FROM WIND TO WHALES

POTENTIAL HYDRODYNAMIC IMPACTS OF OFFSHORE WIND ENERGY ON NANTUCKET SHOALS REGIONAL ECOLOGY

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ABSTRACT. The National Academy of Sciences, Engineering, and Medicine convened a committee in June 2023 to assess the potential hydrodynamic and ecological impacts from offshore wind energy development in the Nantucket Shoals region, with particular attention to impacts on the critically endangered North Atlantic right whale (*Eubalaena glacialis*) that forages on zooplankton aggregations in the region. The assessment suggested that the effects of offshore wind energy development will be difficult to distinguish from the effects of natural variability and climate change in this region. The Consensus Study Report recommendations highlight observational and modeling studies that will advance understanding of potential hydrodynamic effects and impacts on the ecology of the region. A subsequent workshop provided guidance on observational needs and approaches for a field monitoring program to advance model capability to simulate effects of offshore wind energy development on Nantucket Shoals hydrodynamics and ecology. Observational and modeling programs implemented for the Nantucket Shoals region will inform other regions of the US East Coast continental shelf that have been designated for offshore wind energy development.

WIND TO WHALES: CONSENSUS STUDY SUMMARY

Large-scale offshore wind farm development is planned and partially underway for US continental shelf waters. The potential oceanographic impacts from this development remain as open questions. The Nantucket Shoals region on the US continental shelf off the coast of Massachusetts is one area designated for wind farm development (Figure 1a,b). The oceanography of this region is complex (Figure 1c), and warming water temperatures in the North Atlantic, marine heatwaves, and Gulf Stream variability are enhancing and changing the natural oceanographic variability of this region, as summarized in the accompanying Perspective (Gawarkiewicz, 2025, in this issue). The addition of extensive wind farms composed of many individual turbines is anticipated to impose additional oceanographic variability that may change the hydrodynamic environment through flow past turbine structures and removal of wind energy (Figure 1d). This additional variability potentially affects hydrodynamic processes at scales ranging from individual turbines to wind farms to regional (Figure 1; Gawarkiewicz, 2025, in this issue). Separating the effects of wind energy installations from natural hydrodynamic variability presents new challenges for the oceanographic observing and modeling communities.

Changes in hydrodynamic processes can also affect phytoplankton and zooplankton production, distribution, and availability, with consequences for higher trophic level organisms (Figure 1d). Of particular concern for the Nantucket Shoals region are hydrodynamic changes that may affect the distribution and availability of zooplankton species, especially the copepods (e.g., *Calanus finmarchicus*, *Centropages* spp., *Oithonia similis*), that are primary prey for the critically endangered North Atlantic right whale (*Eubalaena glacialis*) that forages in the region (Sorochan et al., 2021). As noted in the accompanying Perspective by Saba (2025, in this issue), copepod species are transported from upstream sources by coastal currents into the Nantucket Shoals region where they form dense aggregations that are targeted by right whales. The concern is that hydrodynamic variability resulting from turbines and wind farms may modify these processes, causing disruptions in prey availability for right whales (Saba, 2025, in this issue). However, the advective supply and physical-biological processes that allow dense copepod aggregations to form are not well understood (Saba, 2025, in this issue). The different scenarios presented by Saba (2025, in this issue) suggest that assessing offshore wind energy development effects on Nantucket Shoals ecosystem production will first require identification and quantification of the relevant processes.

Given the concern about potential offshore wind farm effects on hydrodynamics at local to regional ecosystem scales, the Bureau of Ocean Energy Management (BOEM) requested that the National Academies of Science, Engineering, and Medicine evaluate the potential for offshore wind farms in the Nantucket Shoals region to modify area hydrodynamics with impacts on

