Upscaling CO2 Migration Under Buoyancy and Capillary Heterogeneity Effects – A New Approach Using Optimization

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Abstract

Coarsening a numerical mesh using methods of multiphase flow property upscaling is essential in almost any modeling application due to computational limits. In CO2 storage modeling, after injection wells have been shut off or far away from the wells, CO2 migrates upwards under the influence of gravity and capillary forces. Upscaling permeability (k), relative permeability (kr) and capillary pressure (Pc) is required for grid coarsening these models. However, it has been shown that this is a difficult problem and using conventional upscaling methods such as the common capillary limit upscaling approach leads to large modeling errors. This work presents a new upscaling method based on an effective property formula for k, power law averaging in the capillary limit for kr, and an optimization approach for Pc. The new method is tested on various example cases and coarse-grid simulations are shown to match fine-grid ones with sufficient accuracy. The challenge of upscaling the flows is found to be related to entry pressure trapping and the optimization upscaled Pc is shown to have a unique structure allowing to model the trapping. The method is global, requiring a fine-grid simulation for calibration of the optimized parameters. However, we show that the method reduces computational time dramatically if calibrated parameters are used in similar cases in which the fine-grid solution is unknown, such as for varying k realizations.

Optimization-based Upscaling for Gravity Segregation with 3D Capillary Heterogeneity Effects

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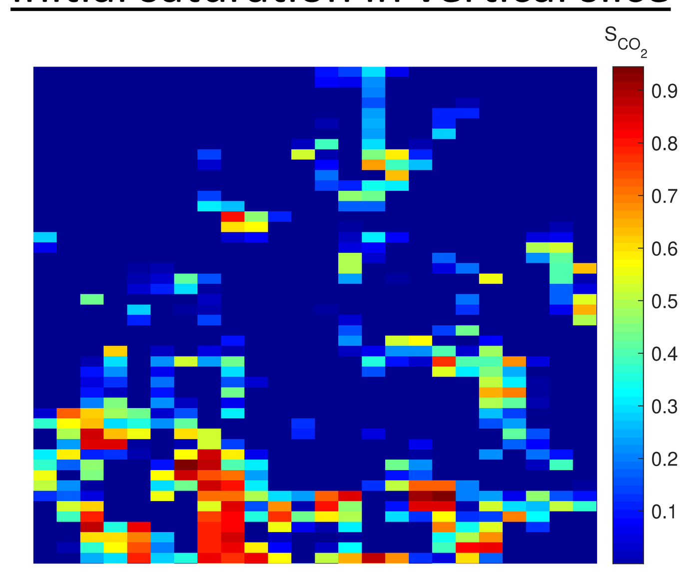
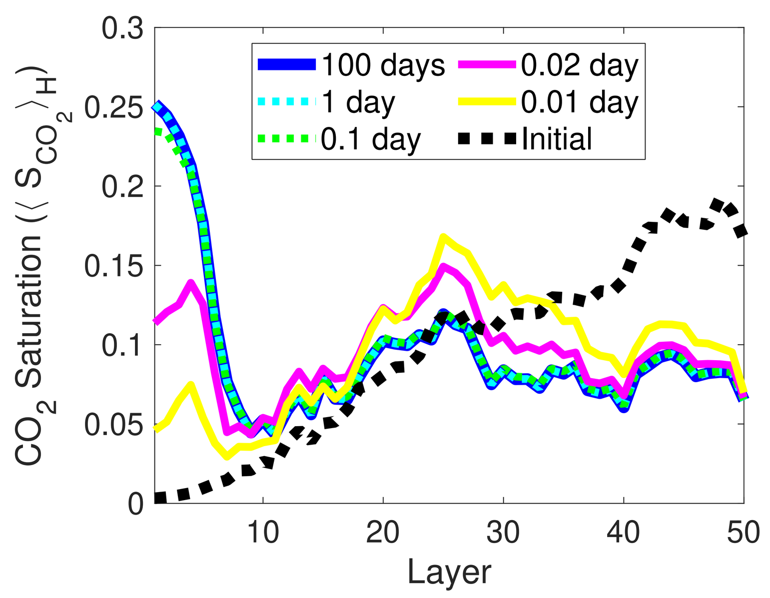
GOAL

