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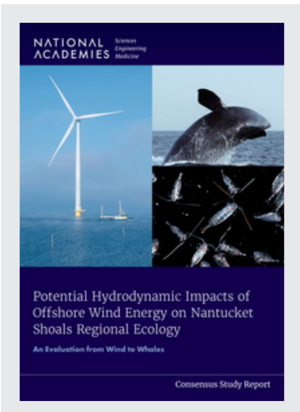

Potential Hydrodynamic Impacts of Offshore Wind Energy on Nantucket Shoals Regional Ecology: An Evaluation from Wind to Whales (2023)

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Committee on Evaluation of Hydrodynamic Modeling and Implications for Offshore Wind Development: Nantucket Shoals

Ocean Studies Board

Division on Earth and Life Studies

Consensus Study Report

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report, nor did they see the final draft before its release. The review of this report was overseen by **RICHARD SEARS**, Stanford University and **KATHERINE FREEMAN**, Penn State University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Preface

The U.S. federal government has set a target of 80 percent renewable energy generation by 2030 and 100 percent carbon-free electricity by 2035. Realizing this goal will require a portfolio of renewable energy sources, one of which is development of a robust offshore wind energy industry in U.S. coastal waters to meet the U.S. target of 30 gigawatts of energy from offshore wind by 2030. Two offshore wind energy farms, with a total of seven wind turbine generators, now operate on the continental shelf of the U.S. East Coast. Plans are underway to expand the number of wind farms in this region by about a factor of 10 and the number of turbines by about two orders of magnitude. The scale of the anticipated expansion of the U.S. offshore wind energy industry has many implications for the coastal environment, one of which is impacts on the oceanography and ecology of the region within and surrounding the wind energy installations.

Beginning in 2009, the Bureau of Ocean Energy Management (BOEM) became responsible for offshore renewable energy (including wind) development in federal waters. The Department of the Interior announced at that time the final regulations for the Outer Continental Shelf Renewable Energy Program, as authorized by the Energy Policy Act of 2005. These regulations, in addition to the National Environmental Policy Act, provide the regulatory framework for the activities supporting the production and transmission of offshore renewable energy.

The Nantucket Shoals region of the U.S. East Coast continental shelf has been designated as a site for expansion of offshore wind energy capability. This region is characterized by complex hydrodynamics and ecology. The hydrodynamics of this region result from processes at spatial scales of variability that extend from oceanic (Gulf Stream warm core rings) to local (tidal mixing) and timescales of seasonal (stratification) to decadal. The ecology of the region is unique in that it supports aggregations of zooplankton that provide prey for the endangered North Atlantic right whales that migrate to the region to forage.

Modeling studies from the North Sea suggest that offshore wind farms can modify the local circulation and ecology with impacts that extend beyond the wind farm region. The extent to which wind energy farms may have similar effects on the hydrodynamics and ecology of the Nantucket Shoals region is of concern because of potential impacts on zooplankton–right whale interactions, a trophic connection not considered in current studies. As such, the charge to this committee was to assess the current state of understanding and the capability to detect impacts of offshore wind farms on the hydrodynamics and ecology of the Nantucket Shoals region.

Support for developing this report was provided by BOEM, and the committee gratefully acknowledges this support. The committee began its work by convening an open community webinar to introduce the committee and its tasks. This was followed by two public meetings to gather information about the current state of knowledge of environmental and ecological aspects of offshore wind energy development and the Nantucket Shoals region. Many individuals generously provided their expertise and time for the public meetings, which is much appreciated given the short notice provided for participating in the meetings. The committee extends its thanks to participants from the federal government, research institutions, private industry, and other stakeholder groups who participated in the public meetings, provided background information, and openly engaged in discussions.

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The committee extends its wholehearted appreciation to the National Academies' staff for providing the organization, support, and direction that made this report possible. The completion of this report in 4 months would not have been possible without the superb efforts of the study director Kelly Oskvig and program assistant Safah Wyne. Their gentle and ongoing guidance is much appreciated.

Offshore wind energy is integral to the future of renewable energy sources. Development of this capability must be such that it preserves the marine environment and its ecosystems and also recognizes changes and variability imposed by climate change. It is the committee's hope that the recommendations in this report be used to stimulate future studies that can answer the questions important for responsible development of offshore wind in the Nantucket Shoals region and elsewhere.

Eileen Hofmann, *Chair*
Evaluation of Hydrodynamic Modeling and Implications for Offshore Wind Development: Nantucket Shoals

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Acronyms and Abbreviations

BOEM	Bureau of Ocean Energy Management
CAST	coastal amplification of supply and transport
DHI-MIKE	Danish Hydraulic Institute water modeling and simulation software
FVCOM	Finite-Volume Community Ocean Model
LES	large eddy simulation
MAB	Mid-Atlantic Bight
MLD	mixed layer depth
NOAA	National Oceanic and Atmospheric Administration
RANS	Reynolds-averaged Navier-Stokes
ROMS	Regional Ocean Modeling System
SST	sea surface temperature
TKE	turbulent kinetic energy
WTG	wind turbine generator
WEA	wind energy area

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Summary

The goal to meet 80 percent of U.S. energy needs with renewable energy generation by 2030 has spurred many efforts to scale up the U.S. portfolio of efficient clean energy resources. One strategy is to build offshore wind farms to serve energy needs along coastlines where more than 40 percent of the U.S. population reside. Although only two offshore wind farms were in operation in U.S. waters as of mid-2023—one offshore Virginia and one offshore Rhode Island—the offshore wind energy industry is expanding rapidly on the Northeast U.S. Continental Shelf, with seven new wind farms in various stages of design and development. The Nantucket Shoals region off the coast of Massachusetts (see Figure S-1) is one of the designated areas for wind farm installation, given that the area has strong but less turbulent winds, shallow waters, and low wave heights, conditions conducive to offshore wind development and operation.

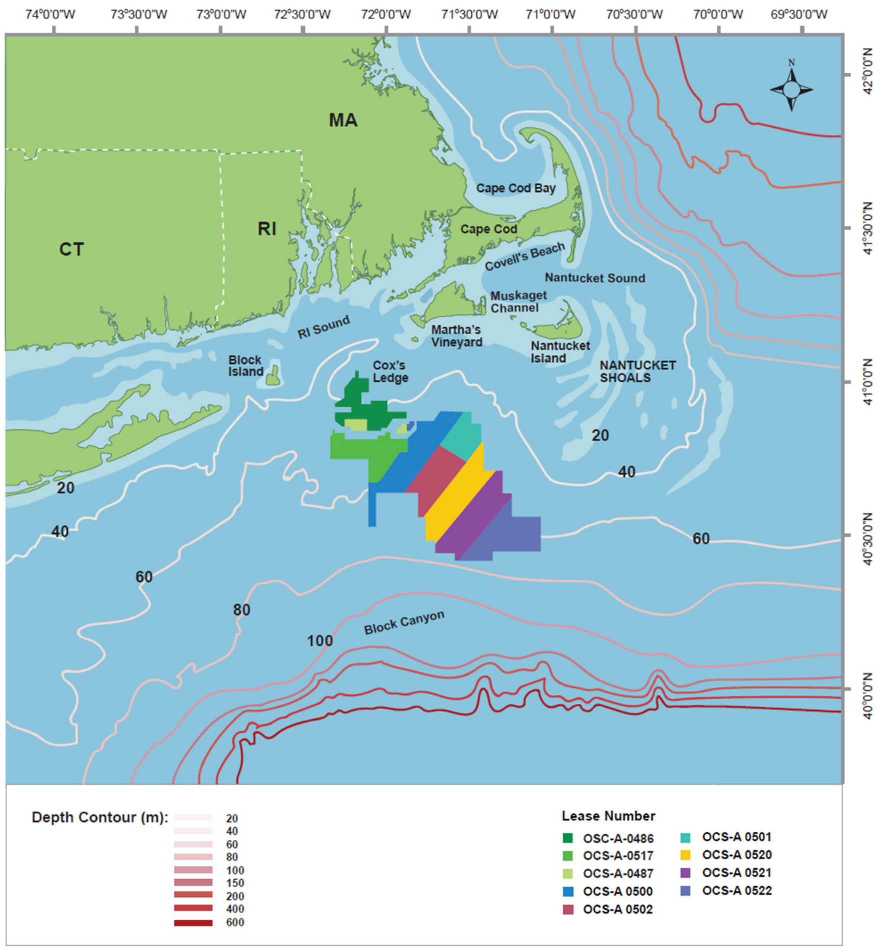

FIGURE S.1 Map of the Nantucket Shoals region showing the wind farm lease areas and bathymetric contours (meters). The lease numbers correspond to BOEM designations.

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As part of the permitting process required to install and operate offshore wind farms, the Bureau of Ocean Energy Management (BOEM) requires assessment of any potential associated ecosystem impacts. To inform its decisions, BOEM requested that the National Academies evaluate the potential for installation and operation of offshore fixed-bottom wind turbine generators to affect physical processes in the Nantucket Shoals region (such as tidal fronts, waves, and currents), and, in turn, how those hydrodynamic alterations might affect ecosystems. Of particular interest to BOEM are the potential effects on zooplankton productivity and aggregations, which may affect foraging for the critically endangered North Atlantic right whale (*Eubalaena glacialis*).

The potential effects of wind turbine generators on the ocean can be due to the physical presence of the structures across the water column and to the effects of wind energy extraction on ocean circulation. A single offshore wind turbine 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 supporting structure, the pile. Moving away from single turbine effects and looking at arrays of turbines in a wind farm or at multiple adjacent offshore wind farms, these effects become more complex with implications for both local and regional circulation. Understanding these hydrodynamic effects is essential to develop predictions of the potential impacts of wind farms on the region's ecosystem, from phytoplankton to marine mammals.

To date, few studies exist to assess the potential hydrodynamic and ecological impacts of offshore wind development, and those that do exist consist of modeling studies with limited observational data developed for wind farms in the North Sea, which have different hydrodynamic and ecosystem characteristics. Based on what is known, the impacts on ecosystems from development and operation of offshore wind may be difficult to distinguish from natural and other anthropogenic variability (including climate change) in the Nantucket Shoals region, where the oceanography and ecology is dynamic and evolving. Targeted observations and studies are critical to understand and quantify the hydrodynamic and ecological effects of offshore wind in the Nantucket Shoals region.

