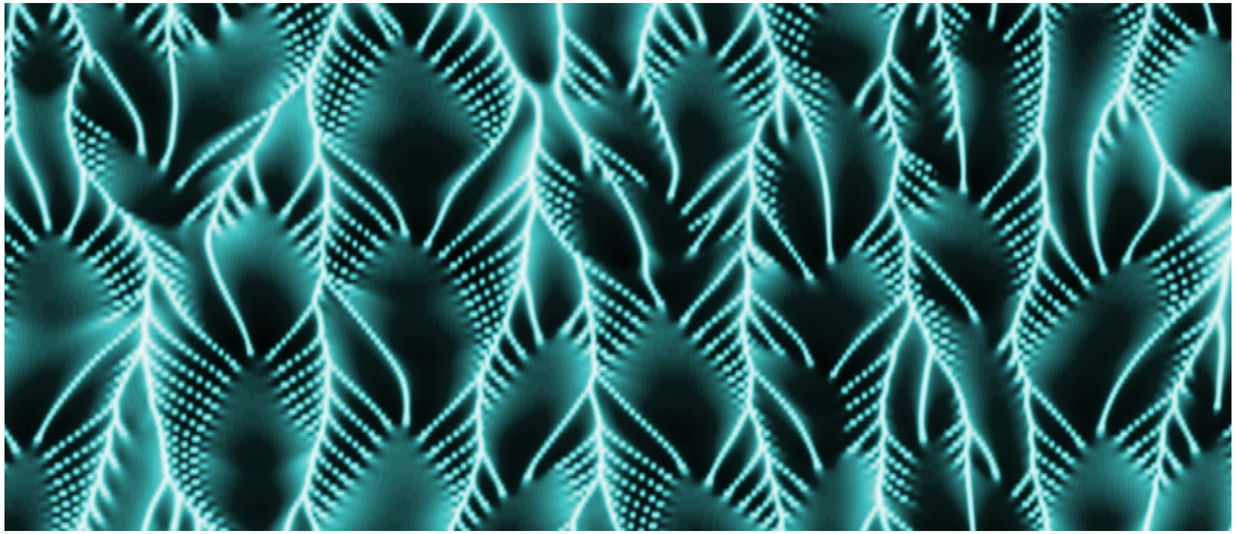
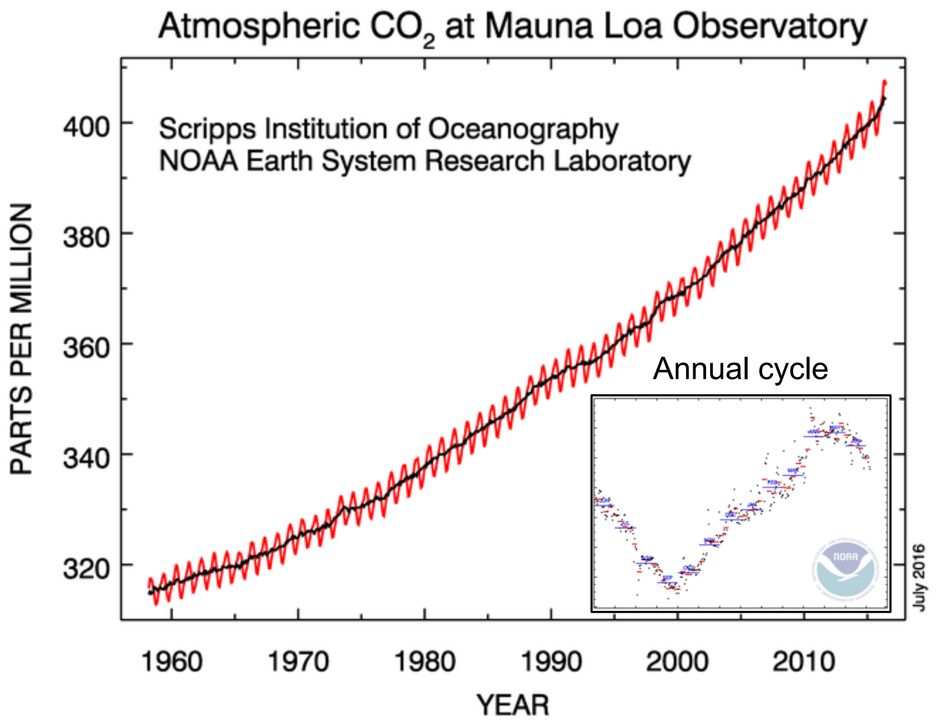
Convection in porous media: An application to CO2 sequestration

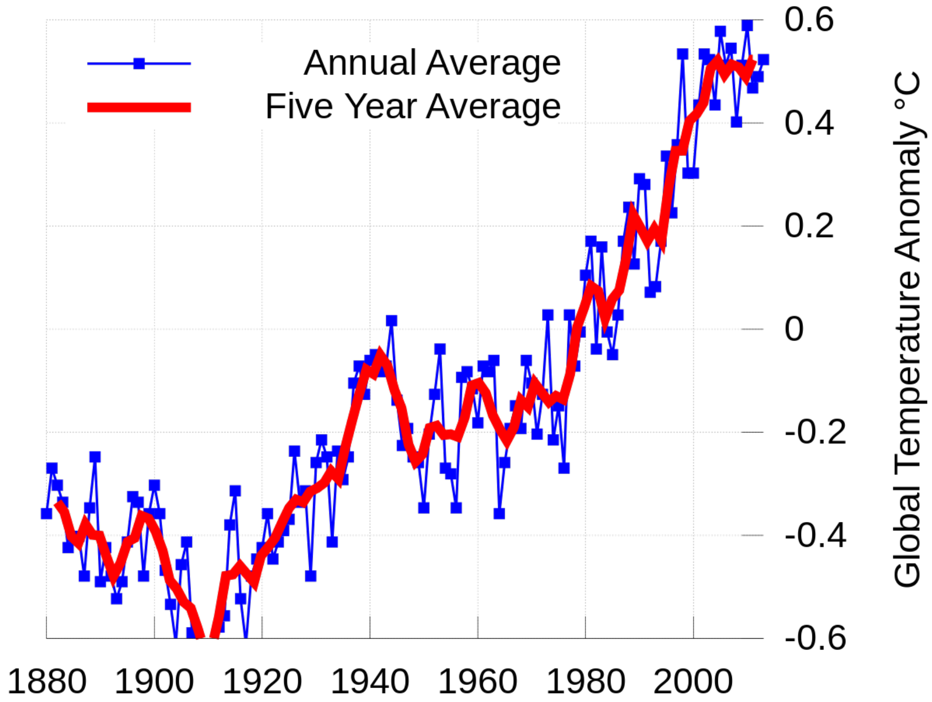


Marco De Paoli

Motivation

80 % of energy is produced from combustion of fossil fuels, and consequent production of Carbon Dioxide (CO_2)

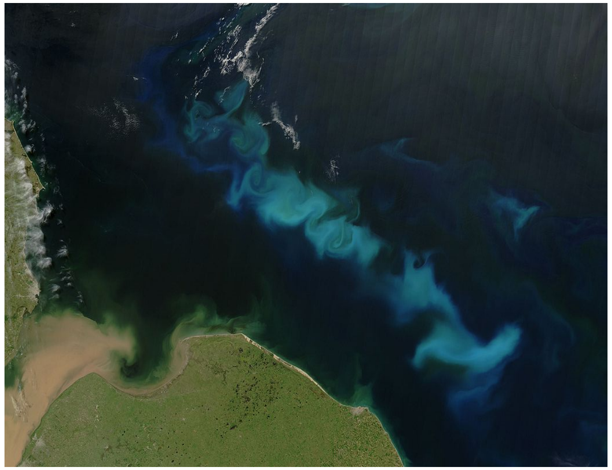




Global average temperatures rise over the last 130 years [Hansen, J., et al., Proc. Natl. Acad. Sci. (2006)]

