Buoyant currents arrested by convective dissolution

Christopher W. MacMinn^{1,2} and Ruben Juanes³

Received 27 February 2013; revised 4 April 2013; accepted 11 April 2013; published 31 May 2013.

[1] When carbon dioxide (CO_2) dissolves into water, the density of water increases. This seemingly insubstantial phenomenon has profound implications for geologic carbon sequestration. Here we show, by means of laboratory experiments with analog fluids, that the up-slope migration of a buoyant current of CO₂ is arrested by the convective dissolution that ensues from a fingering instability at the moving CO₂-groundwater interface. We consider the effectiveness of convective dissolution as a large-scale trapping mechanism in sloping aquifers, and we show that a small amount of slope is beneficial compared to the horizontal case. We study the development and coarsening of the fingering instability along the migrating current and predict the maximum migration distance of the current with a simple sharp-interface model. We show that convective dissolution exerts a powerful control on CO₂ plume dynamics and, as a result, on the potential of geologic carbon sequestration. Citation: MacMinn, C. W., and R. Juanes (2013), Buoyant currents arrested by convective dissolution, Geophys. Res. Lett., 40, 2017-2022, doi:10.1002/grl.50473.

1. Introduction

[2] The large-scale injection of carbon dioxide (CO₂) into deep saline aquifers is a promising tool for reducing CO₂ emissions to the atmosphere [*Bachu et al.*, 1994; *Orr Jr.*, 2009; *Szulczewski et al.*, 2012]. These aquifers are thin, laterally extensive layers of porous rock saturated with saline groundwater. Many are gently sloping, in which case the relatively buoyant CO₂ may migrate laterally up-slope for tens or hundreds of kilometers after injection. Arresting the migration of this buoyant gravity current of CO₂ is essential to prevent leakage into shallower formations. Physical mechanisms that trap the CO₂ include residual trapping, where small blobs of CO₂ are immobilized by capillarity, and solubility trapping, where CO₂ dissolves into the groundwater [*IPCC*, 2005].

[3] Solubility trapping is greatly enhanced by a hydrodynamic instability where dissolved CO₂ is carried away from the buoyant current in dense fingers of CO₂-rich groundwater [*Weir et al.*, 1996; *Lindeberg and Wessel-Berg*,

1997; Ennis-King et al., 2005; Riaz et al., 2006]. Although this process of convective dissolution has been studied recently in the context of a stationary layer of CO₂ [Hidalgo and Carrera, 2009; Pau et al., 2010; Kneafsev and Pruess, 2010: Neufeld et al., 2010: Slim and Ramakrishnan, 2010: Backhaus et al., 2011; Hidalgo et al., 2012; Slim et al., 2013], the interaction of convective dissolution with a migrating current of CO₂ has received comparatively little attention and is not well understood. Numerical simulations and macroscopic theoretical models predict that convective dissolution will arrest the migration of such a current [Pritchard et al., 2001; Pruess and Nordbotten, 2011; Gasda et al., 2011; MacMinn et al., 2011]. MacMinn et al. [2012] recently confirmed this prediction in a horizontal aquifer but found that the effectiveness of this process is greatly limited in horizontal aguifers by the small solubility of CO₂ in groundwater.

[4] Here, we study convective dissolution from a buoyant current in a sloping aquifer. We conduct laboratory experiments using analog fluids, and we compare the results with the predictions of a sharp-interface mathematical model. We then use the experiments to study the detailed dynamics of the fingering instability, and we use the model to quantify the effectiveness of convective dissolution as a large-scale trapping mechanism.

2. Laboratory Experiments

[5] To study buoyant currents with convective dissolution, we employ an analog-fluid system in which water plays the role of the buoyant CO₂ and propylene glycol (PG) plays the role of the denser and more viscous ambient groundwater [*Backhaus et al.*, 2011]. The density of water-PG mixtures is a nonmonotonic function of water concentration so that mixtures with up to about 54% water are denser than pure PG, triggering convective dissolution in a system that is initially stably stratified (see supporting information). The large viscosity contrast between the water and the PG is appropriate for studying a buoyant current of CO₂, which is much less viscous than the ambient groundwater. Unlike CO₂ and groundwater, water and PG are perfectly miscible, so capillarity plays no role in this analog system.

[6] To study buoyant currents without convective dissolution, we replace the PG with a mixture of glycerol and water that has a viscosity similar to that of PG. As in the water-PG system, the buoyant water will mix with the dense glycerol-water mixture along their shared interface. Unlike in the water-PG system, the resulting mixture will have an intermediate density and will never trigger convective dissolution.

