

THE IMPACT OF LOCAL-SCALE PROCESSES ON LARGE-SCALE CO₂ MIGRATION AND IMMOBILIZATION

Sarah E. Gasda*, Jan M. Nordbotten[†] and Michael A. Celia[‡]

*Environmental Sciences and Engineering
University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA e-mail:
sgasda@unc.edu, web page: <http://www.sph.unc.edu/ese>

[†]Department of Mathematics
University of Bergen, Bergen, Norway

[‡]Department of Civil and Environmental Engineering
Princeton University, Princeton, NJ 08544, USA

Key words: CO₂ sequestration, upscaled models, capillary fringe, dissolution

Summary. We present a vertically-integrated approach to CO₂ modeling that employs upscaled representations of local-scale processes. Large-scale migration and immobilization of mobile CO₂ is greatly impacted by modeling choices associated with local capillary and dissolution effects.

1 INTRODUCTION

Geological carbon sequestration is a promising strategy for reducing anthropogenic carbon dioxide (CO₂) emissions from large stationary sources and, as a result, can stabilize atmospheric levels of CO₂ and lessen the impact of climate change¹. Storage security of injected CO₂ during the injection and post-injection phases is an essential component of the ultimate success of this technology. Short-term storage security during the injection phase involves mitigation of vertical CO₂ migration through the overlying caprock, which may in part be minimized by proper site selection and sensible deployment of monitoring and remediation strategies. However, long-term post-injection storage security involves ensuring the eventual immobilization of free-phase CO₂ in a more permanent residual or dissolved state, a process that may take thousands to tens of thousands of years to occur¹. During this time, buoyancy forces and topographical features may allow the free-phase, mobile CO₂ to migrate laterally over very large distances.

An important aspect of long-term solubility trapping of CO₂ is the onset of convective mixing at small length scales which can greatly enhance and accelerate the dissolution process during the post-injection period⁴. In addition, local capillary forces can significantly effect the migration of the CO₂ plume over large distances¹¹. Understanding the

effect of these small-scale processes over large spatial and temporal scales is a critical component of long-term risk assessment. However, traditional numerical methods⁹ are unable to capture both small and large-scale processes in an efficient manner, and analytical methods^{10,7} are limited in their scope. Ultimately, these open issues in long-term storage security can only be addressed through the development of upscaled numerical models that use subscale approximations for critical physical processes. In this paper, we employ approximations to extend our previous work on vertically-averaged numerical models of CO₂ injection and migration to include dissolution-convection processes and local-scale capillary effects. We use this modeling approach to explore the sensitivity of long-term storage security on these subscale processes.

2 MODEL APPROACH

This work is based upon a set of vertically-averaged models that are presented in greater detail elsewhere^{5,7}. The model employs a vertical-equilibrium assumption which allows for derivation of a set of governing equations for the CO₂-brine two-phase system, while also accounting for the dissolved mass fraction of CO₂ in brine. As depicted in Figure 1, the system is composed of four macroscopic interfaces, where $\zeta_T = \zeta_T(x_1, x_2, t)$ and $\zeta_B = \zeta_B(x_1, x_2, t)$ are the top and bottom surfaces of the formation, respectively, and $\zeta_M = \zeta_M(x_1, x_2, t)$ and $\zeta_R = \zeta_R(x_1, x_2, t)$ are the bottom interfaces of the Mobile and Residual CO₂ macroscopic regions, respectively.