Upscaling flow driven by gravity and capillary forces subjected to capillary heterogeneity effects

Initial saturation in vertical slice



Average S_{CO2} - vertical variation



UPSCALING METHOD

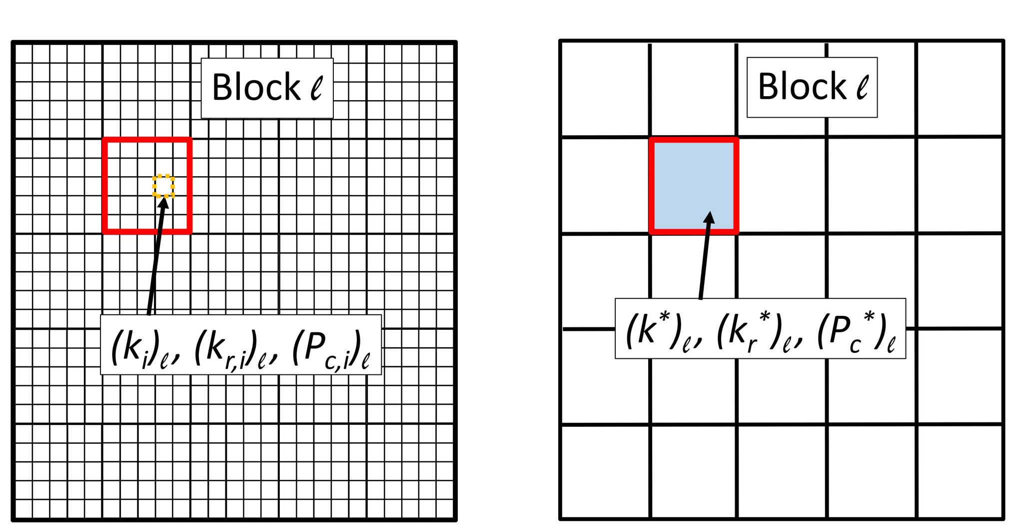
Governing equations:

$$\phi \frac{\partial S_j}{\partial t} - \nabla \cdot \left[\frac{k_{rj}}{\mu_j} \mathbf{k} \cdot \nabla (p_j + \rho_j g z) \right] = 0$$

$$p_{nw} - p_w = P_c(S_w)$$

k upscaling formula:

$$(k^*)_l = \exp \left[\frac{1}{N} \sum_{i=1}^{N} (Y_i)_l \right] \left[1 + \frac{(\sigma_Y^2)_l}{6} + \frac{(\sigma_Y^4)_l}{72} \right]$$



(a) Fine-scale domain (25 x 25 x 50) (b) Upscaled domain (5 x 5 x 10)

$$Y = \ln k$$

l - Coarse scale grid block

i - fine scale grid block

k_r upscaling - power law averaging in capillary limit:

$$(k_{rj}^*)_l = \frac{1}{(k^*)_l} \left(\frac{1}{N} \sum_{i=1}^{N} \left[(K_{j,i})_l \right]^{\omega} \right)^{1/\omega}$$

P_c upscaling - optimization to find entry pressures α_l :

$$(P_c^*)_l = \alpha_l (\widetilde{S}_w)^{-1/\lambda}$$

Table 1
Simulation cases considered in this work.

Case	Initial saturation	Permeability
1	Bottom injection, $\langle S_{CO_2}^{init} \rangle = 0.1$	Isotropic
2	Top injection, $\langle S_{CO_2}^{init} \rangle = 0.28$	Isotropic
3	Top injection, $\langle S_{CO_2}^{init} \rangle = 0.39$	Isotropic
4	Top injection, $\langle S_{CO_2}^{init} \rangle = 0.53$	Isotropic
5	Top injection, $\langle S_{CO_2}^{init} \rangle = 0.64$	Isotropic
6	Bottom injection, $\langle S_{CO_2}^{init} \rangle = 0.05$	Isotropic
7	Bottom injection, $\langle S_{CO_2}^{init} \rangle = 0.17$	Isotropic
8	Bottom injection, $\langle S_{CO_2}^{init} \rangle = 0.1$	Anisotropic

