Numerical modeling of geological storage

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Outline

- Why do numerical modelling?
- Physics of simulation
- Philosophy of model building
- Practical limits to simulation
- Upscaling
- Recent developments

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Why do numerical modeling?

- Data is expensive to collect, which justifies considerable effort to extract the best value from it.
- Data is scarce and limited in resolution and scale, so it needs to be "extended"
- Projects are expensive and risky, so numerical modelling is needed to explore uncertainty and reduce risk.

The dangers of simulation

"If you do it too much, you come to believe that it's the real thing"

- Simpler techniques may be sufficient to address the objectives.
- Complicated is often equated to better, especially in a multi-disciplinary workflow.
- Pictures are a great communication tool, so simulations based on inadequate data and poor methodology still look good!

The physics of simulation

The key governing equations are:

- Mass and energy conservation
- Transport law (e.g. multi-phase Darcy's law)
- Fluid equations of state: CO_2, brine, other gases

These have to be supplemented by initial conditions, boundary conditions and source terms (wells).

What physics is missing?

The software will not include all the physics e.g.

- Darcy's law starts to break down at high flow rates, as can occur in some gas wells. An additional term is then needed in the flow equations
- Hydrodynamic dispersion (along and normal to the direction of flow) is often neglected This is usually much larger than molecular diffusion.
- Wellbore storage effects may be absent unless a well model is included in the simulation.

Philosophy of model building

Define your objectives first!

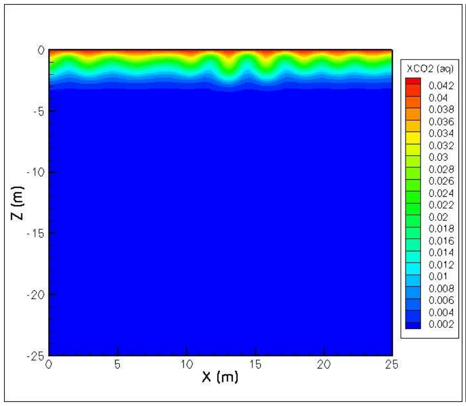
- What questions are you trying to answer with the simulation?
- How accurate an answer do you need?
- What limits are there to time/resources for the simulation study?
- How much data is there to base a model on?

First kind of objective

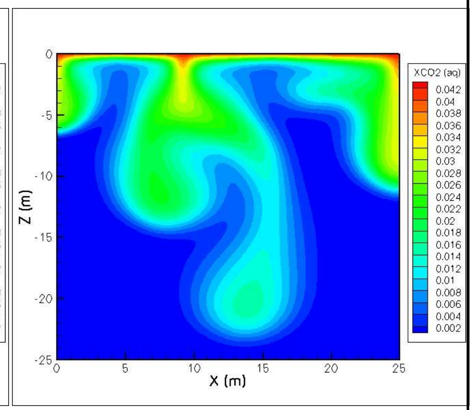
Research questions e.g. How does the hydrodynamic gradient affect CO_2 migration?

- These are often based on relatively small amounts of representative data.
- Realism is not important, so significant simplifications can be made.
- There may be a way to compare to another theoretical treatment

Example of a research question: convection of dissolved CO_2



27 years



90 years

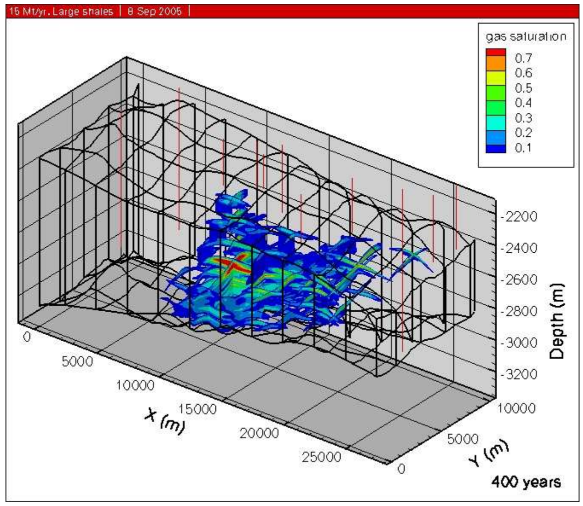
k_h=100 mD, k_v=50 mD

Second kind of objective

Make technical prediction in a site-specific context to support decisions e.g.

- **How much CO_2 can be stored? How should it be monitored? What are the risks?**
- **Data may be sparse (high-level site assessment) or relatively abundant (commercial prospect or depleted field).**
- **Small models may be adequate, but will likely lead to full-field 3D as data becomes available.**

Example:Timing of vertical migration of CO_2



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Seek understanding!

"The purpose of computing is insight, not numbers" Richard Hamming.

