ZOOPLANKTON AND OFFSHORE WIND
DRIFTERS IN A SEA OF UNCERTAINTY

By Grace K. Saba

Scientists are often tasked with addressing challenging, seemingly impossible questions. An example is the recent Consensus Study Report (NASEM, 2024a)—summarized by Hoffman et al. (2025, in this issue)—asking: "How will potential offshore wind-induced changes in ocean physical dynamics affect the North Atlantic right whale in the Nantucket Shoals region?" Most concerns about potential direct impacts of offshore wind farms (OSW) on the North Atlantic right whale (NARW) focus on noise interference and higher vessel activity increasing the risk of vessel strikes. The impact of OSW on ocean physics or hydrodynamics and subsequently NARWs is more difficult to gauge because the effects are indirect and likely highly variable. We do not yet know enough to accurately predict when and where zooplankton will aggregate at concentrations that support NARW foraging and success. Additionally, the underlying confounding challenge is how to decipher turbine-induced hydrodynamic changes relative to the background of extremely high spatiotemporal variability in oceanographic conditions and zooplankton dynamics in the Nantucket Shoals region. When posed as a modified question—"How will potential OSW-induced changes in ocean physical dynamics affect *zooplankton* in the Nantucket Shoals region?"—a variety of scenarios come to mind along with three questions that need to be addressed in order to move closer to understanding whether and how OSW may impact zooplankton.

WHAT CONTROLS ZOOPLANKTON SUPPLY AND THE FORMATION OF AGGREGATIONS AT LEVELS SUFFICIENT FOR NARW FEEDING?

The number of NARWs in the Nantucket Shoals region has increased over the past decade, and although their peak foraging occurs during the winter and spring seasons, their presence has been observed year-round (Quintana-Rizzo et al., 2021). Successful NARW foraging requires an adequate supply and concentration of zooplankton (10^3–10^4 individuals m^{-3}; Baumgartner and Mate, 2003) as well as mechanisms that produce high-density aggregations at 100–1,000 m spatial scales (Sorochan et al., 2021), which coincidentally match those of potential single turbine impacts. Coastal currents from the Gulf of Maine and the Great South Channel control the supply of NARWs' primary prey, late stages of *Calanus finmarchicus*, to Nantucket Shoals, while alternative copepod prey species (*Centropages* spp., *Pseudocalanus* spp. *Paracalanus* spp., *Oithona similis*) occur year-round with relatively different times of peak abundance (Sorochan et al., 2021). We do not yet fully understand the specific mechanism(s) that facilitate the production of high-density zooplankton layers and aggregations in and around Nantucket Shoals, as simultaneous NARW sightings and copepod aggregations have not been observed at either tidal mixing fronts or in a locally persistent wintertime upwelling gyre (Leiter et al., 2017; Sorochan et al., 2021). The interactions between source and advective supply, behavior (e.g., vertical migration), ontogenetic cycles, food availability and distribution, and ocean physical conditions that regulate these variables likely influence zooplankton aggregation in the Nantucket Shoals region. These dynamics are likely species-specific. Therefore, observational studies in this region need to focus on determining which prey species NARWs are targeting and on collecting high-resolution spatiotemporal observations of concurrent physical oceanographic properties, copepod species distributions and aggregation dynamics, and NARW presence.

HOW MIGHT OSW AFFECT ZOOPLANKTON ABUNDANCE AND AGGREGATION POTENTIAL?

A severe lack of observational data means that we do not know the potential turbine-induced downstream and surrounding increased turbulence and wake effects at scales of 0.1–1.0 km. This could lead to, or alternate between, different scenarios of OSW acting on zooplankton that are dependent on seasonal ocean physical structure, circulation patterns, biological processes, and highly variable wind, current, mixing, and tidal dynamics. An added layer of complexity is that different zooplankton species may respond differently to hydrodynamic changes due to variable behaviors, preferred food resources, and seasonal cycles.

Five possible scenarios are outlined here. One scenario is that there is no overall effect; **Figure 1** depicts the remaining four. Scenario A would act to disperse surface zooplankton aggregations and potentially those in diapause at depth (Incze et al., 2001). Whether this scenario could negatively change zooplankton availability and aggregations at a level that would impact NARW foraging is an open question. This scenario may be of most relevance to NARW ecology because it encompasses the timeframe when NARW are most abundant and actively foraging in Nantucket Shoals waters. In Scenario B, OSW effects are strong enough to slightly disrupt stratification, permitting nutrient injection upward into the surface layer, but not strong enough to break down stratification and disperse aggregating zooplankton. These higher nutrient conditions could enhance primary production and therefore zooplankton (Carpenter et al., 2016; Floeter et al., 2017). Scenario C would destabilize stratification (Carpenter et al., 2016; Miles et al., 2017), which could potentially disperse zooplankton aggregations similarly to Scenario A. However, current velocities would need to be high enough, and stratification weak enough, for OSW-induced turbulence to break down stratification (Carpenter et al., 2016) and negatively impact zooplankton aggregations. Scenario D involves a more biological mechanism whereby high colonization and abundances of filter feeding invertebrates (e.g., mussels) on turbine structures facilitate a top-down decrease in zooplankton abundance (Perry and Heyman, 2020). Although this scenario is independent of season, different physical conditions and levels of turbulence will create variable encounter rates and interaction times between sessile predators and zooplankton prey (Prairie et al., 2012).