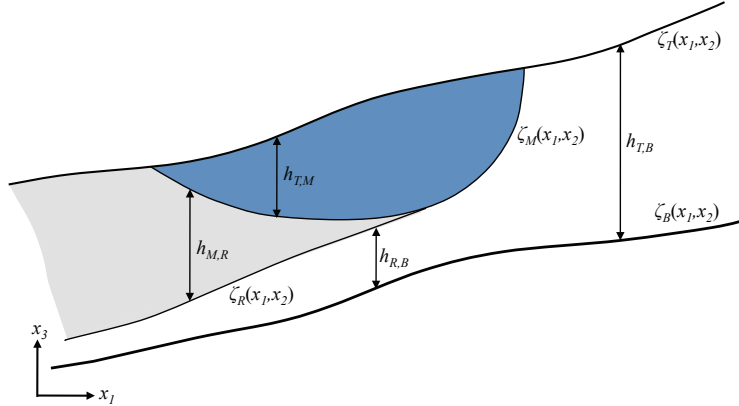


Figure 1: Schematic of CO₂-brine system. The relevant macroscopic interfaces are the top and bottom surfaces of the formation, ζ_T and ζ_B , and the bottom of the mobile and residual CO₂ regions, ζ_M and ζ_R .

The conservation of mass equations for each component M^α are

$$\frac{\partial M^\alpha}{\partial t} + \nabla \cdot \mathbf{F}^\alpha = 0, \quad \alpha = c, b. \quad (1)$$

with component fluxes \mathbf{F}^α obtained from the vertically-integrated fluid fluxes that satisfy Darcy's Law.

The conservation of total dissolved CO₂ in the brine phase, M_b^c , is modeled with the following transport equation,

$$\frac{\partial M_b^c}{\partial t} + \nabla \cdot \int_{\zeta_B}^{\zeta_T} \mathbf{u}_b \rho_b m_b^c dx_3 = C_{diss}(\omega, \zeta_R), \quad (2)$$

where the second term on the left hand side represents the total flux of dissolved CO₂ in the brine phase, and the right hand side represents kinetic mass exchange for dissolved CO₂ that is governed by the vertically-averaged concentration dissolved CO₂ in brine, ω . Equation (2) holds subject to the constraint that $0 \leq \omega \leq 1$.

Equation (2) captures two dissolution mechanisms: 1) equilibrium between the mobile CO₂ phase and region of pure residual brine during drainage and residual CO₂ and mobile brine during imbibition; and 2) mass transfer of CO₂ into the brine region through dissolution combined with convective mixing. For the latter kinetic process, a number of detailed numerical and experimental studies have found that the overall mass transfer rate due to the dissolution-convection process is roughly constant in time^{13,12}, which is adopted in this model.

The final equation accounts for hysteresis and evolution of the residual CO₂ interface ζ_R . This is done by considering the conservation equation for mobile CO₂,

$$-\phi(1 - s_{c,r} - s_{b,r}) \frac{\partial \zeta_M}{\partial t} + \nabla \cdot \int_{\zeta_M}^{\zeta_T} \mathbf{u}_c \rho_c m_c^c dx_3 = 0 \quad (3)$$

where ϕ is the porosity, $s_{\alpha,r}$ are the residual saturations for each phase, and the second term represents the vertically-integrated phase velocity \mathbf{u}_c .

In previous work⁶, the model derivation presented above employed an additional assumption regarding complete gravity segregation and a sharp interface between the two fluids. In this study, the sharp-interface assumption has been relaxed to include the presence of local capillary effects that creates a transition zone of CO₂ saturation, referred to as the capillary fringe. The inclusion of the capillary fringe in vertically-integrated models is described in detail elsewhere^{8,11}. In regard to Figure 1, the interface ζ_M indicates the bottom of the capillary transition zone.

The above system of equations, (1)-(3), is solved in an IMPES-type strategy whereby a pressure is solved implicitly under the assumption of an incompressible system. For the transport equations, we consider an splitting type approach, evolving ζ_M first, then ζ_R , and finally the concentration ω . The system is solved numerically using a standard finite-difference approximation.

3 MODEL APPLICATION

The above described model is applied to the Johansen formation², which is a large saline aquifer approximately 3,000 below the North Sea and is a prospective site for

injection of on-shore Norwegian emissions. The Johansen formation is characterized by large areal extent, heterogeneity, a significant dip, and a major fault line splitting the formation³. For this problem, CO₂ is injected through a vertical well ($x = 32.25$ km, $y = 29.75$ km) at a constant rate of 30 kg/s for 50 years and then allowed to migrate due to buoyancy forces until the plume is immobilized by residual and/or solubility trapping mechanisms.

