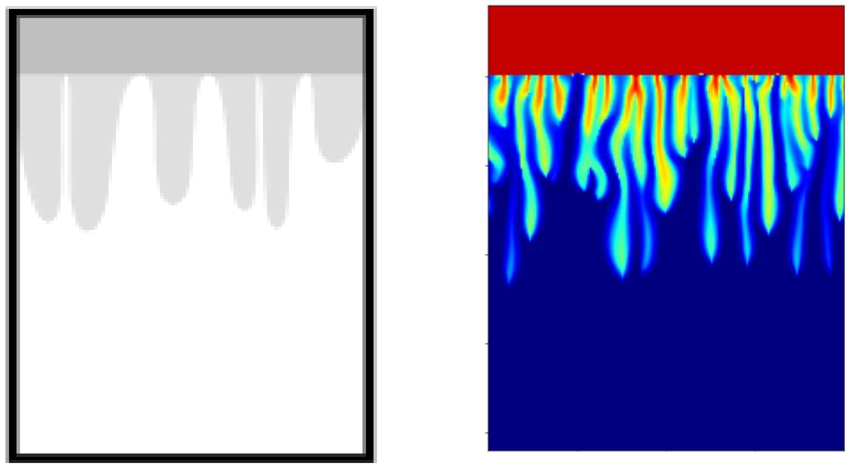
Sub-grid model

Conceptual model:

1. Initial instantaneous dissolution if both phases coexist
2. **Linear accumulation proportional to Rayleigh number**







$$F = \chi \frac{x^{\mathrm{c}}_{\mathrm{w,sat}} K_z \Delta\rho g}{\mu_{\mathrm{w}} \phi S_{\mathrm{w}} D_z}, \qquad t_0 < t \le t_1$$

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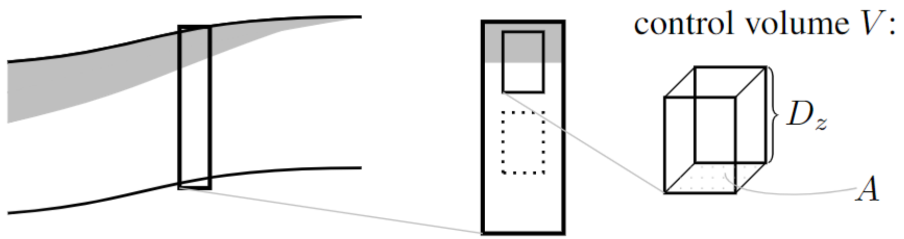
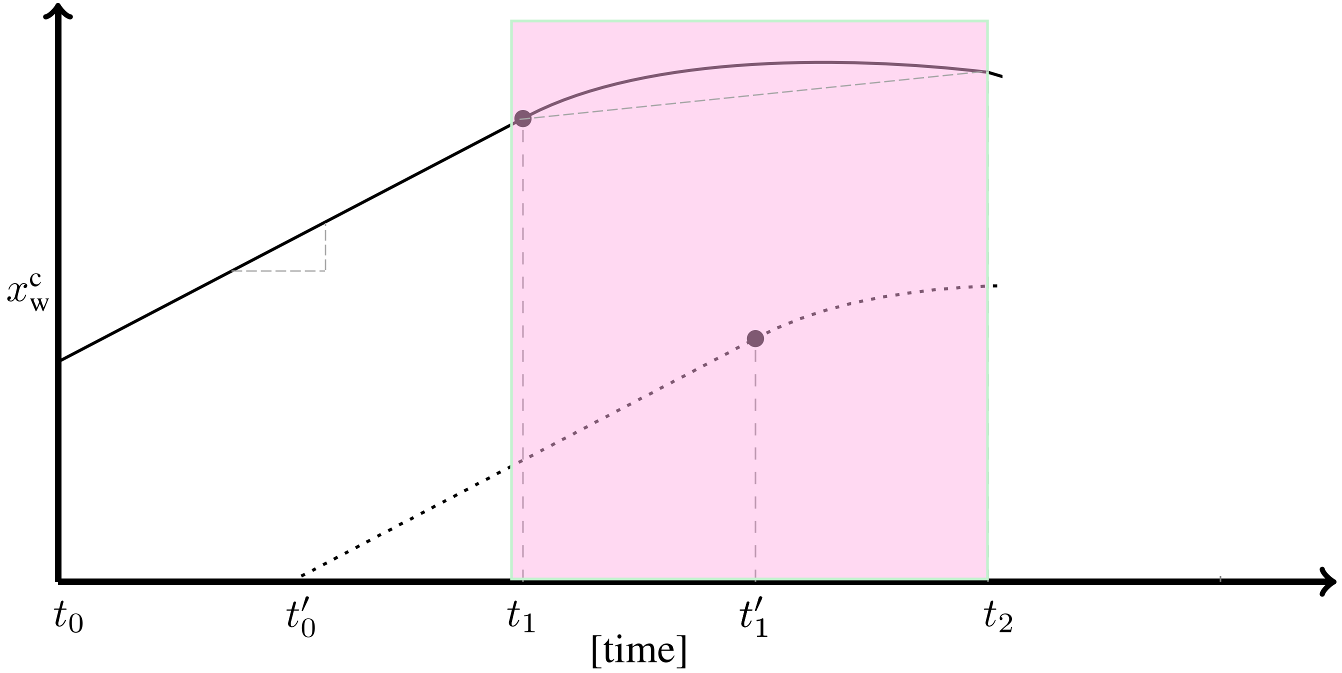
Sub-grid model

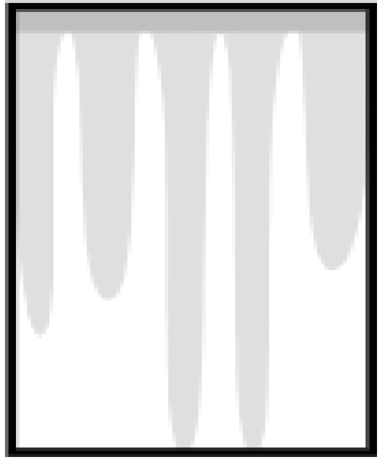
Conceptual model:

1. Initial instantaneous dissolution if both phases coexist
2. Linear accumulation proportional to Rayleigh number
3. **Transition to steady state as fingers reach cell edge**

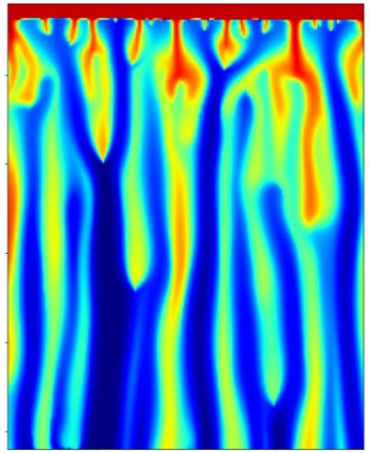




conceptual:



high-resolution:



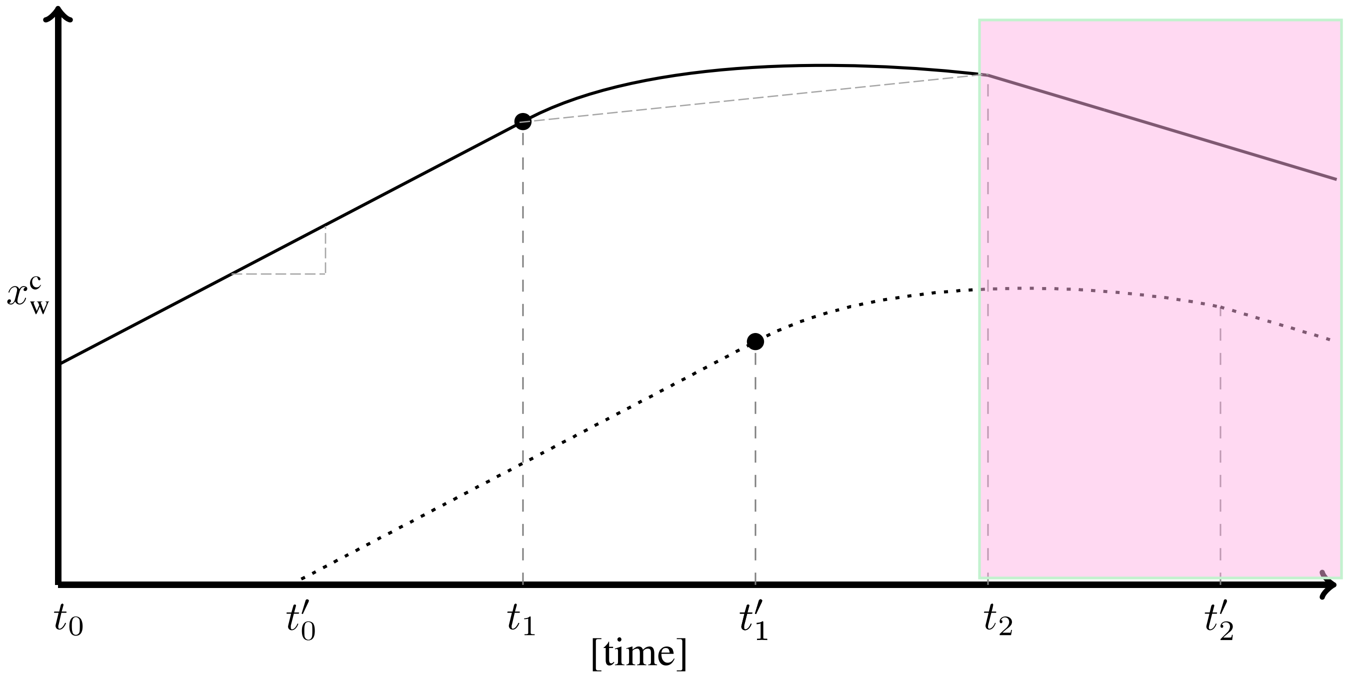
$$X = \frac{x_{\mathrm{w}}^{\mathrm{c}} - x_{\mathrm{w,sat}}^{\mathrm{c}} S_{\mathrm{n}}}{x_{\mathrm{w,sat}}^{\mathrm{c}}(1 - S_{\mathrm{n}})} \qquad X|_{t_1} = \psi$$

