Model Coupling for Feasibility Studies of CO_2 Storage in Deep Saline Aquifers

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Outline

- Motivation
- Coupling concept
- First example application

CO_2 storage gets real

source: www.geozentrum-hannover.de

Present state:

large scale R&D projects
(e.g. two in Germany in 2010)

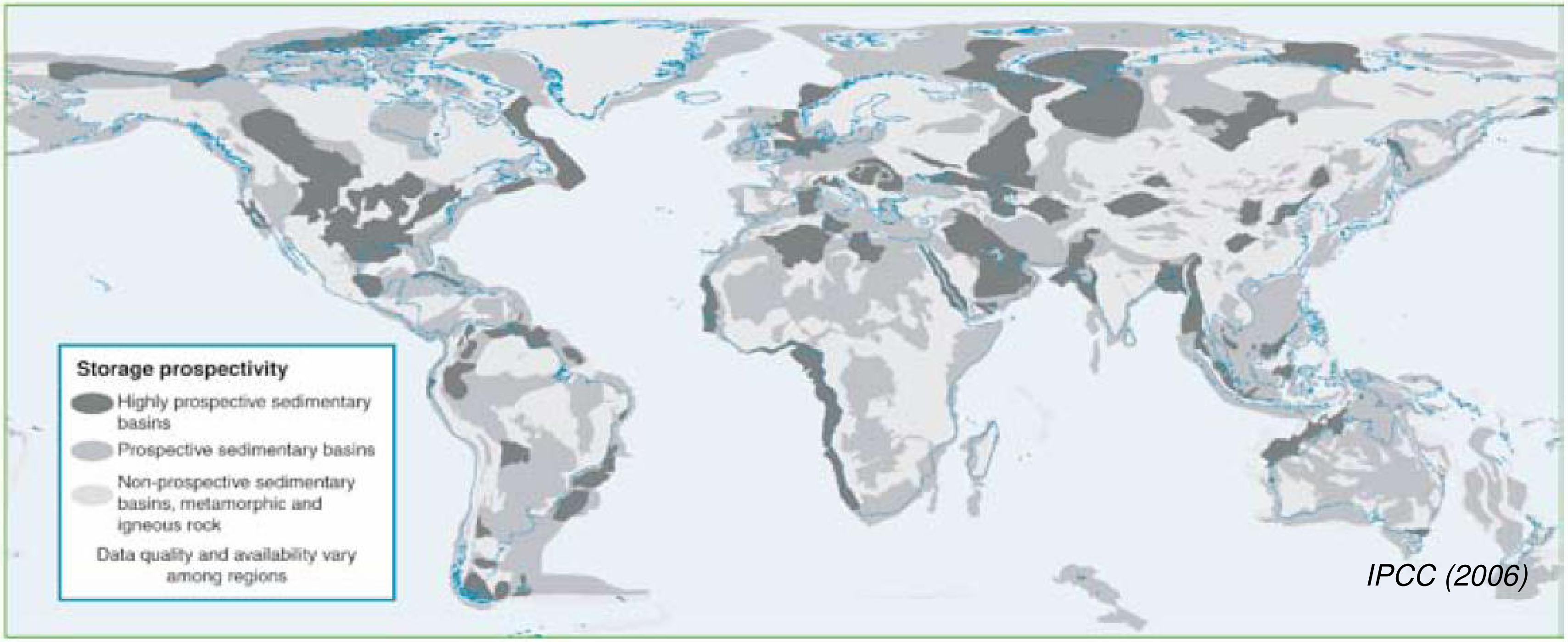
Important step for realisation:

find suitable sites for CO_2 storage
→ site characterisation and risk analysis

Efficient model tools are needed:

model tools capable of describing complex physical processes on and above the reservoir scale.

Finding a suitable site



IPCC (2006)

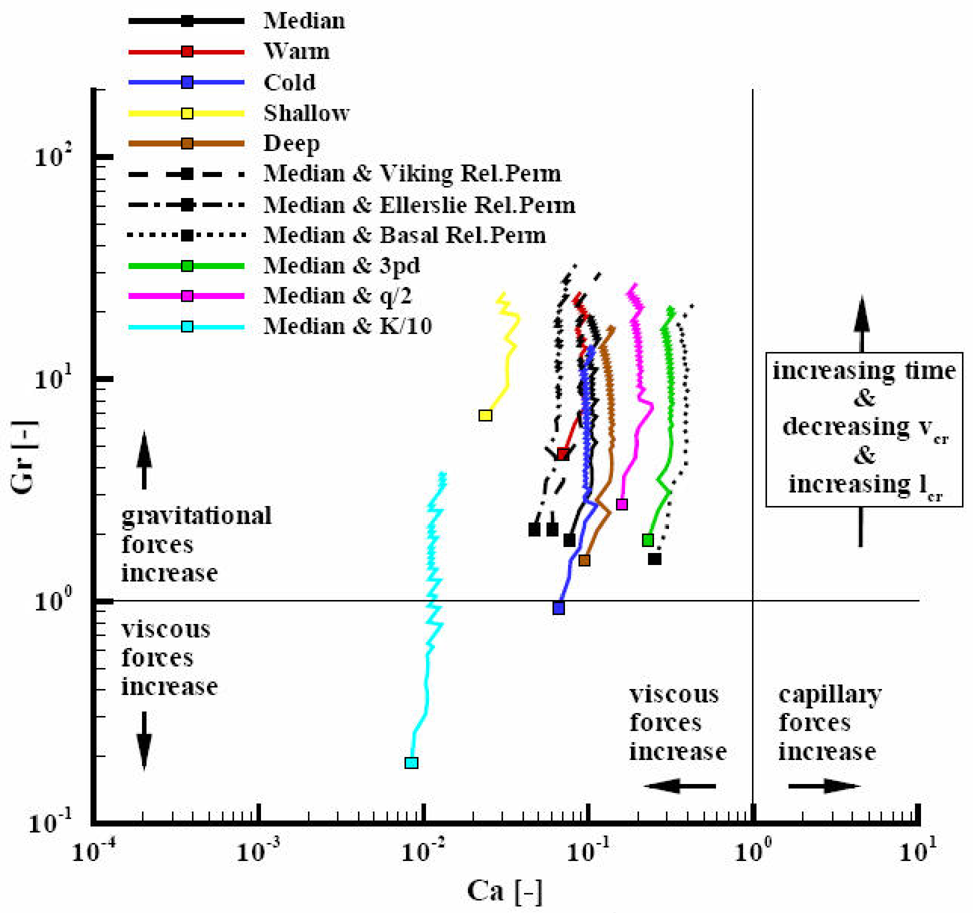
Worldwide CO_2 storage prospectivity according to IPCC report.
Regions suitable for storage need to be further determined by screening methods.

Finding a suitable site

Screening methods developed by Kopp et al. 2009 (Intern. Journal on Greenhouse Gas Control):

Cases	M_{eff}
Shallow R.	0.09
Warm R.	0.38
Median R.& $\frac{q}{2}$	0.77
Median Reservoir	1.00
Median R.&3p_d	1.11
Deep R.	1.21
Median R.&V.-kr	1.29
Median R.&E.-kr	1.45
Cold R.	1.57
Median R.&B.-kr	1.88
Median R.& $\frac{K}{10}$	1.94