[7] To perform an experiment, we release a fixed quantity of the buoyant fluid in the lower corner of a sloping aquifer (either a Hele-Shaw cell or a quasi-two-dimensional flow cell packed with glass beads; see supporting information).

Additional supporting information may be found in the online version of this article.

¹Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

²Department of Geology and Geophysics, Yale University, New Haven, Connecticut, USA.

³Department Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Corresponding author: R. Juanes, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. (juanes@mit.edu)

^{©2013.} American Geophysical Union. All Rights Reserved. 0094-8276/13/10.1002/grl.50473



Figure 1. Convective dissolution arrests the up-slope migration of a buoyant current. Here we show snapshots of two buoyant currents migrating up-slope in a sloping aquifer (a Hele-Shaw cell for illustration). The CO_2 analog is water (dark) in both cases. When the denser and more viscous ambient fluid is a mixture of glycerol and water (left), the fluids mix by diffusion-dispersion only, and the buoyant current migrates to the top of the cell and accumulates there. When the ambient fluid is propylene glycol (right), the dense mixture of the two fluids drives convective dissolution, which dissolves the buoyant current as it migrates.

This fluid rises toward the top of the cell and migrates up-slope as a buoyant current. Without convective dissolution, the buoyant current migrates to the upper corner of the cell and accumulates there. With convective dissolution, the upward migration of the buoyant current slows and is ultimately arrested (Figure 1).

3. Mathematical Model

[8] We have elsewhere developed and discussed a sharpinterface model for the evolution of a buoyant current in a sloping aquifer, subject to residual and solubility trapping [*MacMinn et al.*, 2011]. The model is derived from Darcy's law and conservation of mass after assuming that the pure fluids are separated from each other by a sharp interface, neglecting capillarity, and neglecting the vertical component of the fluid velocity relative to the horizontal one (see supporting information). For simplicity, we ignore the accumulation of dissolved buoyant fluid beneath the migrating current. This effect can in some cases suppress further convective dissolution, but it does not play a strong role in the scenarios considered here. In addition, there is no residual trapping in our experiments since the analog fluids are perfectly miscible.

[9] The model takes the form of a partial differential equation to be solved for the local plume thickness h(x, t):

$$\frac{\partial h}{\partial t} + \kappa \frac{\partial}{\partial x} \left[\sin \vartheta \left(1 - f \right) h - \cos \vartheta \left(1 - f \right) h \frac{\partial h}{\partial x} \right] = -\frac{q_d}{\phi}, \quad (1)$$

where x is the coordinate along the sloping aquifer, t is time, ϑ is the aquifer slope measured from horizontal, $\kappa = \Delta \rho g k / \phi \mu_g$ is the characteristic velocity of the buoyant current, and q_d is the volumetric rate of convective dissolution per unit area of fluid-fluid interface (ϕ and k are the porosity and permeability of the aquifer, respectively, $\Delta \rho$ is the amount by which the density of the ambient fluid exceeds the density of the buoyant one, μ_g is the dynamic viscosity of the buoyant fluid, and g is the force per unit mass due to gravity). The function *f* is given by $f(h) = \mathcal{M}h/[(\mathcal{M}-1)h+H]$, where $\mathcal{M} = \mu_w / \mu_g$ is the mobility ratio, with μ_w the dynamic viscosity of the ambient fluid. This fractional-flow function reflects the fact that, in a confined aquifer, the viscosities of both fluids exert resistance to flow. The term proportional to $\sin \vartheta$ in equation (1) represents up-slope migration, the term proportional to $\cos \vartheta$ represents spreading against the top of the aquifer, and the sink term on the righthand side represents convective dissolution of CO_2 into the brine.

[10] We make equation (1) dimensionless using characteristic thickness H, length L, and time T, where H is the thickness of the aquifer, L is the initial width of the buoyant current, and $T = L^2/(H\kappa \cos \vartheta)$ is the diffusive spreading timescale. The result is

$$\frac{\partial \eta}{\partial \tau} + \frac{\partial}{\partial \xi} \left[N_s \left(1 - f \right) \eta - \left(1 - f \right) \eta \, \frac{\partial \eta}{\partial \xi} \right] = -N_d, \tag{2}$$

where $\eta = h/H$, $\xi = x/L$, and $\tau = t/T$. Equation (2) is uniquely characterized by three dimensionless parameters: $N_s = (L/H) \tan \vartheta$, which measures the importance of up-slope migration; $N_d = L^2 q_d/(H^2 \phi \kappa \cos \vartheta)$, which measures the importance of convective dissolution; and \mathcal{M} , the mobility ratio.