We investigate the effect of four different modeling choices on the evolution of mobile and trapped CO₂ over tens of thousands of years. The first case considers only structural CO₂ trapping and no solubility or residual trapping. The second case only considers trapping of CO₂ in the residual phase and employs the sharp-interface assumption. The third case includes capillary fringe effects with residual trapping but does not model dissolution. The local capillary-saturation model employed for this case is $P_c = \alpha(S_{w,n})^{-1/2}$ with the parameter $\alpha = 2 \times 10^4$ Pa. Finally, the last case extends the second case by modeling the additional mechanism of dissolution through convective mixing but does not include capillary fringe effects. The upscaled dissolution rate is modeled as $C_{diss} = 1$ kg/m²/yr unless otherwise noted.

For the above cases, we consider an incompressible system and assign the fluid and porous media properties defined in the original benchmark definition^{2,6}. The post-injection period is modeled for 5,000 years or until the mobile plume reaches the edge of the domain, a minimum distance of 25 km from the injection point for this problem.

3.1 Results and Discussion

When the sharp-interface model is applied to the Johansen formation (Figure 2) without considering trapping by either residual or solubility processes, the CO₂ travels as far as 10 km from the injection well in the upslope direction within the first 50 years post-injection. After 1,000 years, the maximum travel distance is approximately 30 km, and the far right edge of the plume reaches the outer boundary, which is 25 km away, within that time. The plume thickness varies significantly over its areal extent, which is due to a combination of structural and heterogeneity effects. Eventually, most of the CO₂ will reach the outer boundary when residual and solubility trapping mechanisms are not modeled.

In comparison, Figure 3 shows the effect of residual trapping, where in this case the residual saturation of CO₂ is assigned to be 50%. The maximum travel distance is nearly the same after the first 100 years. However, by 1,000 years, the mobile CO₂ travels as far as the far right boundary, but by this time, approximately 90% immobilized by residual trapping mechanisms.

The model results with capillary effects are shown in Figure 4. At the end of the 50-year injection period, the maximum extent CO₂ plume is approximately 5 km in the updip direction. After 100 years, the the mobile CO₂ only migrates a few more kilometers upslope while trapping approximately 40% of the CO₂ mass in residual phase. After 1,000 years, some mobile CO₂ remains but is essentially immobilized by a combination of capillary