A DYNAMIC AND EVOLVING OCEANOGRAPHIC REGIME

The hydrodynamics of the Nantucket Shoals region are driven by complex interactions among shelf-break processes, seasonal stratification, interannual variability, bottom friction, tides, and flows over complex bathymetry. This complex oceanography is additionally influenced by region-specific processes such as long-term surface densification, onshore midwater intrusions of slope water, warm core rings, onshore displacement of the shelf-break front, and interdecadal variability in circulation (See Figure S.2).

Major oceanographic changes have occurred in the region since 2000, including warming of surface and bottom temperatures, increased frequency of Gulf Stream warm core rings, and midwater intrusions into the tidally mixed inshore region. Warming water temperature affects onset, decay, and intensity of seasonal stratification. These changes affect the oceanography of the region, but the long-term trends and consequences remain to be determined, particularly because the system is subject to additional changes.

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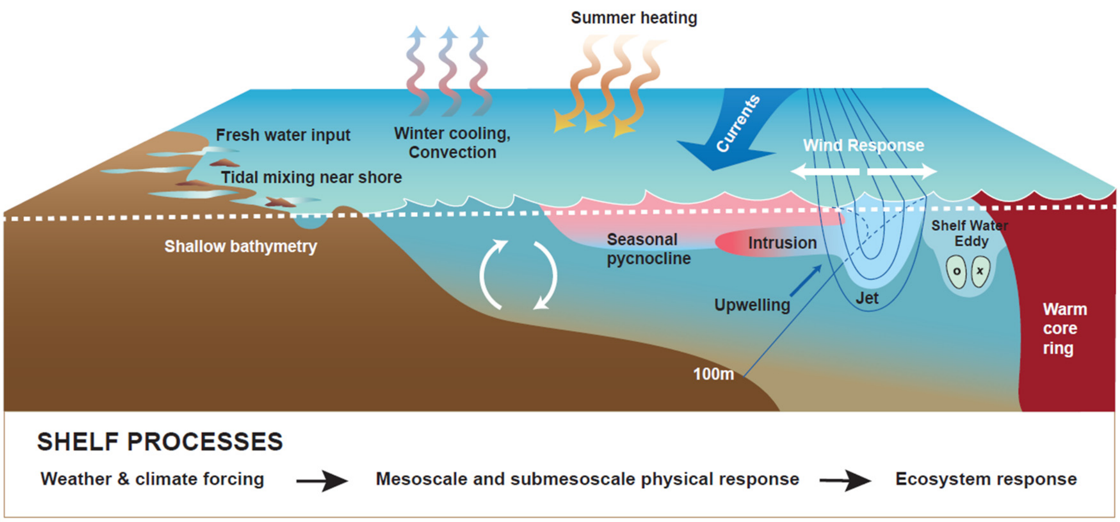

FIGURE S.2 Schematic of shelf processes in the Nantucket Shoals region. SOURCE: Adapted from Gawarkiewicz and Plueddemann, 2020.

Phytoplankton productivity is primarily controlled by water column stratification and seasonal solar insolation, with a dominant seasonal bloom in autumn/winter associated with a weaker stratification. Zooplankton forage on the phytoplankton produced in these seasonal blooms and most higher-trophic-level species associated with the Nantucket Shoals region feed either directly or indirectly on zooplankton found in the region. High concentrations of zooplankton, including the primary prey of right whales—the copepod *Calanus finmarchicus* in winter–spring—may account for the great numbers of right whales observed feeding in the Nantucket Shoals region and other areas of high productivity in Southern New England, for example, Cape Cod Bay.

UNDERSTANDING HYDRODYNAMIC EFFECTS

As the wind blows across a turbine or wind farm, wind energy is extracted, thus creating a wind wake behind the turbine (Figure S.3) and reducing wind-driven circulation in the upper ocean. Additionally, the turbine structure in the water column causes an ocean wake, meaning the water becomes more turbulent behind the turbine (Figure S.3). The increased turbulence and decreased wind forcing both affect the structure and movement of the water as it passes the turbine, referred to as the hydrodynamics. Knowledge of the effects of offshore wind turbine structures on hydrodynamics is limited and primarily based on modeling studies in the North Sea that have not been validated by observations. The structure and magnitude of the wind wake at the sea surface is poorly understood, with most of the observational and modeling studies focused on wind speed reductions at the height of the turbine and not at the sea surface. The effect of ocean surface roughness on wind stress reductions at the sea surface is also poorly understood.

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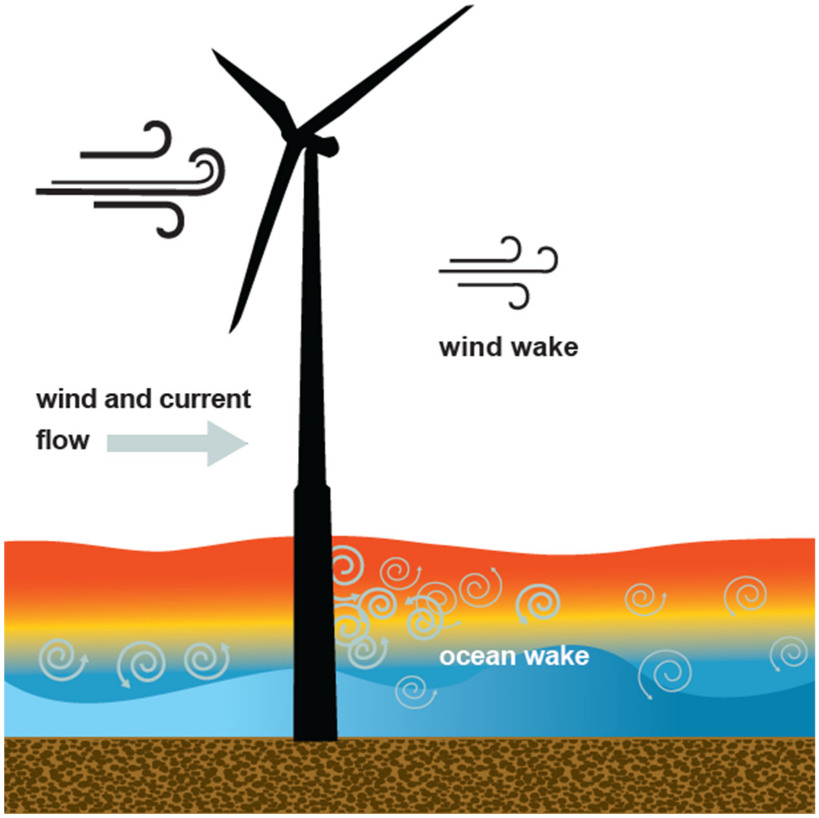

FIGURE S.3 Schematic of the effects of an individual turbine on local hydrodynamics.

At the turbine scale, there are few observations that can be used to verify turbine-scale wake behavior. At the wind farm scale, the potential impacts include reductions in ocean current speeds, stratification, ocean surface wind speed, and deflection of the pycnocline.[1] At the regional scale, perturbations due to offshore wind turbines are difficult to quantify because of the natural processes that drive significant environmental variability across the region.

Given the significant uncertainties in the hydrodynamic response of the wind wake and ocean wake, hydrodynamic effects of turbines are difficult to isolate from natural and other anthropogenic variability (including climate change). Some hydrodynamic observations are available at the regional scale, but there is a scarcity of observations at the turbine and wind farm scales that can be used to quantify hydrodynamic perturbations and provide validation and calibration of hydrodynamic models used to assess effects at these scales.

Recommendation: The Bureau of Ocean Energy Management, 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 the

[1] ***A boundary layer of water with a large density gradient, separating low-density surface water and higher-density deeper water.***

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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 foundation, and sizes and spacing of turbines.

For a hydrodynamic model to be suitable for the Nantucket Shoals region, the key physical oceanographic processes should be represented. In addition to tide- and wind-driven circulation on the continental shelf, the hydrodynamic models implemented for the Nantucket Shoals region must include the seasonal progression of stratification and capability to simulate interannual variability scenarios as well as the effects of long-term surface densification, onshore advection of warm core rings, and onshore migration of the shelf-break front. Accurate representation of these complex oceanographic processes is difficult because of the open boundaries and atmospheric forcing, as well as the imperfect parameterizations of turbulent mixing and turbine-induced ocean and atmospheric wakes. The hydrodynamic modeling studies funded by BOEM (DHI-MIKE 3 Flexible Mesh [FM], Delft3D FM, Finite-Volume Community Ocean Model [FVCOM]) differ in parameterizations and/or representations of offshore wind turbines and wind energy areas, and therefore produce differences in simulated hydrodynamic wind and ocean wake impacts.

Model inaccuracies and uncertainty propagate through to the predictions and introduce associated uncertainty in assessing hydrodynamic and ecological impacts. Taking a hierarchical approach to model calibration, verification, and validation would reduce error and uncertainty. Such an approach would begin with small-scale idealized simulations and large eddy simulation (LES) models that resolve individual turbines and progress to larger-scale fully dynamic models at the regional scale.

Recommendation: The Bureau of Ocean Energy Management, 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. These studies should:

- **Evaluate the ability of the model to represent the physical complexity of the processes specific to the questions asked (from small-scale idealized and large eddy simulation models to fully dynamic models at the regional scale).**
- **Evaluate model sensitivity to selection of model configuration, parameterization, and/or wind turbine representation.**
- **Quantify the uncertainty in the model's output and implications for interpretation of results.**
- **Evaluate model performance through intercomparisons with other models and, once available, data from observational studies at the turbine and wind farm scales.**
- **Make parameterizations, model configurations, and solutions publicly available to encourage engagement by the broader community to assess model predictions of offshore wind turbine impacts.**

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POTENTIAL IMPACTS TO RIGHT WHALE PREY

Right whales feed on small, energy-rich zooplankton and, in particular, copepods such as *C. finmarchicus,* in New England waters. Successful foraging depends on copepods being found in sufficient densities and at appropriate depths, and as such right whales are sensitive to disturbances of their prey in the water column.

The paucity of observations and uncertainty of the modeled hydrodynamic effects of wind energy installations make potential ecological impacts of offshore wind farms difficult to detect, particularly considering the scale of natural variability as well as other anthropogenic variability of the Nantucket Shoals region's evolving oceanography and ecology. Though studies exist, the spatial and temporal coverage of studies concentrated at the proposed wind energy lease sites do not adequately capture broad-scale right whale use of the Nantucket Shoals region and potential impacts from offshore wind farms.