[11] We compare the predictions of the model with experiments in the packed flow cell at different values of the slope ϑ with the same initial condition of height H = 5.2 cm and $L \approx 5.2$ cm (see supporting information). The parameter N_s then depends only on the slope, whereas the parameter N_d is a very weak function of the slope for the small angles used here. This allows us to adjust the value of N_s essentially independently from the other parameters. We vary it here from 0 to about 0.3 by changing the angle from 0 to about 16°. We are also able to add or remove the effect of convective dissolution while keeping all other parameters nearly constant by switching the fluid pair since, by design, the value of \mathcal{M} is similar for the water/glycerol-water system (\approx 39) and for the water-PG system (\approx 48). N_d takes a constant value of 0 for the water/glycerol-water system and a nearly constant value of about 2×10^{-4} for the water-PG system.

[12] From each experiment, we measure the migration distance of the buoyant current as the position x_N of its leading edge or nose as a function of time. The predictions of the model agree well with the experiments for buoyant currents both without and with convective dissolution (Figures 2a and 2b, respectively), differing most for the smallest slopes where the current dissolves before reaching the long and thin aspect ratio assumed in developing the model (see supporting information).



Figure 2. Migration distance as a function of time (both dimensionless) from the experiments (circles) and the model (solid lines) for several different slopes (a) without convective dissolution (water/glycerol-water system) and (b) with convective dissolution (water-PG system). Buoyant currents in the water/glycerol-water system all hit the end of the cell, located at a dimensionless distance of about 10. In contrast, buoyant currents in the water-PG system reach a maximum migration distance and then begin to retreat as they dissolve completely (with the exception of the largest slope, for which the current hits the end of the cell before reaching its maximum migration distance). We mark with an 'x' the first data point after the maximum migration distance (the first point of the retreat) and truncate the data thereafter because the buoyant fluid breaks up into patches, no longer behaving as a gravity current.

4. Coarsening Dynamics

[13] Our experiments also reveal the detailed dynamics of this hydrodynamic instability: the formation, descent, and coarsening of the fingers. These small-scale features are explicitly absent from macroscopic theoretical models and are challenging to resolve in numerical simulations simultaneously with the long, thin current [Ennis-King et al., 2005; Pruess and Nordbotten, 2011]. A migrating current provides a unique setting for studying the evolution of the fingering instability because a single experiment provides data on the evolution of many fingers. A snapshot in time shows fingers at different levels of maturity: younger near the nose of the current and older further away from it (Figure 3a). The typical morphology of the fingers exhibits a thin neck at the root, a winding core along which the finger widens, and a round bulb at the tip (Figure 3a; see also Riaz et al. [2006], Backhaus et al. [2011], Hidalgo et al. [2012], and *Slim et al.* [2013]).

[14] We focus here on the evolution of two quantities: the speed at which the fingers fall and the spacing of the fingers. The finger speed has macroscopic importance since the dynamics of convective dissolution change when the fingers begin to interact with the bottom of the aquifer, and the finger speed determines the time at which this occurs. The finger spacing informs the spatial resolution necessary for numerical simulations to accurately capture the physics of convective dissolution. The size and spacing of the fingers are also essential aspects of understanding how they will interact with a heterogeneous permeability field.

[15] We find that all fingers descend with roughly the same characteristic speed, which we estimate from the experiment to be $v_f \approx 0.54$ cm/min (Figure 3c). All fingers slow gradually as they begin to interact with the bottom of the aquifer. We also estimate the onset time for the instability from the experiment, finding $t_{\text{onset}} \approx 0.42 \text{ min}$. From these observations, we propose a simple model for the thickness h_f of the fingering front that grows beneath the migrating plume: $h_f(x,t) = v_f t_{conv}(x,t) \mathcal{U}(t_{conv})$, where \mathcal{U} is the Heaviside step function and $t_{conv}(x, t)$ is the *convective time*, measuring the amount of time that has passed since fingers first formed at a location x. The nose of the migrating current arrives at location x at time $t_N(x)$, and fingers form a time t_{onset} thereafter, so $t_{conv} = t - t_N(x) - t_{onset}$. In other words, the fingering front grows at a constant rate v_f at each location x, starting at a different time for each x based on when the current arrives there. Here, we measure the function $t_N(x)$ from the experiment directly—in field applications, when the nose position is not available for observation, it can be predicted from equation (1). This model provides an excellent approximation for the growth of the fingering front (Figure 3a).