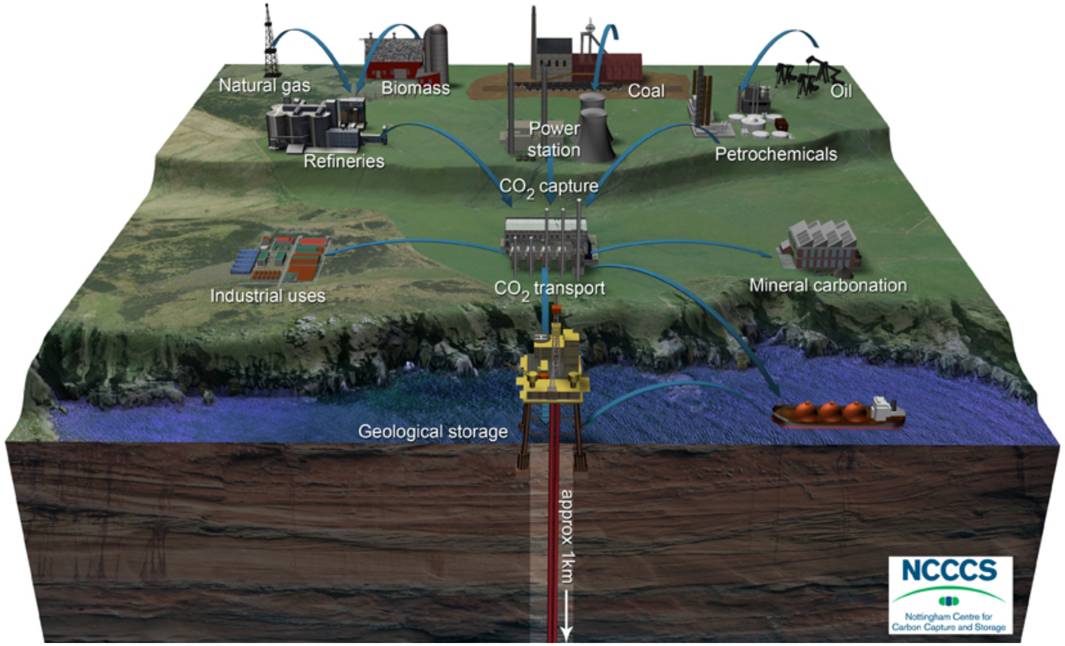
Carbon Sequestration

Iron fertilization of **phytoplankton**



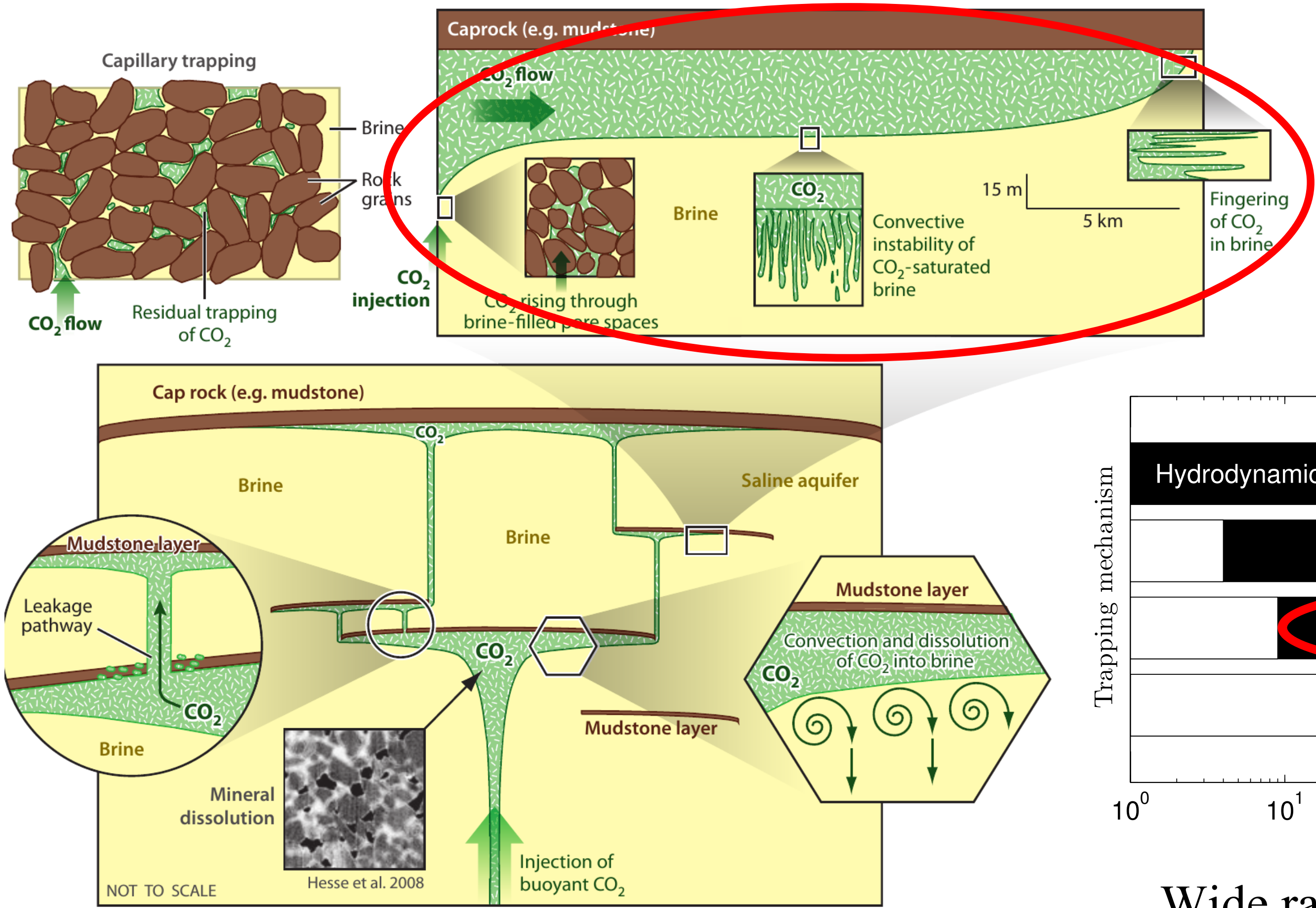
Chemical scrubbers

Carbon Capture and **Storage** (CCS) has been identified as a possible solution to the greenhouse effect [Intergovernmental panel on Climate Change, (IPCC) 2005]



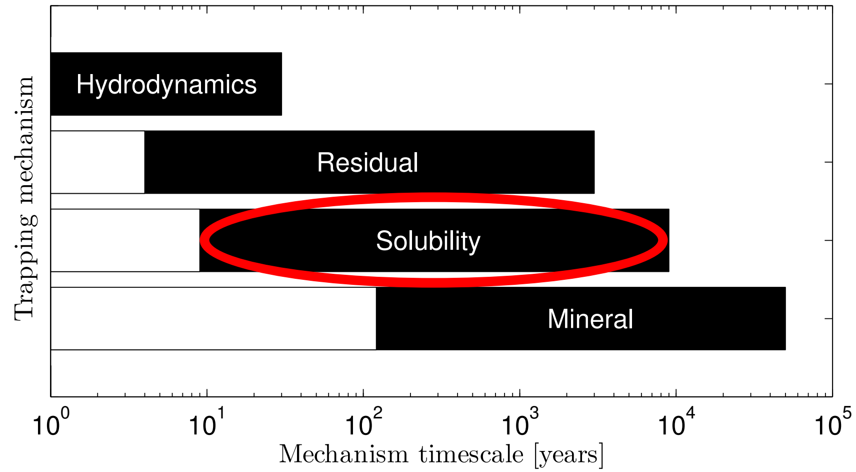
Injection point

Trapping mechanisms



CO_2 dissolution mechanisms [*Huppert & Nuefeld, Ann. Rev. Fluid Mech. (2014)*]

Leakage is undesirable for efficient long-term storage

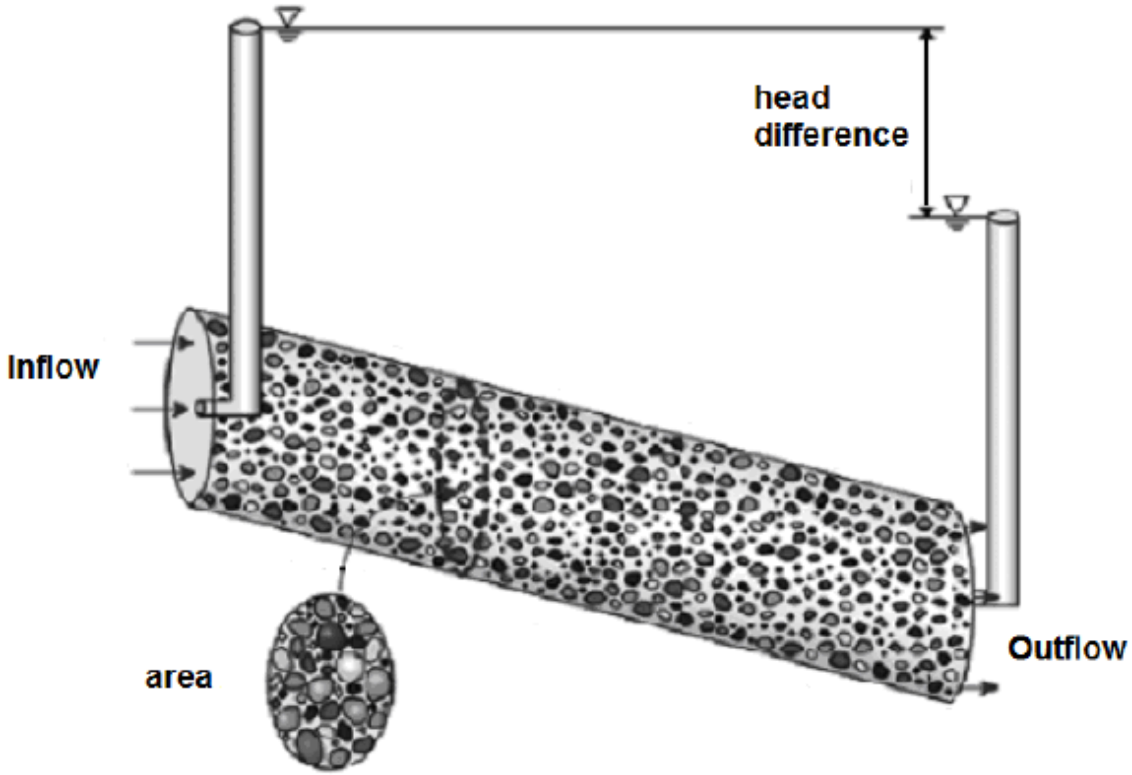


Wide range of space and time scales to consider

Darcy law and porous media

Dimensional equations

$$\frac{\mu}{k_h} u^* = -\frac{\partial p^*}{\partial x^*} \quad , \quad \frac{\mu}{k_v} w^* = -\frac{\partial p^*}{\partial z^*} - \rho^* g$$