Additionally, there are gaps in understanding of foraging by right whales in the Nantucket Shoals region, including the basic question of which zooplankton taxa right whales are feeding on and how this prey changes seasonally. Surveys of zooplankton associated with foraging right whales as well as simultaneous collection of oceanographic data linked to zooplankton variability would improve this understanding. Given the limited state of understanding of the entire system and the changing oceanography and ecology, identification of substantial impacts on zooplankton, and specifically on right whale prey, that may result from wind energy development in the Nantucket Shoals region is difficult to assess.

Recommendation: The Bureau of Ocean Energy Management, 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. Observations should:

- **Include concurrent measures of relevant physical processes and ecological effects through upper trophic levels at the turbine, wind farm, and regional scales.**
- **Be expanded to identify the links and relevant processes between zooplankton supply, abundance, and aggregation and right whale habitat use in the Nantucket Shoals region.**
- **Use combined observational and modeling studies to isolate potential effects of wind farms from those resulting from natural and/or other anthropogenic drivers, recognizing that this will take dedicated long-term studies.**
- **Sample zooplankton at appropriate spatiotemporal scales necessary to characterize prey availability, including zooplankton life history and behavior.**
- **Monitor right whale habitat use within and outside of wind energy areas.**
- **Maintain existing long-term monitoring programs to provide insight on regional and ocean-basin scale changes to right whales and their prey.**

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Right whale distribution and demography has been shown to depend on the distribution and density of zooplankton, in particular the late-stage of the copepod *C. finmarchicus*, but studies focusing on the link between right whale habitat use and zooplankton in the Nantucket Shoals region are limited. The supply of zooplankton to the Nantucket Shoals region is dependent on regional circulation, but aggregation is presumably dependent on local physical processes and zooplankton behavior.

Overall, there is a lack of robust (coupled physical/biological) models that can effectively incorporate the supply of zooplankton, their behavior, and the physical oceanographic processes that aggregate the zooplankton in the Nantucket Shoals region in sufficient densities for right whale foraging. Given this lack of models, it will be difficult to predict potential effects of wind farms on right whales. Regarding the right whale prey field, there are potential hydrodynamic mechanisms to support each of these three possibilities: (1) turbines could cause an increase in zooplankton productivity and/or aggregation of zooplankton into high-density patches to support right whale foraging and increase right whale use of this habitat; (2) turbines may decrease zooplankton productivity and/or reduce the potential for high-density aggregations, thus potentially reducing foraging opportunities for right whales in the region; or (3) wind farm development may have no appreciable impact on right whale foraging dynamics.

Recommendation: The Bureau of Ocean Energy Management, 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. This modeling should:

- **Include zooplankton life history and behavior modeled at appropriate scales.**
- **Identify and model the mechanisms that drive supply, abundance, and aggregation of zooplankton.**
- **Utilize improved hydrodynamic models that represent the mechanisms that drive regional transport, supply, and local aggregation processes.**
- **Be expanded to identify and incorporate the link between zooplankton supply, abundance, and aggregation and right whale habitat use in the Nantucket Shoals region.**
- **Be conducted at the appropriate spatiotemporal scales necessary to isolate effects driven by wind turbines from those resulting from natural and/or other anthropogenic drivers.**
- **Incorporate physical and ecological information pertinent to right whale foraging outside of the Nantucket Shoals Region, because right whale foraging in this region may depend on the availability of alternative foraging areas.**

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1
Introduction

In early 2023, the United States set an ambitious goal to meet 80 percent of U.S. energy needs with renewable energy generation by 2030. This transition away from fossil fuel sources will require scaling up of a portfolio of efficient clean energy resources. One such potential resource is offshore wind. The National Renewable Energy Laboratory estimates the potential for offshore wind to generate more than 4,200 gigawatts of capacity/year, fulfilling energy needs along U.S. coastlines, where nearly 40 percent of the nation's people reside.

In the United States, offshore wind is in the early stages of implementation with (at the time of this study) only two offshore wind farms in operation in U.S. waters—one offshore Virginia and one offshore Rhode Island. However, there are ambitions and plans for potential build-out of additional offshore wind farms on the U.S. East, West, and Gulf coasts. Part of the permitting process required to install and operate offshore wind farms includes assessing any potential ecosystem impacts, regulated by the Bureau of Ocean Energy Management (BOEM).

Assessing the ecosystem impacts of offshore wind development has a unique set of challenges. One challenge is to understand how the oceanography might be altered by the presence of a single offshore wind turbine, by an offshore wind farm, or by a region of adjacent offshore wind farms. An offshore wind turbine can alter flow by interrupting the winds that drive circulation processes and by causing turbulence in the water column surrounding the pile. The associated challenge is understanding how the altered flow may potentially affect the ecosystem, from phytoplankton to marine mammals.

Offshore wind development activity, specifically in the Nantucket Shoals region[1] of the Atlantic Northwest (Figure 1.1), is the impetus for this study. BOEM is seeking to understand how offshore fixed-bottom wind turbines in this unique region may alter physical processes such as seasonal stratification, tidal fronts, waves, and currents on local to regional scales with the key motivation to assess the potential impacts of offshore turbines on zooplankton productivity and aggregations, which may affect foraging for higher-trophic-level organisms such as the North Atlantic right whale (*Eubalaena glacialis*).

The North Atlantic right whale is critically endangered with an estimated population size of 340 animals (Pettis et al., 2022). This species of baleen whales is threatened by elevated mortality rates caused by ship strikes and fishing gear entanglement (Knowlton et al., 2012; Moore et al., 2021), and depressed reproduction rates linked to fluctuations in prey availability (Meyer-Gutbrod et al., 2015, 2021). Preliminary studies of right whale occurrence in wind energy lease areas off the coast of Massachusetts and Rhode Island indicated that use of this area was seasonally restricted to the winter and spring (Leiter et al., 2017; Stone et al., 2017). However, more recent studies show that right whales are increasing their use of this region and have been observed in this location during all times of the year, with peak occurrences in the winter and spring (Quintana-Rizzo et al., 2021; Meyer-Gutbrod et al., 2022; O'Brien et al., 2022). Right whales have been observed foraging in this region year-round, and social behaviors associated with mating have been observed in the winter and spring seasons (Leiter et al., 2017; Quintana-Rizzo et al., 2021).

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[1] The Nantucket Shoals region is defined as the geographic area including the nine offshore wind lease areas sited to the west of Nantucket Shoals.

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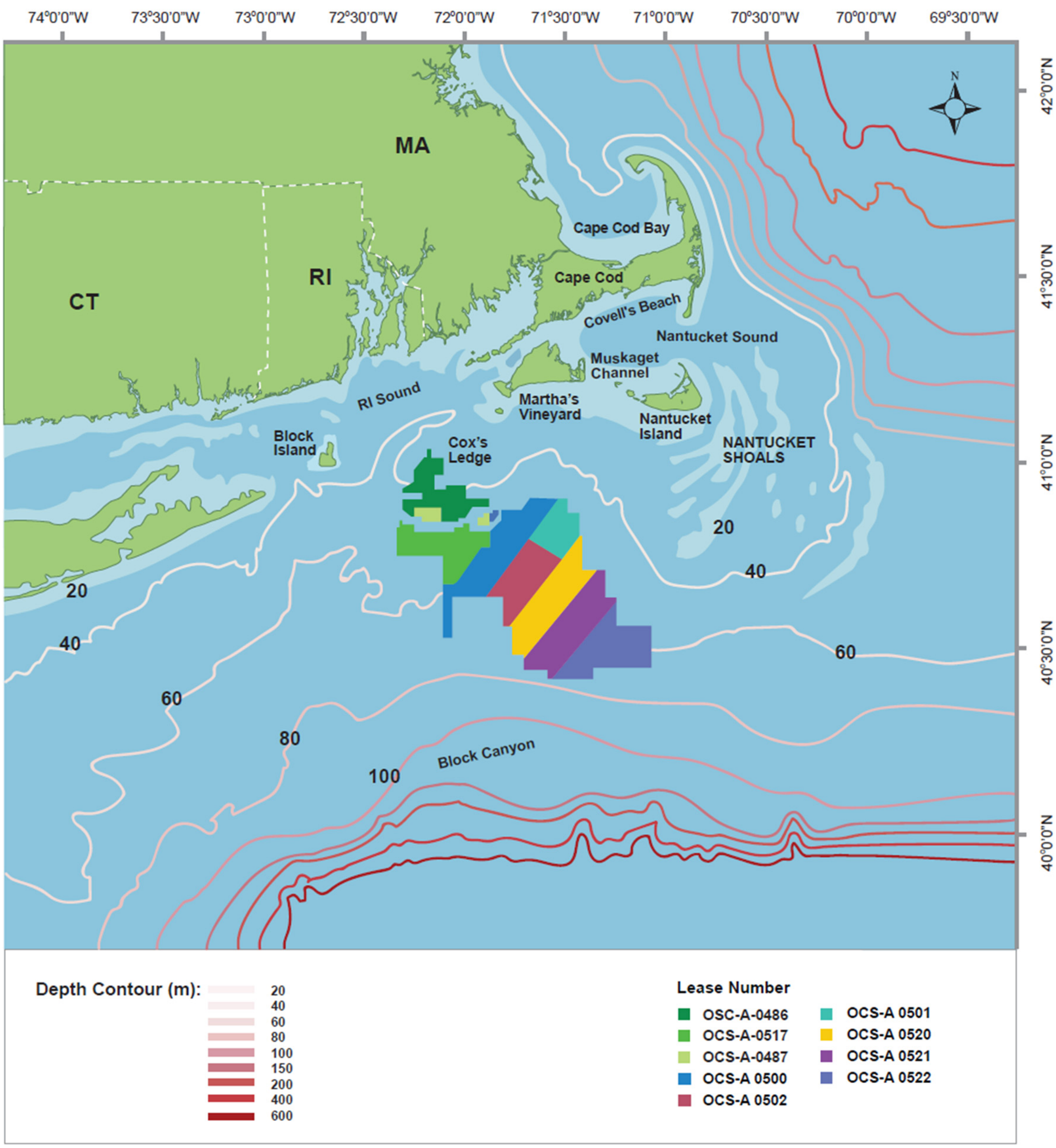

FIGURE 1.1 Map of the Nantucket Shoals region showing the wind farm lease areas and bathymetric contours (meters). The lease numbers correspond to BOEM designations.