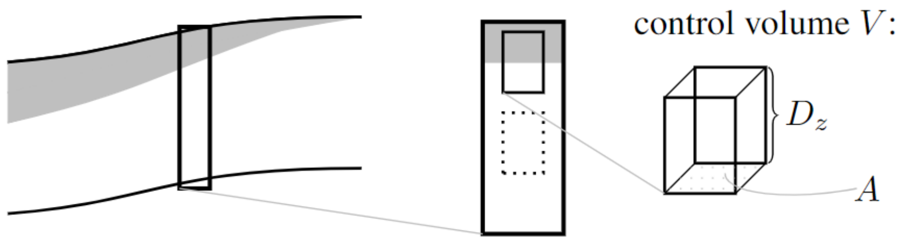
$$F = \omega \qquad t_1 < t \leq t_2$$

Sub-grid model

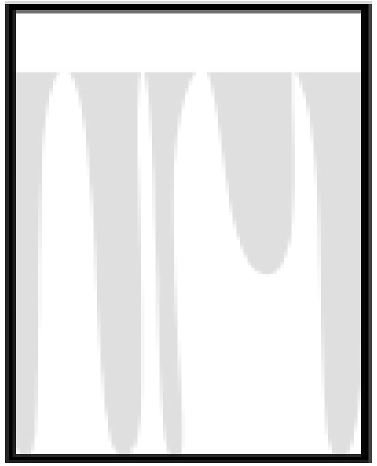
Conceptual model:

1. Initial instantaneous dissolution if both phases coexist
2. Linear accumulation proportional to Rayleigh number
3. Transition to steady state as fingers reach cell edge
4. **Decline phase**

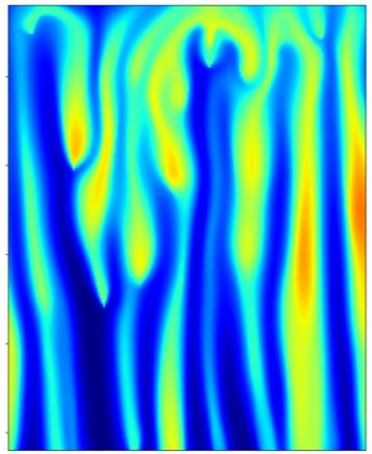




conceptual:



high-resolution:

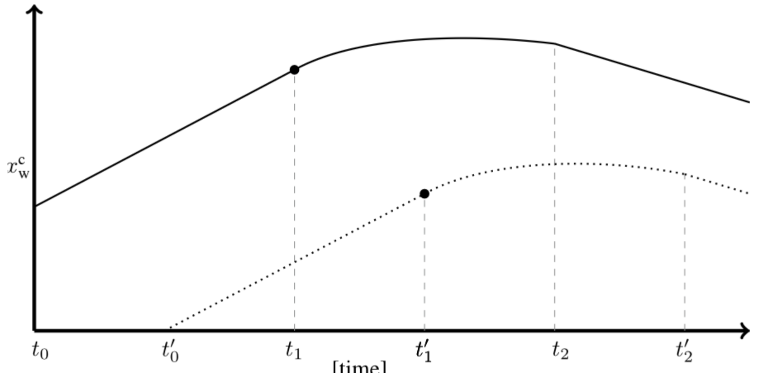


Sub-grid model

Dynamic partitioning model

- Modify equilibrium partitioning
- Time-dependent solubility based on Rayleigh number

$$F = \begin{cases} \chi \dfrac{x^{\mathrm{c}}_{\mathrm{w,sat}} K_z \Delta\rho g}{\mu_{\mathrm{w}} \phi S_{\mathrm{w}} D_z}, & t_0 < t \leq t_1 \\ \omega, & t_1 < t \leq t_2. \end{cases}$$

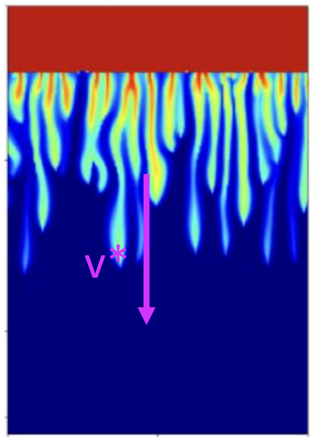


Effective component transport

- Modify CO_2 component velocity
- Eliminate spurious convection

$$\frac{\partial}{\partial t}\left(\phi S_{\mathrm{w}} \rho_{\mathrm{w}} x^{\mathrm{c}}_{\mathrm{w}} + \phi S_{\mathrm{n}} \rho_{\mathrm{n}} x^{\mathrm{c}}_{\mathrm{n}}\right) + \nabla \cdot \left(\rho_{\mathrm{w}} x^{\mathrm{c}}_{\mathrm{w}} \hat{\mathbf{v}}_{\mathrm{w}} + \rho_{\mathrm{w}} \left(\min(x^{\mathrm{c}}_{\mathrm{w}}, \psi x^{\mathrm{c}}_{\mathrm{w,sat}}) \mathbf{v}^* + \rho_{\mathrm{n}} x^{\mathrm{c}}_{\mathrm{n}} \mathbf{v}_{\mathrm{n}}\right) - q^{\mathrm{c}} = 0.$$

$$\mathbf{v}^* = \chi \frac{\mathbf{K} k_{r\mathrm{w}}}{\mu_{\mathrm{w}}} \Delta\rho \mathbf{g}.$$



Three sub-grid parameters calibrated to high-resolution simulations

χ ψ ω

Mykkeltvedt, T.S., et al. New Sub-grid Model for Convective Mixing in Field-Scale Storage Simulation.Transp Porous Med 152, 9, 2025

DRSDTCON – CO2 CONVECTIVE DISSOLUTION PARAMETERS (χ, ψ , ω)

Extended with regimes (SGM)

OPM OPEN POROUS MEDIA

Dynamic partitioning model

opm/simulators/flow/MixingRateControls.cpp

```
Scalar factor = 1.0;
Scalar X = (rs - rssat * sg) / (rssat * ( 1.0 - sg));
Scalar omega = 0.0;
const Scalar pCap = Opm::abs(pg - p);
if ((rs >= (rssat * sg)) || (pCap < 1e-12)) {
    if (X > Psi) {
        factor = 0.0;
        omega = omegainn;
    }
} else {
    factor /= Xhi;
    deltaDensity = (saturatedDensity - co2Density);
}
```

opm/simulators/flow/FlowProblem.hpp

```
+                opm/models/blackoil/blackoilconvectivemixingmodule.hh
```

```
        convectiveDrs_[compressedDofIdx]
-           = permz * rssat * max(0.0, deltaDensity) * gravity / (so * visc * distZ * poro);
+           = factor * permz * rssat * max(0.0, deltaDensity) * gravity / ( std::max(sg_max - sg, 0.0) * visc * distZ * poro) + (omega/Xhi);
```

Effective component transport

opm/models/blackoil/blackoillocalresidual.hh
opm/models/blackoil/blackoillocalresidualtpfa.hh
opm/models/blackoil/blackoilintensivequantities.hh

```
+                opm/models/blackoil/blackoilconvectivemixingmodule.hh
```

DRSDTCON – CO2 CONVECTIVE DISSOLUTION PARAMETERS (χ, ψ , ω)

Extended with regimes (SGM)

parameters (χ, ψ , ω) that controls
convective dissolution of CO_2 into in situ brine within a grid cell [Mykkeltvedt et. al. (2025)],

```
OIL
GAS
CO2STORE
DISGAS


DRSDTCON
- - χ     ψ     ω   option
0.04 0.34 3.0E-09 ALL/
```

```
WATER
GAS
CO2STORE
DISGASW


DRSDTCON
- - χ     ψ     ω   option
0.04 0.34 3.0E-09 ALL/
```