- **Simulations can produce vast quantities of data, and beautiful pictures.**
- **You should NEVER rely on results you don't understand**
- **The hardest part of simulation is to develop an intuition for the physical processes. You need a good understanding of reservoir engineering and the physics of multiphase flow in porous media.**

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Small is beautiful?

Models should be fit-for-purpose:

• Resist the “one big model” temptation.

• Multi-disciplinary workflows encourage big models if you can’t easily iterate.

• Early models should be small so you can run a lot of them, and investigate sensitivities.

• Mature models (with field data) should be bigger, but still allow for a suite of models.

Practical limitations

To solve the governing equations requires:

- discretization in space – splitting the domain up into gridblocks
- discretization in time – advancing in finite timesteps.

This has a series of consequences

- limitations on size
- numerical artifacts
- upscaling and resolution of data

Size limits

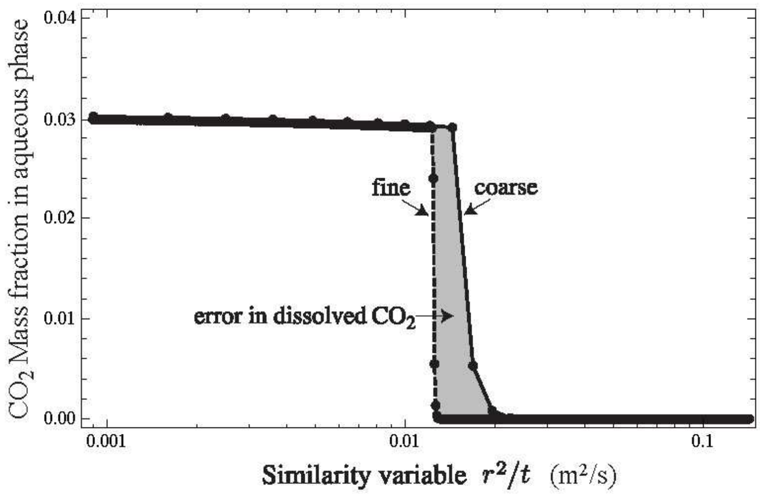
Call the number of equations n (= number of gridblocks times number of mass components)

- **The memory requirements are proportional to n**
- **The CPU time scales between $n^{1.5}$ and n^2. Single CPU allows ~10^5 blocks. Parallelism helps but still limited to millions of blocks.**
- **Field-scale models are coarse: 10-50m blocks width is common.**

Numerical Artifacts

- **Orientation effects e.g. fluid flow is easier along grid axes rather than diagonally across them**
- **Numerical diffusion is proportional to v Δt where v is the flow velocity. This can be more significant than real physical diffusion or dispersion.**
- **Local equilibrium assumed in each gridblock. Thus during the injection phase, the amount of dissolved CO_2 will be overestimated. This can be corrected for: Green and Ennis-King, (2012) *Comput. Geosci.* 16: 1153-1161**

Effect of grid refinement on CO_2 dissolution



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Upscaling of data

Each grid block only has one value for porosity, permeability, saturation, composition etc. This has two important consequences:

• we cannot resolve anything in the results below the size of a grid block.

• geological data measured on different scales e.g. core data, has to "upscaled" or averaged in an intelligent way.

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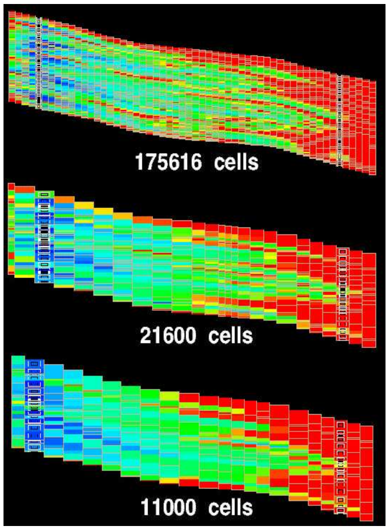
Example of permeability upscaling



Issue is what to preserve with the upscaling:

- **average migration speed?**
- **breakthrough time?**
- **plume shape?**

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Vertical permeability

- **Due to the density difference between CO_2 and water, vertical migration is important except in thin reservoir or for short times.**
- **Deep injection schemes rely on tortuosity of migration paths – two phase model can use object modelling of barriers.**
- **It's common to characterize through the ratio k_v/k_h where k_v Is vertical perm and k_h is horizontal perm. "Default" often k_v/k_h = 0.1**