Methodology

Dimensional equations

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial w^*}{\partial z^*} = 0$$

$$\frac{\mu}{k_h} u^* = -\frac{\partial p^*}{\partial x^*} \quad , \quad \frac{\mu}{k_v} w^* = -\frac{\partial p^*}{\partial z^*} - \rho^* g$$

$$\rho^* = \rho_s^* \left[1 - a(C_s^* - C^*)\right]$$

$$\Phi \frac{\partial C^*}{\partial t^*} + u^* \frac{\partial C^*}{\partial x^*} + w^* \frac{\partial C^*}{\partial z^*} = \Phi D \left(\frac{\partial^2 C^*}{\partial x^{*2}} + \frac{\partial^2 C^*}{\partial z^{*2}} \right)$$

$$\boxed{Ra = \frac{g H^* k_v \Delta\rho^*}{\mu \Phi D}}$$

$\Delta\rho = 10.45\ kg/m^3$
$\mu = 5.95\times10^{-4}\ Pa\times s$
$D = 2\times10^{-9}\ m^2/s$
$H = 20\ m$
$\phi = 0.3$
$k_v = 3\times10^{-12}\ m^2$
$Ra \approx 17\times10^3$

[Data refer to a depth of 1 km at the Sleipner Site (North Sea)]

For geological reservoirs, $\boldsymbol{Ra \approx 10^4 - 10^5}$

Methodology

Dimensionless equations

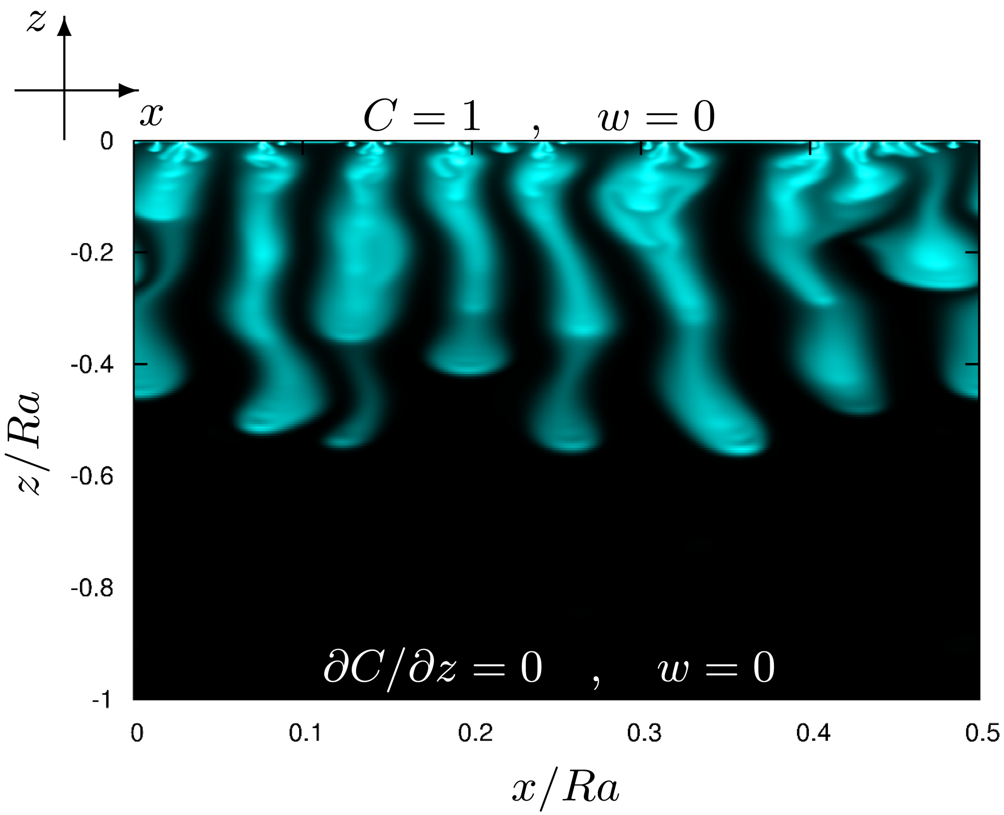
$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = \frac{1}{Ra}\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

$$u = -\frac{\partial P}{\partial x} \quad , \quad w = -\frac{\partial P}{\partial z} - C$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0$$

Governing parameter

$$Ra = \frac{g H^* k_v \Delta\rho^*}{\mu \Phi D}$$



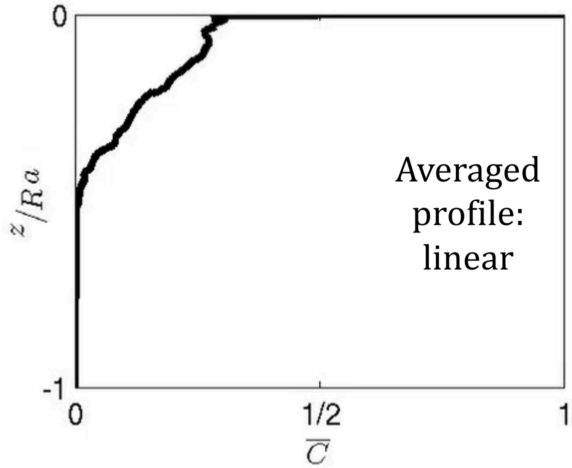
Numerical details
We realized 2D Direct Numerical Simulations (DNS) using a pseudo-spectral method (Fourier + Chebyshev) up to 8192x1025 collocation points.

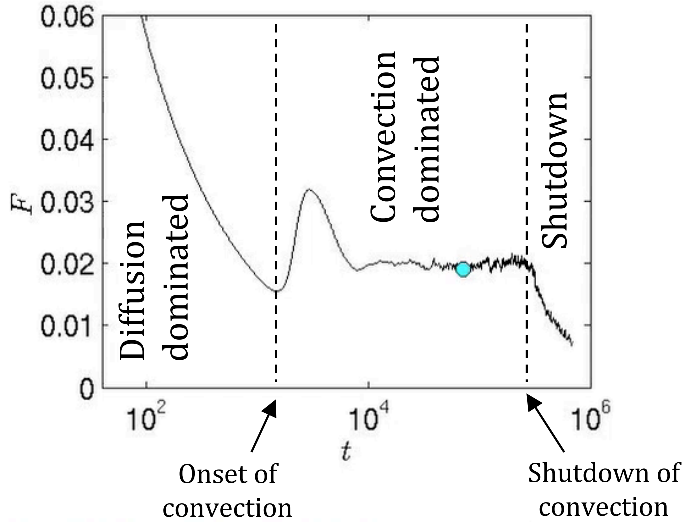
Simulations performed on the supercomputers MARCONI (Bologna, Italia), VSC (Vienna, Austria) and MIRA (Chicago, USA) using up to 512 CPUs.