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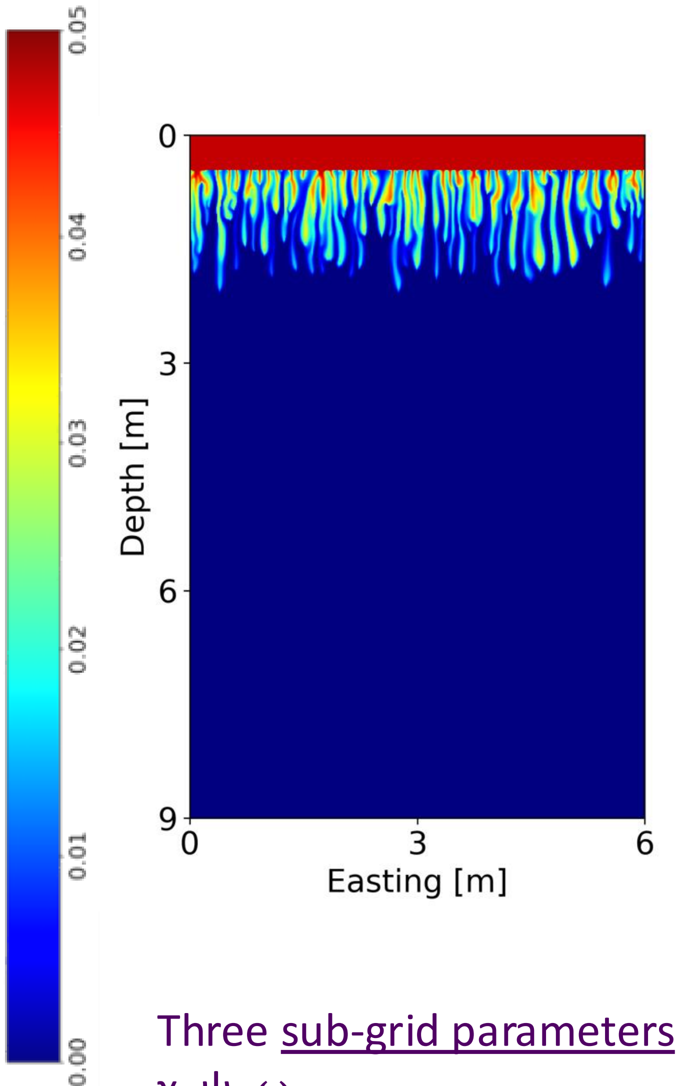
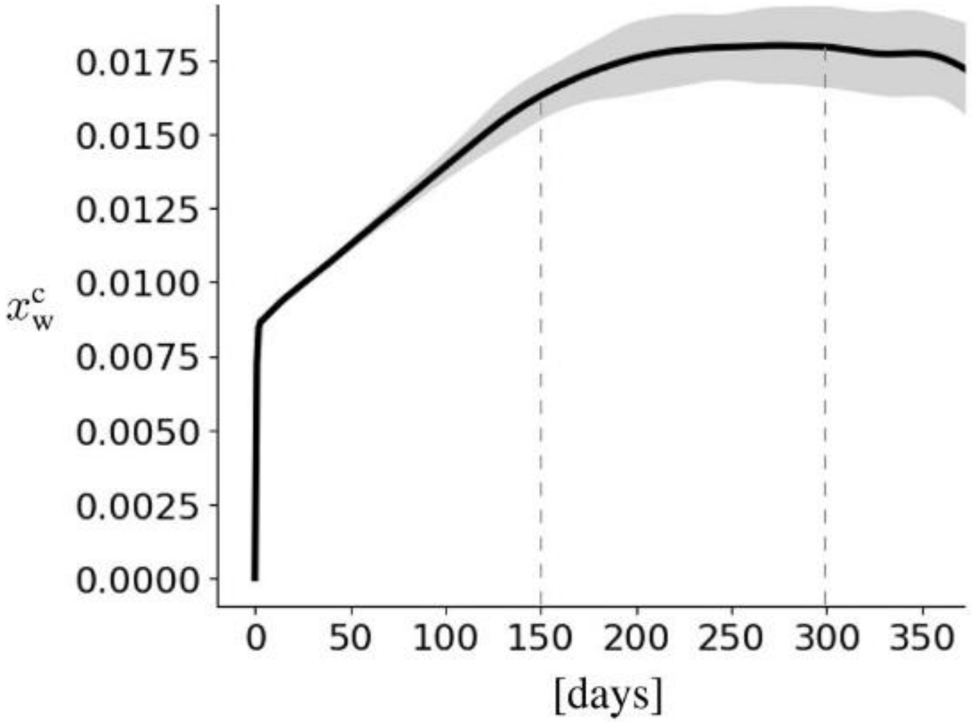
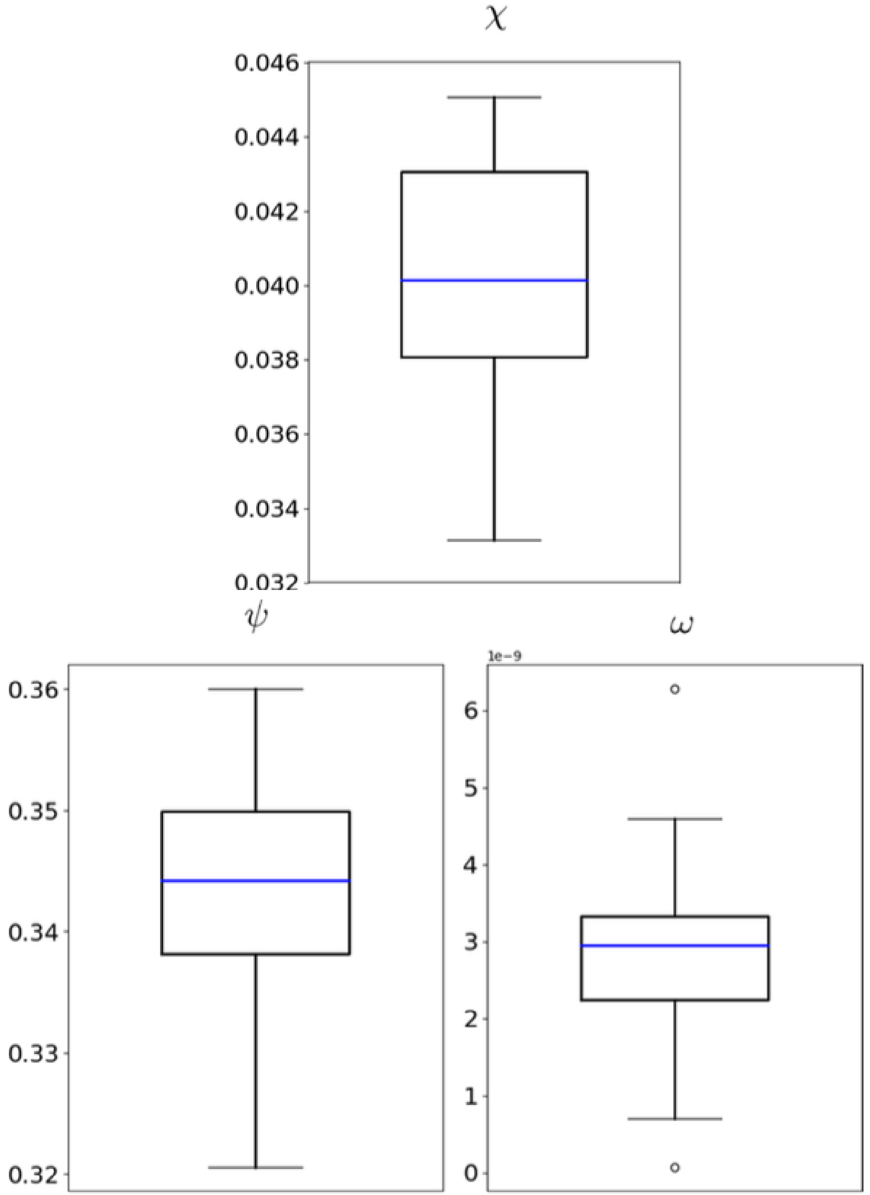
Sub-grid model parameters