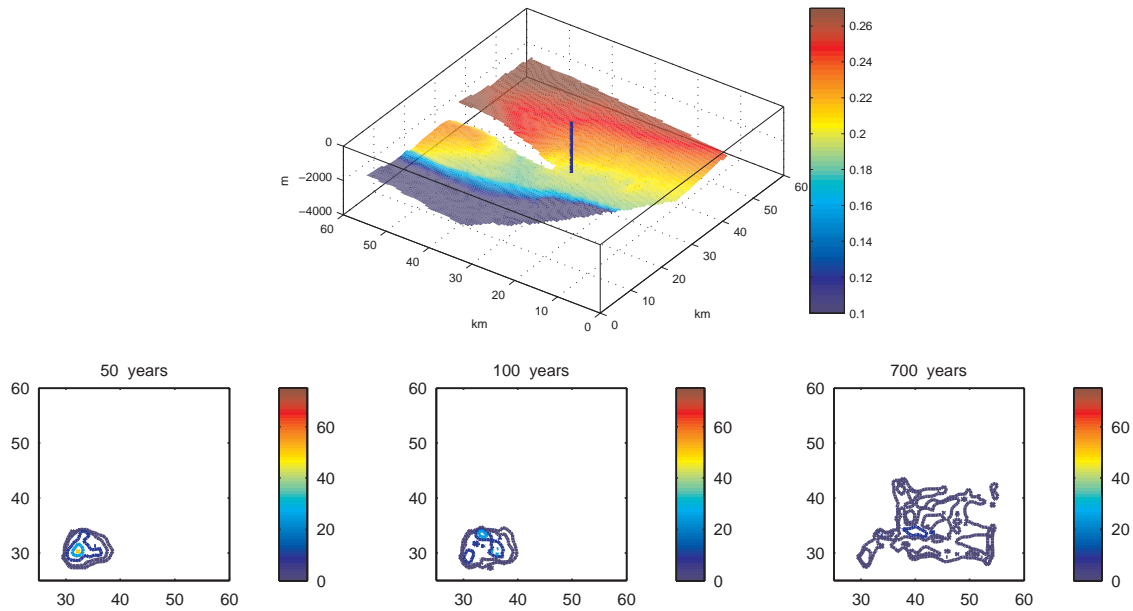


Figure 2: Sharp-interface model results of post-injection CO₂ migration without trapping in the Johansen formation. The geometry and porosity distribution of the formation and the location of the injection well are shown at top. At bottom is the thickness in meters of the mobile CO₂ over 1,000 yrs.

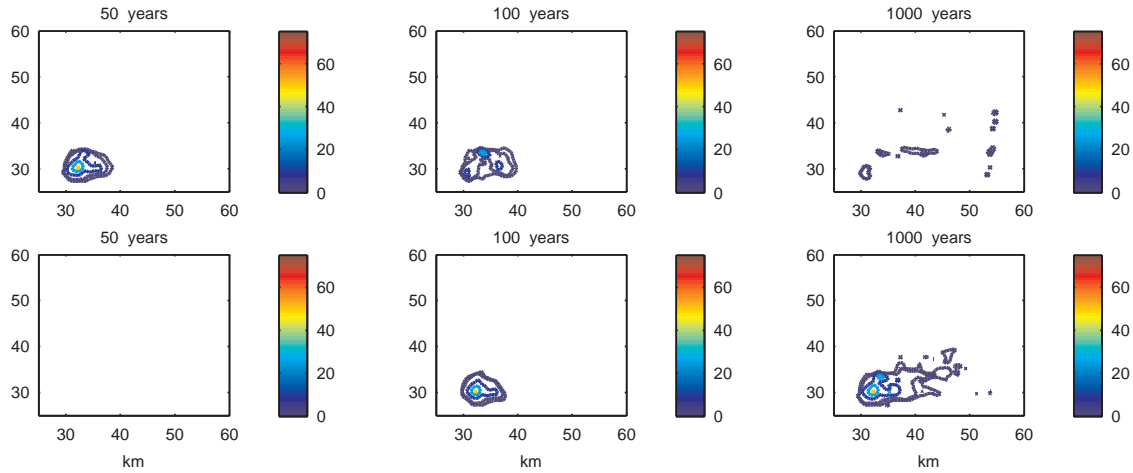


Figure 3: Sharp-interface model results of post-injection CO₂ migration with residual trapping in the Johansen formation. Shown is the thickness in meters of the mobile CO₂ in the top panels and of the residual CO₂ in the bottom panels over 1,000 yrs.

effects and topographical features. The CO₂ mass trapped residually is approximately 70% of the total mass.

