

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

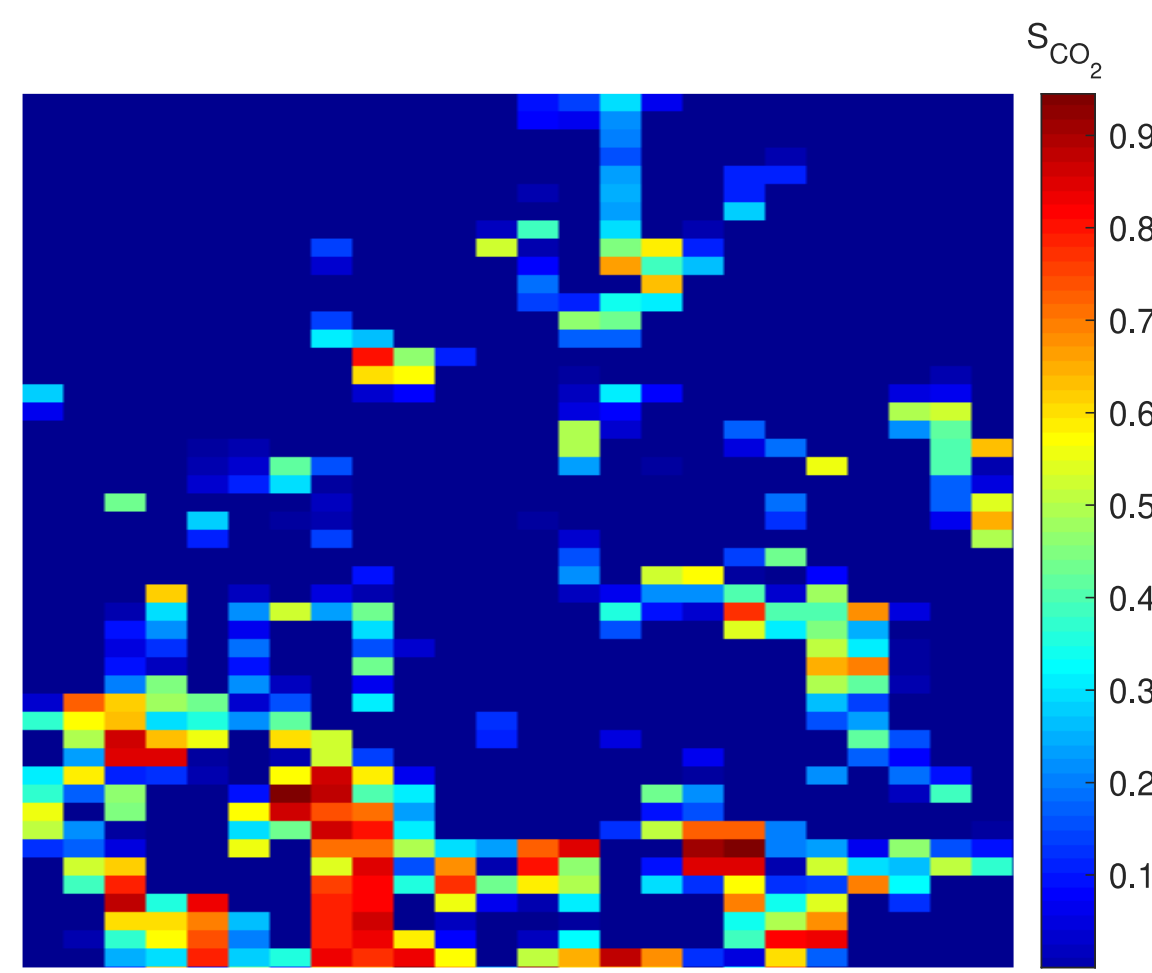