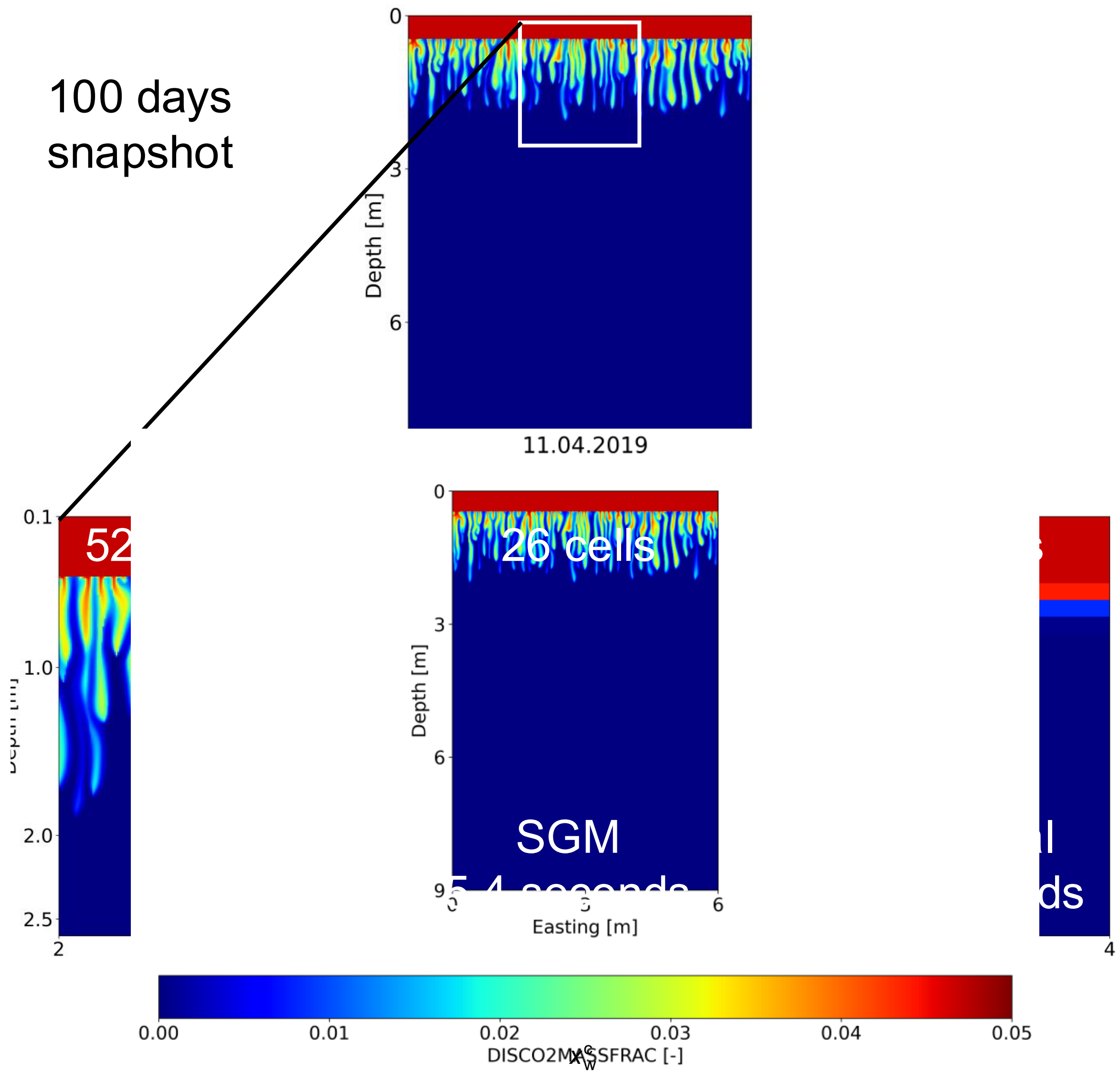


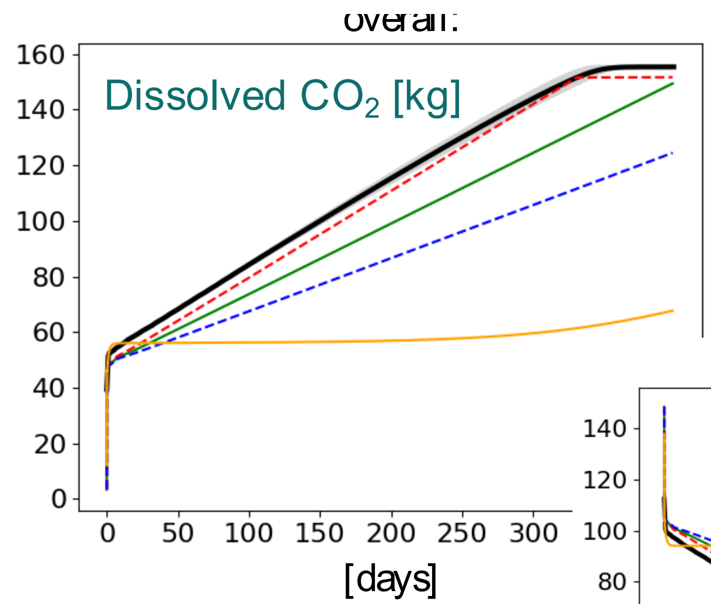


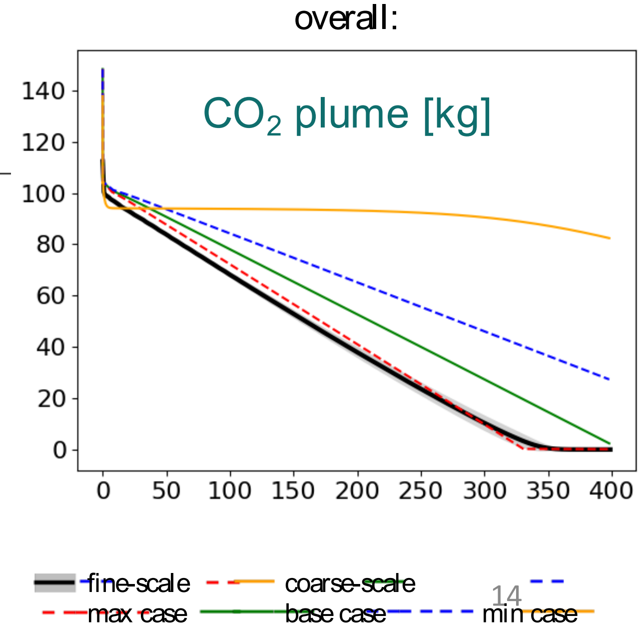
Three sub-grid parameters calibrated to high-resolution simulations

