Deeper Dive: Ocean Hydrodynamics, Offshore Wind Farms, and the Mid-Atlantic Bight Cold Pool

Ocean hydrodynamics (the scientific study of the motion of liquids) consists of a complex system of currents, occurring both in the surface waters of the first few hundred meters of the ocean and in the deeper waters below. The upper surface of the ocean is characterized by wind driven currents, where ocean water is pushed by moving air masses. Deep ocean circulation is referred to as “thermohaline circulation”, as it is largely dictated by the temperature (“thermos”) and salinity (“haline”) of sea water. Less dense, warmer water flows towards the surface, while denser, colder water sinks. Both current systems are driven by differences in air or water temperature on regional and global scales. As climate change continues to cause global temperatures to rise, these currents may change, which will have repercussions on weather patterns across the planet.

The installation and operation of wind turbines in the offshore environment can modify small-scale atmospheric and oceanographic processes associated with hydrodynamic circulation. These modifications can be localized immediately around a wind turbine or spread well beyond the boundaries of wind farms (Christiansen et al., 2022; Daewel et al., 2022; Dorrell et al., 2022; Schultze et al., 2020). The localized removal of kinetic energy from the atmosphere by wind turbines leads to a reduction in mean wind speed on the leeward side of the turbines, creating atmospheric wakes (also referred to as wind wakes) (Akhtar et al., 2021). Given the decreased wind speeds associated with these atmospheric wakes, wind-driven turbulent mixing at the ocean surface may also be reduced. This impact on wind-driven turbulent mixing can reduce gas exchange, vertical mixing, and heat flux, all of which can lead to decreased phytoplankton productivity. The effect of atmospheric wakes on sea surface boundary processes (e.g., vertical mixing, heat flux) can vary depending on localized atmospheric stability, water depth, and the strength of water column stratification (Christiansen et al., 2022); thus, in some areas, atmospheric wakes may have little effect on surface water dynamics or productivity. In the case of taller turbines, the wind wake may be elevated too high above the ocean surface to reduce wind driven mixing at all (Golbazi et al., 2022).

The introduction of offshore wind infrastructure into the open waters of the continental shelf can also lead to localized changes in water flow. The presence of structures in the water can enhance water column mixing in the downstream direction of turbine substructures through the creation of turbulent wakes (also referred to as ocean wakes) (Dorrell et al., 2022; Schultze et al., 2020). As ocean currents flow past a wind turbine foundation, small-scale turbulence is produced, causing mixing in the vertical direction (Schultze et al., 2020). The amount of vertical mixing resulting from turbulent wakes is dependent on the type of foundation installed and other site-specific conditions (Dorrell et al., 2022).

Seasonal phytoplankton production is primarily controlled by water column stratification (the formation of layers of water masses with different properties that act as barriers to water mixing) and light intensity. Ocean stratification weakens with the cooler temperatures of winter in the northern hemisphere, allowing deeper nutrient-rich waters to mix into the photic zone (nearest the surface of the ocean). This influx of nutrients stimulates phytoplankton blooms in the spring due to the increased sunlight and temperature. By the summer, when water temperature at the surface reaches its highest, the water column is stratified again, and nutrient mixing is reduced. In the waters of the Mid-Atlantic Bight, seasonal stratification creates a phenomenon known as the Cold Pool. In the spring, cold glacial water from the arctic moves southward. This water gathers below the warm, sun-heated surface waters and continues to move southward before stratification is broken in the fall and winter (Lentz, 2017).

In the case of offshore wind, enhanced vertical mixing caused by the turbulent wakes of offshore wind turbine foundations can cause localized increases in phytoplankton activity (Figure 1) and corresponding ecosystem effects (Dorrell et al., 2022). While turbulent wake effects have been observed within a few hundred meters of wind turbine structures (Schultze et al., 2020), atmospheric wakes in North Sea wind farms were found to affect a sea surface area within tens of kilometers (Platis et al., 2018; Akhtar et al., 2021). The reduction in wind-driven current velocities may change water column stratification intensity and reduce circulation over these larger areas, which subsequently could alter primary production, trophic dynamics, and ecosystem functioning (Daewel et al., 2022).