[16] The finger spacing coarsens as the fingers fall: older fingers are wider and spaced further apart (Figure 3a). Two different physical mechanisms are involved in the coarsening process: "mergers and acquisitions," when two finger tips interact and then merge, and "finger suppression," when the root feeding an older finger consumes the root feeding a younger one, diverting the flux and causing the younger finger to retreat and be absorbed (see Video S0 in the supporting information). We highlight the evolution of the fingertip spacing by tracing the trajectories of the finger tips as they fall (Figure 3b).

[17] Since $t_{conv}(x, t)$ reflects the age of the fingers at location x and time t, it is also the appropriate independent variable for studying finger coarsening. We compute the average spacing between *finger tips* λ_{tips} as a function of t_{conv} from Figure 3b. We find that the tip spacing increases almost linearly with convective time by a factor of about 3 over the course of the experiment (Figure 3d, blue line). We study the coarsening of the finger roots by analyzing, as a function of convective time, the color of the fluid mixture in a strip running along the underside of the water-PG "interface" (Figure 3e). We find that, after some early-time merging of the young fingers that form simultaneously at the onset of the instability $[t_{conv} \in (3, 6) \text{ min}]$, new fingers always migrate laterally to merge with a neighboring, well-developed finger (Figure 3e). We compute the average spacing between *finger roots* λ_{roots} as a function of t_{conv} from Figure 3e. The root spacing (Figure 3d, black line) increases more slowly than the tip spacing and appears to remain constant during an intermediate period of time [$t_{conv} \in (6, 10)$ min] when finger



Figure 3. Experiments in a Hele-Shaw cell allow us to study the detailed dynamics of convective dissolution from a migrating current. (a) The fingering front grows as the current migrates, illustrated here with snapshots at two different times and the prediction of a simple model (cyan line, see Video S1). (b) The fingering pattern coarsens as the fingers grow and merge, illustrated here with the paths that the finger tips follow over time (see Video S2). (c) All fingers fall with roughly the same characteristic speed until nearing the bottom of the cell, illustrated here with finger depth versus convective time for those fingers that reach the bottom. (d) The fingering pattern coarsens over time, illustrated here with the mean spacing of the finger tips (blue line) and finger roots (black line) as a function of convective time, as extracted from Figures 3b and 3e, respectively. (e) The dynamics of the finger roots are illustrated here via the evolution of the color intensity of a fluid strip located along the underside of the water-PG interface.

formation balances finger merging and before the buoyant fluid is exhausted [$t_{conv} \sim 12 \text{ min}$].

[18] Although the scalings behind finger coarsening remain to be explored quantitatively, this analysis suggests that the finger roots and tips exhibit different coarsening dynamics: the root spacing saturates at a quasi-steady value, while the tip spacing coarsens over the entire finger lifetime. Further study will likely require insight from high-resolution simulations.

5. Convective Dissolution at Geologic Scale

[19] Our results suggest that convective dissolution can play a key role in arresting the migration of a buoyant current of CO₂, rapidly transforming the CO₂ from a buoyant fluid into a sinking fluid. We now use the model to consider trapping effectiveness in the context of large-scale carbon sequestration: a migrating current of CO₂ in the Mt. Simon sandstone, a large deep saline aquifer in the Midwestern United States (Region **a** as discussed in §S5.1 of *Szulczewski et al.* [2012]). In particular, we compare the effectiveness of solubility trapping from convective dissolution with that of residual trapping due to imbibition at the back end of the CO₂ plume [*Juanes et al.*, 2006].