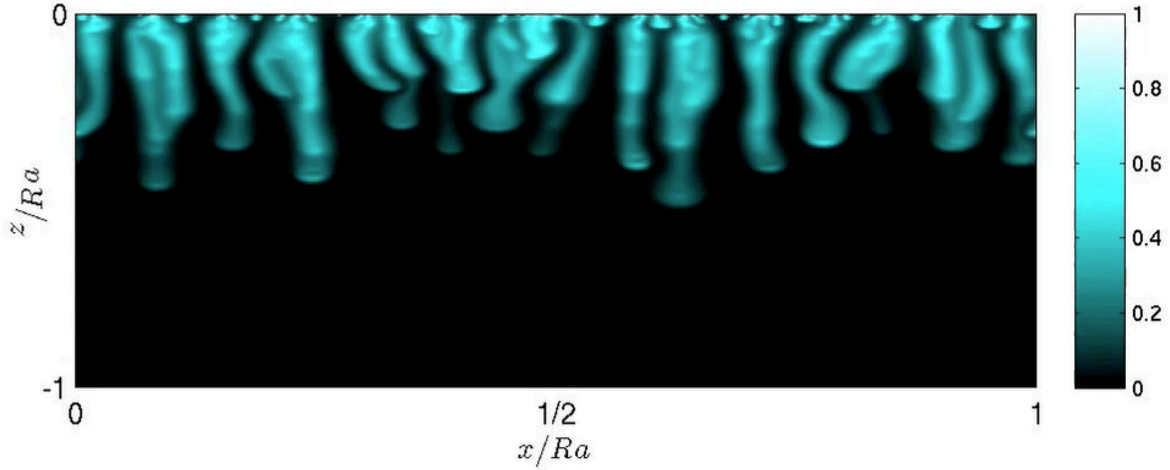
Dissolution process description

$$\overline{C}(z,t) = \frac{1}{L}\int_0^L C(x,z,t)\,dx \qquad F(t) = \frac{1}{L}\int_0^L \left.\frac{\partial C}{\partial z}\right|_{z=0} dx$$

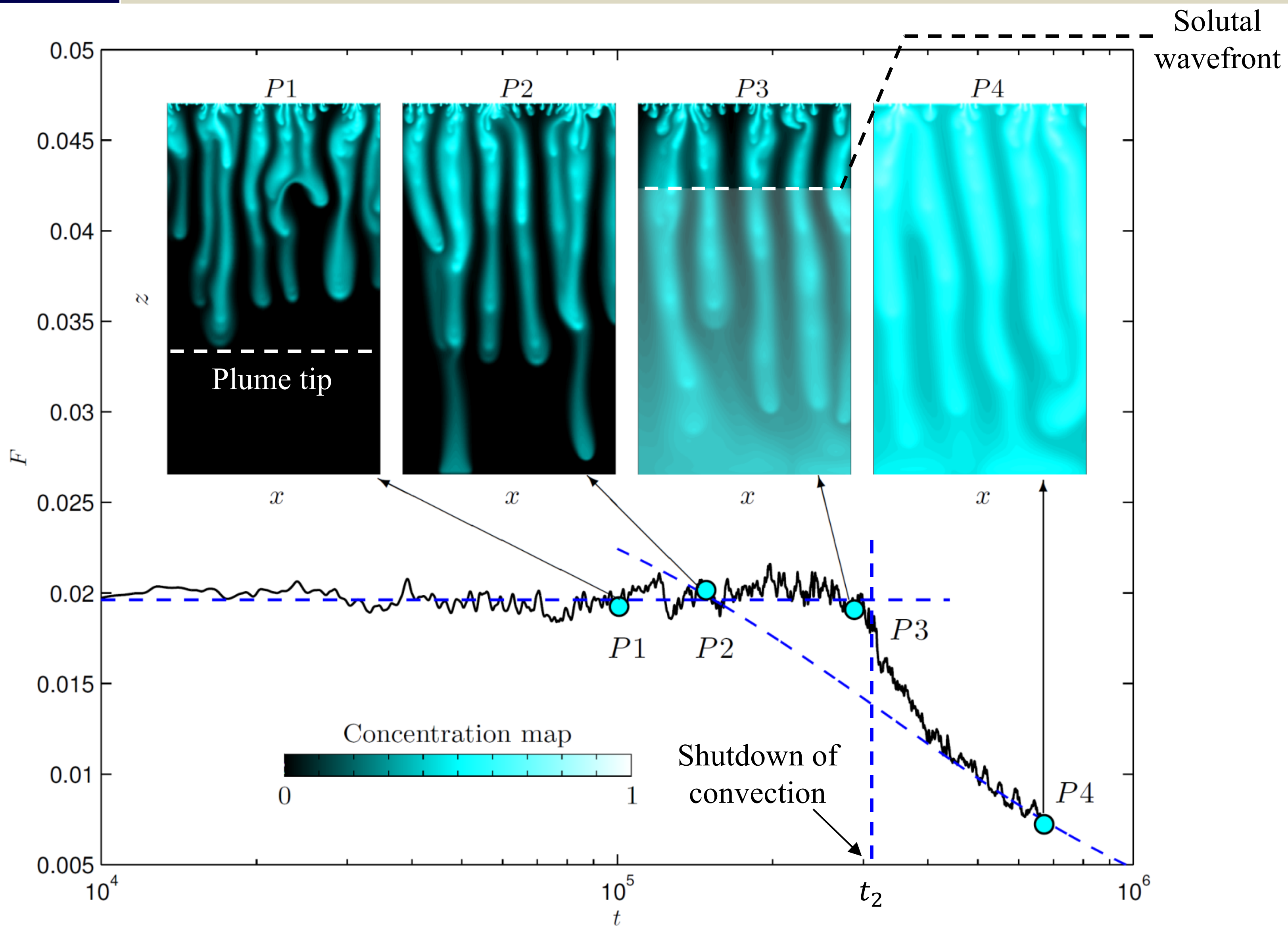
$Ra = 2\times 10^4$





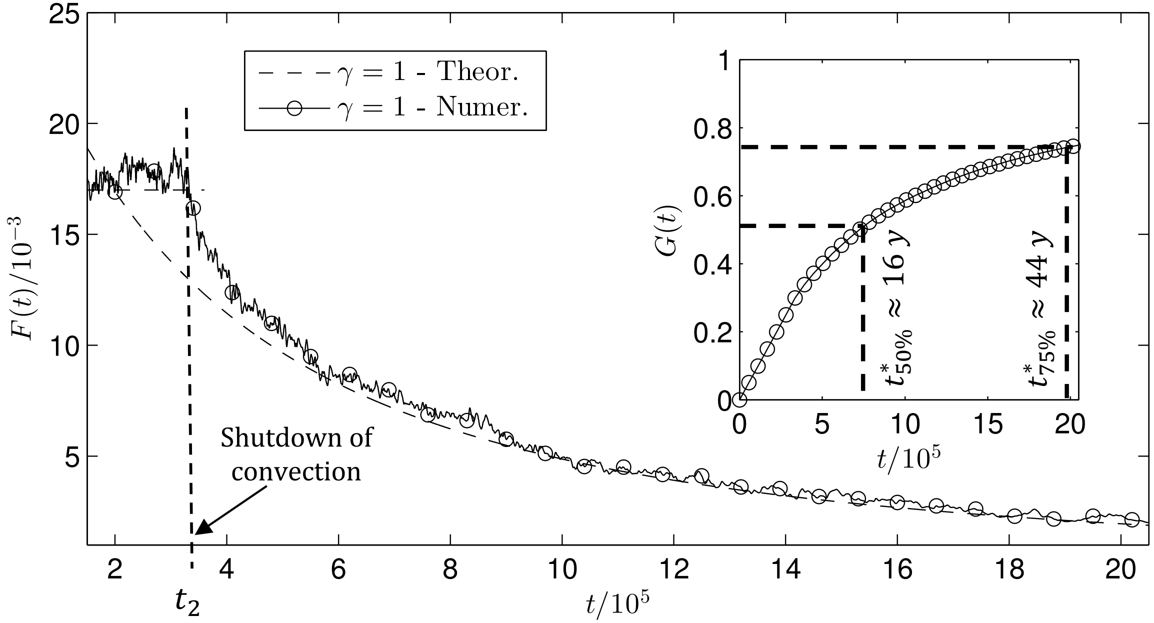


Shutdown of convection



Theoretical model for dissolution flux

We generalized an existing model [Hewitt et al. , JFM, 2013] for the prediction of the CO_2 dissolution rate using the new scaling law



$$C(t) \approx \frac{1}{1 + 4\alpha\gamma^{n} Ra\, t}$$

$$F(t) \approx \frac{4\,\alpha\,\gamma^{-1/4} Ra}{[1 + 4\alpha\gamma^{-1/4} t]^2}$$

$$G(t) = \int_{t_0}^{t} F(\tau)d\tau$$

$$t_2 = \frac{(2+\eta)C_1}{0.017} Ra$$

De Paoli M., Zonta F. and Soldati A., *Influcence of anisotropic permeability on porous media convection: Implications for geological CO2 sequestration*, Physics of Fluids, 2016.