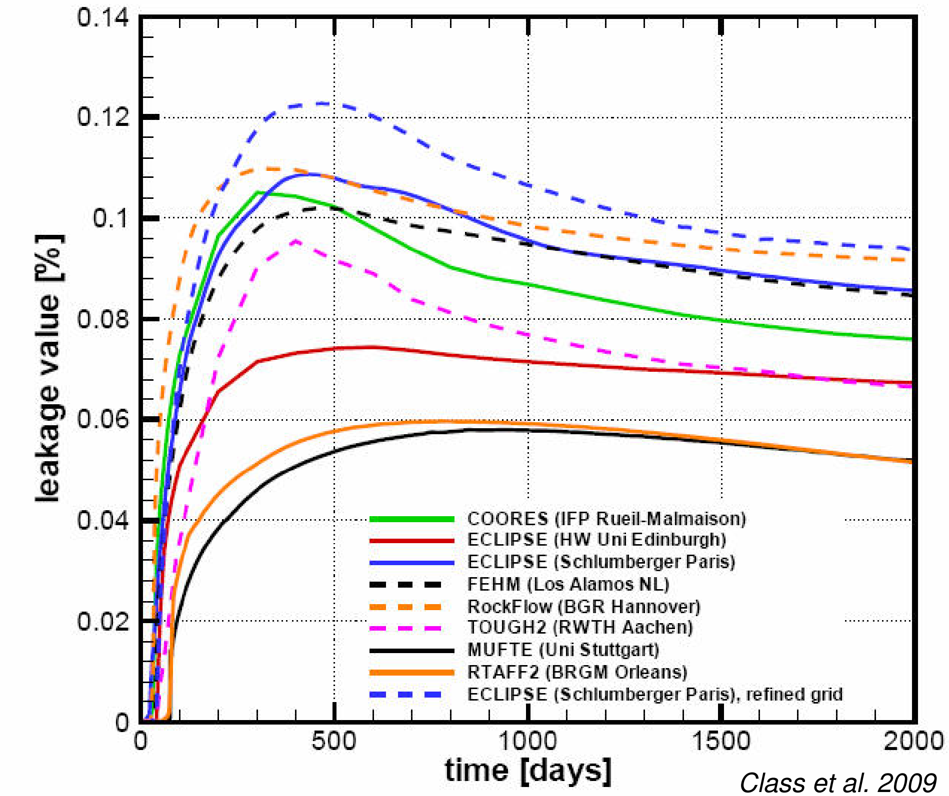
M_{eff} : effective storage capacity
Gr: gravitational number
Ca: capillary number



$(\hat{\nabla}\hat{p}_c \overset{!}{=} 1$ over the front width$)$

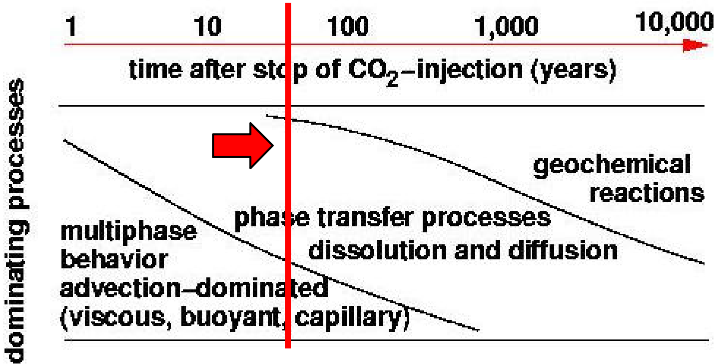
Available model tools for further investigations

Benchmark study (CO_2 Workshop, Stuttgart, April 2008):



Class et al. 2009

International intercomparison of different models for nonisothermal multiphase multicomponent processes.



modified after IPCC

Benchmark studies were restricted on a timescale of less 50 years.

Further site investigations

Examples for site investigations after first screening:

Cap rock security and injectivity?

→ hydraulic, thermal, geochemical and geomechanical effects near injection well

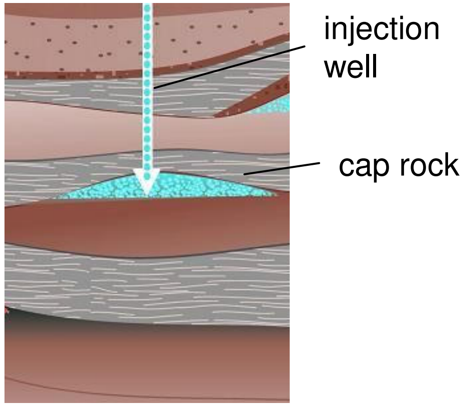
Storage security and sustainability?

→ long term simulation of hydraulic, thermal and geochemical processes.

Large scale effects?

→ simulation of pressure development, brine migration

small scale



Source IPCC

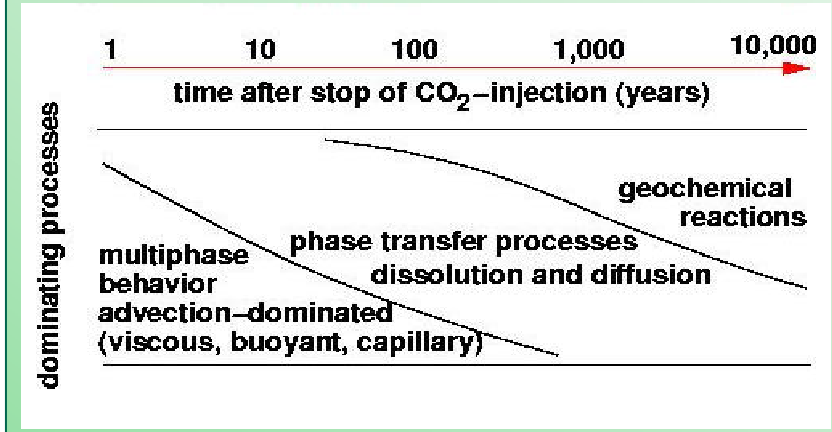
large scale

Diercke Weltatlas 2

Challenges for the modellers

needed:

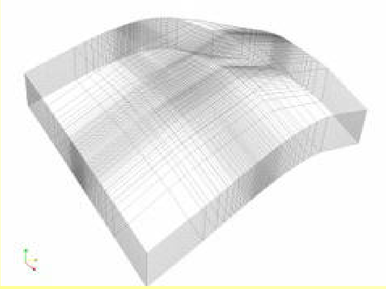
problem:



long term simulations

High Computational Cost !

processes
thermal, hydraulic, chemical, mechanical

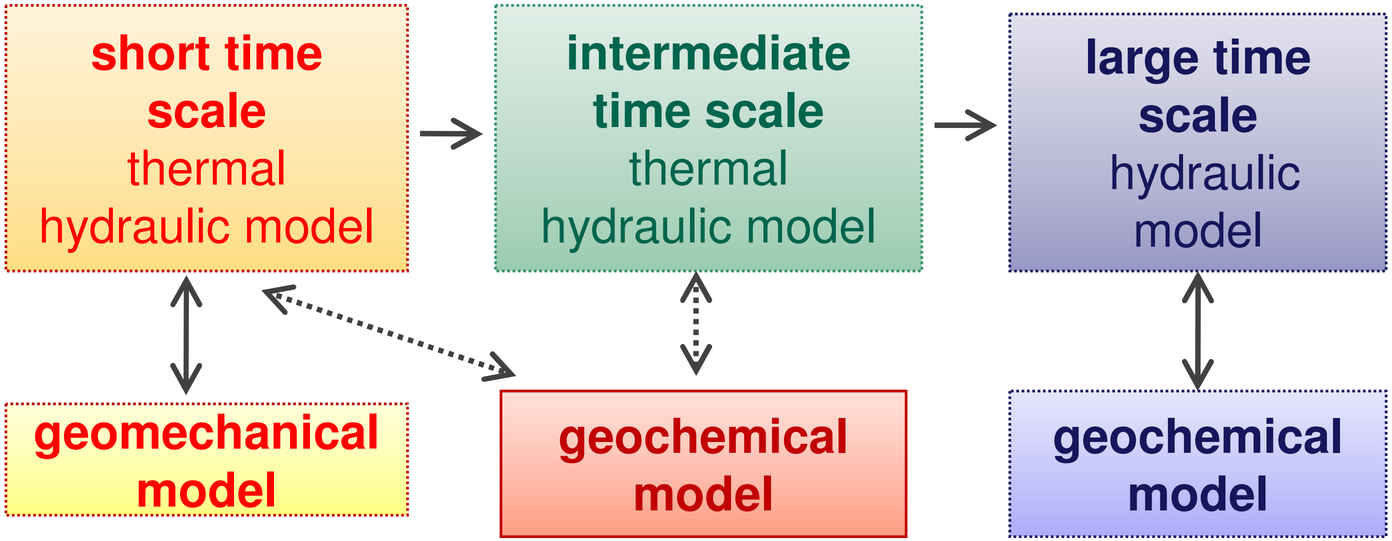


complex geometries

Model coupling

Most of the existing models are only capable of describing parts of the required complexity.