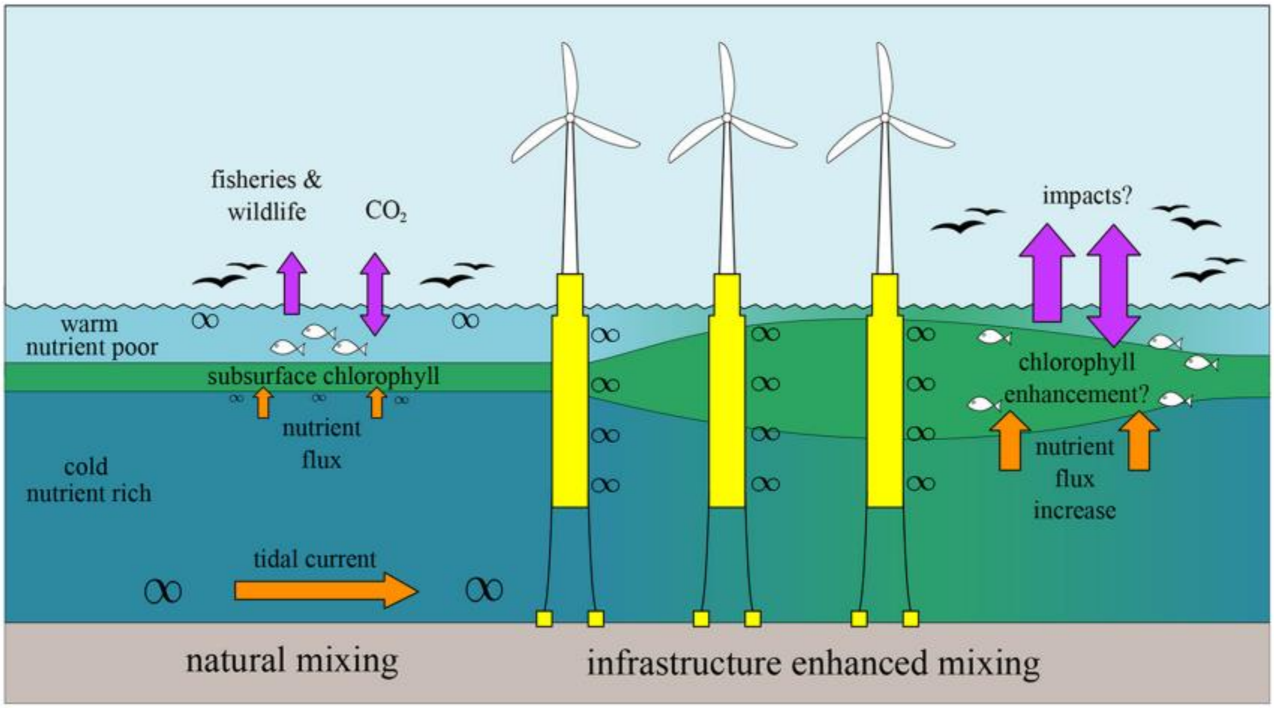

Figure 1. Potential ecological effects of turbulent wakes from offshore wind infrastructure (Dorrell et al., 2022).

Ocean circulation patterns are influenced by several factors, including wind stress at the sea surface. While the atmospheric wake produced by a single offshore wind turbine is unlikely to affect wind-driven ocean circulation, the cumulative atmospheric wake produced by an offshore wind farm array can be significant enough (National Academies of Sciences, Engineering, and Medicine [NASEM], 2023). By inducing large-scale atmospheric wakes above the water and smaller-scale structural wakes below the water, offshore wind farms have the potential to alter the distribution of planktonic organisms that serve as prey for higher trophic levels (Floeter et al., 2017) and alter larval dispersal patterns (Johnson et al., 2021). Floeter et al. (2017) found evidence that an offshore wind farm in the North Sea with 80 wind turbine foundations could decrease water column stratification within the wind farm and surrounding area, thus leading to increased nutrient levels and phytoplankton concentrations (i.e., increased primary production). High densities of meroplankton (i.e., planktonic larval stages of benthic organisms) were also found at the boundaries of the offshore wind farms indicating favorable conditions to support these benthic species. However, stratification off the U.S. Mid-Atlantic coast in the summer is much stronger than in the North Sea, and thus may be more resilient to influences of atmospheric and structural wakes from wind farm structures. That said, it is still unclear how the presence of wind farms would impact the setup of the Cold Pool in spring and its breakdown in the fall (Miles et al., 2021). A hydrodynamic modeling study, within the southern New England lease areas, investigating the effect of offshore wind farm structures on larval dispersal found that wind farm structures reduce current speeds and lead to shifts in larval settlement locations (Johnson et al., 2021). However, results from this study were season-, species-, and region-specific. Further research on a multi-year time frame with different species, locations, and offshore wind development scenarios were suggested to better understand long-term structural shifts in larval dispersal and settlement patterns (Johnson et al., 2021).

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