Methodology

Governing equations

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = \frac{1}{Ra_0}\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

$$u = -\frac{\partial P}{\partial x} \quad , \quad w = -\frac{\partial P}{\partial z} - C$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0$$

$$Ra_0 = \frac{g\Delta\rho^* k H^*}{\mu\Phi D} \in [\,46\,;19953]$$

Mixing length:

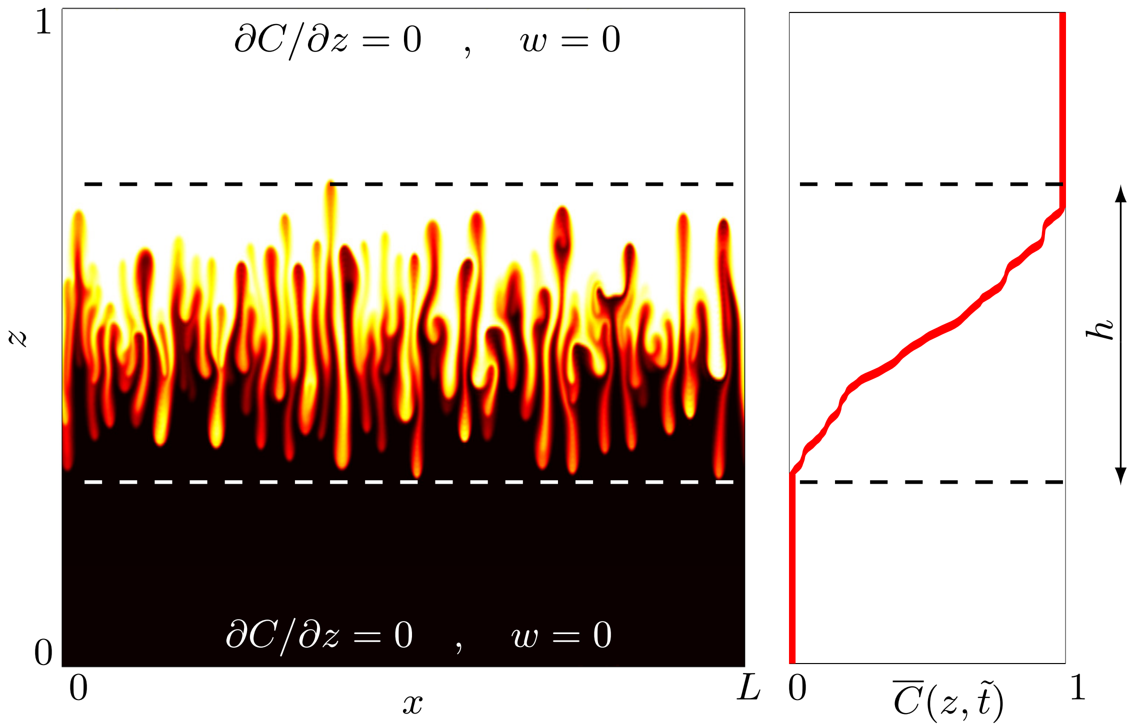
$$h \;:\; \varepsilon < \overline{C}(z,t) < 1-\varepsilon \quad , \quad \varepsilon = 10^{-2}$$

$$\overline{C}(z,t) = \frac{1}{L}\int_0^L C(x,z,t)\,dx$$

Importance of boundaries (Chebyshev polynomials)

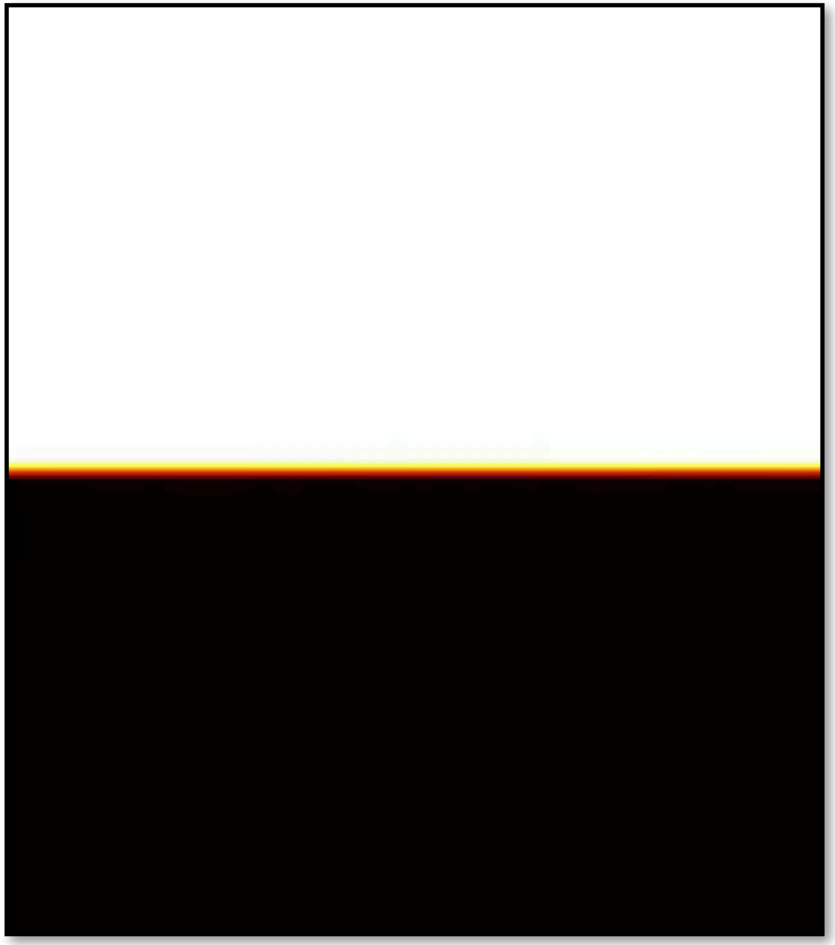
Initial condition:

$$C(x,z,t=0) = \frac{1}{2}\left[1 + \mathrm{sgn}\left(z - \frac{1}{2}\right)\right]$$