→ couple models and adapt model complexity in an efficient way.



short time scale
thermal hydraulic model

intermediate time scale
thermal hydraulic model

large time scale
hydraulic model

geomechanical model

geochemical model

geochemical model

Development of the new simulator DuMu^X that allows a flexible implementation of model interfaces.

Simulator DuMu^X

Dune for **Mu**lti-{phase,
component, scale, physics, …}
Flow in Porous Media

DuMu^X

www.dumux.uni-stuttgart.de

- Inherits functionality from all available Dune modules (Dune is a free software licensed under GPL: www.dune-project.org).
- Provides a framework for easy and efficient implementation of models from porous media flow problems:
  - problem formulation.
  - spatial and temporal **discretization schemes**.
  - nonlinear solvers.
  - concepts for **model coupling**: horizontally (subdomains), vertically (spatial scales), temporally (time integrators), problem dimensions.
- Includes ready to use numerical models and example applications.

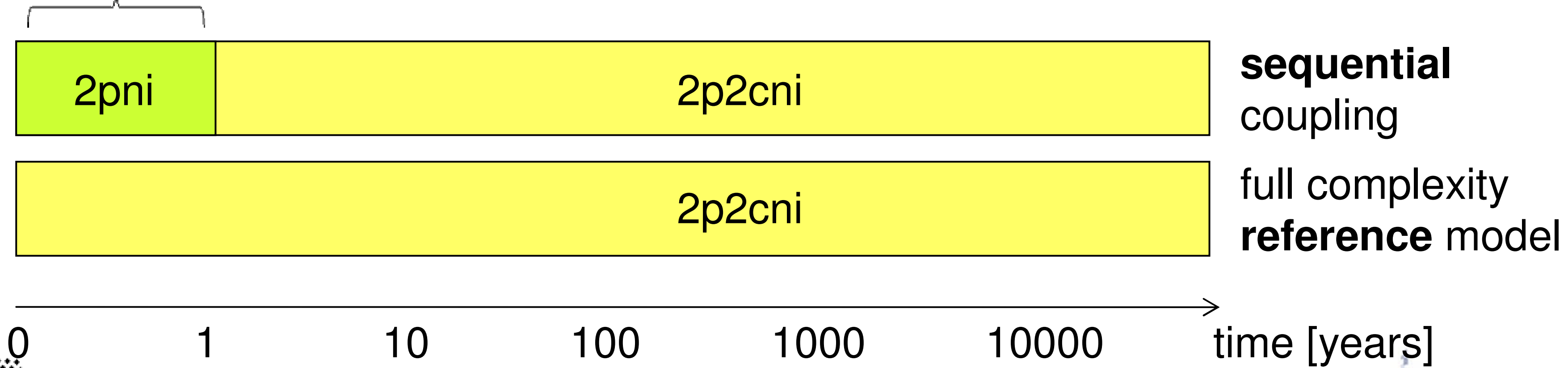
→ first DuMuX release in July 2009 on our webpage: dumux.uni-stuttgart.de

Sequential coupling

Coupling for the simulation of large time scales:

short term: advective and gravitational forces dominate, temperature effects (Joules Thompson, injection temperature)
→ nonisothermal twophase model (2pni)
multicomponent behaviour neglected

long term: residual trapping, diffusion and density-driven convection, chemical reactions, reestablishment of geothermal gradient
→ nonisothermal twophase twocomponent model (2p2cni)
full thermal hydraulic complexity



Switch from 2pni to 2p2cni model

primary variables 2pni model:
- p_{brine}
- temperature
- S_{CO2}

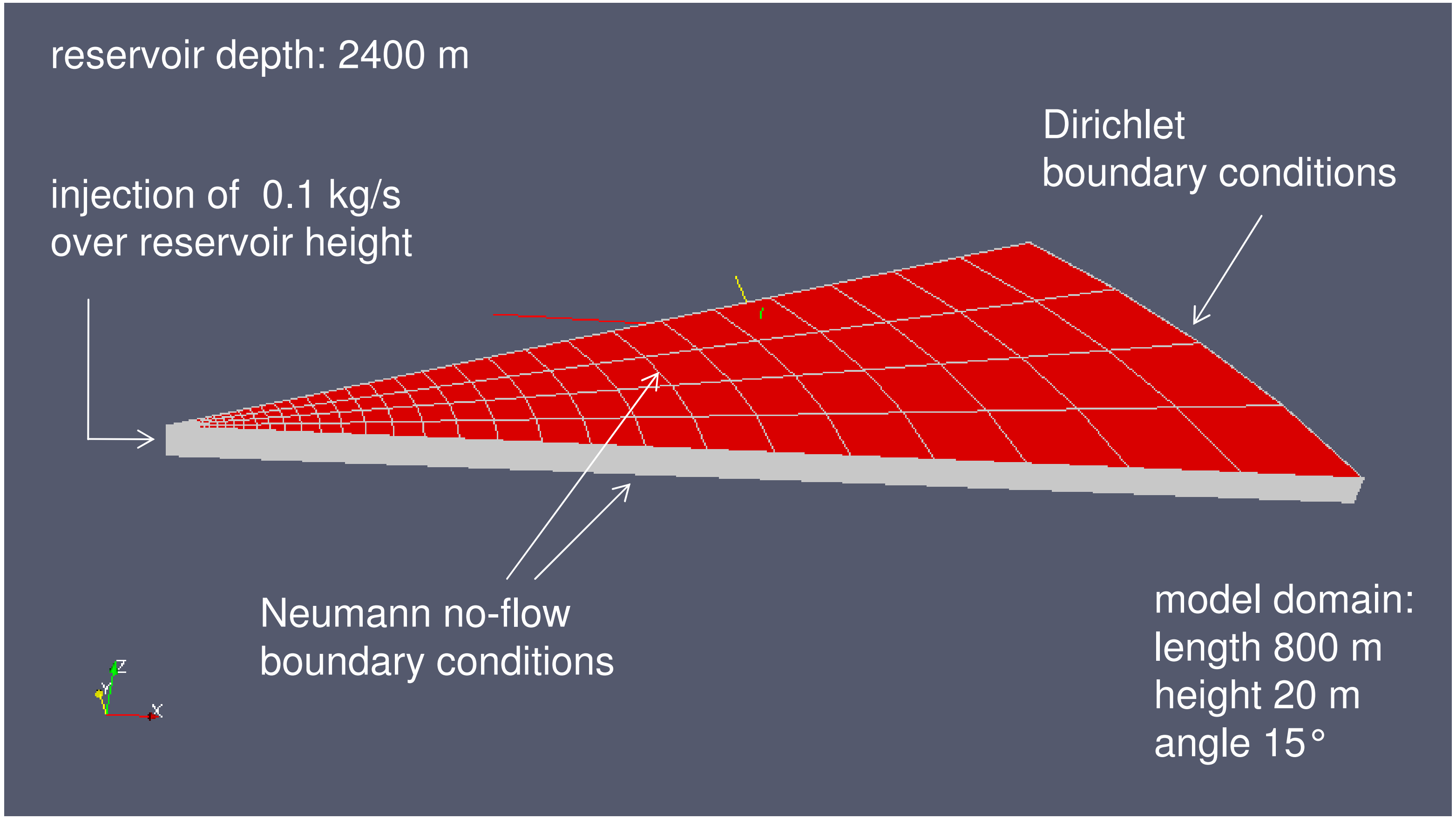
➡

primary variables 2p2cni model:
- p_{brine}
- temperature
- phase state dependent variable:
  - -X_{CO2} in brine (brine phase)
  - -X_{H2O} in CO_2 phase (CO_2 phase)
  - -S_{CO2} (both phases)

$\mathbf{p_{brine}}$ and **temperature** remain constant
$\mathbf{S_{CO2}}$ needs to be transformed:

2pni model old values	$\mathbf{S_{CO2} = 0}$ **(brine phase)**	$\mathbf{S_{CO2} = 1}$ **($\mathbf{CO_2}$ phase)**	$\mathbf{0 < S_{CO2} < 1}$ **(both phases)**
2p2cni model initial values	$X_{CO2} = 0.0$	$X_{H2O} = 0.0$	mass correction due to dissolved CO_2 → $S_{CO2\_2p2cni} < S_{CO2\_2pni}$

3D radially symmetric model setup



reservoir depth: 2400 m

injection of 0.1 kg/s
over reservoir height

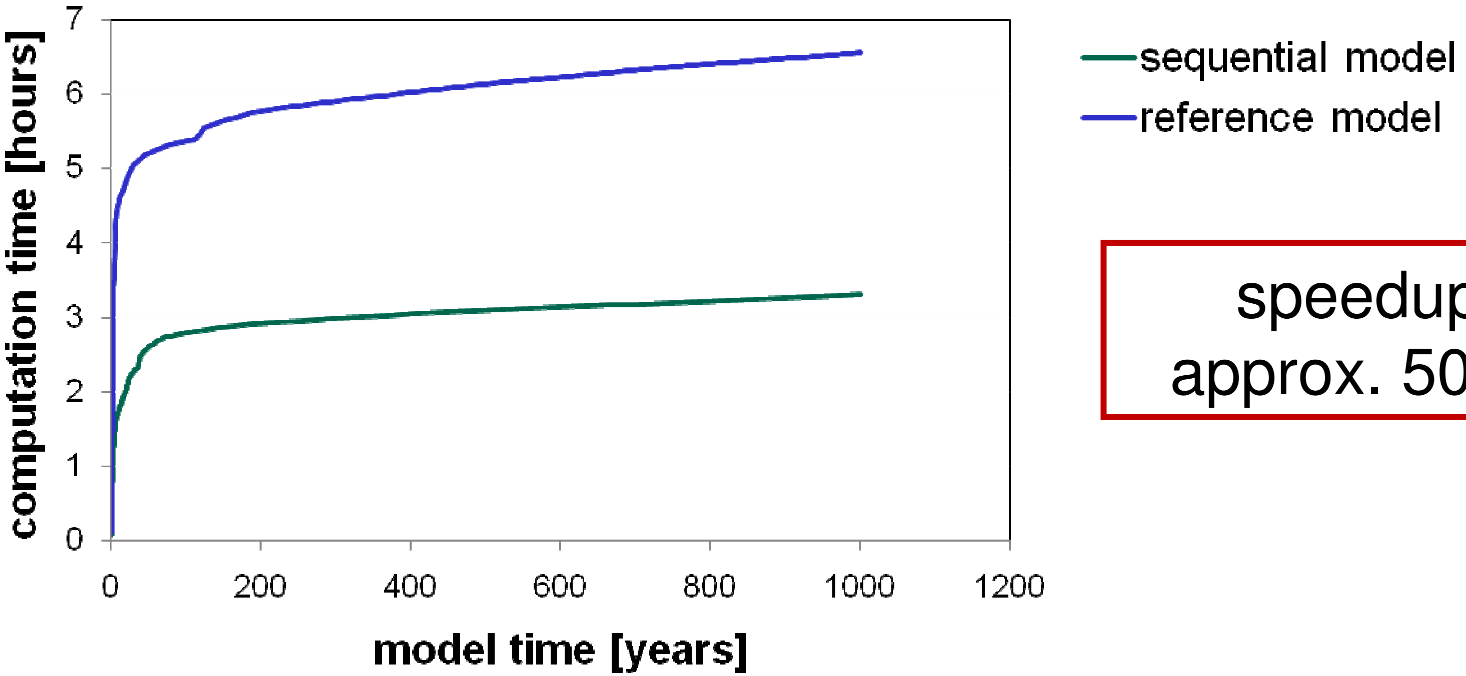
Dirichlet
boundary conditions

Neumann no-flow
boundary conditions

model domain:
length 800 m
height 20 m
angle 15°

Comparison – sequential coupling vs. reference

First comparison of computational cost:



speedup
approx. 50 %

sequential model:

- 2pni model (injection 1 year)
- 2p2cni model (postinjection 1000 years)

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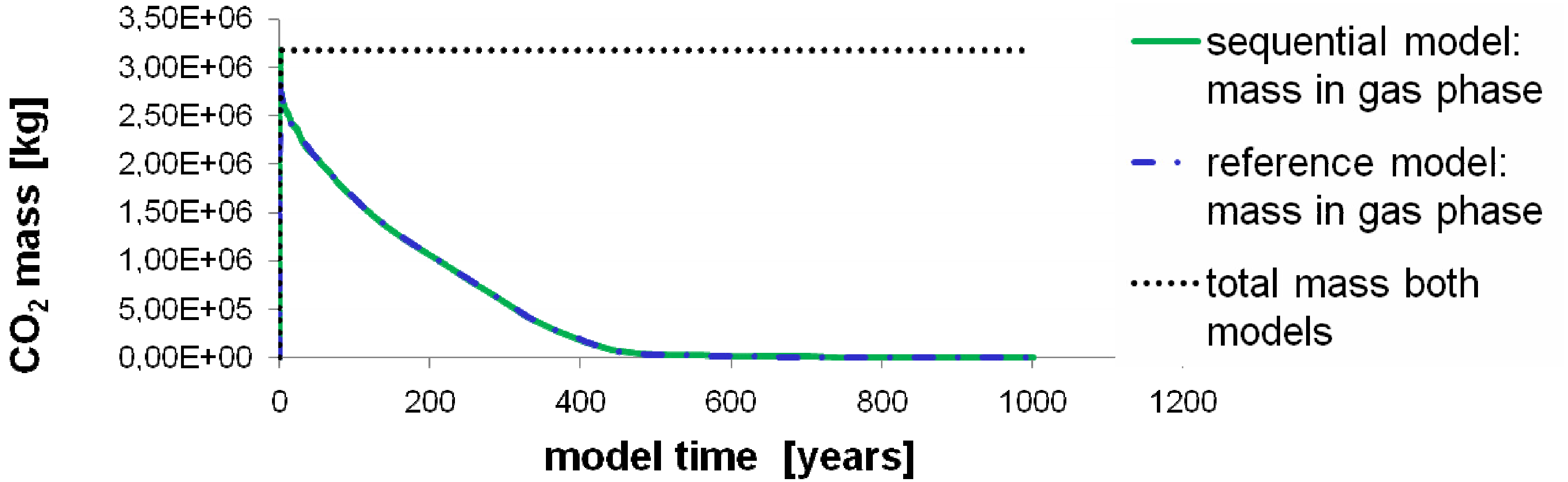
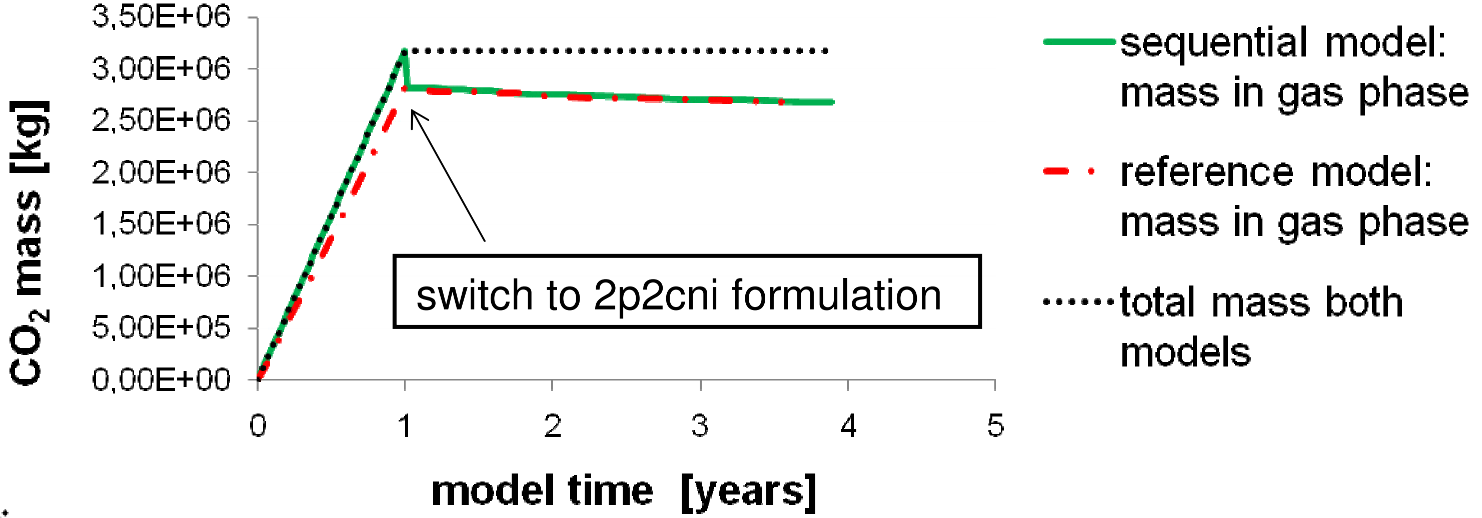
reference model:

- 2p2cni model (injection and postinjection)

Comparison – sequential coupling vs. reference

CO_2 mass in gas phase compared to total CO_2 mass:

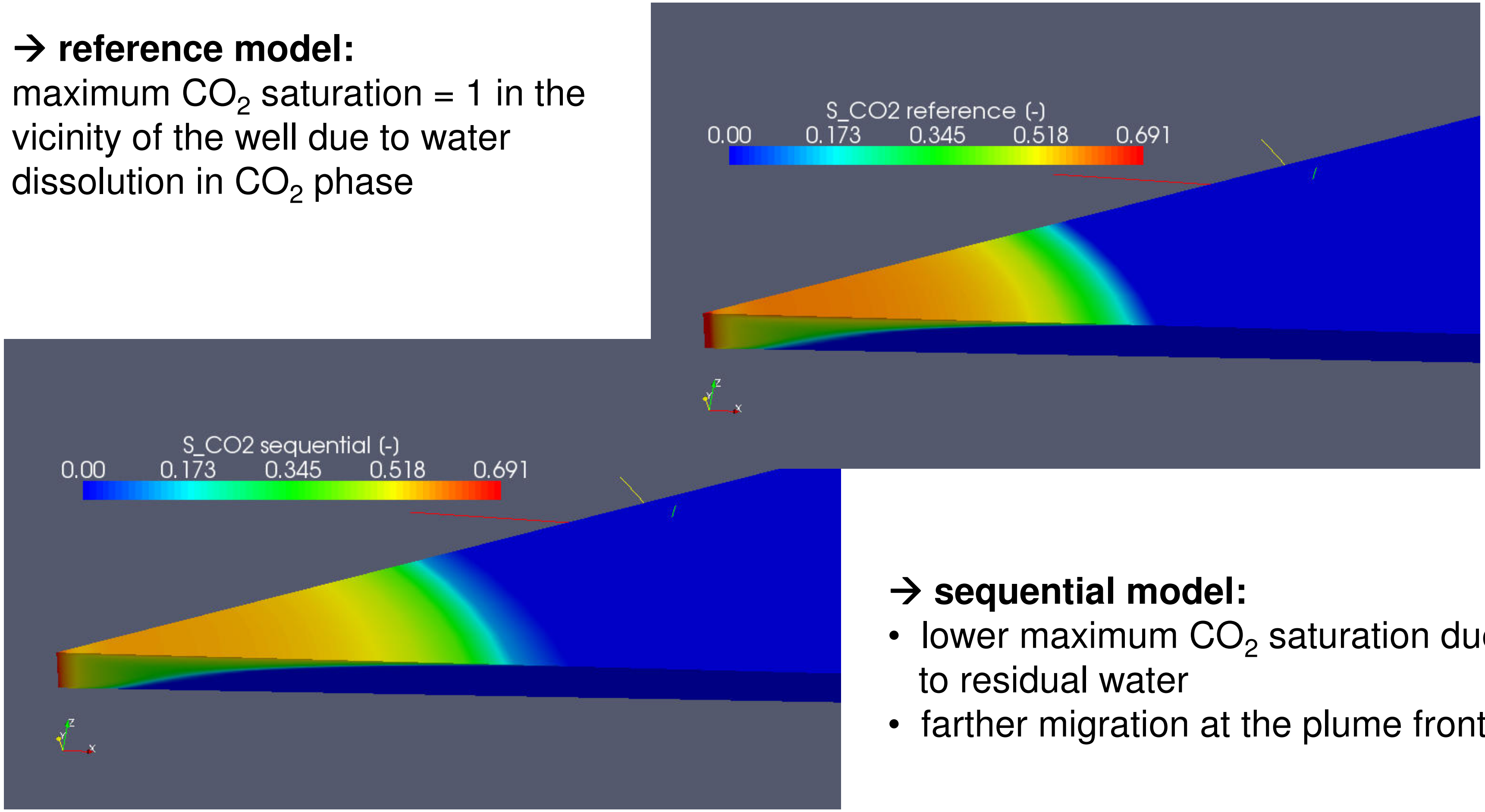




Comparison – sequential coupling vs. reference

local saturation distribution after 1 year of injection:

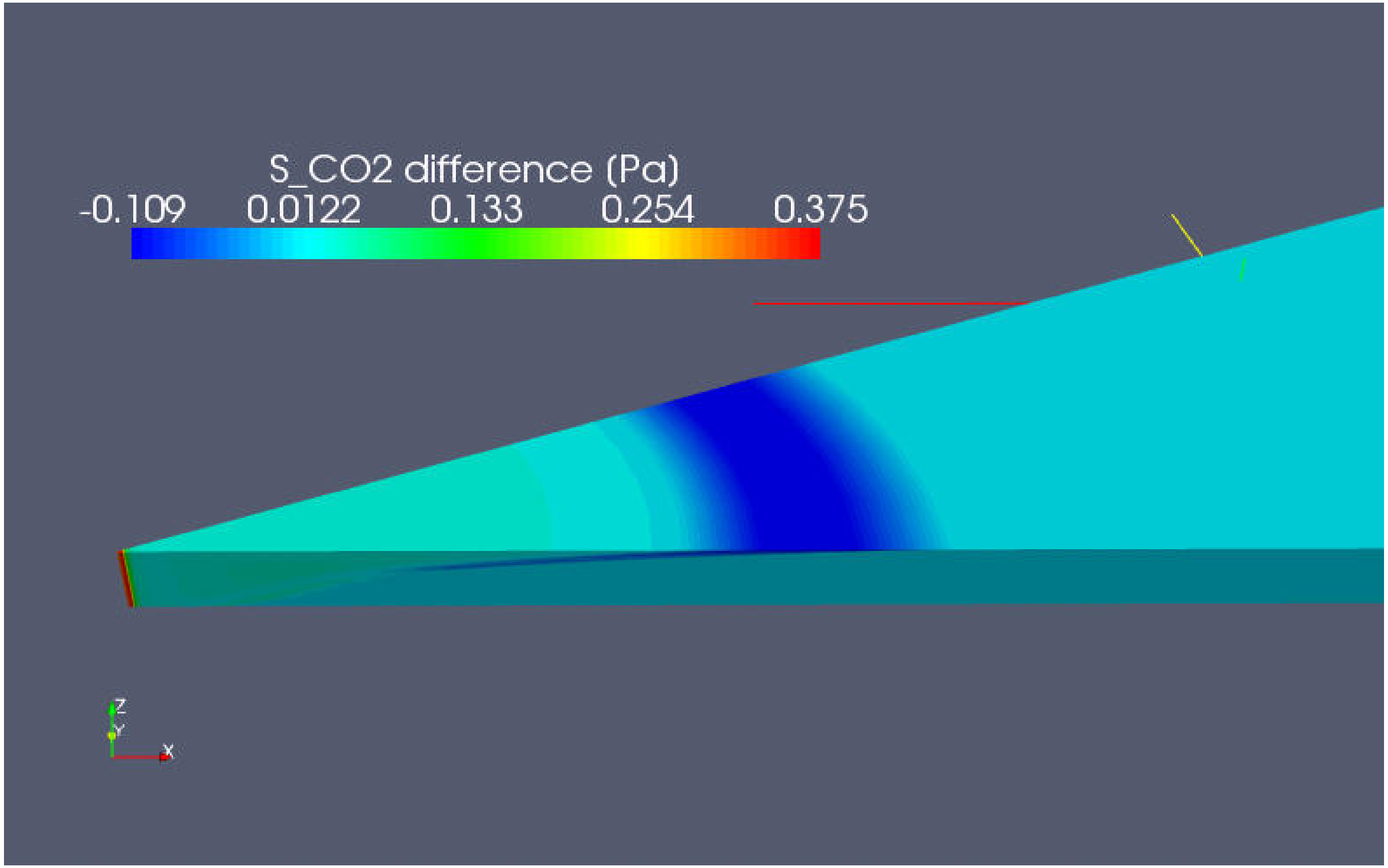
→ **reference model:**
maximum CO_2 saturation = 1 in the vicinity of the well due to water dissolution in CO_2 phase