Zooplankton taxa that right whales feed on in this region are likely similar to their prey in the nearby Cape Cod Bay, which consists of *Calanus finmarchicus*, *Pseudocalanus* spp. complex, and *Centropages* spp. (Pendleton et al., 2009; Hudak et al., 2023). This study will review the known mechanisms for zooplankton production and aggregation in the Nantucket Shoals wind energy area and the potential hydrodynamic effects of bottom-fixed wind turbines on these mechanisms. Direct and indirect impacts of wind turbine–induced hydrodynamic effects on right whales will be considered.

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ORIGIN AND PURPOSE OF THE STUDY

This study is sponsored by BOEM for the purposes of informing environmental impact assessment of the Nantucket Shoals region and informing future work so that impacts of offshore wind farm turbines on hydrodynamics and associated changes to ecosystem dynamics can be better understood in the Nantucket Shoals region and elsewhere. The specific charge to the committee is provided in Box 1.1.

BOX 1.1
Statement of Task

The objective of this study is to understand potential effects of offshore fixed-bottom wind turbine generators (WTGs) on marine hydrodynamics and resulting impacts on marine mammals, specifically the North Atlantic right whale prey. The study will be focused on WTGs in the Nantucket Shoals region, with hub heights above 100 m and at depths between 36 and 60 m. The study will consist of a literature review, an evaluation of the applicability of existing hydrodynamic models to the Nantucket Shoals region, and recommendations on measures needed to detect and assess changes in hydrodynamics due to interactions with WTGs that may impact the surrounding ecosystem. Specifically, the committee will:

1. Conduct a literature review covering the state of the science on the effects of offshore wind turbine structures at local to regional scales on hydrodynamic process and the scale of change related to natural variability.

Based on the literature review and public information-gathering sessions:

2. Comment on the ability to estimate the extent of perturbations (distance and magnitude) caused by WTG installation and operation, to the oceanographic regime. This will include potential changes to ecosystem dynamics, specifically for assessing whether these facilities could substantially affect North Atlantic right whale prey availability near Nantucket Shoals.

3. Evaluate the applicability of models used by the Bureau of Ocean Energy Management (BOEM) in EIS analysis or studies in conjunction with U.S. Atlantic Wind Energy Areas (e.g., MIKE/DHI, FVCOM, Delft3D) to the Nantucket Shoals region. How do the methods, assumptions, and conclusions from the models translate to the Nantucket Shoals region (including wind-forced effects due to the atmospheric wakes caused by turbines and ocean mixing/turbulence effects from ocean currents and waves interacting with turbine structures)? What are the key parameters to include in a model to assess the effects of WTGs on hydrodynamics in the Nantucket Shoals region and how well do existing models meet these needs? What other models should BOEM consider?

4. Suggest approaches for assessing the hydrodynamic impacts of WTGs.

STUDY APPROACH AND REPORT ORGANIZATION

The deliberations and resulting conclusions and recommendations from the committee relative to its specific charge (Box 1.1) were informed by the committee's collective expertise,

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review of scientific literature, and public information-gathering meetings. The public meetings (see Appendix B) included discussions and presentations with additional experts from academia, government, and nongovernmental organizations, including perspectives from offshore wind developers in the United States and from countries with a more mature offshore wind industry.

The committee responded to the statement of task at three main levels of questioning. The first focus was on understanding the hydrodynamic effects—how well can existing hydrodynamic models estimate the effects of fixed-bottom wind turbines on local hydrodynamics and what are the key parameters to include in a model? The second main question is, given estimated changes to the hydrodynamics, what are the potential local and regional effects on the ecosystem? The third question is then, how might the estimated potential effects on the hydrodynamics and subsequent changes to the ecosystem directly or indirectly affect endangered species, specifically the North Atlantic right whale's prey field?

The report is organized to answer the three levels of questioning in the broad sense and in the context of the Nantucket Shoals region. Based on the literature review and information gathering, Chapter 2 provides a description of the Nantucket Shoals region in terms of geography, oceanography, meteorology, biology, and ecology. Chapter 3 then summarizes what is known about the effects of offshore wind turbine structures and operation on marine hydrodynamics, including the application of that knowledge to the Nantucket Shoals region, as well as the applicability of existing hydrodynamics models to the Nantucket Shoals region. Chapter 4 discusses potential effects of hydrodynamic perturbation on the offshore ecosystem broadly, and potential effects specific to the environmental characteristics of the Nantucket Shoals region, including North Atlantic right whale foraging. The committee's conclusions and recommendations are included within the supporting text.

Some terminology related to the statement of task varies in context and across sectors. Appealing to a wide range of audiences and for general readability, the following terminology is adapted in this report:

- **Hub height**: Distance from the sea surface to the middle of the turbine's rotor.
- **Mid-Atlantic Bight**: Offshore coastal region extending from Cape Hatteras to the south and Cape Cod to the north; Nantucket Shoals is at the extreme northern end of the Bight.
- **Nantucket Shoals region**: Geographic area including the nine offshore wind lease areas sited to the west of Nantucket Shoals.
- **North Atlantic right whale**: *Eubalaena glacialis;* also referred to as "right whale" throughout the report, in the context of the North Atlantic.
- **Offshore wind farm**: An offshore wind turbine development, array of turbines, or wind plant, sometimes referred to as wind energy field or wind energy area (WEA).
- **Offshore wind region**: Multiple, adjacent offshore wind farms.
- **Offshore wind turbine**: For the purpose of this report, an individual, fixed-bottom, offshore wind turbine generator (WTG); in the context of offshore wind, also referred to simply as "turbine" throughout the report.
- **WEA**: a region of proposed and/or developed wind farms; can be a single farm/lease or a grouping of farms/leases; terminology commonly used by BOEM for federal offshore wind leases.

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2
Oceanography in Nantucket Shoals

GENERAL DESCRIPTION

The area identified by the Bureau of Ocean Energy Management (BOEM) as the Nantucket Shoals region is coterminous with the Massachusetts and Rhode Island wind energy areas (WEAs) (Figure 1.1). Strictly speaking, none of the WEAs overlap the actual Nantucket Shoals, but the Massachusetts WEA is referred to as the WEA southwest of Nantucket Shoals and the Rhode Island WEA is referred to as the Cox's Ledge WEA.

The combined WEA begins roughly 20 km south of Martha's Vineyard and 24 km southwest of Nantucket. From its northern boundary, the area extends 133 km southward to approximately the 60-m depth contour and has an east–west extent of approximately 106 km. The WEA is approximately 3,673 km^2 (907,728 acres) and contains nine wind farm projects (Table 2.1; Figure 1.1). The Massachusetts WEA is located within 40- to 60-m depths southwest of Nantucket Shoals, while the Rhode Island WEA is generally located in 20- to 60-m depths surrounding Cox's Ledge (Figure 1.1).

Physical characteristics of the turbines to be constructed for each project are variable (Table 2.2). Overall, a maximum of 700 turbines are planned for the seven projects in active development. Turbine spacing in the project area will be an approximately 1-NM (1.85-km) grid with turbine hub heights between 101 and 214 m, and rotor diameters between 150 and 300 m.

Two projects are currently in the construction phase in U.S. federal waters. Vineyard Wind 1 (OCS-A-0501) was the first offshore wind farm to be approved for construction (July 15, 2021). The project will consist of 62 turbines (800 MW). Energy will be transported via an export cable running through the Muskeget Channel (see Figure 1.1) and Nantucket Sound, which will connect to the Massachusetts shore at Covell's Beach. Construction of the project began in June 2023 and is expected to be fully operational in summer–fall 2024.

A second project, South Fork Wind (OCS-A-0517), was approved for construction on November 1, 2021, which will include 12 turbines (132 MW) exporting energy to East Hampton, New York. Construction of the project began in June 2023 and is expected to be operational by summer 2024.

In 2021, BOEM submitted four notices of intent to prepare environmental impact statements for the following projects: Revolution Wind (OCS-A-0486), Park City Wind/Vineyard Wind South (OCS-A-0534), Sunrise Wind (OCS-A-0487), and South Coast Wind/ Mayflower Wind (OCS-A-0521). Two additional projects, Beacon Wind (OCS-A-0502) and Bay State Wind (OCS-A-0500), have received site assessment plan approval for site characterization; however, little activity has occurred.

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TABLE 2.1 Descriptive Characteristics of the Rhode Island and Massachusetts Wind Energy Areas

Characteristic	RI WEA[a]	MA WEA[a]
Distance from coast	9.5 NM south of Newport, RI; 12.5 NM east of Block Island, RI; 10.5 NM southwest of Martha's Vineyard, MA	12 NM south of Martha's Vineyard, MA; 12.5 NM southwest of Nantucket, MA; 24 NM southeast of Block Island, RI
Total geographic area (acres; km^2)	164,750; 667	742,978; 3,007
Depth range (m)	31–51	30–64
Bottom type	Sand 35% Gravel 60% Sand/silt/clay 5%	Sand 90% Gravel 5% Sand/silt/clay 5%
Bathymetric features	Cox's Ledge and RI Sound	Southwest of Nantucket Shoals
Projects in construction	South Fork, OCS-A-0517	Vineyard Wind I, OCS-A-0501
Projects in review	Revolution Wind, OCS-A-0486 Sunrise Wind, OCS-A-0487	South Coast Wind, OCS-A-0521 Park City Wind/Vineyard Wind South, OCS-A-0534 Beacon Wind, OCS-A-0500
Projects in early stages of development		Bay State Wind, OCS-A-0520 Vineyard Northeast, OCS-A-0522

NOTE: MA= Massachusetts; NM = nautical mile; RI = Rhode Island WEA = wind energy area.
[a]Projects have undergone name changes during development; the project name is given with the BOEM lease area designation, shown in Figure 1.1, are given.

TABLE 2.2 Physical Characteristics of Wind Farm Projects in the Rhode Island and Massachusetts Wind Farm Areas

Project Name and BOEM Lease Number	Turbines (number)	Hub Height (m)	Rotor Diameter (m)	Tower design: Type, Blade Diameter (m), Array Spacing (NM)
Vineyard Wind I OCS-A-0501	62, actual	109-144	163-222	Monopile, 10, 1
South Fork Wind OCS-A-0517	12, actual	101–144	150–224	Monopile, 11, 1
Revolution Wind OCS-A-0486	≤100	115–156	164–200	Monopile,12, UA
Park City Wind/Vineyard Wind South OCS-A-0534	≤130	214	285	Monopile or piled jacket, 12, 1
Sunrise Wind OCS-A-0487	≤94	140	200	Monopile, 12, 1
South Coast Wind/Mayflower Wind OCS-A-0521	≤149	128–184	220–280	Piled jackets, suction bucket jackets, monopiles, 12, 1
Beacon Wind OCS-A-0502	≤155	180	300	Piled jackets, suction bucket jackets, monopiles, 13, 1
Vineyard Northeast OCS-A-0522	UA	UA	UA	UA
Bay State Wind OCS-A-0500	UA	UA	UA	UA

NOTES: All statistics are from the Construction and Operations Plan for a given project, except for those indicated as "actual." Projects have undergone name changes during their development; the project name and BOEM lease area, shown in Figure 1.1, are given.UA = unavailable at this time because the project is in early development.