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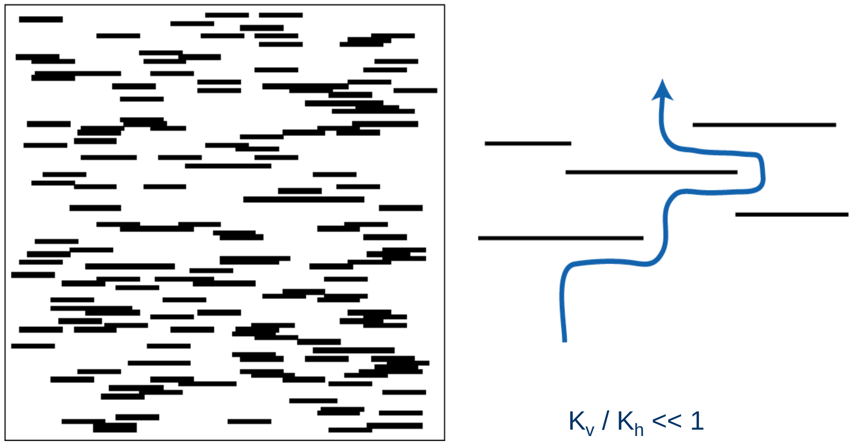
Vertical permeability



Upscaling of relative permeability

Core-measured properties aren't always appropriate for grid blocks thicker than the capillary transition zone.

A variety of schemes exist to make this upscaling correction:

• analytic (vertical equilibrium) – tend to straighten the rel. perms.

• "dynamic" – rely on matching fine scale cross-section simulations to coarser ones.

Geostatistics

- Fine scale data (e.g. porosity and permeability) is only available at wells.
- Geostatistics fills in everything else, based on estimates of correlations (variograms).
- Don't put too much faith in nice pictures
- Don't trust a single realisation
- Gridding should follow geological features

Be nice to geologists on your team

- The building of the geological model requires significant time and effort, even for simple models.
- Good communication requires understanding of geological terms and their implications e.g. depositional environments.
- It's very desirable to be able to iterate!
- Simulation efficiency must be balanced against faithfulness to geology.

Software for simulation

Large variety of choices

- **Commercial codes: Eclipse, GEM, Tempest, MoReS etc**
- **Research codes: TOUGH (LBNL), GPRS (Stanford), PFLOTRAN (LANL), STOMP (PNNL), VESA (Princeton), NUFT (LLNL), etc**
- **Open source codes: DUMUX, OPM**

See Class et al. (2009). A benchmark study on problems related to CO_2 storage in geologic formations. *Comput. Geosci.*, *13*(11), 409-434.

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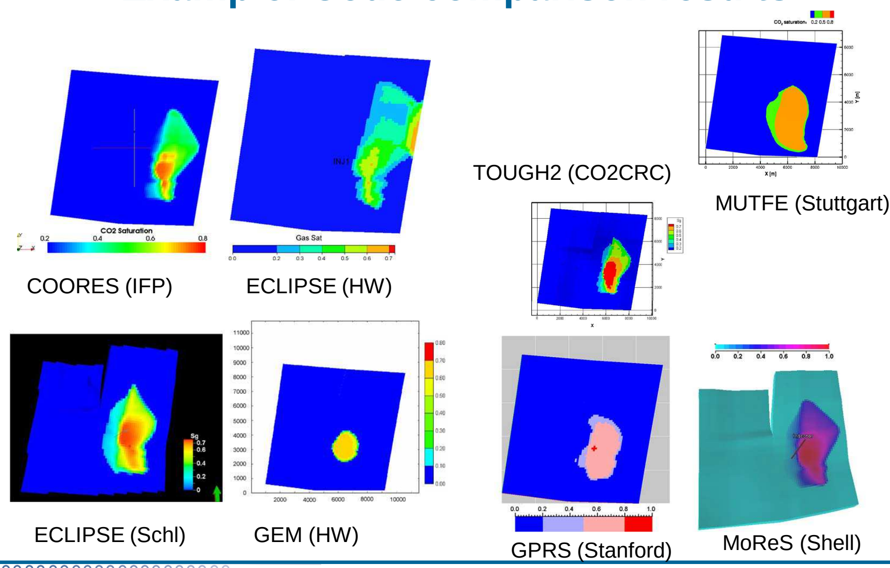
Example: Code comparison results



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Directions in numerical simulation

Focus on more coupled problems and additional physics

- Chemical reactions coupled to multiphase flow (e.g. TOUGHREACT, NUFT)
- Geomechanics coupled to multiphase flow (e.g. TOUGH/FLAC)
- Wellbore coupling issues (e.g. T2well)
- Tracers

Focus on field projects and monitoring

- Interpreting monitoring data (e.g. P/T gauges)
- Designing monitoring e.g. seismic forward modeling

CO2CRC Participants

Supporting Partners: The Global CCS Institute | The University of Queensland | Process Group | Lawrence Berkeley National Laboratory
CANSYD Australia | Government of South Australia | Charles Darwin University | Simon Fraser University