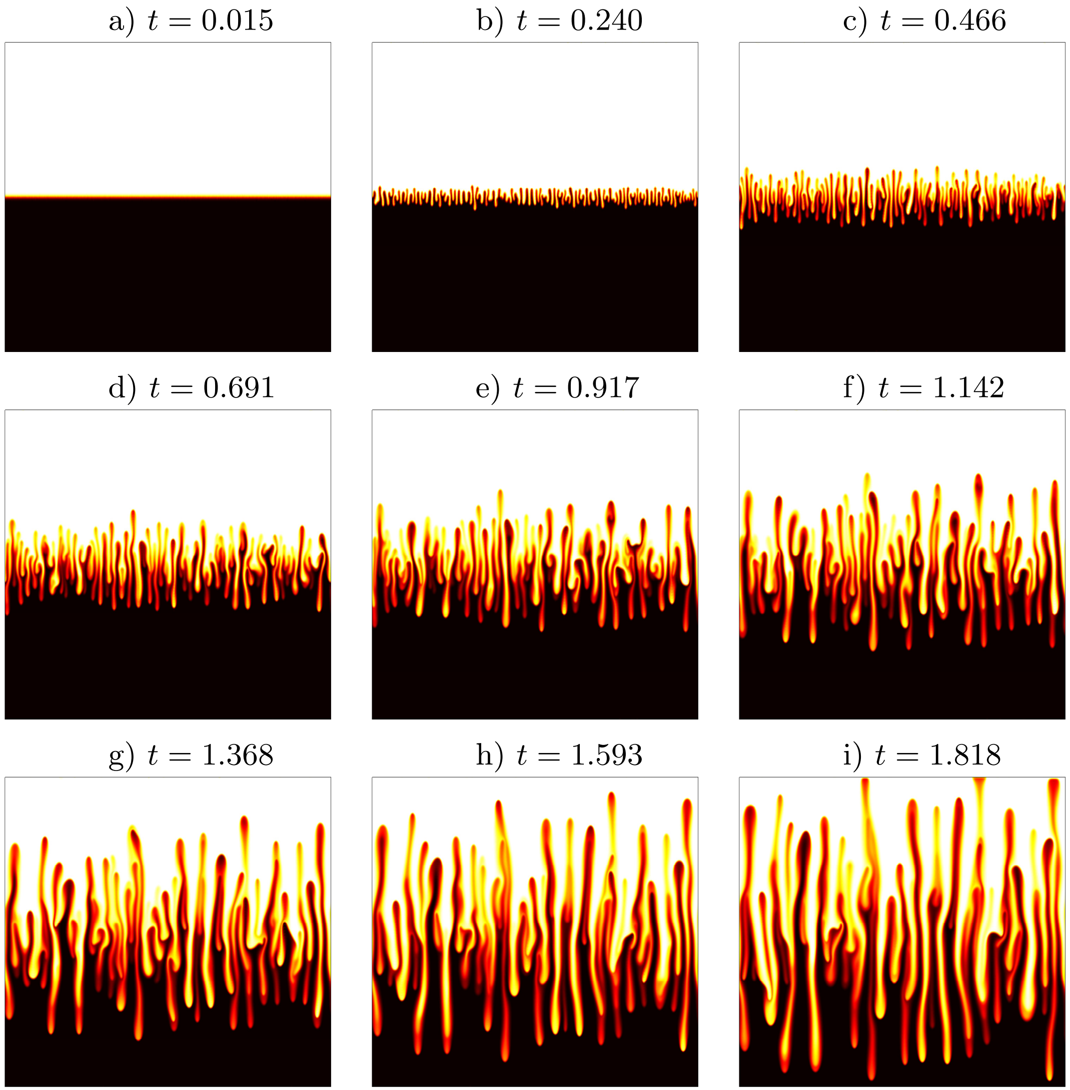


Rayleigh-Taylor: miscible fluids

$Ra_0 = 12023$



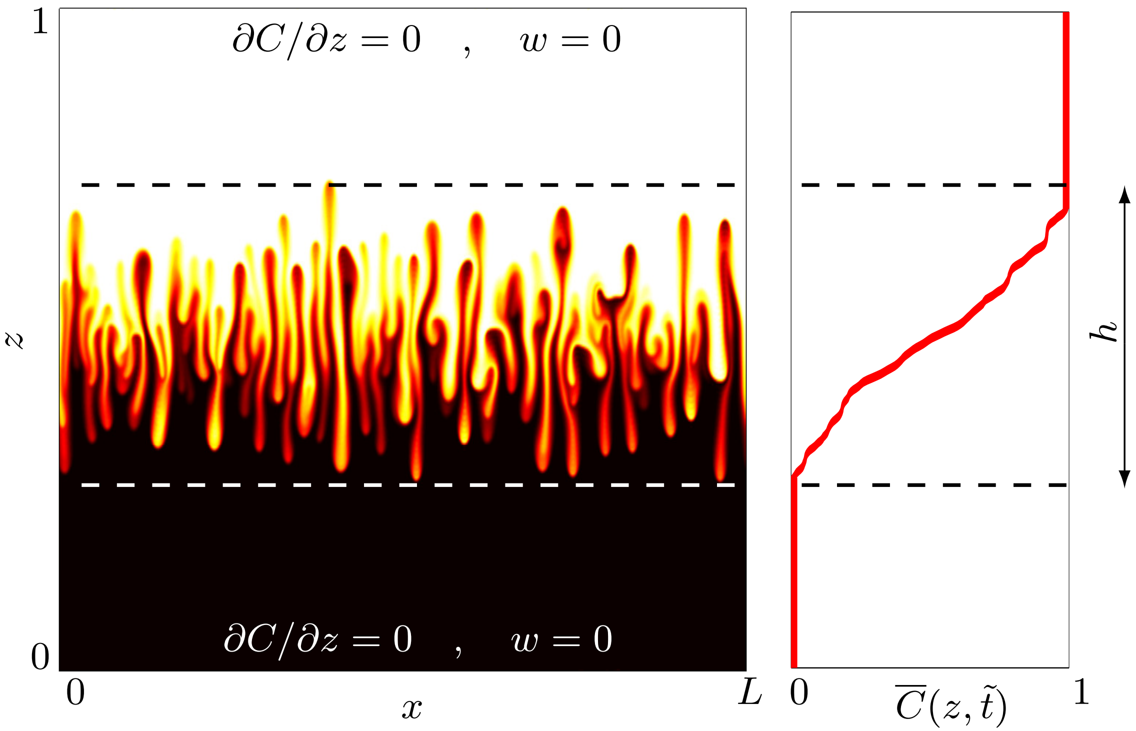
How does h^* evolves? What is the plume time impingement time?



Scaling of physical quantities

$$t_t : \forall t \geq t_t \quad , \quad h(t) \geq 1 - \varepsilon$$

Mixing length definition

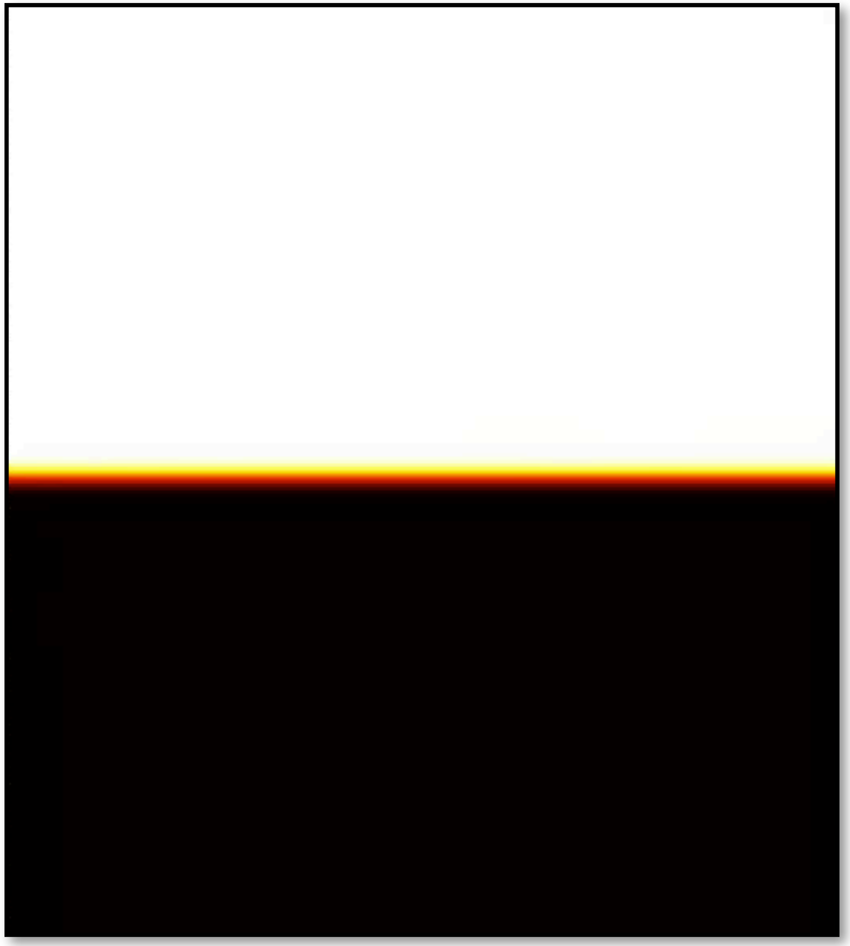


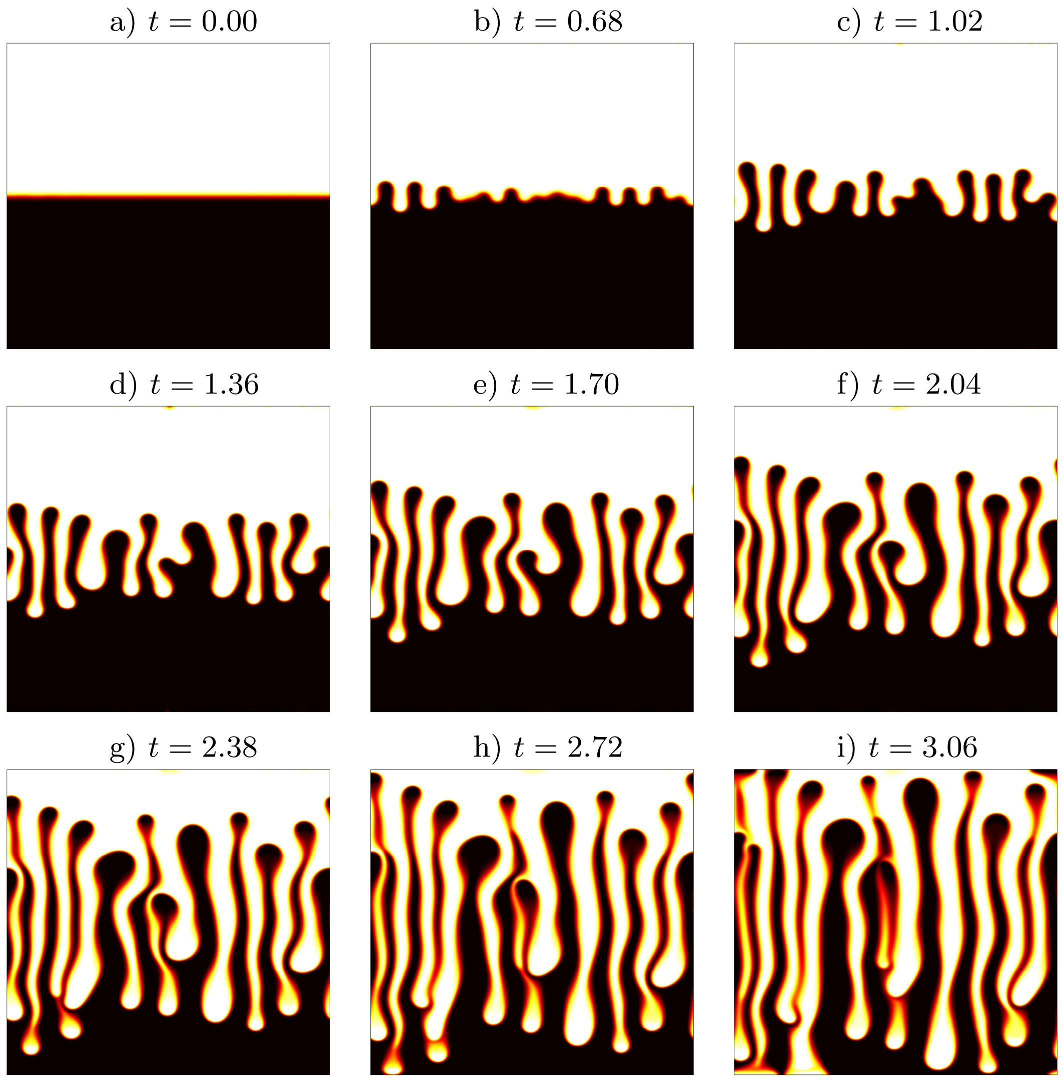
$$t_t^* \sim \left(\frac{gk\Delta\rho}{\mu\Phi}\right)^{-1.27} D^{0.27} (H^*)^{0.73}$$

De Paoli M., Zonta F. and Soldati A., *Solutal fuxes scalings in Rayleigh-Taylor convection in porous media*, Physical Review Fluids (to be submitted).