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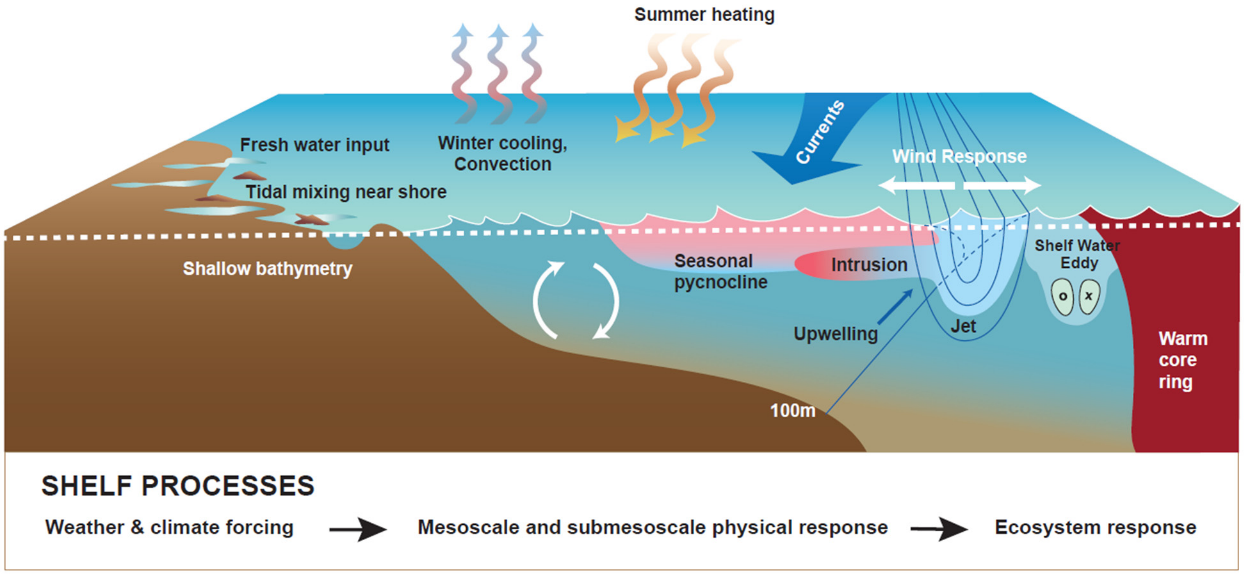

FIGURE 2.1 Shelf processes in the Nantucket Shoals region. Adapted from Gawarkiewicz and Plueddemann, 2020.

PHYSICAL OCEANOGRAPHY

The physical oceanography of the Nantucket Shoals region is influenced by a variety of shelf processes, including winds, waves, currents, tides, temperature, and stratification (Figure 2.1). The oceanography of the Nantucket Shoals region has also undergone significant changes that have been documented since about 2000, particularly since 2010-2011 when both surface and bottom temperatures increased significantly.

Winds

The wind pattern over the Mid-Atlantic Bight[1] (MAB) is characterized by a spatially varying mean northwest wind with significant temporal variability that in the Nantucket Shoals region is larger than the mean (Roarty et al., 2020). Scales of variability range from longer seasonal scales to individual storm events. During summer months, there are predominantly alongshore southwesterly winds, which change to cross-shelf winds from the northwest during winter. During the fall and spring transition seasons, alongshore winds are from the northeast and the southwest.

The alongshore summer winds are correlated with cross-shelf transport over most of the mid to outer MAB shelf. In winter, the correlation between the northeast alongshore winds and the cross-shore currents is small, with the dominant correlation of cross-shore currents being with cross-shore winds. Alongshore currents over the inner portion of the MAB shelf are correlated with alongshore winds, and this correlation extends over much of the shelf during the fall and spring transitions (Schofield et al., 2008).

[1] The Mid-Atlantic Bight (MAB) is a coastal region extending from Cape Hatteras to the south and Cape Cod to the north. Southern New England is a subregion at the northern end of the MAB from the eastern end of Long Island to Georges Bank. Nantucket Shoals is at the extreme northern end of the MAB and SNE.

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The seasonal wind patterns over the Nantucket Shoals region are similar. Northwesterly winds dominate during the winter months and shift from northwest winds to southwest winds in March. Winds from the southwest are frequent from April through September, with transition to northwesterly winds in October and November (Wood et al., 2014).

Monthly mean surface wind speeds in the region range from 4.1 m/s (8.0 kts) in July to about 8.7 m/s (16.9 kts) in January, reflecting the increase to stronger winter winds. Higher winds speeds are associated with storms and extreme events, such as the 64-m/s (124-kts) winds associated with Hurricane Gloria in 1979 (NOAA NDBC, 2017; Epsilon Associates, 2019, 2020).

Currents

The physical oceanography characteristics of the Nantucket Shoals region are representative of tidal and subtidal flows associated with an inner- to middle-shelf domain. There is a general pattern of stronger tidal velocities over Nantucket Shoals that decrease to the west with shelf flows of 20 cm/s that increase to 100 cm/s near inlets (Stevenson et al., 2004). There are likely to be differences in the monthly bottom stress along the southern New England inner shelf as the tidal currents decrease substantially from east to west (Moody et al., 1984; Shearman and Lentz, 2004). He and Wilkin (2006) used data assimilative models to spatially map tides across the Nantucket Shoals region and surrounding areas and identified regions with a higher occurrence of tidal mixed fronts, driven by underlying bathymetry and tidal current magnitude. Ullman and Cornillon (1999) used satellite sea surface temperature data to map the thermal signature of these fronts that separate colder water inshore of the front from warmer surface waters offshore. Their frontal climatology in the Nantucket Shoals region identified tidal mixed fronts that occur ~10–20 km inshore of the 50-m isobath in the summer stratified season.

Coastal radar measurements of surface currents and high-resolution numerical models indicate that these tidal currents likely contribute to subtidal variability in the along-shelf currents and dynamics (Ganju et al., 2011; Kirincich et al., 2013).

The subtidal currents in the Nantucket Shoals region are broadly influenced by a cold current flowing from Gulf of Maine southwestward along the coast (Figure 2.2), generally following the bathymetry at speeds of 5–10 cm/s at the surface and less than 2 cm/s near the seafloor (Shearman and Lentz, 2003). This slow southwestward flow through the middle shelf is interrupted by warm core rings or meanders from the Gulf Stream and onshore deflections of the shelf-break front. Most of the variance in the depth average of the along-shelf current, including the annual cycle and at least one-half of the month-to-month and year-to-year variability about the annual cycle, can be attributed to the along-shelf wind stress (Lentz, 2022). Fluctuations in the along-shelf wind stress relative to local tides accounts for most of the variance (Kirincich et al., 2013; Lentz, 2022). Monthly to annual variations of this mean flow range from approximately 2 cm/s to 7 cm/s without a significant trend or obvious multiyear variability. Interrupting these mostly along-shelf flows are storm-driven wind events and shelf-break exchange processes that can cause significant variations in flow, such as the eddy off the southern coast of Martha's Vineyard (Kirincich et al., 2013) and another counterclockwise gyre farther to the west of Nantucket Shoals located to the southeast of Martha's Vineyard (Ganju et al., 2011).

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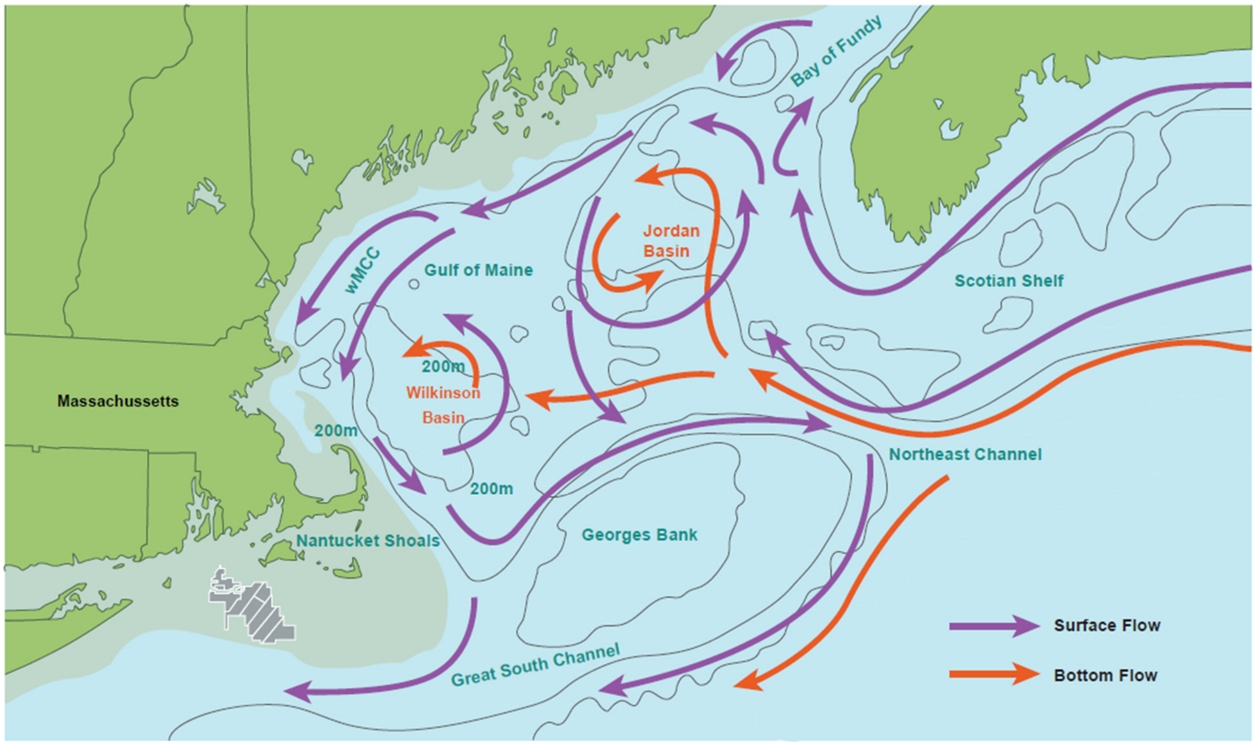

FIGURE 2.2 Schematic mean circulation pattern for the Gulf of Maine and Nantucket Shoals region. The 50-, 100-, and 200-m isobaths (solid black lines) and depths shallower than 50 m (gray shading) and deeper than 200 m (blue shading) are indicated. The proposed wind farm lease area southwest of Nantucket Shoals (dark gray, white hatching) is shown for context. SOURCE: Adapted from Ji et al., 2017.