χ ψ ω

Example: 2D small domain

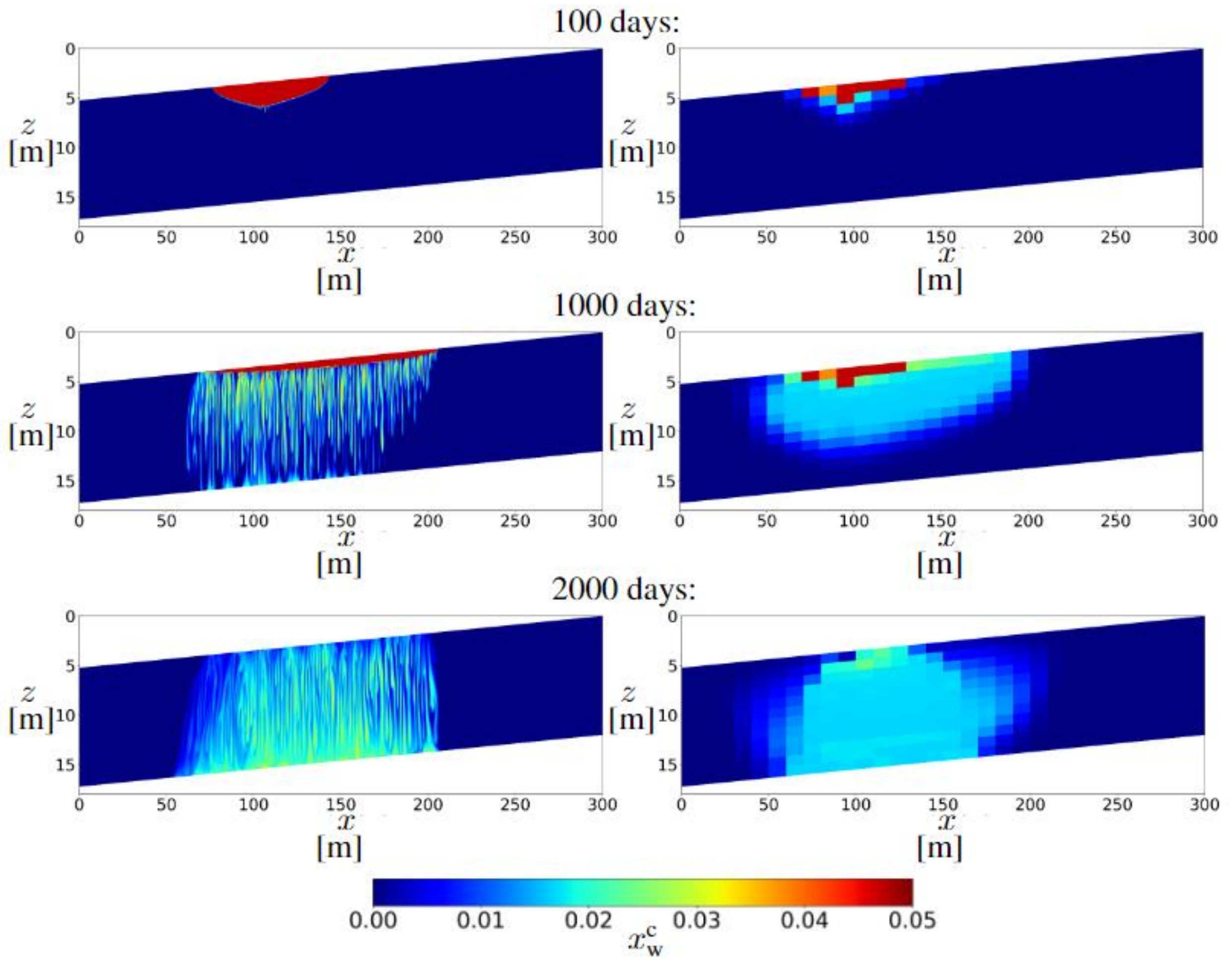






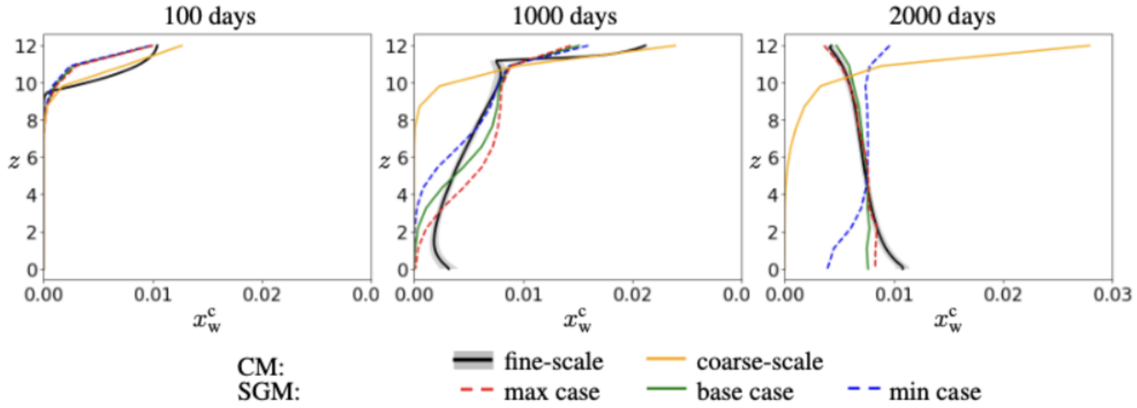
Mykkeltvedt, T.S., et al. New Sub-grid Model for Convective Mixing in Field-Scale Storage Simulation.Transp Porous Med 152, 9, 2025

Example: 2D larger domain

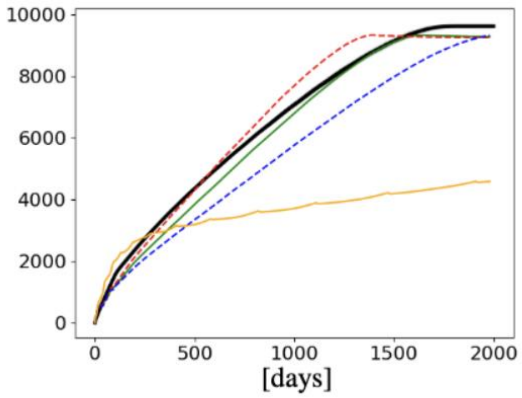


Model implementation and benchmarking
2.5 hours vs 2.5 seconds

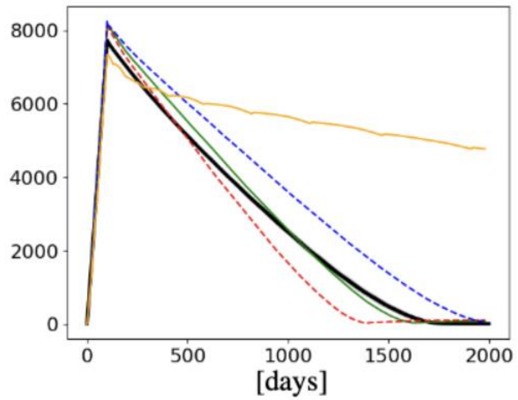
Vertical concentration profile



Dissolved CO_2



CO_2 plume



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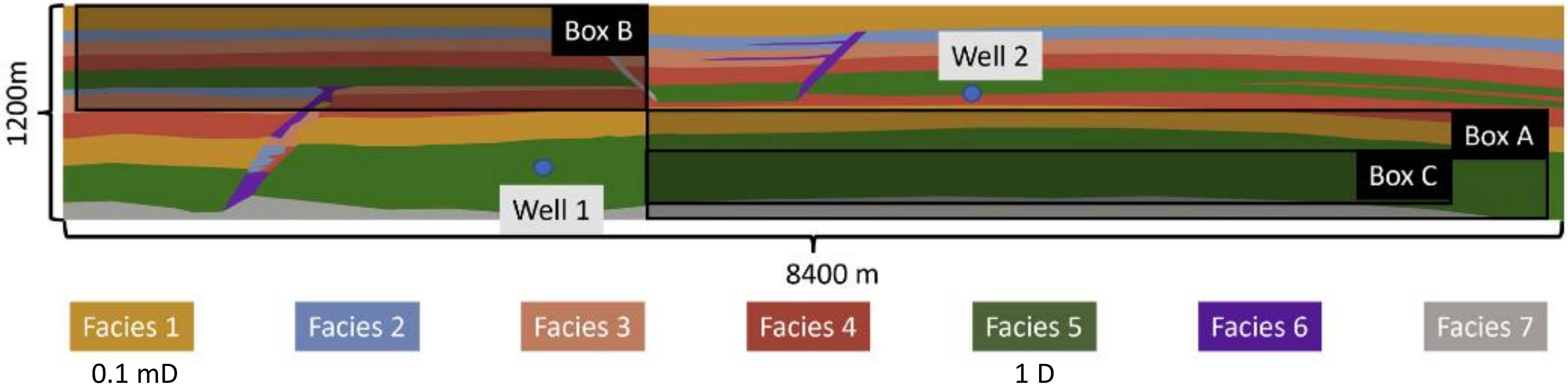
Example: SPE 11B