Upscaling methods implemented (number of variables in parentheses):

CL – capillary limit (no opt)

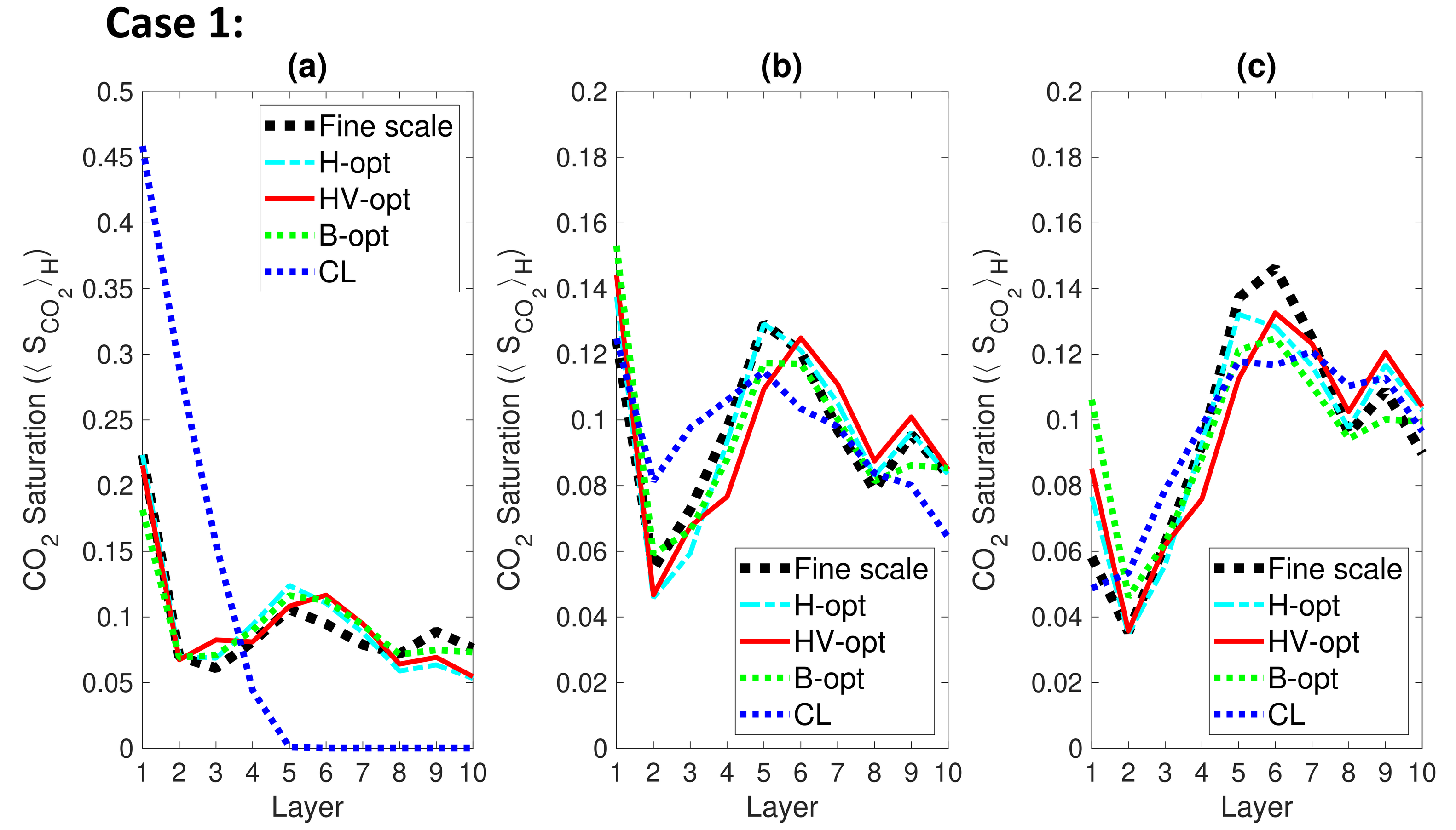
B-opt – block optimization (250)