At the wind farm scale (10–100 km), cumulative impacts of multiple turbines may act to reduce surface current speeds and stratification and create horizontal shear-induced upwelling and downwelling dipoles that could differentially aggregate or disaggregate zooplankton (Carpenter et al., 2016; Sorochan et al., 2021; Christiansen et al., 2023). Evaluating wind farm-scale impacts on oceanographic and zooplankton dynamics will be more difficult to isolate from regional high natural environmental variability.

ARE THESE POTENTIAL OSW IMPACTS ON ZOOPLANKTON GREATER THAN NATURAL PROCESSES THAT DRIVE A RANGE OF SCALES OF SPATIOTEMPORAL VARIABILITY?

Oceanographic conditions on Nantucket Shoals and on the broader US Northeast shelf are subject to high daily to decadal variability, driven by local wind conditions, tidal forcing, storm

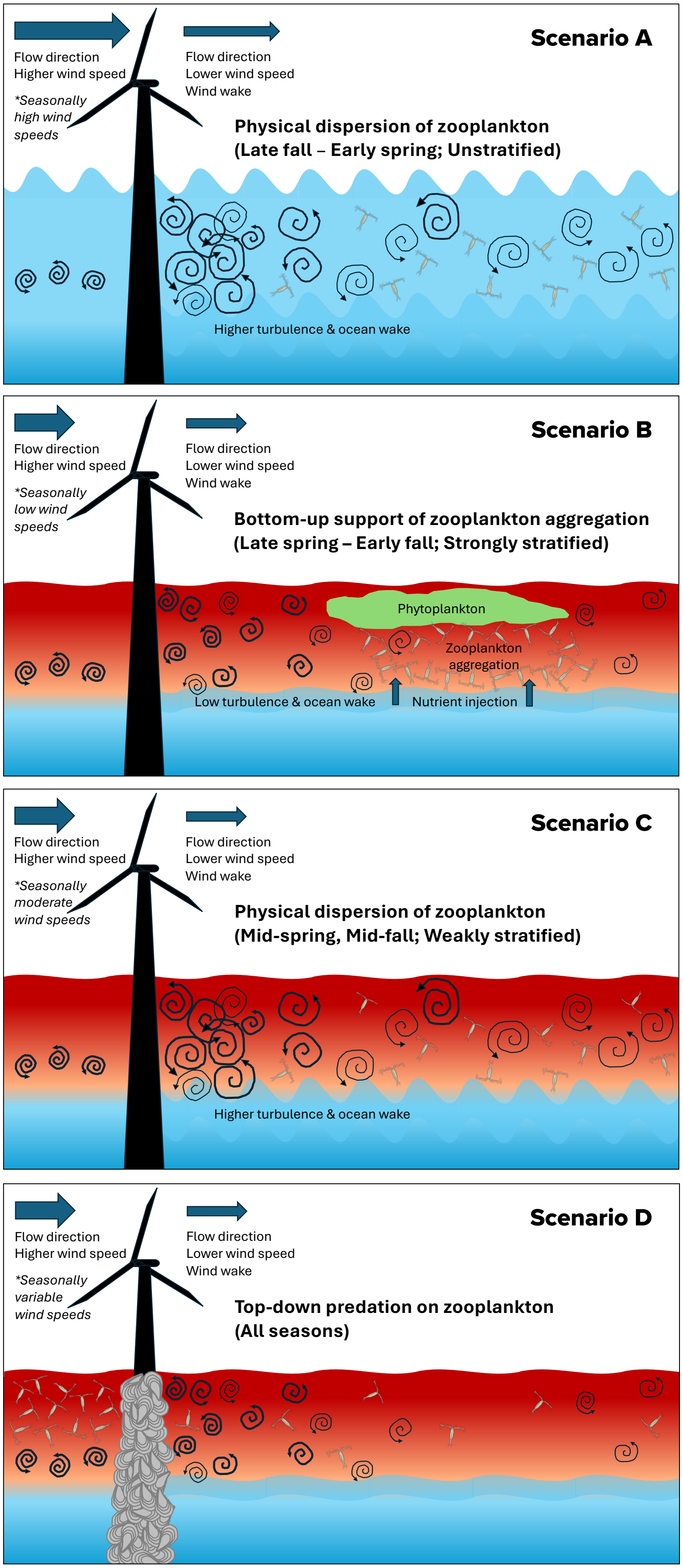

FIGURE 1. Four potential scenarios of offshore wind turbulence and wake effects on zooplankton in Nantucket Shoals waters.

activity, and fluctuations in large-scale circulation (summarized in NASEM, 2024a). Furthermore, increased frequency of mid-water salt intrusions into shelf waters has been associated with recent warming, an inshore movement of the shelf-break front, and changes in water column structure (Harden et al., 2020; Gawarkiewicz et al., 2022). Zooplankton abundance and distribution follow similar trends of variability, leading to spatiotemporal fluctuations in NARW foraging habitat, including warming-associated declines in *C. finmarchicus* and *Pseudocalanus* spp. (Record et al., 2019).

Given the significant uncertainty outlined here, the initial question really should be *how* do we determine if OSW will affect zooplankton and NARW in the Nantucket Shoals region? Luckily, as Hoffman et al. (2025, in this issue) indicate, the community now has some guidance through the recently released workshop proceedings, *Nantucket Shoals Wind Farm Field Monitoring Program* (NASEM, 2024b). Isolating OSW impacts from natural variability will require monitoring and modeling studies designed to target specific impacts at relevant scales with sufficient resolution. Localized field efforts should sample along a gradient inside and outside OSW fields or include "control" areas outside of OSW areas, before, during, and after construction. Monitoring should also include simultaneous physical and biological observations at both the turbine and wind farm area scale as well as repetition during variable oceanographic conditions.

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