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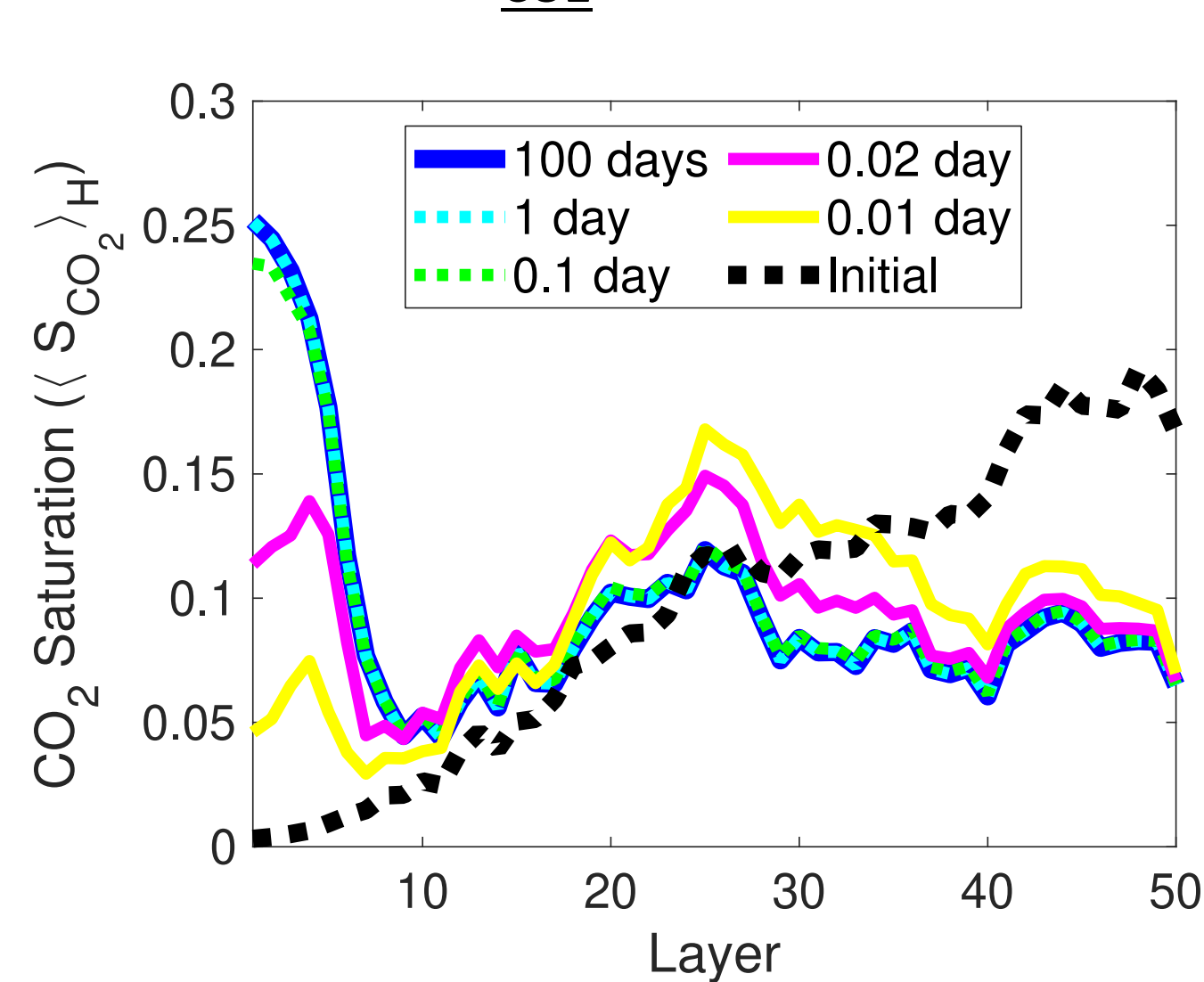
GOAL