Hydrography

The hydrography of the Nantucket Shoals region is primarily influenced by the cooler and fresher source waters north of the region and the warmer and saltier waters sourced offshore from Gulf Stream warm core rings, and slope seawaters beyond the shelf-break jet (Figure 2.1). Sea surface temperatures (SSTs) in the Nantucket Shoals region vary widely between seasons, ranging from a minimum of 0 ºC to 3ºC during February–March and a maximum of 20 ºC to 22ºC during August–September (Fewings and Lentz, 2011). Much of the SST variability results from the intrusion of the colder waters from the northeast balanced by seasonal warming. During the winter months (especially February through March), the temperature over the shelf in the Nantucket Shoals region becomes nearly uniform, seemingly due to enhanced vertical mixing caused by storm-induced turbulence and convective overturning at the surface. As summer progresses (August–September), the thermocline deepens to almost 40 m, and the waters with temperatures lower than 10 °C significantly decrease in size. During June–July, the cold pool stretches from the southern flank of Georges Bank southwest to the MAB (Beardsley and Flagg, 1976; Houghton et al., 1982). As defined by the 10°C isotherm, the cold pool extends over the MAB shelf to the 90-m isobath underlying warmer surface waters, but generally does not reach the Nantucket Shoals region. Analysis of 11 years (2003–2013) of repeat temperature and salinity sections during early summer (June–July) from across the New England shelf break (inshore of the 100-m isobath) south of Cape Cod found that surface waters are warming by

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0.26°C/yr (Harden et al., 2020). In addition to the general freshening of surface salinity in the region, the frequency and complexity of mid-water salt intrusions from the shelf break north across the shelf have increased (Gawarkiewicz et al., 2022). Moored and vessel-based observations show an increase in the northward extent of these intrusions across the shelf as evidenced by vertical profiles that show multiple occurrences of intrusions relative to a salinity climatology for the region (Lentz, 2003). The extension of these intrusions into shallower water and the increase in the number of intrusions contribute to the complexity of the vertical structure of seasonal stratification in the region between the surface mixed layer and the cold pool. The mixed-layer depth reaches a minimum in July or August (7.9 ± 2.7 m). Convective overturning in late fall (October–November) restores the shelf waters to a vertically well-mixed state (38.3 ± 9.5 m; Cai et al., 2021). From 1993 to 2018 the mixed-layer depth has shown a significant increase in both winter (+0.46 m/yr) and summer (+0.11 m/yr) (Cai et al., 2021).

Waves

Wave conditions in the Nantucket Shoals region can be described as persistent southeasterly swell from the North Atlantic Ocean combined with local multidirectional wind-driven waves. The mean significant wave height at the Nantucket Shoals weather monitoring buoy ranged from about 1.0 m in July to 2.4 m during December–January. Extreme wave conditions are associated with extreme storms such as the passage of hurricanes and nor'easters. A maximum significant wave height of up to 11.5 m was measured during the passage of Hurricane Floyd in September 1999, while the maximum wave period of 15.9 seconds occurred in February 2004 (NOAA NDBC, 2017; Epsilon Associates, 2019, 2020).

Tides

Tidal currents contribute to variability of continental-shelf circulation and mixing of shelf waters. Along the MAB, the New England shelf is relatively minimum in tidal amplitude. However, observations show that the barotropic and baroclinic tidal variability of this shelf region is complex, with the barotropic semidiurnal (M2) tide accounting for most of the current variability (Shearman and Lentz, 2004). The M2 tidal elevations decrease toward the northeast to a minimum of about 34 cm over Nantucket Shoals (Shearman and Lentz, 2004). The amplitudes of the barotropic tidal current increase toward the northeast, reaching a maximum of about 35 cm/s over Nantucket Shoals (Shearman and Lentz, 2004). The complex bathymetry of Nantucket Shoals may result in some influence on tidal variability on the New England shelf through the development of an along-isobath M2 pressure gradient (Shearman and Lentz, 2004). Kirincich et al. (2013), using a high-resolution, high-frequency coastal radar system combined with SST and in situ observations, found maximum M2 tidal velocities that increased from 5 to 35 cm/s across the inner shelf south of Martha's Vineyard. Analysis of the observations showed that tidal stresses were the dominant control in determining the spatial variability of the along- and across-shelf flows.

A modeling study of tides on the New England shelf showed that the tidal amplitude decreased from 0.4 m offshore of Martha's Vineyard to about 0.1 m over Nantucket Shoals, rapidly increasing to about 1 m northward toward the Gulf of Maine (He and Wilkin, 2006). This change in tidal amplitude, indicative of a significant along-isobath pressure gradient, is

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consistent with observations (He and Wilkin, 2006). The modeling study reproduced the observed tidal elevation minimum on Nantucket Shoals and noted that this is a transition region between the MAB to the west and the semidiurnally amplified Gulf of Maine to the northeast (He and Wilkin, 2006). The strongest M2 tidal currents of 1.5 m/s were found in Muskeget Channel and southeast of Nantucket Island, with a rapid decrease in tidal speed west of Nantucket Shoals (He and Wilkin, 2006). Tidal mixing was strongest over Nantucket Shoals, suggesting that tidally induced mixing is important in the formation of property fronts in this region (He and Wilkin, 2006). A subsequent combined model–data analysis showed that tidal rectification is the dominant formation mechanism for the summer circulation south of Martha's Vineyard and identified the importance of the inner-shelf bathymetry for the tidal circulation (Ganju et al., 2011).

Regime Shifts and Extreme Events

The oceanography of the Nantucket Shoals region has undergone significant changes that have been documented since about 2000. Between 2004 and 2012 the cold pool exhibited a warming trend with temperatures more than 2°C warmer in 2012 than in 2004 (Harden et al., 2020). A significant warming event occurred in 2012 and after that, the bottom water remained warmer. Following 2012, the mean SST was about 1.0°C higher than the climatological SST mean averaged over 1982–2011 (Chen et al., 2021), suggesting that a warming regime shift occurred. A result of this warming is increased buoyancy of surface water. There is also evidence of a transition during 2010–2011 when both surface and bottom temperatures increased significantly (Chen et al., 2014a; Friedland et al., 2020). This was followed by distinct ocean heat waves in 2012 and 2017 that have been attributed to atmospheric forcing and Gulf Stream warm core rings, respectively (Chen et al., 2014b; Gawarkiewicz et al., 2019). Gulf Stream meanders have moved progressively westward toward the MAB shelf, resulting in increasing frequency of the intrusion of warm core rings onto the shelf. These intrusions have moved farther inshore into the tidal mixed area (Gawarkiewicz et al., 2022). Up to 50 percent of the profiles now show intrusions in summer, and 70 percent of the intrusions occurred in proximity to warm core rings (Silver et al., 2023). As a result, the shelf-break front is moving farther inshore. Seasonal stratification is thus changing and extending further into the fall. Effects on the spring season are unclear.

Summary of Physical Oceanography

The nine wind farm projects planned for the Nantucket Shoals region are in an inner- to mid-shelf region that has historically been characterized by significant southwestward currents and strong seasonal stratification of the water column from June through September with waters well mixed the remainder of the year. This stratification is moderated by significant tidal mixing around the actual Nantucket Shoals and south of Martha's Vineyard with tidal effects declining to the west. Advection is driven by the westward coastal currents along the shelf with transport from both the Gulf of Maine through the Great South Channel and over Nantucket Shoals, and over the mid-shelf by transport from Georges Bank. The mean bottom flow is offshore.

Major oceanographic changes have occurred in the region since 2000, including warming of surface and bottom temperatures and increased frequency of intrusion of Gulf Stream warm

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core rings inshore into the tidal mixed area. Temperature warming has implications for the onset, decay, and intensity of seasonal stratification. Gulf Stream warm core ring intrusions affect the location of the shelf-break front, which appears to be moving inshore. These changes are affecting the oceanography of the region, but the long-term trends and consequences remain to be determined.

BIOLOGICAL OCEANOGRAPHY

Primary Production

Spatial time series from the MAB have documented cross-shore transport of large winter phytoplankton blooms driven by northwest winds, with the offshore extent of these blooms occurring inshore of the 100-m isobath. In the spring, the onset of stratification supports phytoplankton blooms in the deeper waters of the MAB continental shelf that are then advected alongshore by alongshore winds. During the summer months, when the shelf is highly stratified, primary production is low except in nearshore waters, where coastal upwelling occurs. The autumn seasonal productivity largely reflects the timing of shelf stratification breakdown (Schofield et al., 2008).

The effect of ocean warming on trends in phytoplankton productivity from 1997 to 2020 in the Gulf of Maine, Georges Bank, and the MAB was analyzed by Friedland et al. (2023). This analysis showed little phenological shift associated with spring thermal conditions in any of the regions. The autumn–winter bloom was the dominant seasonal bloom and was detected in 16 of 23 years, but no trend was found in bloom start date or duration. The bloom start date and duration also showed no trend over the 23 years, except for the Georges Bank region which showed significant changes in the onset of the autumn bloom (33 days later) and bloom duration (2.5 weeks shorter).

Secondary Production

The zooplankton community in the Nantucket Shoals region is not well characterized, particularly compared to the communities associated with the Gulf of Maine and Georges Bank. The series of focused studies by NOAA's Northeast Fisheries Science Center (NEFSC) since 2020 provide limited information on the distribution and abundance of zooplankton in the Nantucket Shoals region. Sampling during 2020–2021 identified eight copepod species that were primarily found in the Nantucket Shoals region (Figure 2.3). The highest concentrations of copepods during winter–spring were *Centropages* spp., *Pseudocalanus* spp., and *Calanus finmarchicus*, and during summer–fall were *Centropages* spp., and *Paraocalanus* spp. *Oithona similis* was also collected. These results align with long-term NEFSC surveys in the Nantucket Shoals region that suggest increasing zooplankton diversity that has been attributed to increased abundance of several taxa and stable or declining dominance of other taxa (NMFS, 2023).