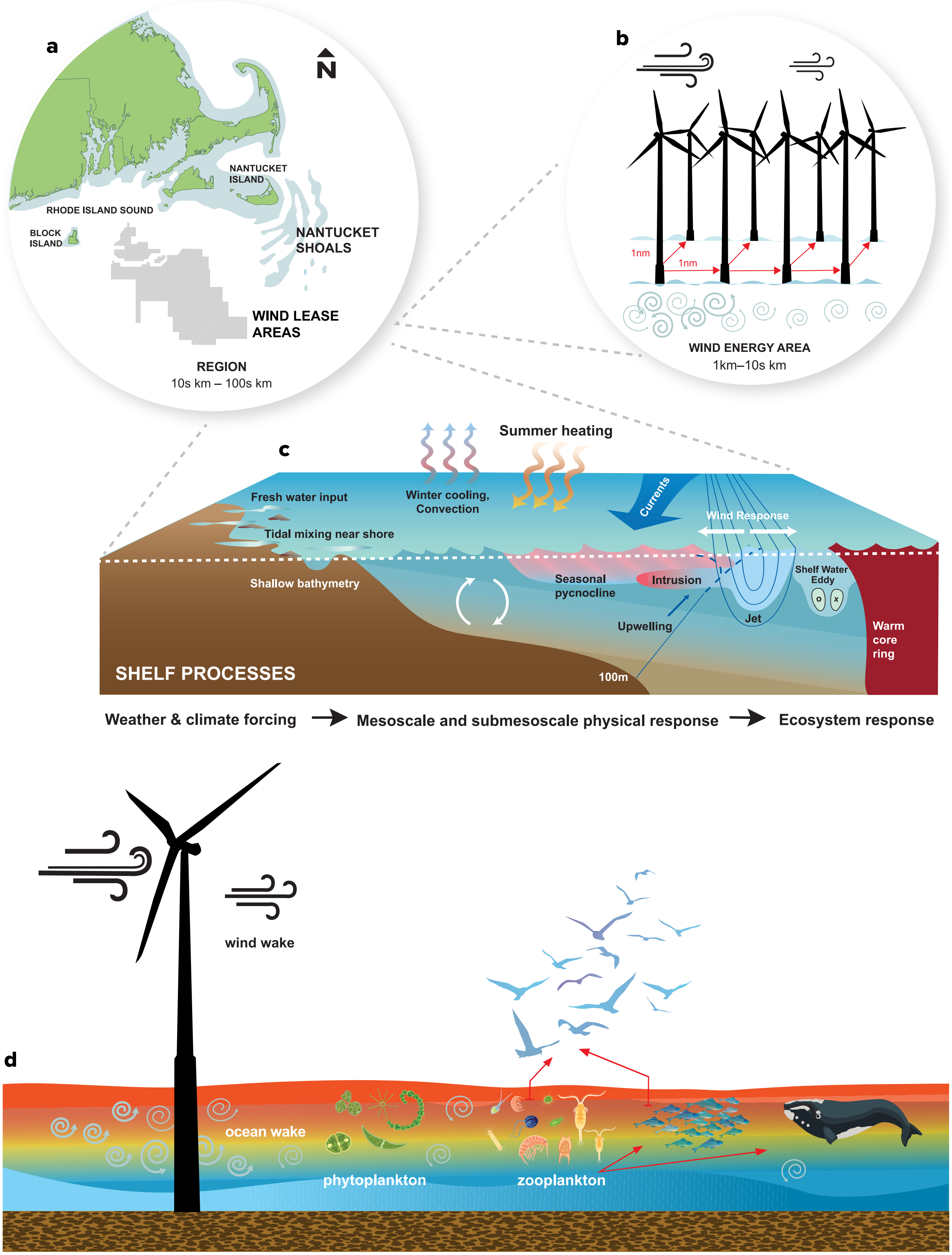

FIGURE 1. (a) Nantucket Shoals region with proposed wind lease areas indicated (gray shading). (b) Offshore wind farm showing potential wind reduction and ocean turbulence effects (swirls) from wind turbine structures. (c) Schematic of oceanographic processes that influence the hydrodynamics of the Nantucket Shoals region (adapted from Gawarkiewicz and Plueddemann, 2020). (d) Schematic of potential wind turbine effects. The wind, blowing from left to right, decreases in energy as it passes the turbine. Ocean circulation, flowing from left to right, becomes more turbulent downstream of the turbine (indicated by swirls) with potential effects on water column stratification (gradient shading with red to blue indicating transition from low-density surface water to more dense water at depth). Ecological effects of a turbine extend from phytoplankton to whales. The turbine, phytoplankton, zooplankton, and higher trophic level organisms are not shown to scale.

the ecology of the region. The Committee on Evaluation of Hydrodynamic Modeling and Implications for Offshore Wind Development: Nantucket Shoals was convened in June 2023. This summary provides the findings and recommendations from the resulting Consensus Study Report (NASEM, 2024a) as well as from a subsequent BOEM-sponsored workshop (NASEM, 2024b). The accompanying Perspectives by Gawarkiewicz (2025) and Saba (2025) provide additional insights about offshore wind energy development in the Nantucket Shoals region.

Evaluation of the understanding of potential hydrodynamic effects of offshore wind farms, based on observations and modeling studies for wind installations in European waters, shows that offshore wind turbines can alter local hydrodynamics by interrupting circulation processes through a wake effect and induce turbulence in the water column surrounding and downstream of the turbine (Figure 1d; e.g., Schultze et al., 2020). Wind speed reduction occurs downstream of the turbines, but its effects on the sea surface are poorly understood (Golbazi et al., 2022). These effects become more complex when extended to arrays of turbines in an offshore wind farm or multiple adjacent wind farms with implications for both local and regional circulation. Evaluation of these complex interactions with hydrodynamic models requires that key processes be included at appropriate spatial and temporal scales. The limited studies to date suggest that the hydrodynamic effects of turbines will be difficult to isolate from the much larger variability introduced by natural and other anthropogenic sources (including climate change; Schultze et al., 2020; Floeter et al., 2017, 2022). These findings support two recommendations for observations and modeling studies for assessing the hydrodynamic impacts of offshore wind energy installations in US continental shelf waters:

- **RECOMMENDATION.** The Bureau of Ocean Energy Management, the National Oceanic Atmospheric Administration, and others should promote, and where possible require, observational studies during all phases of wind energy development—surveying, construction, operation, and decommissioning—that target processes at the relevant turbine-to-wind farm scales to isolate, quantify, and characterize their hydrodynamic effects. Studies at Block Island, Dominion, Vineyard Wind I, and South Fork Wind should be considered as case study sites given their varying numbers of turbines, types of foundations, and sizes and spacing of turbines.
- **RECOMMENDATION.** The Bureau of Ocean Energy Management, the National Oceanic Atmospheric Administration, and others should require model validation studies to determine the capability and appropriateness of a particular model to simulate key baseline hydrodynamic processes relevant at turbine, wind farm, and/or regional scales.