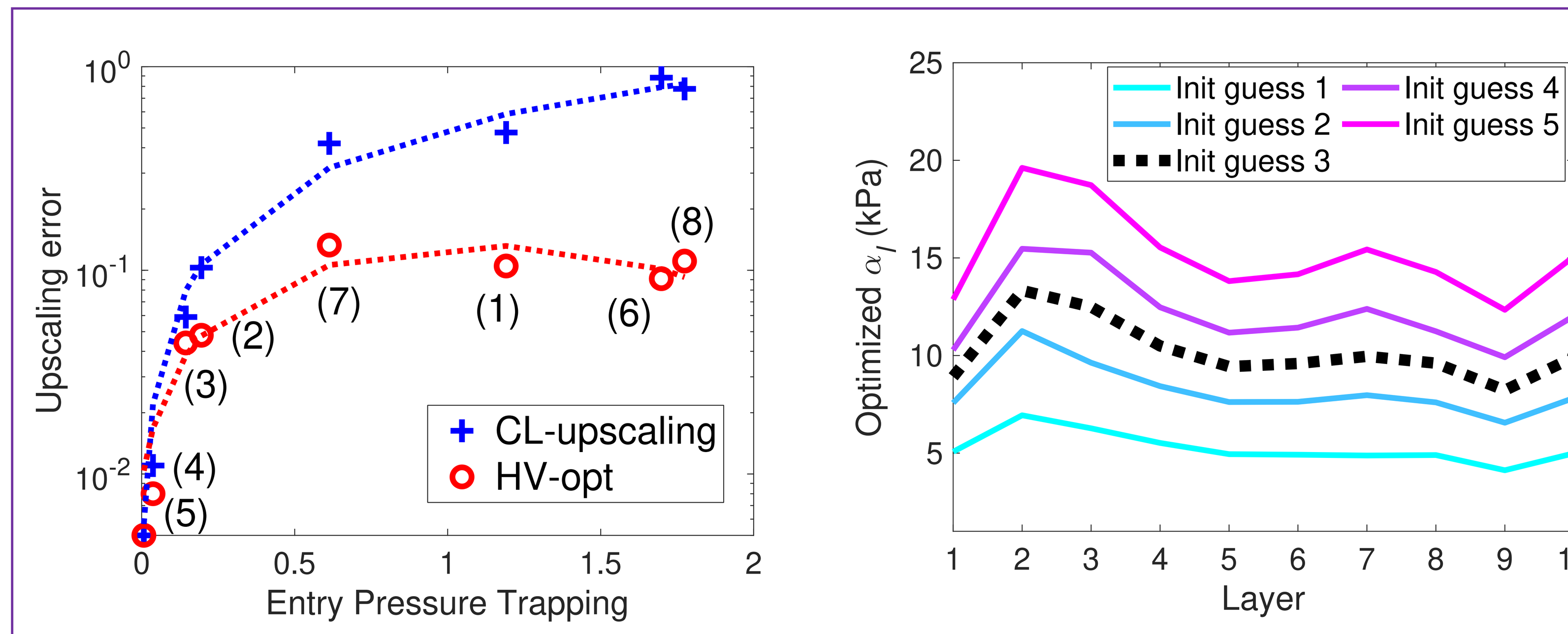
HV-opt – horizontal and vertical plane optimization (20)

H-opt – horizontal plane optimization (10)