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

Initial saturation in vertical slice



Average S_{CO_2} - vertical variation



UPSCALING METHOD

Governing equations:

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

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

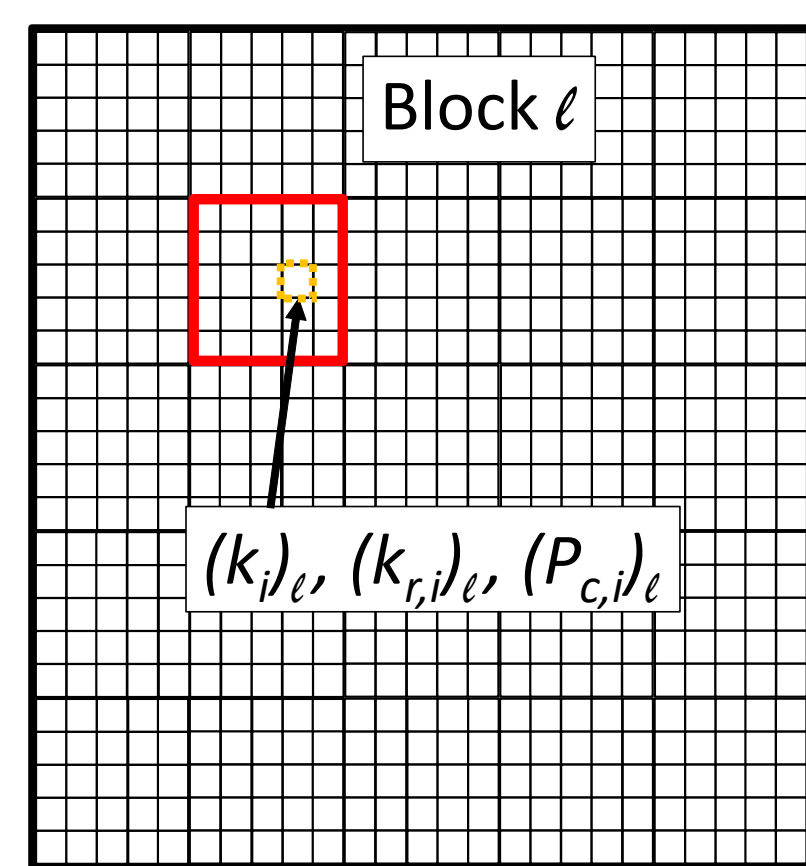
k upscaling formula:

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

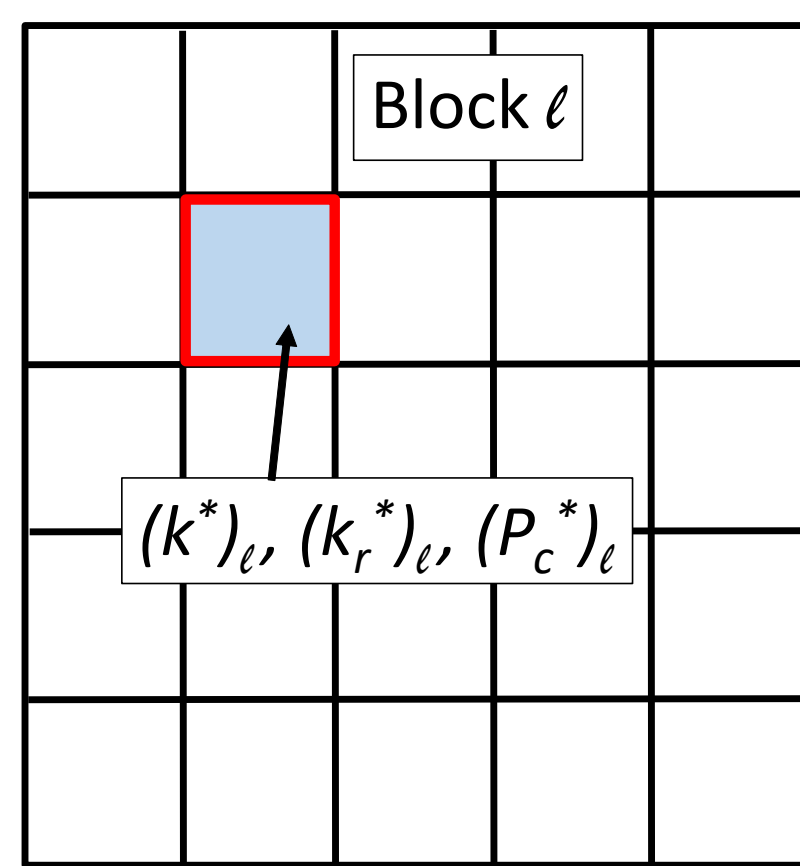
$$Y = \ln k$$

l - Coarse scale grid block

i - fine scale grid block



(a) Fine-scale domain (25 x 25 x 50)



(b) Upscaled domain (5 x 5 x 10)

k_r upscaling - power law averaging in capillary limit:

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

P_c upscaling - optimization to find entry pressures α_l :

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

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):