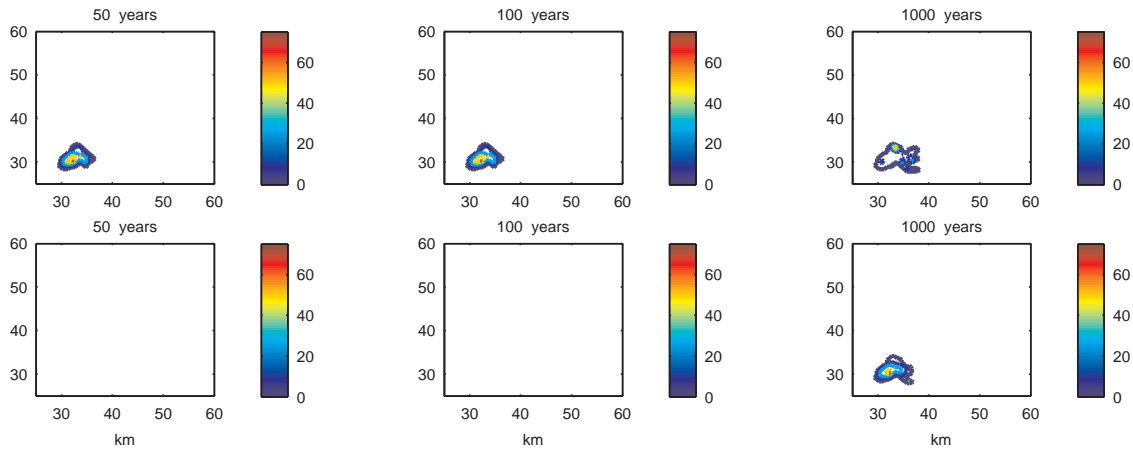


Figure 4: Capillary fringe model results of post-injection CO_2 migration and trapping in the Johansen formation. Shown is the thickness in meters of the mobile CO_2 in the top panels and of the residual CO_2 in the bottom panels over 1,000 yrs.

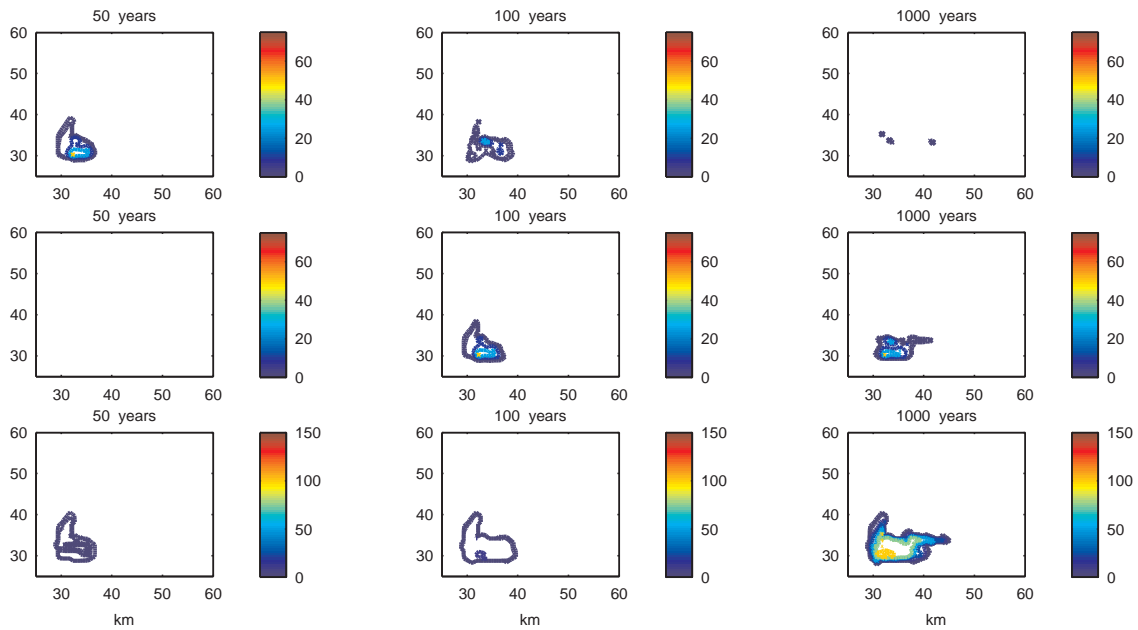


Figure 5: Dissolution model results of post-injection CO_2 migration and trapping in the Johansen formation (shown at top). Shown is the thickness in meters of the mobile CO_2 in the top panels, of the residual CO_2 in the middle panels, and of the dissolved CO_2 in the bottom panels over 1,000 yrs.