RESULTS

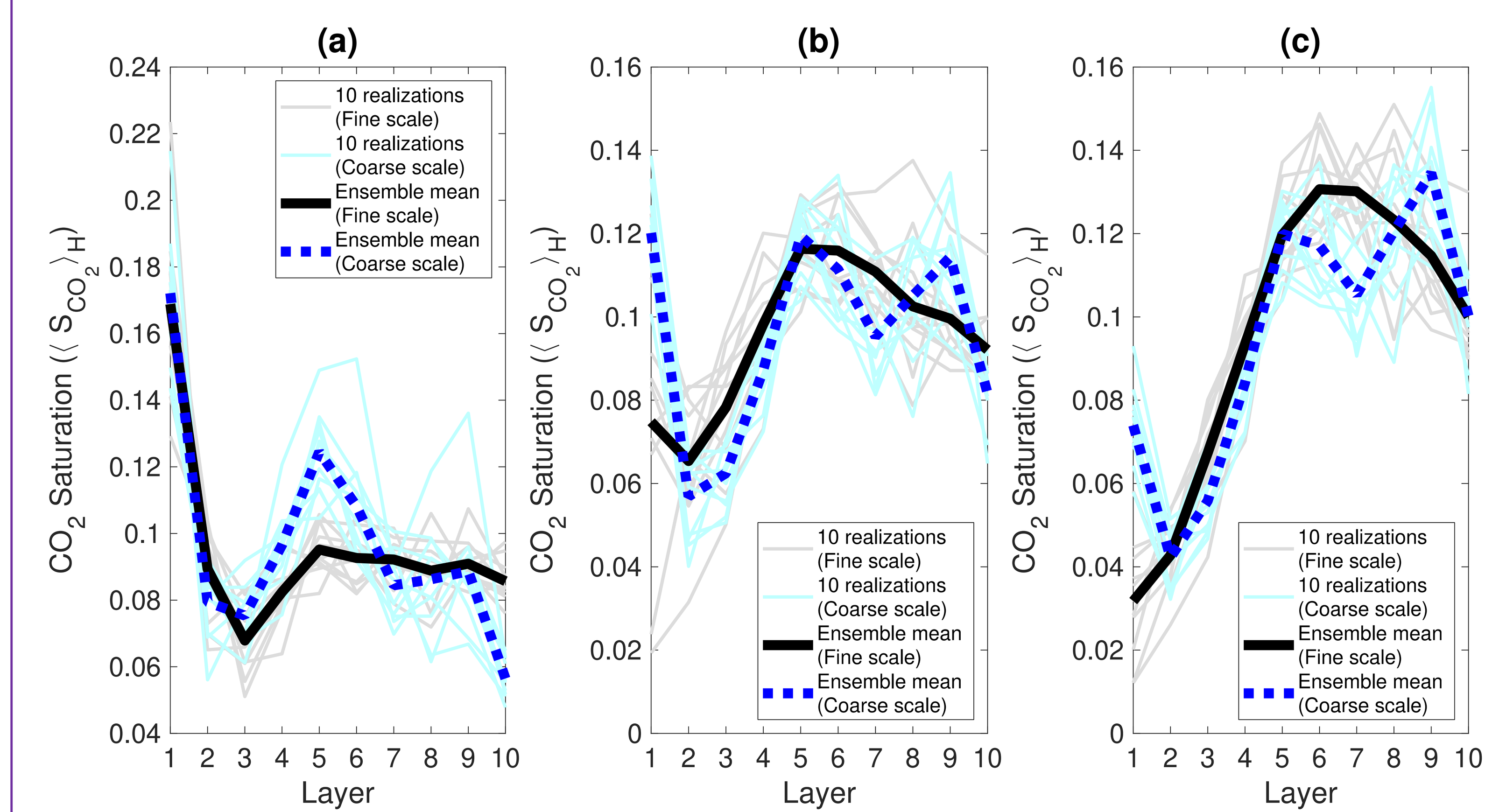
Case 1:





Reusing optimized variables for different k realizations:

- P_c^* curves from case 1 are used in all 10 coarse simulations
- Speedup: fine scale simulations - 8 hours, opt upscaling - 2 hours



CONCLUSIONS

- Conventional upscaling methods fail to reproduce fine-grid simulations of gravity-capillary driven flow
- New upscaling method is based on effective property formula, power law averaging and optimization
- Optimization upscaled P_c shown to accurately model entry pressure trapping
- Computational time is reduced when upscaled P_c is reused in different k realizations