A May-June 2021 survey in the Nantucket Shoals region that used surface tows (focused in upper 1 m) found *Oithona similis* to be the most abundant copepod in the region (Turner and Weig, 2023). Few *C. finmarchicus* copepodites and no adults were found, possibly because the C5-C6 *C. finmarchicus* were deeper at this time.

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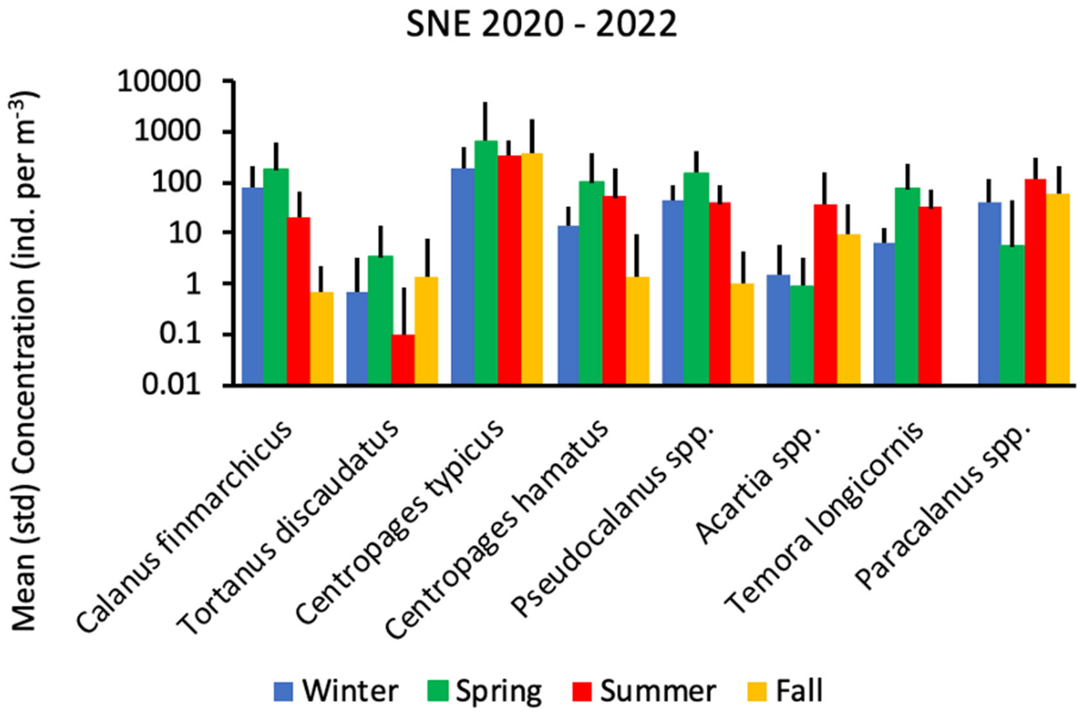

FIGURE 2.3 Seasonal concentrations of eight species of copepods found in the Nantucket Shoal region during 2020–2022. SOURCE: Orphanides and Walsh, 2022, unpublished data.

The spatial distribution of zooplankton throughout the Nantucket Shoals region is variable. Tidal mixing over the Nantucket Shoals region, described above, would likely moderate the formation of persistent vertical layers of zooplankton that have been observed in areas such as Cape Cod Bay. However, interannual and seasonal variation in sightings of foraging right whales south of Martha's Vineyard have been observed by Leiter et al. (2017) and a wintertime "hotspot" was identified within the western area of the Nantucket Shoals region where a counterclockwise gyre or tidal mixing front is located off the southeastern shore (e.g., Ganju et al., 2011; Brink, 2016; Brink and Seo, 2016). This suggests that the abundance of *Calanus* (especially C5) may be high outside of the eastern areas of the Nantucket Shoals region.

Seasonal variation in abundance and energy content is associated with zooplankton development and life cycle (Miller et al., 2000; Michaud and Taggart, 2007; Plourde et al., 2019; Lehoux et al., 2020). The life cycle of *Calanus* spp. is a progression from an egg stage through six naupliar and finally to six copepodite stages (Figure 2.4), each of which is characterized by variability in abundance and energy content. The older copepodites (e.g., C5) may enter diapause and descend to depth as an overwintering strategy. Copepodites, in their active phase, feed on phytoplankton and microzooplankton (Ohman and Runge, 1994) to accumulate energy needed during and immediately after diapause (Hirche, 1996). Diapause (e.g., stage C5 *Calanus*) is associated with the storage of lipids required to meet energy demands and subsequent migration to deep water, with the maximum depth of C5 and adult stages generally restricted by the depth of the continental shelf (Krumhansl et al., 2018).

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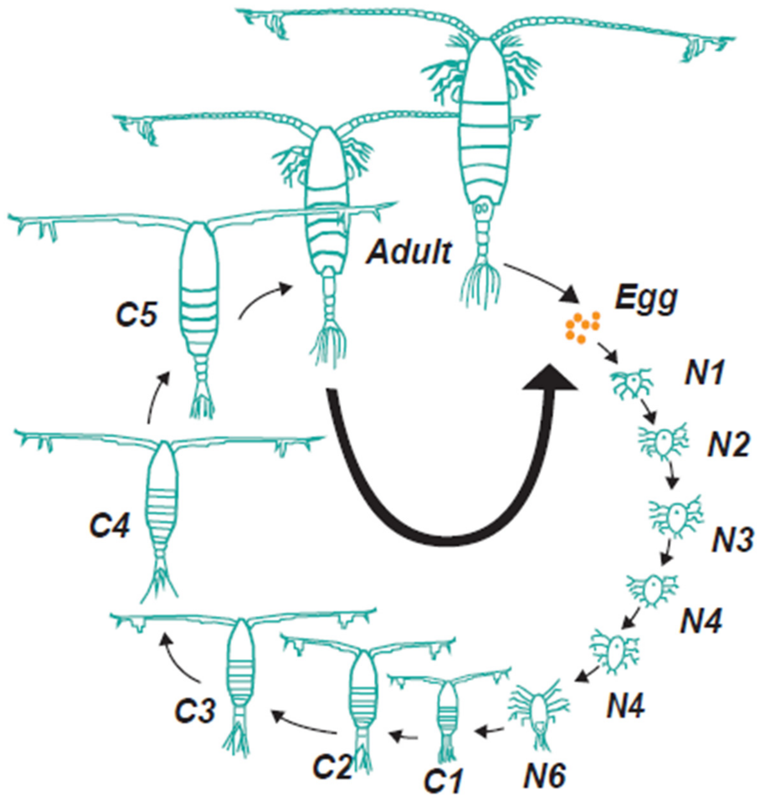

FIGURE 2.4 Life stages of *Calanus finmarchicus*, including egg, six naupliar stages (depicted as N1–N6) and six copepodite stages (depicted as C1–C5 and adult). Copepods may enter diapause in the C5 stage. SOURCE: Adapted from Ji et al., 2017.

Higher Trophic Levels

Higher-trophic-level species reliant on zooplankton for food, such as right whales, may also be affected by the presence of wind farms. Right whale–focused surveys conducted during 2011–2019 have consistently found right whales from Nantucket Shoals westward through the Massachusetts and Rhode Island WEAs. Their presence has increased in all seasons (Quintana-Rizzo et al., 2021). Southern New England is not a new habitat for right whales; this reflects a return to historically important areas in southern New England shelf waters known to have been a whaling ground (O'Brien et al., 2022). This increased presence relates to the region as an important foraging area for right whales either in response to a decline in prey in abandoned feeding areas or as a result of the abundance of prey increasing within the Nantucket Shoals region. The Nantucket Shoals region is also part of the right whales' migratory corridor between summer feeding grounds in the north and calving areas in southern U.S. waters.

North Atlantic right whales feed exclusively on small, energy-rich zooplankton, and in particular, copepods, such as *C. finmarchicus,* in New England waters. Successful foraging depends on copepods being found in sufficient densities and at appropriate depths, and as such right whales will be sensitive to disturbances of their prey in the water column (Gavrilchuk et al., 2021; Sorochan et al., 2021).

Although *C. finmarchicus* is traditionally considered the primary prey of right whales, these whales may be supplementing their diet during winter–spring with other zooplankton (e.g.,

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Centropages spp.) found in greater concentrations. This may account for the great numbers of right whales observed feeding in the Nantucket Shoals region.

Though the focus of this study is on the right whale, other higher trophic species may also be sensitive to hydrodynamic changes caused by offshore wind development in this region. The environmental assessments for the Massachusetts/Rhode Island WEAs (BOEM, 2012, 2014) and environmental impact statements for Vineyard Wind (BOEM, 2018) and South Coast/Mayflower Wind (BOEM, 2023) provide extensive detail on distributions, abundance, and exposure risk of higher-trophic-level species. Summaries of potentially affected fish, invertebrate, seabird, sea turtle, and marine mammal species are included in Appendixes C–E. Suggested impacts, other than hydrological effects, during construction and/or installation, operations and/or maintenance, and decommissioning of offshore wind developments could include those caused by habitat disturbance through the presence of structures and cables, noise, vessel traffic, and potential associated discharges and debris. Benefits of the projects may accrue from increased biological productivity after turbines are installed owing to reef effects and fish aggregation around the towers (BOEM, 2018, 2023).

Summary of Biological Oceanography

In the spring, phytoplankton blooms occur in the deeper waters of the continental shelf of the MAB due to the onset of stratification. During the summer months, primary productivity is low, and the shelf is strongly stratified. The productivity of the autumn bloom largely reflects the timing of the breakdown of shelf stratification. The autumn–winter bloom is the dominant seasonal bloom.

Zooplankton forage on the phytoplankton produced in these seasonal blooms. Recent surveys in the Nantucket Shoals region suggest that there are significant seasonal shifts in the abundance and composition of the zooplankton community. The highest concentrations of copepods during winter–spring are of *Centropages typicus*, *Pseudoccalanus* spp., and *C. finmarchicus*, and during summer–fall are *C. typicus* and *Paracalanus* spp. The sources of these copepods include advection from the east and local production.