The ecological impacts of offshore wind structures can potentially affect all trophic levels (Figure 1d), and changes in zooplankton production, supply, and aggregation may affect right whales that have been frequently observed feeding in the Nantucket Shoals region and other areas of high productivity in Southern New England waters.

Evaluation of the potential impacts on right whale prey show that the paucity of observations and the uncertainty of modeled hydrodynamic effects make it difficult to assess the ecological impacts of offshore wind farms, particularly considering the scale of both natural and human-caused variability in the Nantucket Shoals region. Studies to date do not have the spatial and temporal coverage at the proposed wind energy lease sites to adequately capture broad-scale right whale use of this region and potential impacts from offshore wind farms. Additionally, foraging by right whales in the region is not fully understood, including the basic question of which zooplankton taxa right whales are feeding on and how this prey changes seasonally. Models are needed that can effectively incorporate the supply and behavior of zooplankton as well as the physical oceanographic processes that aggregate zooplankton in the Nantucket Shoals region.

The impacts of offshore wind projects on the right whale and the availability of its prey in the Nantucket Shoals region will likely be difficult to distinguish from the significant impacts of climate change and other influences on the ecosystem. As planning and construction of wind farms in the Nantucket Shoals region continue, further study and monitoring of the oceanography and ecology of the area are needed to fully understand the impact of future wind farms. Advancing understanding of potential impacts is especially important as right whale use of the region continues to evolve (e.g., O'Brien et al., 2022).

These findings support two recommendations for observations and modeling studies for assessing the ecological impacts of offshore wind energy installations:

- **RECOMMENDATION.** The Bureau of Ocean Energy Management, the National Oceanic Atmospheric Administration, and others should support, and where possible require, the collection of oceanographic and ecological observations through robust integrated monitoring programs within the Nantucket Shoals region and in the region surrounding wind energy areas before and during all phases of wind energy development: surveying, construction, operation, and decommissioning. This is especially important as right whale use of the Nantucket Shoals region continues to evolve due to oceanographic changes and/or the activities and conditions relevant to offshore wind farms.
- **RECOMMENDATION.** The Bureau of Ocean Energy Management, the National Oceanic Atmospheric Administration, and others should support, and where possible require, oceanographic and ecological modeling of the Nantucket Shoals region before and during all phases of wind energy development: surveying, construction, operation, and decommissioning. This critical information will help guide regional policies that protect right whales and improve predictions of ecological impacts from wind development at other lease sites.

Subsequent to the Consensus Study Report, a workshop was convened in July 2024 to design a field monitoring program that would respond to the Consensus Study Report recommendations. The diverse expertise of the workshop participants facilitated discussions of observational needs and approaches for a field monitoring program to advance models developed to assess potential effects of offshore wind energy development on Nantucket Shoals hydrodynamics and ecology (NASEM, 2024b). The workshop proceedings identified for the turbine and wind farm scales (1) parameters that should be measured with a focus on the oceanographic and atmospheric parameters necessary to drive models, and (2) specific components for implementing a field monitoring program to resolve key physical and ecological features and processes to improve understanding of potential effects of offshore wind energy development on Nantucket Shoals ecology, including the right whale. There was agreement that existing monitoring programs provide important information but that coordination within and across these efforts is needed and that models and syntheses of existing data should be used to guide the design of observations and field programs. The workshop discussions pointed to a set of science priorities that respond to the recommendations from the Consensus Study, such as monitoring designed to isolate wind farm impacts from natural and anthropogenic variability and studies to advance understanding of prey aggregation processes. The convening of the workshop was an important step toward identifying resources and a timeline for implementing field and modeling studies that address concerns about the effects of offshore wind energy development in the Nantucket Shoals region.

Although the hydrodynamic effects of offshore wind development on the Nantucket Shoals region ecology are not yet well understood, the current state of knowledge and key directions for advancing this understanding are reflected in the Consensus Study Report (NASEM, 2024a). The Workshop Proceedings (NASEM, 2024b) points to specific observational and modeling activities that could be implemented to begin to address the Consensus Study recommendations. The Perspectives provided by Gawarkiewicz (2025) and Saba (2025) in this issue reinforce the need to advance understanding of the hydrodynamics and ecology of the important Nantucket Shoals region. Observational and modeling approaches developed for Nantucket Shoals will provide a framework for areas along the US East Coast continental shelf that are slated for offshore wind energy development over the next decade. It remains for the oceanographic community to undertake the observational and modeling programs necessary to assess the effects of offshore wind energy development on hydrodynamics and the corresponding impact on ecosystems, and for government agencies and the wind energy industry to provide resources for implementation of these programs.

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