Plume dynamics

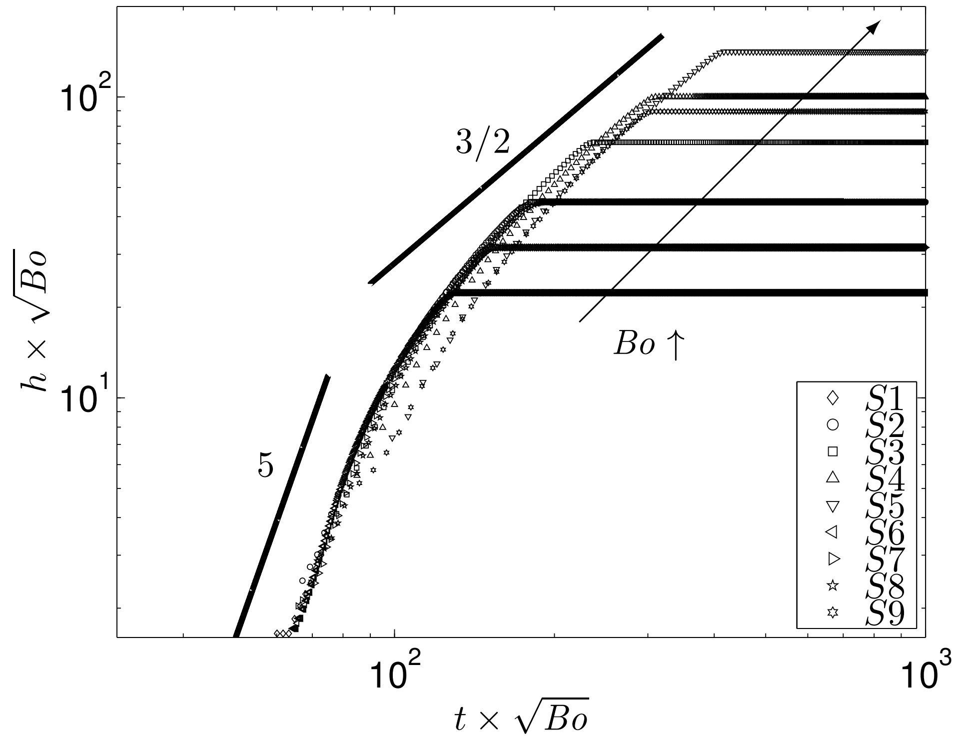
$Bo = 2\times10^{4}, Pe = 2\times10^{-4}, Ch = 5\times10^{-5}$





How does h^* evolves? What is the plume time impingement time?

Scalings obtained

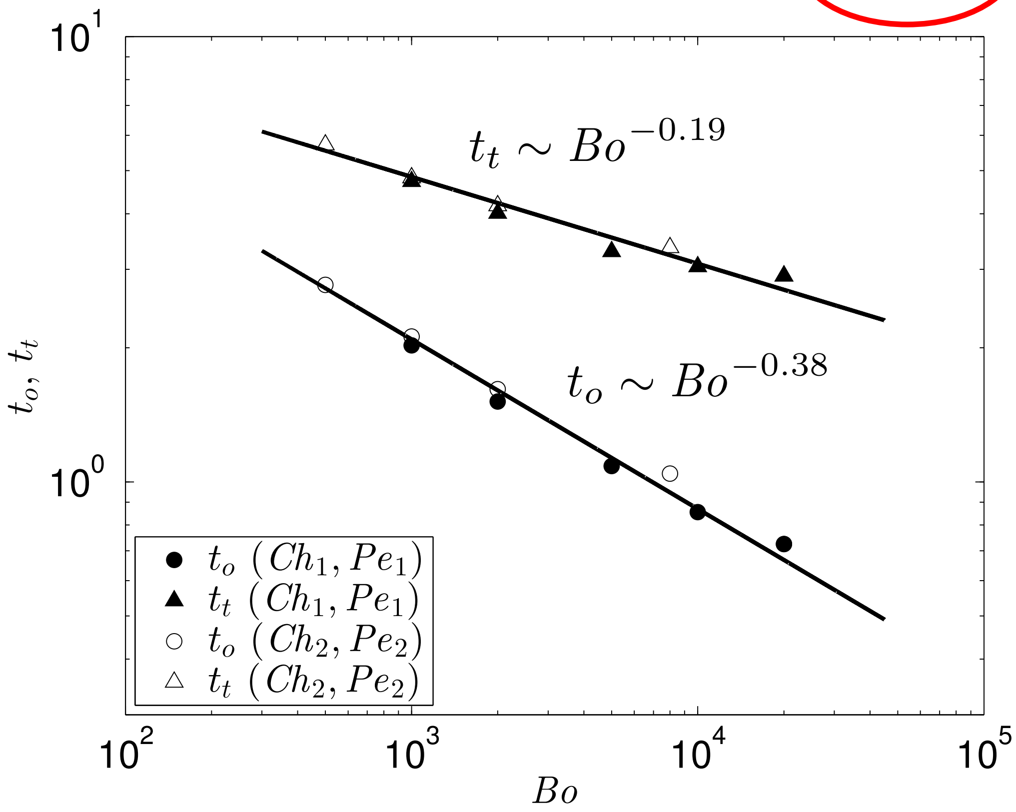


$$h \sim t^5\, Bo^2$$

$$h \sim t^{3/2}\, Bo^{1/4}$$

Immiscible

$$t_o^* \sim (H^*)^{0.24} \quad , \quad t_t^* \sim (H^*)^{0.72}$$



De Paoli M., Zonta F. and Soldati A., *A phase field model for porous media flows: application to Rayleigh-Taylor instability* (in preparation).

Miscible

$$t_t^* \sim \left(\frac{gk\Delta\rho}{\mu\Phi}\right)^{-1.27} D^{0.27} (H^*)^{0.73}$$

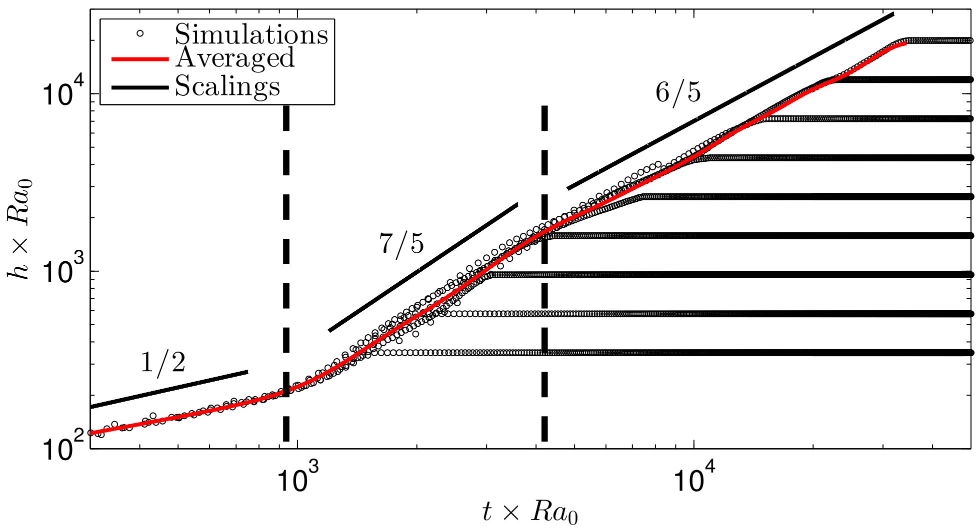
Conclusions

- Phenomenological model for the shutdown time in porous media

$$t_2 = \frac{(2+\eta)C_1}{0.017} Ra$$

- Analytical model for the dissolution flux during the shutdown regime in anisotropic porous media

