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Mixing Dynamics and Flow Topology in Heterogeneous Porous Media

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We study the mixing behavior of a dissolved substance in a Darcy scale heterogeneous porous medium. Flow heterogeneity is induced by spatially variable hydraulic conductivity. The fundamental mechanism governing the mixing dynamics are the competition of stretching and compression of a material element as well as local shear on one hand, and diffusion on the other. In order to quantify these mechanisms and relate them to the flow heterogeneity, we study the evolution of a solute that evolves from an initial distribution that is small compared to the characteristic heterogeneity scale. Our focus is to investigate how the kinematical and topological properties of the flow field enhance mixing of the solute cloud with the surrounding fluid. To this end, we formulate the transport problem in a Lagrangian framework and relate the particle dynamics explicitly to the Lagrangian deformation of fluid elements, and thus to the topology of the flow field. For high Peclet numbers, the solute evolution can be characterized by the time series of Lagrangian stretching and shear rates in the coordinate system of the material element. These processes are quantified by stochastic evolution equations, and linked to the topology of the flow field. We derive a predictive framework for the evolution of mixing, and evaluate the mixing efficiency for different flow topologies.