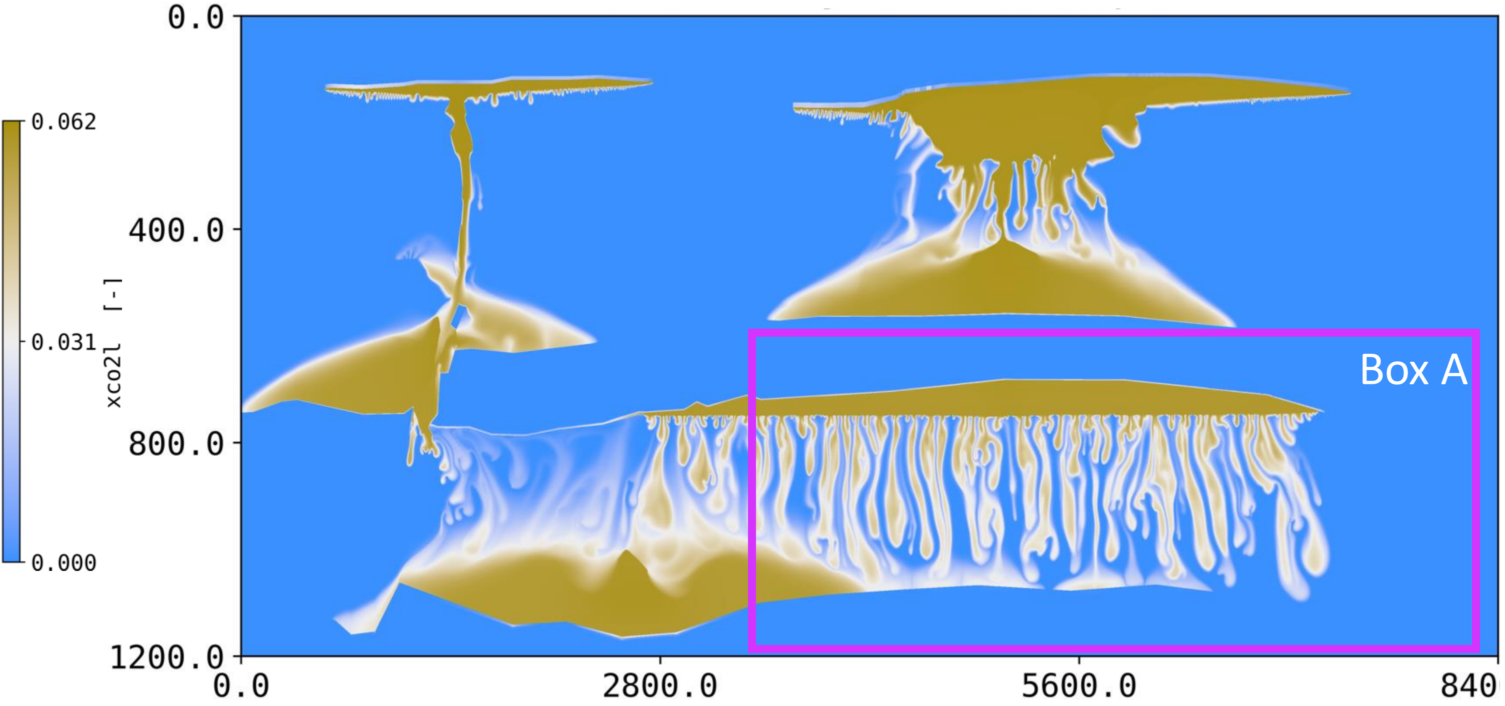


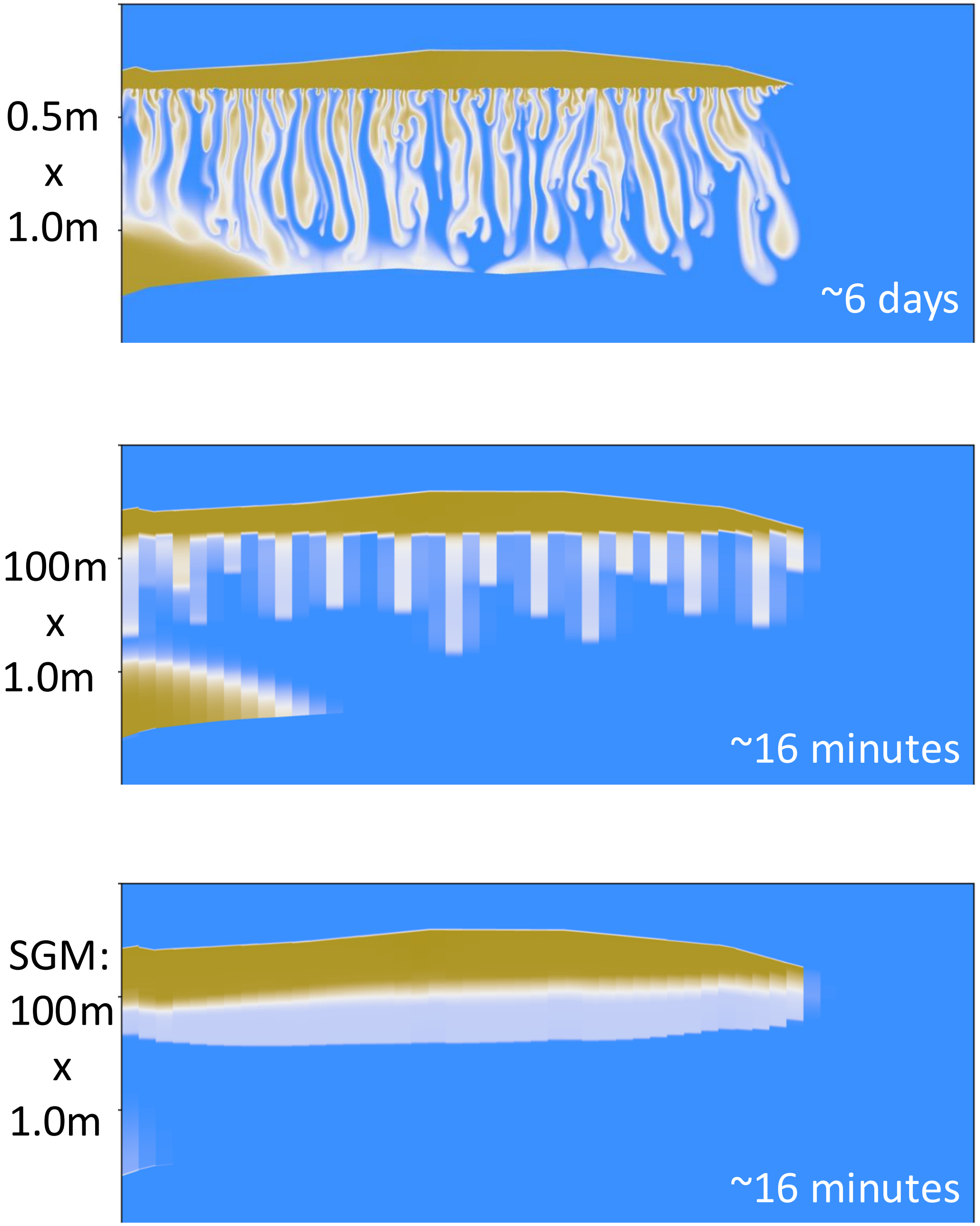
Initial conditions:
pure water at hydrostatic pressure and geothermal gradient pressure, set 1000 years before injection begins.
Injection conditions:
50 years of injection, injection rate is approximately 1100 tons of CO_2 per year for each well

https://opm.github.io/pyopmspe11/

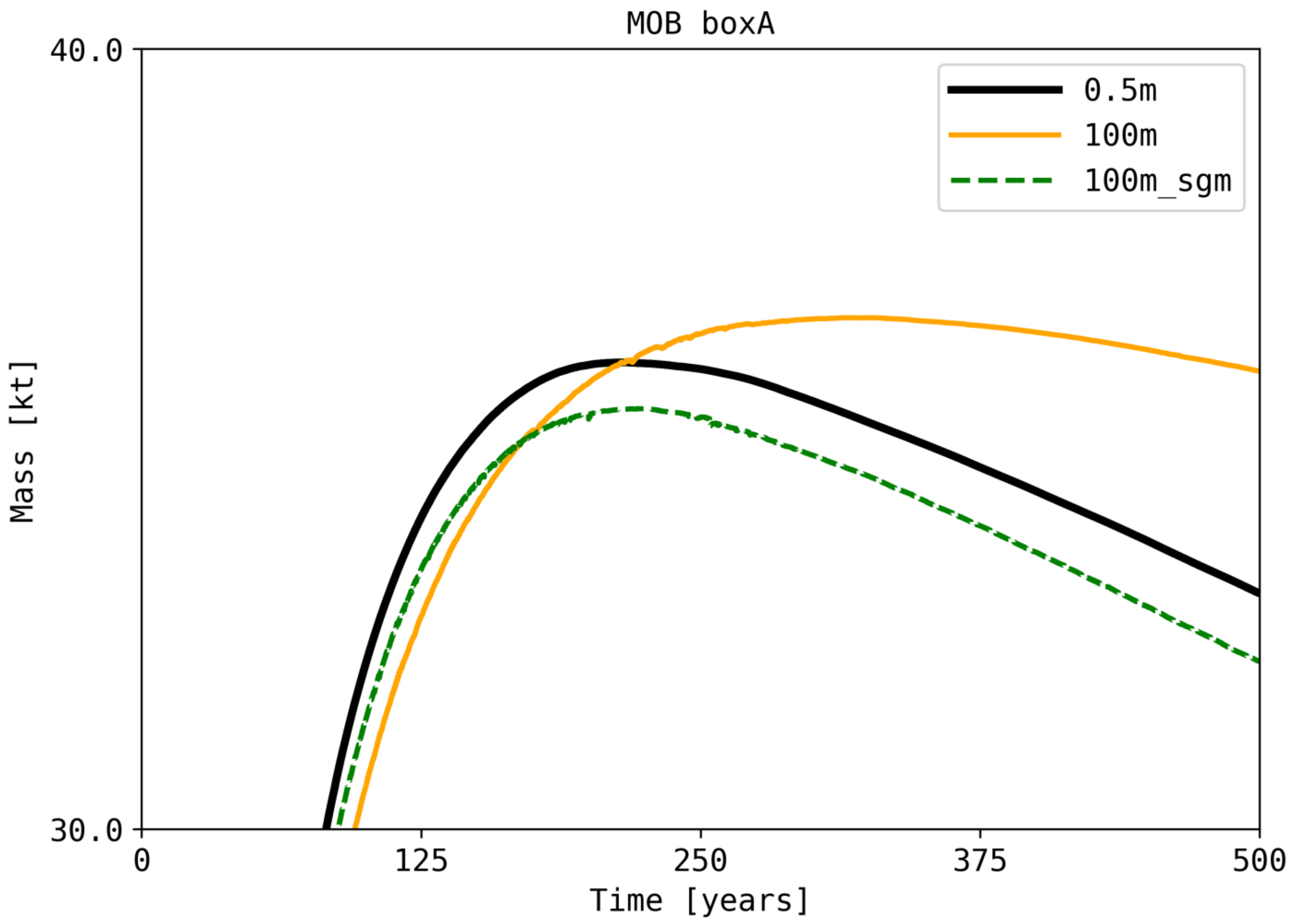
Nordbotten, J. M., et al. The 11th Society of Petroleum Engineers Comparative Solution Project: Problem Definition. *SPE J*. 29: 2507–2524, 2024.