[20] We assume that 10 Gt of CO₂ is injected uniformly along a linear, 200 km array of wells, and we model the evolution of the planar cross-section of the resulting current. Using parameters from *Szulczewski et al.* [2012, Table S2],



Figure 4. We use the model to examine the impact of residual and solubility trapping as a function of slope. We consider a buoyant current of CO_2 in the Mt. Simon sandstone and plot the lifetime of the buoyant current against its maximum migration distance for slopes ranging from $\vartheta = 0$ (horizontal) to 2°. Slope increases along each curve in the direction of the arrow. The actual slope of the Mt. Simon sandstone, about 0.5°, is indicated on each curve by an open circle.

we estimate $\mathcal{M} \approx 13$, $N_d \approx 3.7 \times 10^{-6}$, and $N_s \approx 0$ to 0.078 for angles ranging from 0 to 2° (see supporting information). This viscosity contrast is smaller than the value in our experiments (≈ 48) but still much larger than 1 since CO₂ is much less viscous than groundwater—as a result, the buoyant current will have a similar shape, propagating up-slope in a thin layer. This value of N_d is nearly 2 orders of magnitude smaller than the value in our experiments ($\approx 2 \times 10^{-4}$), meaning that convective dissolution is much weaker in this field case. This range of values of N_s is very similar to the range in our experiments (≈ 0 to 0.3).

[21] As measures of trapping effectiveness, we consider the lifetime of the current (i.e., the time when all of the CO₂ is trapped) and the maximum migration distance. We measure these quantities for the scenario above as functions of the slope ϑ for solubility trapping alone, for residual trapping alone, and for both mechanisms together (Figure 4). We use a residual trapping number of $\Gamma \approx 0.2$, a conservative value [*Szulczewski et al.*, 2012, §5].

[22] With solubility trapping alone, the buoyant current is arrested more quickly but travels much further as the slope increases. The lifetime decreases because the current stretches more quickly as it migrates [*Hesse et al.*, 2008], increasing CO₂-groundwater interfacial area and promoting convective dissolution [*MacMinn et al.*, 2011]. The migration distance increases because the current migrates more quickly as the slope increases [*Hesse et al.*, 2008], traveling further even in less time. With residual trapping alone, both the lifetime of the current and its migration distance decrease as the slope increases. This is because residual trapping is driven by migration [*Hesse et al.*, 2008; *Juanes et al.*, 2010]. As a result, residual trapping is not effective when the slope is small.

[23] The combination of residual and solubility trapping always traps the CO_2 much more effectively than either mechanism alone. This is because the two mechanisms complement one another: residual trapping effectively traps CO_2 at the back end of the plume, whereas solubility trapping effectively dissolves away the long, thin leading edge.

[24] Although we have focused here on the impact of slope, other parameters (*e.g.*, \mathcal{M} , N_d , and Γ) also have important quantitative impacts on trapping efficiency [*MacMinn et al.*, 2011]. However, these do not change the qualitative trends discussed here.

6. Conclusions

[25] Using laboratory analog experiments, we have demonstrated that convective dissolution can arrest the upslope migration of a buoyant current. We have shown that a simple theoretical model captures the macroscopic impact of convective dissolution on the migrating current, and we have used this model to study the effectiveness of convective dissolution as a trapping mechanism in sloping aquifers at the geologic scale.

[26] We found that a small amount of slope is beneficial relative to a horizontal aquifer, leading to a sharp decrease in the lifetime of a buoyant current with only a small increase in the maximum migration distance. Larger slopes lead to much larger migration distances with only small decreases in lifetime, but residual trapping provides a strong complement to convective dissolution as the amount of slope increases.

[27] In many aquifers, the effectiveness of convective dissolution will be limited by the accumulation of dissolved CO_2 in the groundwater near the current [*MacMinn et al.*, 2011, 2012]. This did not play an important role in the scenarios considered here, but we expect the benefit of a small slope to be even stronger in such aquifers since up-slope migration exposes the current to fresh water.

[28] Acknowledgments. This work was funded by the U.S. Department of Energy (grants DE-SC0003907 and DE-FE0002041) and the MIT/Masdar Institute Program. Additional funding was provided by a Martin Fellowship for Sustainability and a Yale Climate & Energy Institute Postdoctoral Fellowship (to C.W.M.).

[29] The Editor thanks Diogo Bolster and an anonymous reviewer for their assistance in evaluating this paper.