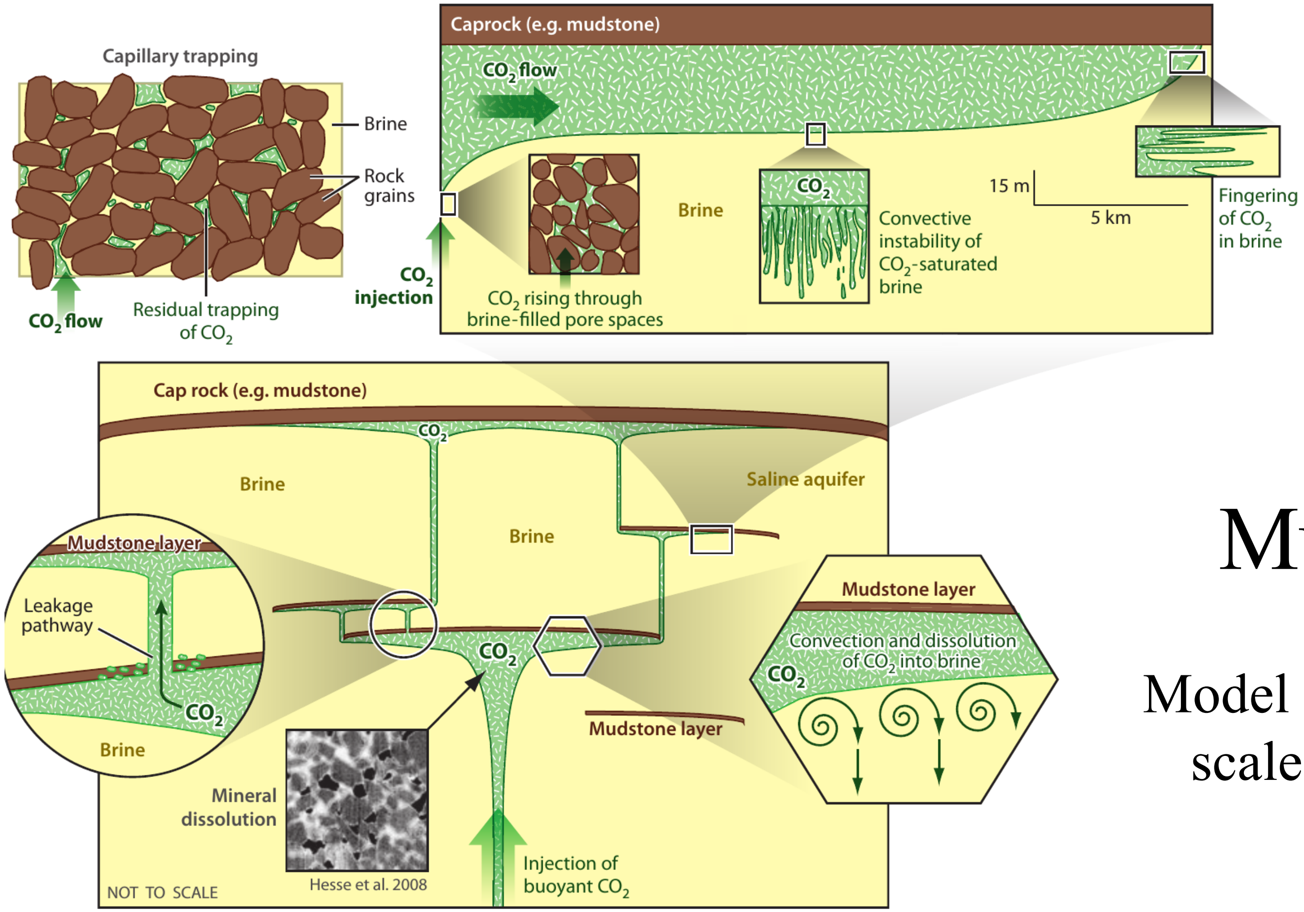
$$F(\gamma, t) \approx \frac{4\alpha\gamma^n\, Ra}{\left[1 + 4\alpha\gamma^n t\right]^2}$$



- Equivalence of system having the same local Rayleigh number *Ra*
- Plume dynamics is controlled by buoyancy and not by miscibility

Thank you for your attention

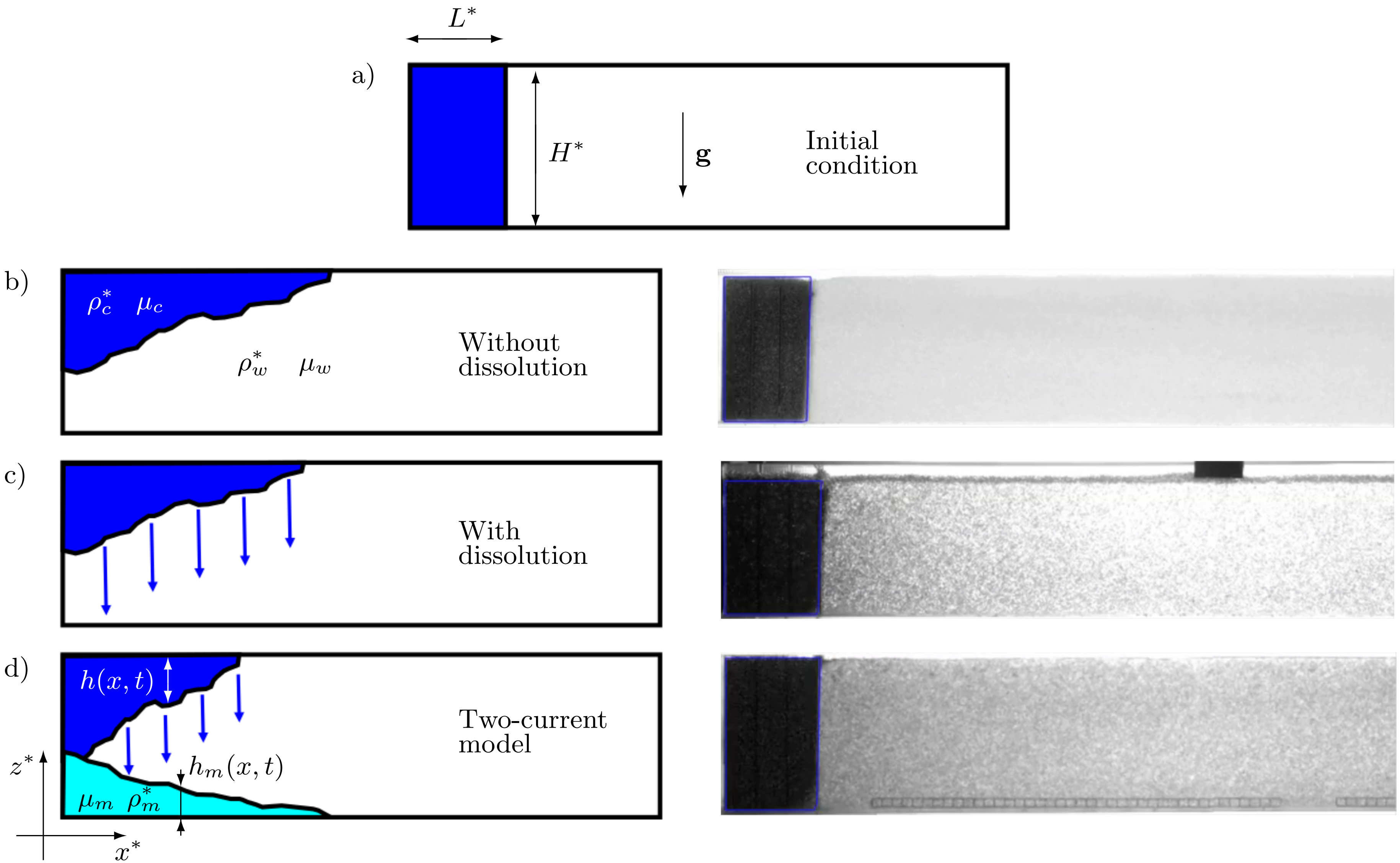
Exam



Multiscale model

Model for CO2 dissolution (small-scale) and buoyancy (large scale)

Experiments and models



Equations

The models is described by the following equations

$$\frac{\partial h}{\partial t} - \frac{\partial}{\partial x}\left[(1-f)h\frac{\partial h}{\partial x} - \delta f h_m \frac{\partial h_m}{\partial x}\right] = -\varepsilon$$

$$\frac{\partial h_m}{\partial t} - \frac{\partial}{\partial x}\left[\delta(1-f_m)h_m\frac{\partial h_m}{\partial x} - f_m h \frac{\partial h}{\partial x}\right] = \frac{\varepsilon}{X_v}$$

$$f = \frac{Mh}{(M-1)h + (M_m - 1)h_m + 1}$$

$$f_m = \frac{M_m h_m}{(M-1)h + (M_m - 1)h_m + 1}$$

Solve numerically the equations in MatLab (or FORTRAN, C, C++, ecc.) using a finite difference method

References

Spreading and convective dissolution of carbon dioxide in vertically confined, horizontal aquifers, CW MacMinn, JA Neufeld, MA Hesse, and HE Huppert, *Water Resources Research*, 2012.

Simulation vs experiments