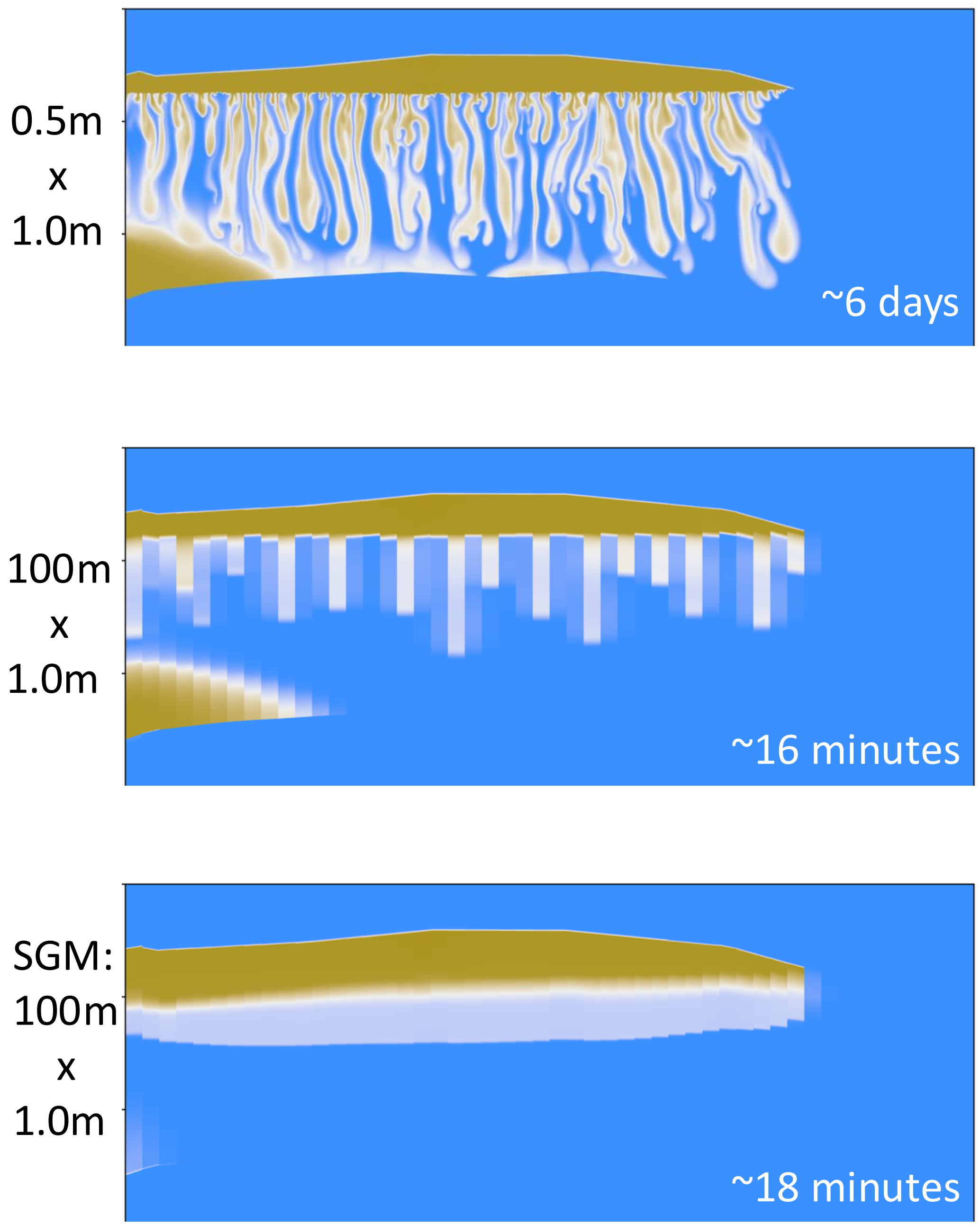
Example: SPE 11B



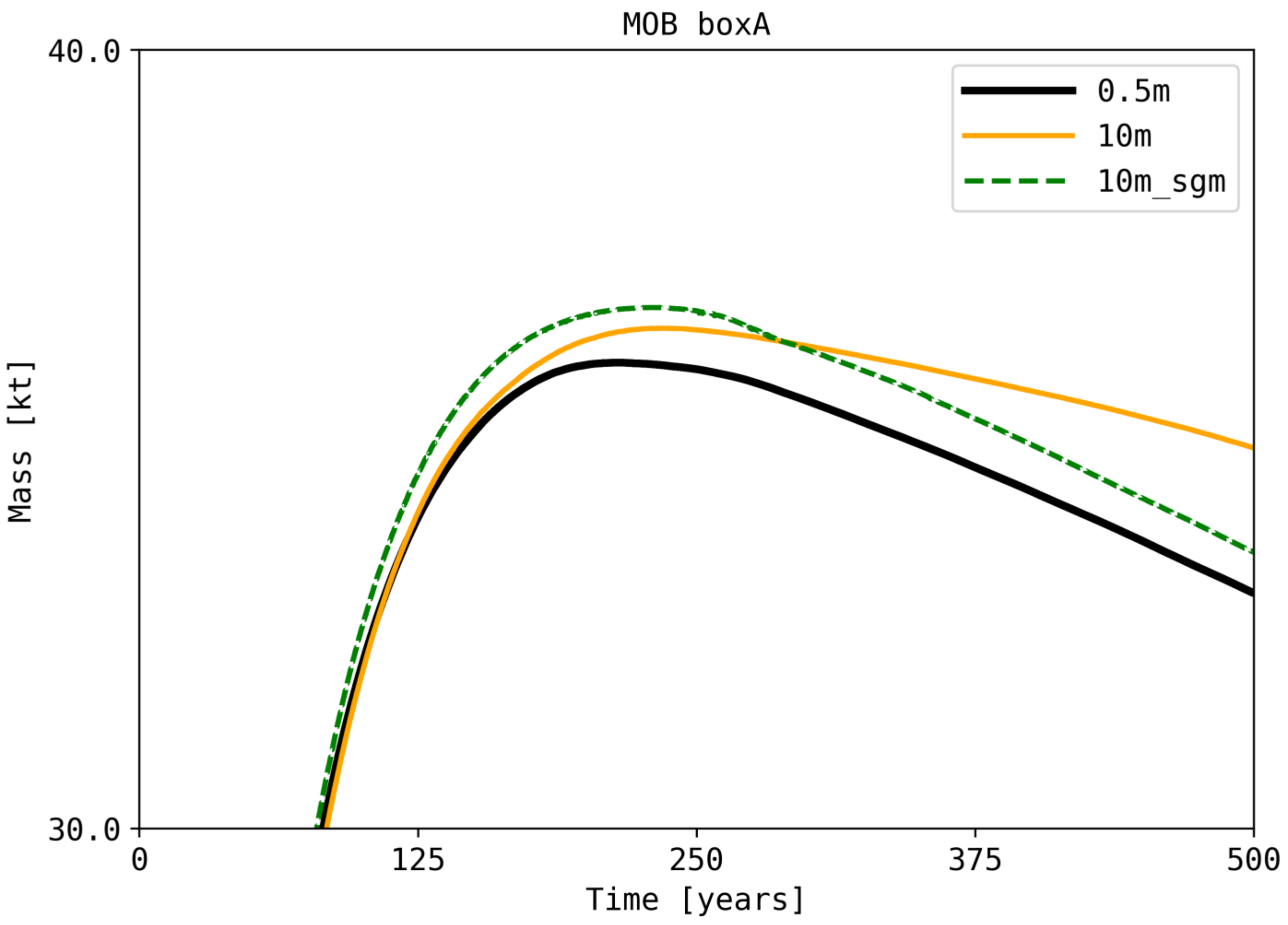


Example: SPE 11B

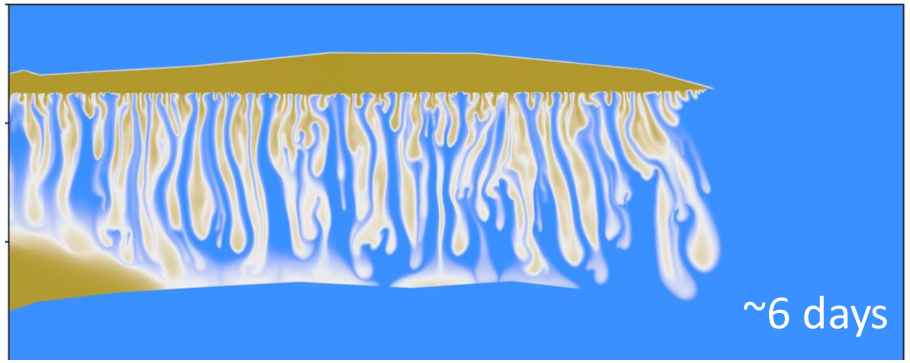




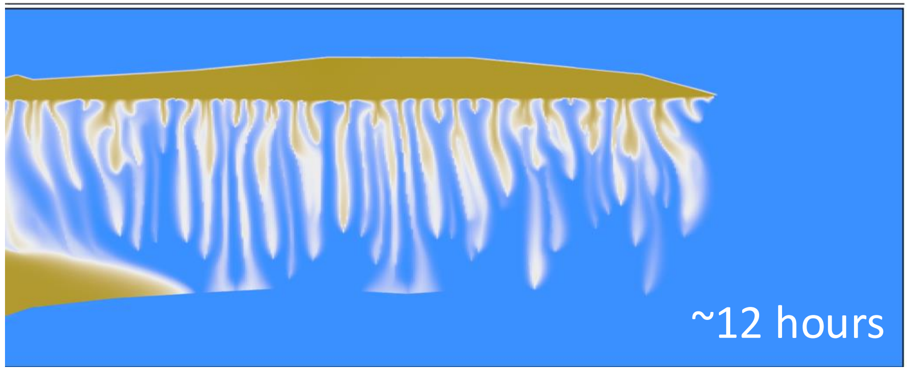
Example: SPE 11B



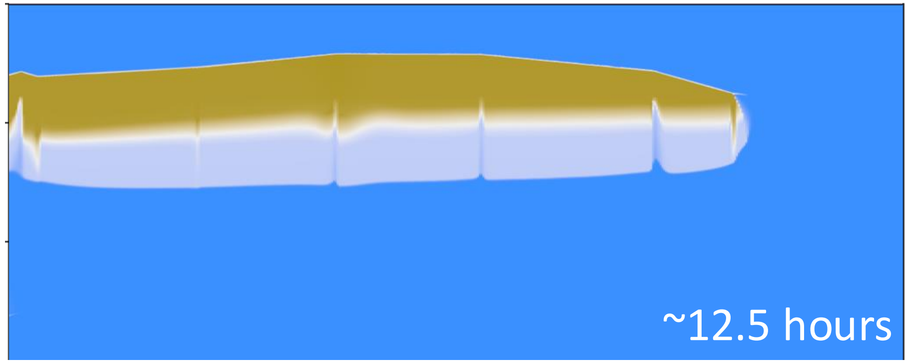
0.5m
x
1.0m



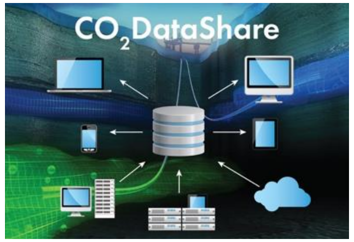
10m
x
1.0m



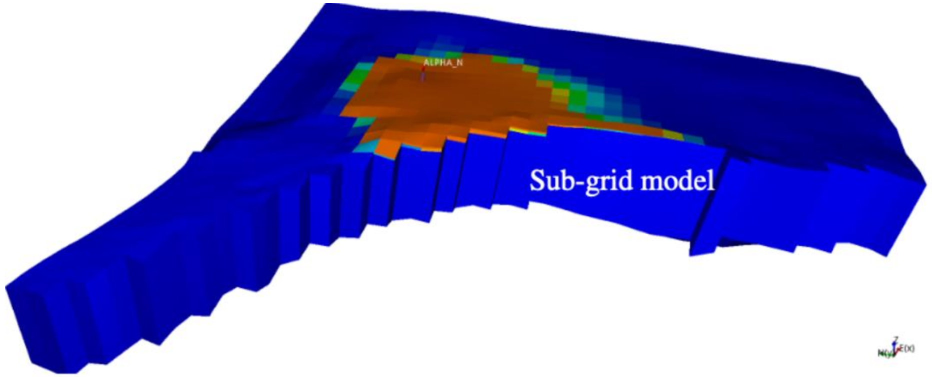
SGM:
10m
x
1.0m

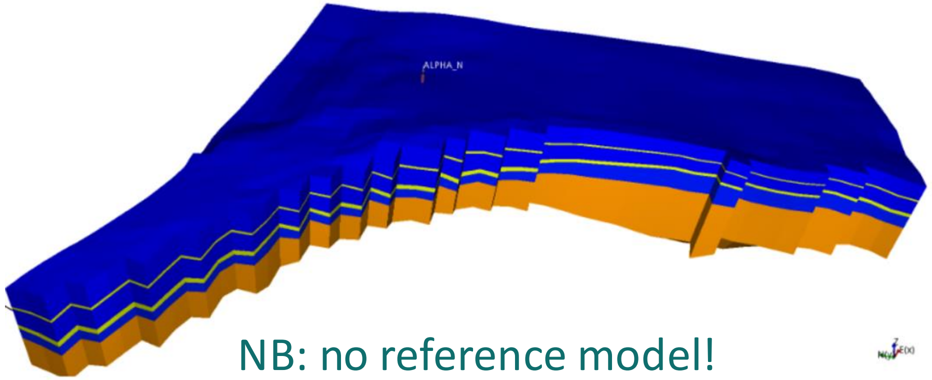


Example: Open Smeaheia field model

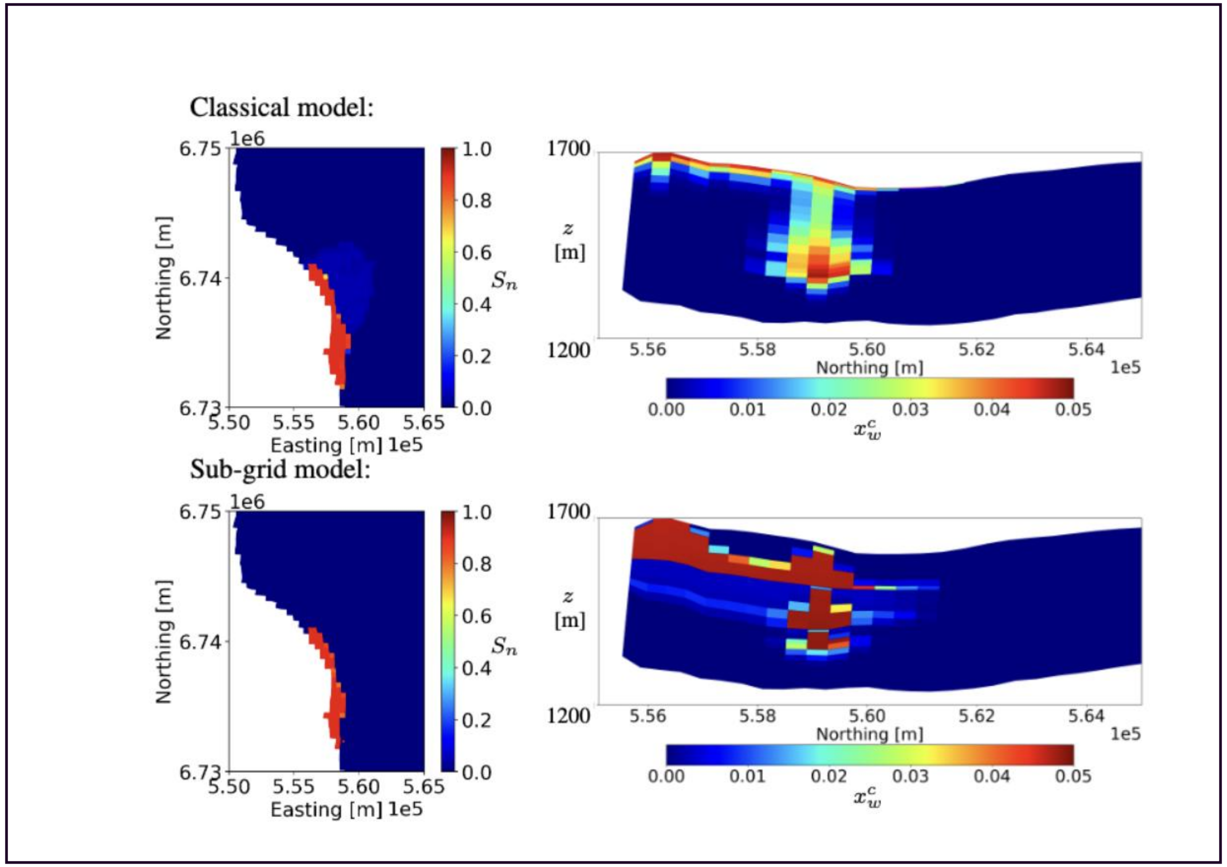


25 years injection and 500 years post-injection
Layered heterogeneity in 10 km x 10 km domain





NB: no reference model!



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Summary

- Developed, implemented and tested a new sub-grid model that incorporates the impact of convective mixing on the cm-scale into field-scale
- Through benchmark tests it is demonstrated that the model effectively replicates the behaviour of dissolved CO_2 in brine, even when using coarse resolution grids
- Easily implemented in field-scale simulation tools OPM Flow + DRSDTCON keyword

Allows for significantly coarser grids while retaining the effect of convective mixing in the simulations

Acknowledgements

- financial support from
  - the CLIMIT-Demo/Gassnova project 622059 and (HPCG)
  - the CLIMIT R&D project 336294 (ExpReCCS)