→ **sequential model:**
- lower maximum CO_2 saturation due to residual water
- farther migration at the plume front

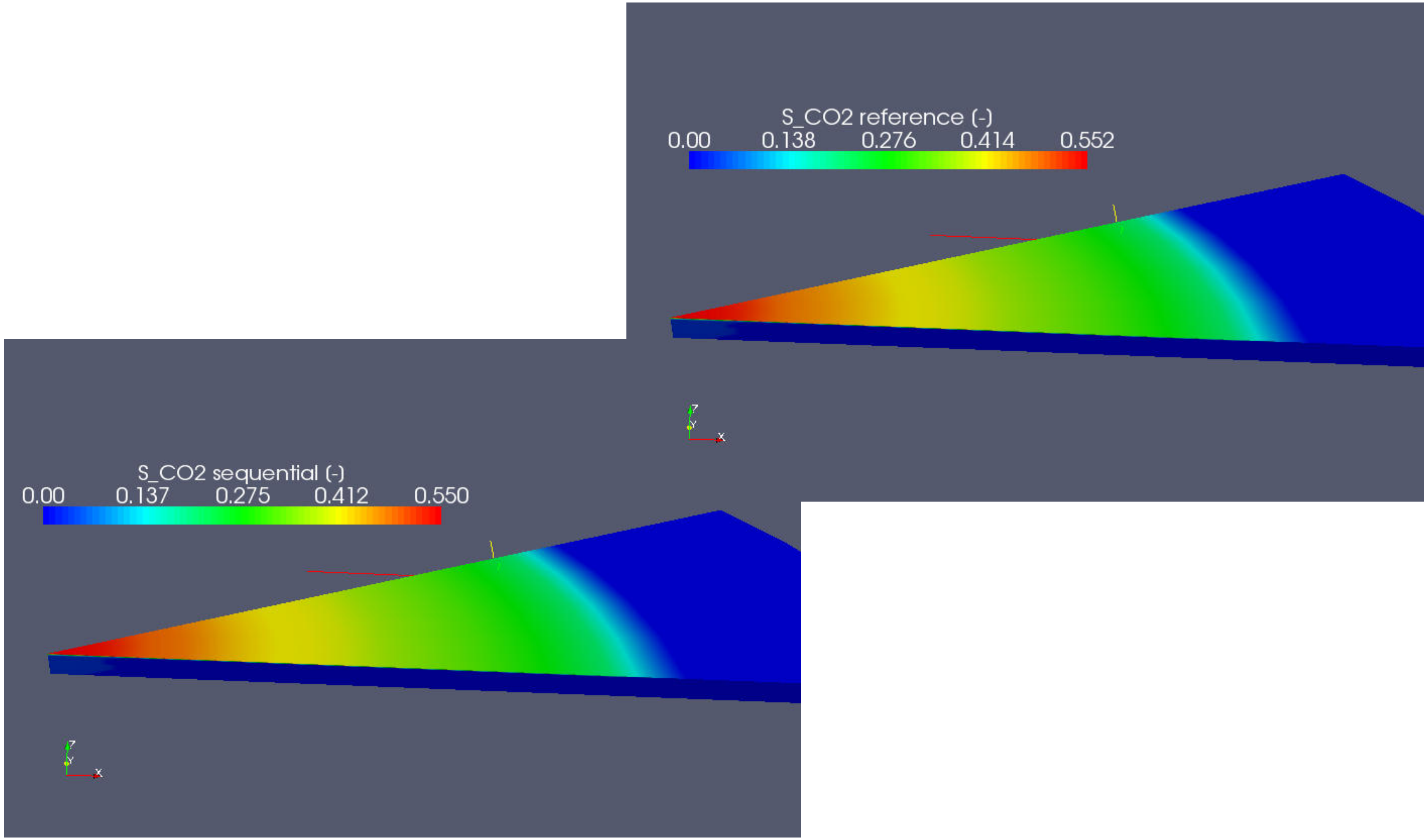
Comparison – sequential coupling vs. reference

local saturation differences after 1 year of injection:



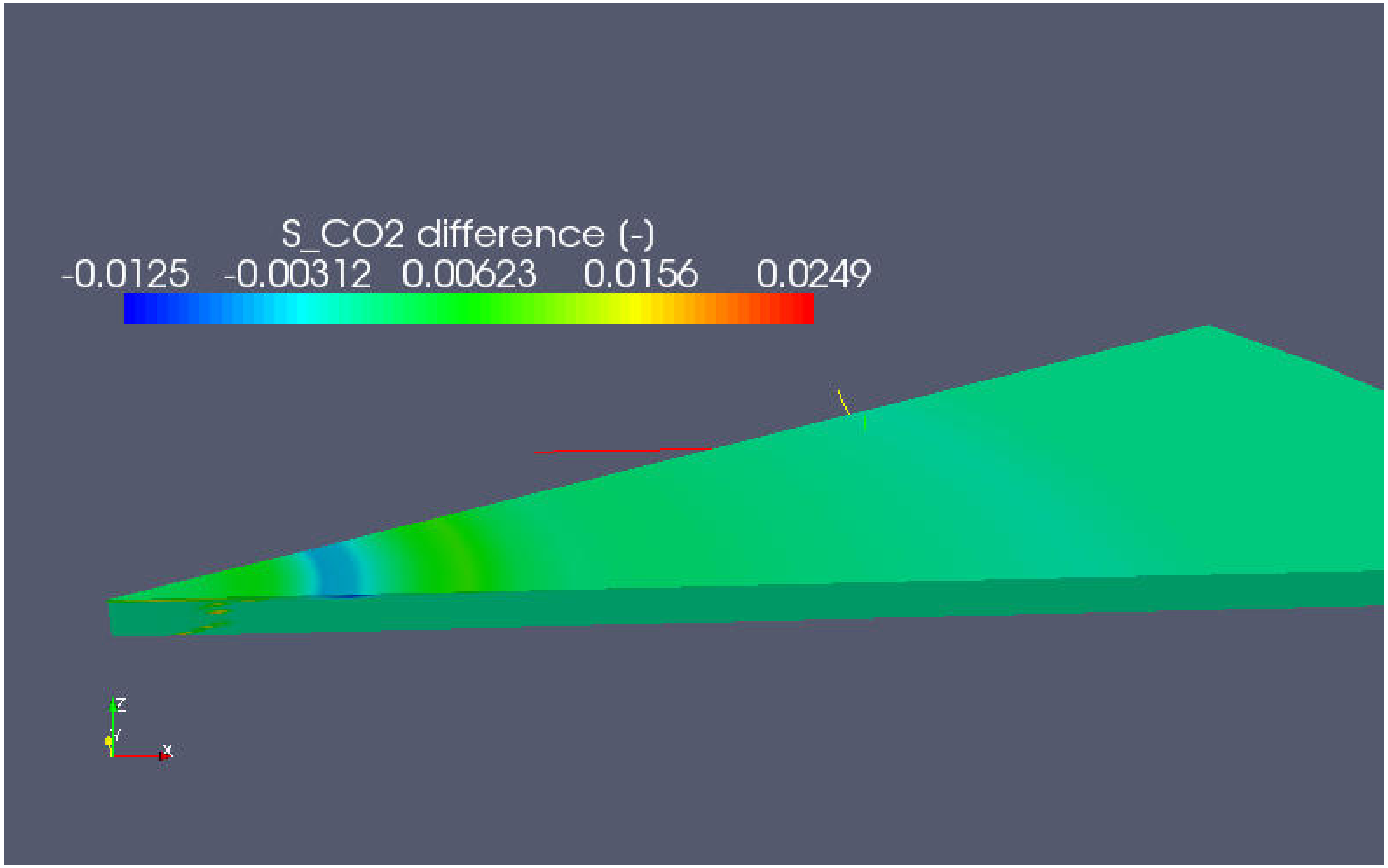
Comparison – sequential coupling vs. reference

saturation distribution 100 years after injection:



Comparison – sequential coupling vs. reference

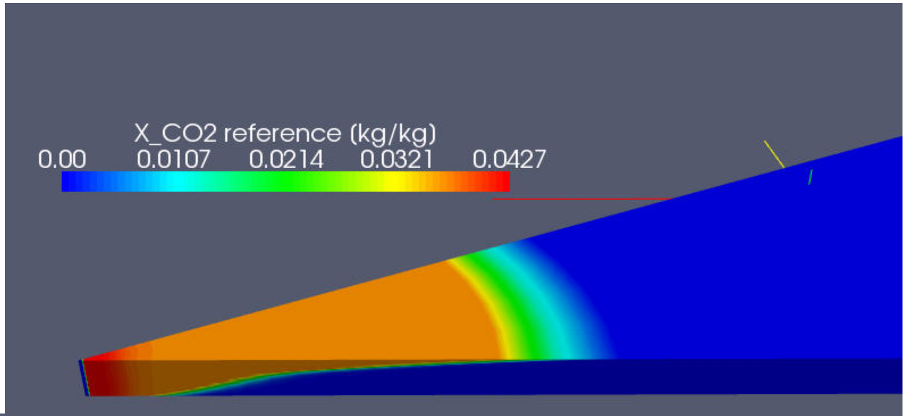
local saturation differences 100 years after injection:

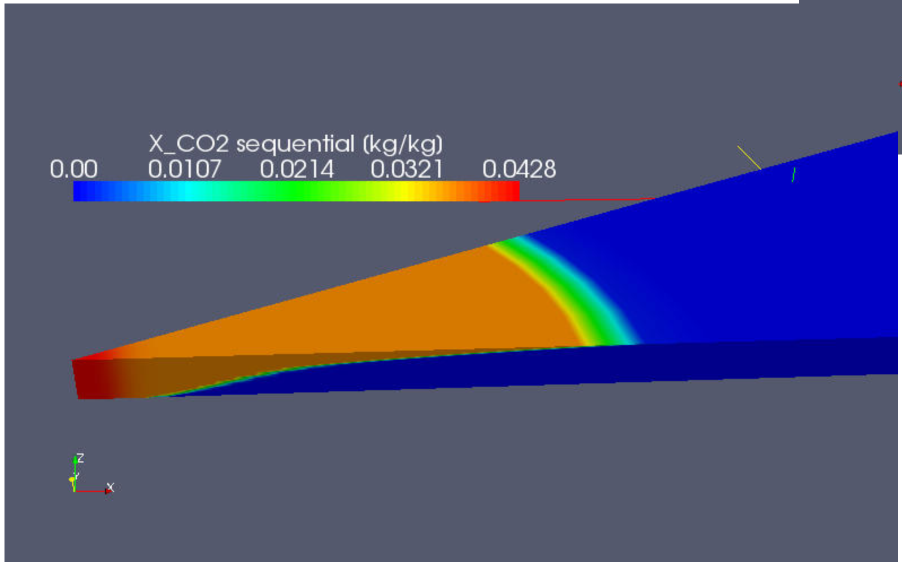


Comparison – sequential coupling vs. reference

local concentration distribution after 1 year of injection (massfraction CO_2 in brine phase):

→ reference model:
pure gas phase in the vicinity of the injection well with $X_{CO2} = 0.0$

