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Recovery processes in coastal wind farms

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Wind turbines in a wind farm extract energy from the atmospheric flow and convert it into electricity, resulting in a localized momentum deficit in the wake that reduces energy availability for downwind turbines. Atmospheric momentum convergence from above, below, and sides into the wakes replenish the lost momentum, at least partially, so that turbines deep inside a wind farm can continue to function. In this study, we explore recovery processes in hypothetical offshore wind farms with particular emphasis on comparing the spatial patterns and magnitudes of horizontal and vertical recovery processes and understanding the role of mesoscale phenomena like sea breezes in momentum recovery in wind farms.

For this study, we use the Weather Research and Forecasting (WRF) model, a state-of-the-art mesoscale model equipped with a wind turbine parameterization, to simulate deep offshore and coastal wind farms with different wind turbine spacings under realistic initial and boundary conditions. The wind farms consist of 10000 turbines rated 3 MW spread over a 50 km x 50 km area. We conduct experiments with various background conditions, including low wind, high wind, and sea breeze cases identified using Borne's method.

Results show that for deep offshore wind farms, power generation peaks at the upwind edge and monotonically decreases downwind into the interior due to cumulative wake effects of multiple rows of turbines. Vertical turbulent transport of momentum from aloft is the main contributor to recovery except in cases with strong background winds and high inter-turbine spacing where horizontal advective momentum transport can also contribute equally. Coastal wind farms behave similarly in the absence of sea-breezes. However, under sea breeze conditions, the power production is high at the upwind edge and decreases thereafter but starts to increase again towards the downwind edge of the wind farm because of the sea breeze. The results further show that the contribution of horizontal (vertical) recovery in case of sea breeze conditions increases (decreases) to around 14% (86%) as compared to the non-sea breeze conditions where the horizontal (vertical) recovery contributes 9% (90%) to the momentum recovery in the wind farms. Vertical recovery shows a systematic dependence on wind farm density and wind speed. This relationship can be quantified using low-order empirical equations that can perhaps be used to develop parameterizations for replenishment in linear wake models. Overall, this study is likely to significantly advance our understanding of recovery processes in wind farms and wind farm-ABL interactions.