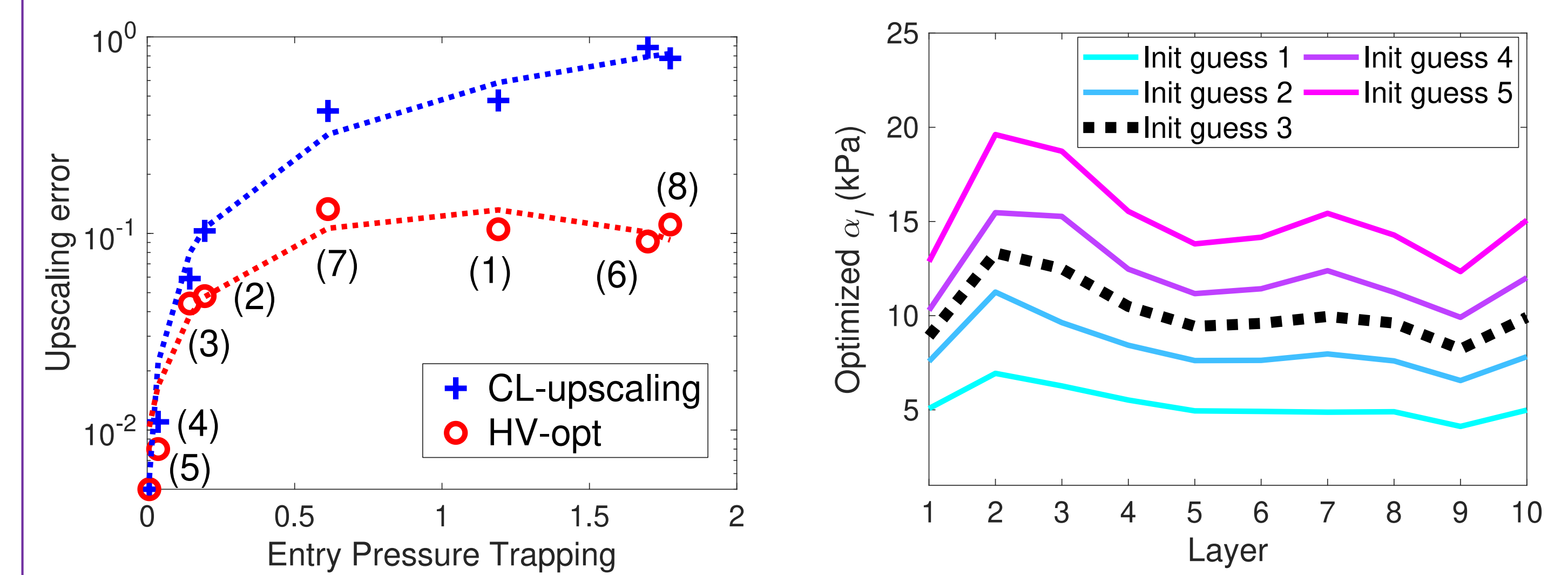
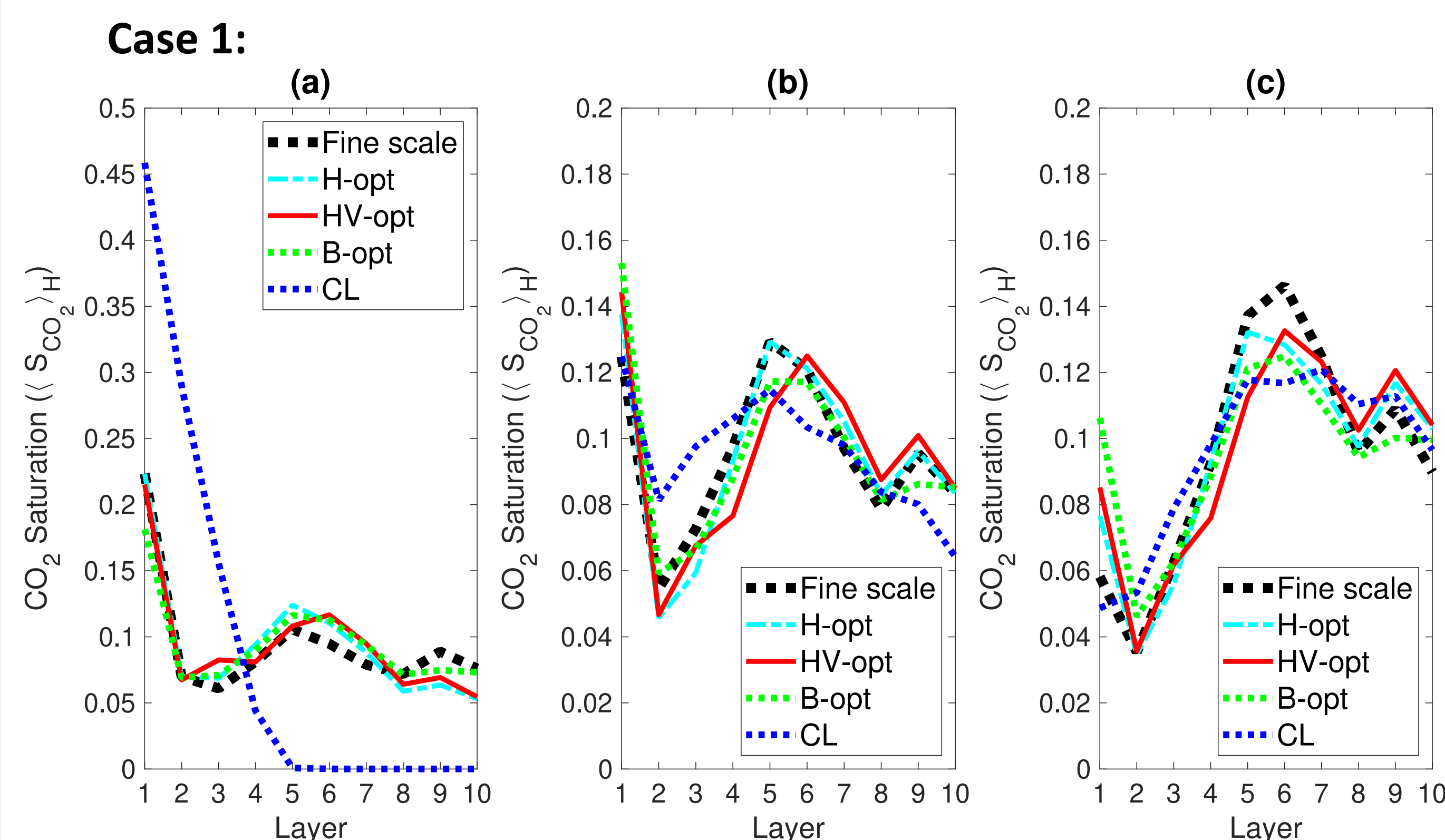
CL - capillary limit (no opt)

B-opt - block optimization (250)