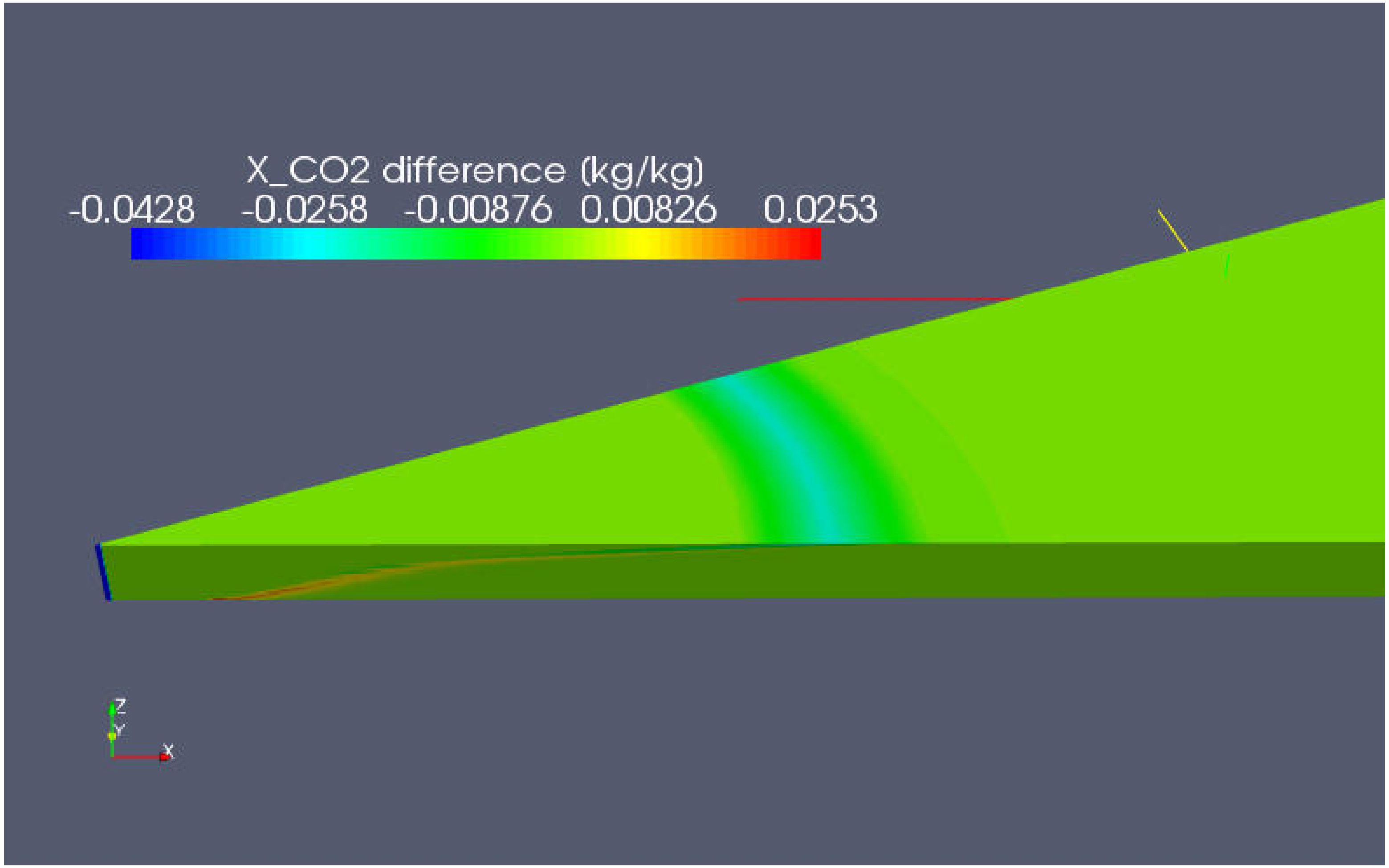




→ sequential model:
gas phase and water phase in the whole plume $X_{CO2} > 0.0$

Comparison – sequential coupling vs. reference

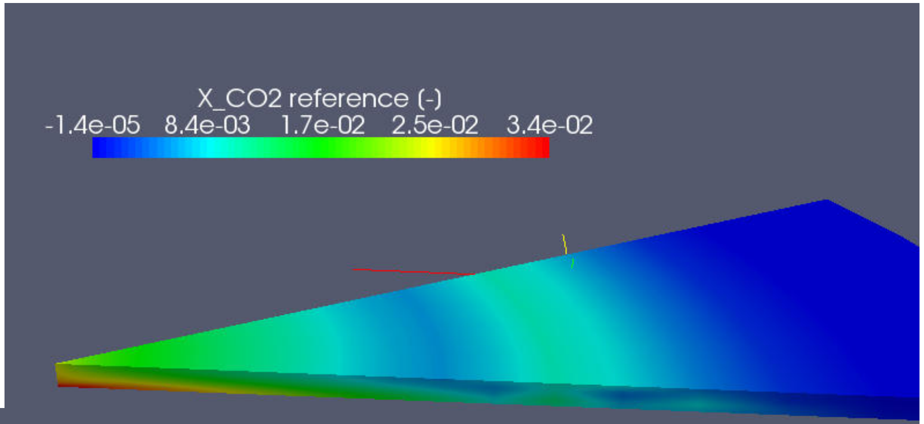
local concentration differences after 1 year of injection:

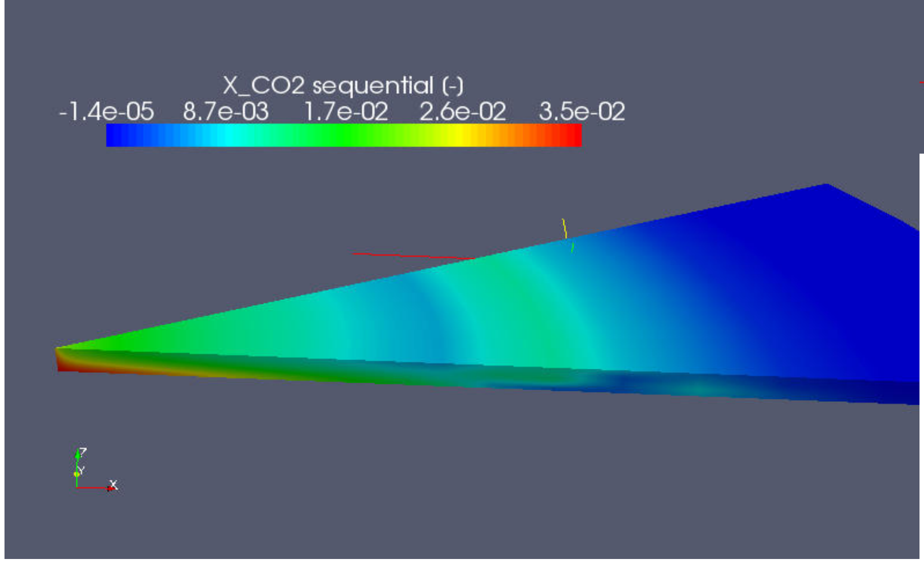


Comparison – sequential coupling vs. reference

local concentration distribution 1000 years after injection:

→ reference model:
density driven fingering leads to mixture of CO_2 rich brine and resident brine

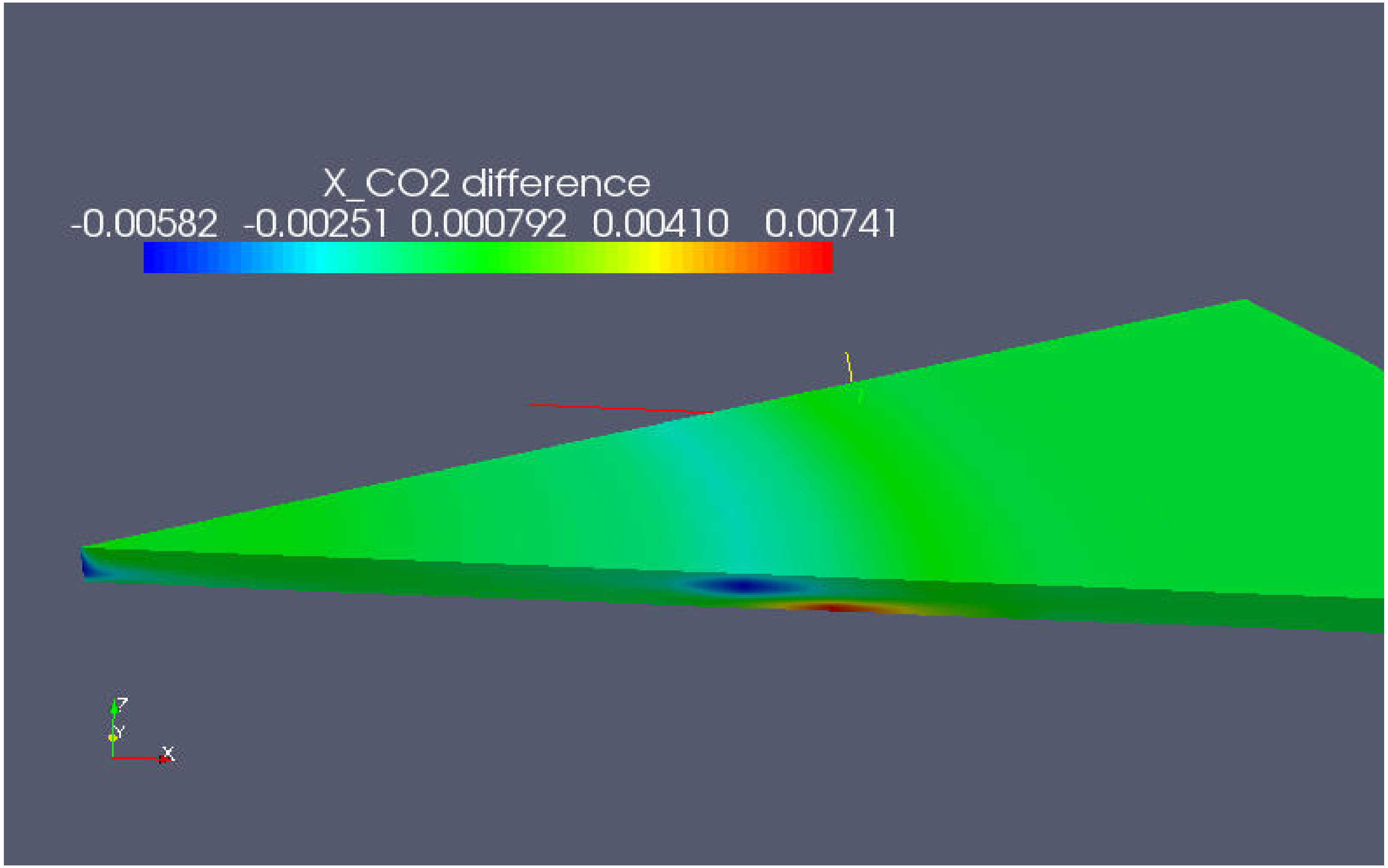




→ sequential model:
fingering not identical to reference case since fingers are triggered by minimal numerical inaccuracies

Comparison – sequential coupling vs. reference

local concentration differences 1000 years after injection:



Summary and Outlook

What was done:

- Implementation of a mass conservative sequential coupling concept
- Test simulations on a relatively small example domain
- First investigation of speedup potential (approx. 50% for this example)
- Comparison of model results

What is planned for the future:

- Further investigations on sequential coupling for a more realistic model setup and for larger timescales
- Further investigations on model reduction with respect to long term simulations
- Implementation of a linear elastic geomechanical model
- Implementation of a coupling interface to a geochemical code