Detection and Attribution of Carbon Removal via Large-Scale Ocean Iron Fertilization in Emission-Driven Simulations

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Marine Carbon Dioxide Removal (mCDR) strategies such as large-scale ocean iron fertilization (OIF) are being evaluated for their potential to reduce atmospheric CO2 concentrations. However, assessing their efficacy requires distinguishing the mCDR-induced carbon removal signal from the background variability of the coupled climate-carbon system. In this study, we use the fully coupled Earth system model, GFDL-ESM4.1, under emission-driven simulations, we investigate the detectability and attribution of atmospheric CO_2 removal resulting from large-scale iron fertilization across multiple ocean basins. Our results show that the carbon removal signal must exceed the internal variability of the Earth system, which includes both the natural variability of the land carbon system and the carbon-climate feedback. Among the regions studied, only the southern sector of the Southern Ocean exhibits a statistically significant and detectable reduction in atmospheric CO_2 attributable to iron fertilization. In contrast, other fertilized regions, including the North Pacific, Equatorial Pacific, and Atlantic sector of the Southern Ocean, show insignificant CO_2 removal signals that are not consistent with fertilization-induced ocean carbon uptake and largely obscured by decadal-scale variability due to the terrestrial carbon cycle. These findings underscore the importance of using fully coupled, emission-driven simulations to rigorously assess the detectability of mCDR strategies. Attribution of mCDR efficacy at the global scale cannot rely on simplified or concentration-driven scenarios, as they underestimate the role of feedbacks and natural variability. Our study

highlights the critical need for robust detection frameworks when evaluating geoengineering interventions in the Earth system.