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Assessing the impact of vertical mixing and dilution in plume-discharge mCDR interventions via 1D semi-analytic model

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To optimize the efficiency of mCDR interventions, it is assumed imperative that the perturbed water mass maintain contact with the atmosphere for as long as possible. However, the effect of dilution associated with the release of the perturbation and the subsequent impact of vertical mixing remain underappreciated. We explore the effect of variable vertical mixing and dilution on plume-discharge marine carbon dioxide removal (mCDR) interventions using a novel, semi-analytical 1D model. The perturbation introduced by an arbitrary plume-discharge intervention is represented by a three-layer system, consisting of a surface effluent layer of prescribed depth and dilution ratio, a mixed layer of prescribed depth and vertical eddy diffusivity, and an infinite ocean interior. We model the exchange of carbon dioxide with the atmosphere and the turbulent diffusion of TA and DIC through the water column under a range of scenarios. This setup provides a cost-effective model which enables parameter sweeps for understanding the system's sensitivity to different variables. Through analogy with the well-studied fields of heat- and mass-transfer, an insightful nondimensional parameter is derived and shown to govern the efficiency of such plume-discharge mCDR interventions. The nondimensional analysis identifies the leading-order parameters and their relative impacts on intervention efficiency. The results from numerical experiments using the 1D model illustrate that variability in the near-field conditions generates strong feedback into efficiency at long timescales, underpinning the importance of near-field observations of the intervention and surrounding waters to achieve accurate estimation of carbon drawdown using regional models.