The dissolution model results in Figure 5 show that plume migrates approximately 5 km upslope from the injection well by the end of injection, which increases to 7 km

within 100 years. By 1,000 years, the CO₂ has been almost completely immobilized by either residual or solubility trapping processes. The extent of the dissolved CO₂ shows that mobile CO₂ traveled as far as 10 km from the injection well, but since the outer plume edge is very thin under the sharp interface assumption, the mobile CO₂ in those regions is dissolved relatively quickly. At 100 years, approximately 50% of the total mass is trapped residually and 15% is trapped in the dissolved state. After 1,000 years, 90% of the total mass is immobilized, with 40% in the residual state and 50% trapped in the dissolved state. Over time, the residual CO₂ dissolves until the thickness of the dissolved region reaches the bottom of the aquifer.

4 CONCLUSIONS

- Vertically-integrated approaches to modeling CO₂ injection can be used to investigate CO₂ migration and trapping over length scales on the order of 100 km and time scales greater than 10,000 years.
- Subscale models for local effects such as a capillary fringe and convective-mixing enhanced dissolution can be included in vertically-integrated models and applied to realistic geologic systems.
- Capillary fringe effects result in slower rate of upslope migration and decreased maximum travel distances by several kilometers for systems with large capillary transition zones.
- CO₂ dissolution enhanced by convective mixing can immobilize injected CO₂ within a few hundred years.
- Vertically-intergrated models can be used to assess the impact of different processes on CO₂ immobilization and are important tools for managing long-term risk of CO₂ injection operations.

References

- [1] Benson, S., et al., Underground geological storage, in *Carbon Dioxide Capture and Storage. Intergovernmental Panel on Climate Change Special Report*, edited by B. Metz et al., Cambridge Univ. Press, Cambridge, United Kingdom, 2005.
- [2] Class, H., et al., A benchmark study on problems related to CO₂ storage in geologic formations, *Comp. Geosci.*, 13(4), 409–434, 2009.
- [3] Eigestad, G. T., H. K. Dahle, B. Hellevang, F. Riis, W. T. Johansen, and E. Øian, Geological modeling and simulation of CO₂ injection in the Johansen formation, *Comp. Geosci.*, 13(4), 435–450, 2009.

- [4] Ennis-King, J., and L. Paterson, Role of convective mixing in the long-term storage of carbon dioxide in deep saline formations, *SPE J.*, *10*(3), 349–356, 2005.
- [5] Gasda, S.E., J.M. Nordbotten, and M.A. Celia, Vertical equilibrium with sub-scale analytical methods for geological CO₂ sequestration, *Comp. Geosci.*, *13*(4), 435–450, 2009.
- [6] Gasda, S.E., J.M. Nordbotten, and M.A. Celia, Vertically-integrated approaches to CO₂ sequestration with solubility trapping, *Water Resour. Res.*, under review.
- [7] Hesse, M.A., F.M. Orr, Jr., and H.A. Tchelepi, Gravity currents with residual trapping, *J. Fluid Mech.*, *611*, 35–60, 2008.
- [8] Lake, L., *Enhanced Oil Recovery*, Prentice-Hall, Inc., Upper Saddle River, NJ, 1989.
- [9] Lindeberg, E., and D. Wessel-Berg, Vertical convection in an aquifer column under a gas cap of CO₂, *Energy Conv. Manag.*, *38*(Suppl. S), S229–S234, 1997.
- [10] Nordbotten, J.M., and M.A. Celia, Similarity solutions for fluid injection into confined aquifers, *J. Fluid Mech.*, *561*, 307–327, 2006.
- [11] Nordbotten, J.M., H.K. Dahle, Impact of the capillary fringe in vertically integrated models for CO₂ storage, *Water Resour. Res.*, under review.
- [12] Pruess, K., Numerical modeling studies of the dissolution-diffusion-convection process during CO₂ storage in saline aquifers, *Tech. Rep. LBNL-1243E*, Lawrence Berkeley National Laboratory, 2008.
- [13] Riaz, A., M. Hesse, H.A. Tchelepi, and F.M. Orr, Onset of convection in a gravitationally unstable diffusive boundary layer in porous media, *J. Fluid Mech.*, *548*, 87–111, 2006.