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

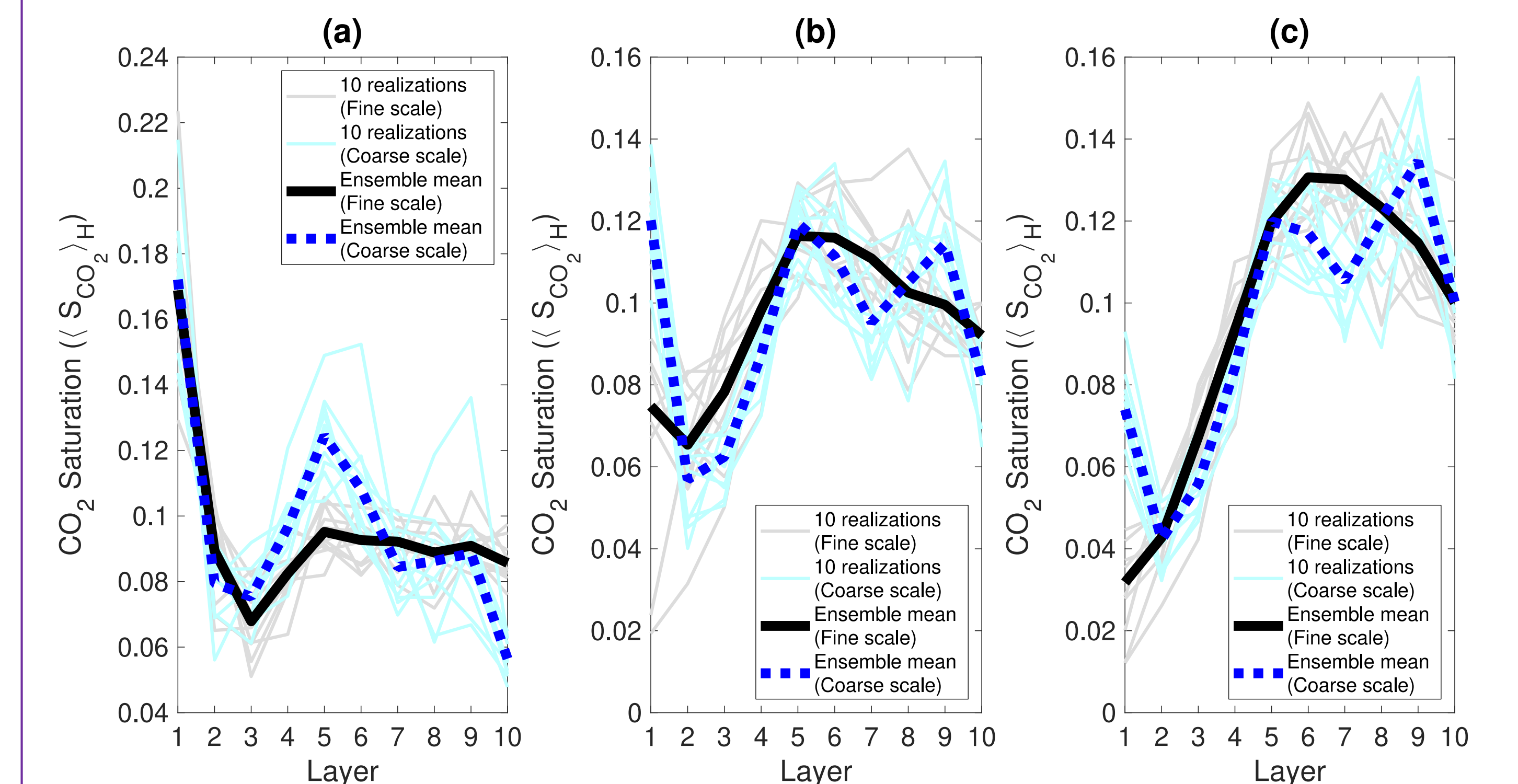
H-opt - horizontal plane optimization (10)

RESULTS



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