References

- Bachu, S., W. D. Gunter, and E. H. Perkins (1994), Aquifer disposal of CO₂: Hydrodynamic and mineral trapping, *Energy Convers. Manage.*, 35(4), 269–279.
- Backhaus, S., K. Turitsyn, and R. E. Ecke (2011), Convective instability and mass transport of diffusion layers in a Hele-Shaw geometry, *Phys. Rev. Lett.*, 106(10), 104501.
- Ennis-King, J., I. Preston, and L. Paterson (2005), Onset of convection in anisotropic porous media subject to a rapid change in boundary conditions, *Phys. Fluids*, 17, 084107.
- Gasda, S. E., J. M. Nordbotten, and M. A. Celia (2011), Vertically-averaged approaches for CO₂ migration with solubility trapping, *Water Resour*. *Res.*, 47, W05528.
- Hesse, M. A., F. M. Orr Jr., and H. A. Tchelepi (2008), Gravity currents with residual trapping, J. Fluid Mech., 611, 35–60.
- Hidalgo, J., and J. Carrera (2009), Effect of dispersion on the onset of convection during CO₂ sequestration, J. Fluid Mech., 640, 441–452.
- Hidalgo, J. J., J. Fe, L. Cueto-Felgueroso, and R. Juanes (2012), Scaling of convective mixing in porous media, *Phys. Rev. Lett.*, 109(26), 264503.
- IPCC (2005), Special Report on Carbon Dioxide Capture and Storage Metz, B., et al. (eds), Cambridge University Press, New York.
- Juanes, R., E. J. Spiteri, F. M. Orr Jr., and M. J. Blunt (2006), Impact of relative permeability hysteresis on geological CO₂ storage, *Water Resour*. *Res.*, 42, W12418.
- Juanes, R., C. W. MacMinn, and M. L. Szulczewski (2010), The footprint of the CO₂ plume during carbon dioxide storage in saline aquifers: Storage efficiency for capillary trapping at the basin scale, *Transp. Porous Media*, 82(1), 19–30.

- Kneafsey, T. J., and K. Pruess (2010), Laboratory flow experiments for visualizing carbon dioxide-induced, density-driven brine convection, *Transp. Porous Media*, 82(1), 123–139.
- Lindeberg, E., and D. Wessel-Berg (1997), Vertical convection in an aquifer column under a gas cap of CO₂, *Energy Convers. Manage.*, *38*, S229–S234.
- MacMinn, C. W., M. L. Szulczewski, and R. Juanes (2011), CO₂ migration in saline aquifers. Part 2. Capillary and solubility trapping, J. Fluid Mech., 688, 321–351.
- MacMinn, C. W., J. A. Neufeld, M. A. Hesse, and H. E. Huppert (2012), Spreading and convective dissolution of carbon dioxide in vertically confined, horizontal aquifers, *Water Resour. Res.*, 48, W11516.
- Neufeld, J. A., M. A. Hesse, A. Riaz, M. A. Hallworth, H. A. Tchelepi, and H. E. Huppert (2010), Convective dissolution of carbon dioxide in saline aquifers, *Geophys. Res. Lett.*, 37, L22404.
- Orr Jr., F. M. (2009), Onshore geologic storage of CO₂, *Science*, 325(5948), 1656–1658.
- Pau, G. S. H., J. B. Bell, K. Pruess, A. S. Almgren, M. J. Lijewski, and K. Zhang (2010), High-resolution simulation and characterization of density-driven flow in CO₂ storage in saline aquifers, *Adv. Water Res.*, 33(4), 443–455.

- Pritchard, D., A. W. Woods, and A. J. Hogg (2001), On the slow draining of a gravity current moving through a layered permeable medium, *J. Fluid Mech.*, 444, 23–47.
- Pruess, K., and J. Nordbotten (2011), Numerical simulation studies of the long-term evolution of a CO₂ plume in a saline aquifer with a sloping caprock, *Transp. Porous Media*, 90(1), 135–151.
- Riaz, A., M. Hesse, H. A. Tchelepi, and F. M. Orr Jr. (2006), Onset of convection in a gravitationally unstable diffusive boundary layer in porous media, J. Fluid Mech., 548, 87–111.
- Slim, A. C., and T. S. Ramakrishnan (2010), Onset and cessation of timedependent, dissolution-driven convection in porous media, *Phys. Fluids*, 22(12), 124103.
- Slim, A. C., M. M. Bandi, J. C. Miller, and L. Mahadevan (2013), Dissolution-driven convection in a Hele-Shaw cell, *Phys. Fluids*, 25, 024101.
- Szulczewski, M. L., C. W. MacMinn, H. J. Herzog, and R. Juanes (2012), Lifetime of carbon capture and storage as a climate-change mitigation technology, *Proc. Natl. Acad. Sci. U.S.A.*, 109(14), 5185–5189.
- Weir, G. J., S. P. White, and W. M. Kissling (1996), Reservoir storage and containment of greenhouse gases, *Transp. Porous Media*, 23(1), 37–60.