Most higher-trophic-level species associated with the Nantucket Shoals region feed either directly or indirectly (i.e., by preying on species that feed on the zooplankton) on zooplankton found in the region. Large cetaceans and seabirds are particularly associated with dense concentrations of zooplankton. *C. finmarchicus* is a primary prey of North Atlantic right whales, and these concentrations of *Calanus* as well as other zooplankton species during winter–spring may account for the great numbers of right whales observed feeding in the Nantucket Shoals region and other areas of high productivity in southern New England. Given the high energetic demands of right whales, dense concentrations of copepods are important for successful foraging.

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3
Hydrodynamic Effects of Offshore Wind Developments

STATE OF UNDERSTANDING

The potential effects of offshore wind turbines on the ocean can be due to the physical presence of the structures across the water column and from the effects of wind energy extraction on wind-driven ocean circulation (Figure 3.1). The impacts of offshore wind energy installations on coastal and oceanic environmental conditions and habitats have been examined in terms of the effects on bottom stress, turbulent mixing, along- and cross-shelf transport, and wind stress curl-effects of offshore wind turbines on the hydrodynamics and subsequent physical and biological systems, a substantial amount of information has been gleaned from studies done for European driven (Ekman pumping) upwelling due to vertical motion arising from Ekman divergence. Although there are still significant knowledge gaps in understanding the potential offshore wind farms. However, despite the knowledge base from European waters, there are substantial and significant differences in both the oceanography and the wind farm structures and geometries so that a simple transfer of results is not possible.

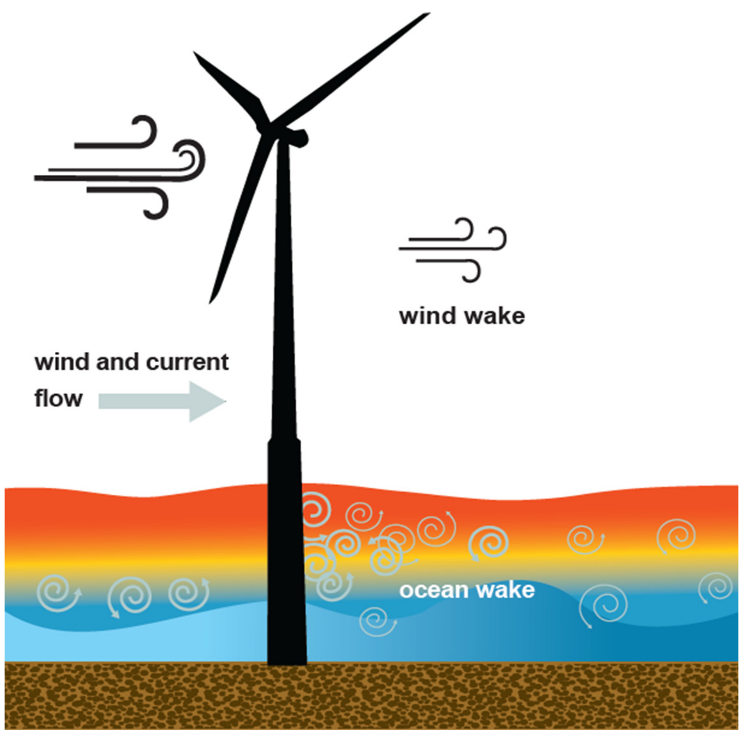

FIGURE 3.1 Schematic of the effects of an individual turbine on local hydrodynamics. The wind blowing from left to right decreases in speed as it moves across the turbine. Ocean circulation, flowing from left to right, becomes more turbulent (shown by increased swirls) as it flows past the turbine, with potential effects on water column stratification (gradient shading, red to blue representing transition from low-density surface water to higher-density water at depth). Wind and ocean wake effects are not shown to scale.

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THE CASE OF THE NORTH SEA: HYDRODYNAMICS

The North Sea, a shallow (mean depth 80 m) shelf sea in northwestern Europe, accounts for more than 75 percent of offshore wind energy capacity in European waters as of 2021 (WindEurope, 2022). The London Array[1], a wind farm that spans 100 km^2 and became operational in 2013, sits on two natural sandbanks in depths of 25 m. This site was chosen because of its proximity to onshore electric power infrastructure and distance away from main shipping lanes in the area. Other wind farms, including Thanet[2] and the northern half of Greater Gabbard[5], span 147 km^2 and are at depths of 24–34 m. These turbines were built to take advantage of the fast-blowing winds over the North Sea's surface (NASA, 2015). Geyer et al. (2015) provided a comprehensive overview of the wind power potential and variability in the North Sea based on simulated wind speed data from 1958 to 2012 and an assessment of the thermal effects on estimates of wind power potential. They found that wind energy potential was largest during the 1990s and 2000s and interannual and decadal variability is an important consideration for offshore wind energy. Therefore, the North Sea's strong winds and shallow shelf made it an ideal location for offshore wind farm construction.

Shelf seas are dynamic environments subject to seasonal heating, atmospheric fluxes, river inputs, and open ocean exchange and are strongly influenced by tidal motion (Cazenave et al., 2016). The North Sea waters can be strongly stratified in the summer with a warm nutrient-deficient upper ocean layer overlying a cool nutrient-dense layer at depth. This steep temperature gradient inhibits the exchange of nutrients, oxygen, and phytoplankton. Mixing of these two layers occurs during certain times of the year when air temperatures drop and vertical stratification weakens, resulting in an almost homogeneously mixed water column during winter in extensive shallow regions (van Leeuwen et al., 2015). When deep, nutrient-rich water mixes with surface water, primary production increases (Gronholz et al., 2017).

The presence of offshore wind farm foundations will lead to enhanced turbulent mixing in a downstream wake. This increased mixing occurs in addition to naturally occurring turbulent mixing processes that act on stratification (Schultze et al., 2017, 2020; Christiansen et al., 2023). Seasonal stratification is known to reduce vertical fluxes, which control nutrient transport to the upper layer and increase primary production. Vanhellemont and Ruddick (2014) analyzed high-resolution imagery in the London Array and found a significant increase in suspended sediments in the wakes of individual turbine monopiles. The plumes were observed to be 30–150 m wide and extended 1 km or more downstream. The spatial extent of the plume effect produced by the turbines was extensive, highlighting the need for further research.

The effects of an offshore wind turbine array in the North Sea on waves, sound, and biogeochemistry were modeled by van der Molen et al. (2014). The effects of the turbines on biogeochemistry were modeled through a constant 10 percent reduction in wind speed within the wind farm area. However, the turbine-structure wake effects were not included in the analyses, and sensitivity studies of the parameterization used to specify changes in wind speed were not done. The simulations of biogeochemical effects showed that wind turbines can result in about an 8 percent increase in net primary production, with an associated reduction in nitrate concentrations of 6 percent and a 3 percent increase in chlorophyll concentration. This had cascading effects throughout the trophic system, including increased sinking of particulate material, resulting in an increase of 35 percent and 20 percent in phytoplankton and zooplankton

[1] Details and specifications for the London Array are provided in Olabi, et al., 2023.
[2] Details and specification for the Thanet and Greater Gabbard Arrays are provided in Higgins and Foley (2014).

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and an increase in food sources for benthic suspension feeders. Overall, these simulation results suggested relatively weak environmental changes, with most of the changes occurring within the wind turbine array and smaller changes occurring several tens of kilometers outside the wind energy array.

Daewel et al. (2022) used a high-resolution atmospheric model to force a coupled physical–biogeochemical model configured for the North Sea and the Baltic Sea. Their simulations provided evidence that increasing the amount of future offshore wind installations will change stratification intensity and pattern, slow circulation, systematically decrease bottom shear stress, and alter primary production. While regionwide averages in estimated annual primary production remained almost unchanged, there were local increases and decreases to primary production of up to 10 percent. Carpenter et al. (2016) created ad hoc idealized models to estimate stratification changes given a mixing rate from offshore wind structures and the residence time of a water parcel within a wind farm. The models showed increases in ocean mixing within a wind farm. However, the analyses indicated that extensive regions of the North Sea must be covered with offshore wind turbines to produce a significant impact on stratification, and a wind farm of the required size has yet to be installed. Cazenave et al. (2016) expanded on this work by including an additional 242 offshore wind turbine monopiles and simulating the effects on seasonal stratification of the United Kingdom shelf with an emphasis on the Irish Sea. The result was increased mixing and decreased stratification. Even though these monopiles are less than 20 m in diameter, their effect was detected over areas of approximately 250 km^2 (Cazenave et al., 2016).

Ocean Effects

The physical presence of wind turbines acts as a barrier to hydrodynamic flow around which a baseline flow (no turbines) must pass, as well as a source of additional turbulent mixing (Figure 3.2, left panel). Miles et al. (2021) summarizes existing laboratory and modeling studies that describe the influence of turbine-induced ocean wakes on downstream hydrodynamics. Laboratory (Miles et al., 2017) and numerical modeling studies (Carpenter et al., 2016; Cazenave et al., 2016; Schultze et al., 2020) focused on monopile structures similar to the structures planned for wind farm deployment in the Nantucket Shoals region. These studies concluded that the magnitude and extent of the turbine's impact varies depending on the magnitude of the existing ocean currents, including subtidal and tidal flows around the structure, the strength of stratification, and the turbine structure geometry and farm layout. Miles et al. (2017) showed that at the individual turbine scale, the peak turbine-induced turbulence occurs within one monopile diameter of the structure, with weaker downstream effects extending 8–10 monopile diameters. This scale of direct influence is confirmed with high-resolution numerical modeling, with modeled turbulence impacts extending up to 100 m downstream of an individual turbine (Schultze et al., 2020). As noted in the previous section on the North Sea case study, the scale of impacts on other environmental variables, such as temperature and suspended sediment, has been found to extend up to 1 km from the turbine structure (Vanhellemont and Ruddick, 2014; Schultze et al., 2020). Using an idealized one-dimensional mixing parameterization, Carpenter et al. (2016) estimated that the impact of offshore wind turbines on the duration of typical North Sea seasonal stratification was uncertain. Variations in the turbine structure geometries and layouts alone could produce a factor of 4.6 difference in the expected turbulence production. Combining this uncertainty with the different possible evolutions of the stratification under

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turbine-enhanced mixing produced mixing rates capable of eroding typical summer stratification in the wind farm region as rapidly as 37 days and as long as 688 days, values that are shorter and significantly longer than the typical length of seasonal stratification in this region of ~80 days. This variability in the turbulence-induced mixing is dependent on the magnitude of the water velocity moving past the turbine, the strength of stratification and its evolution under turbine-enhanced mixing, and turbine structures and farm layouts.

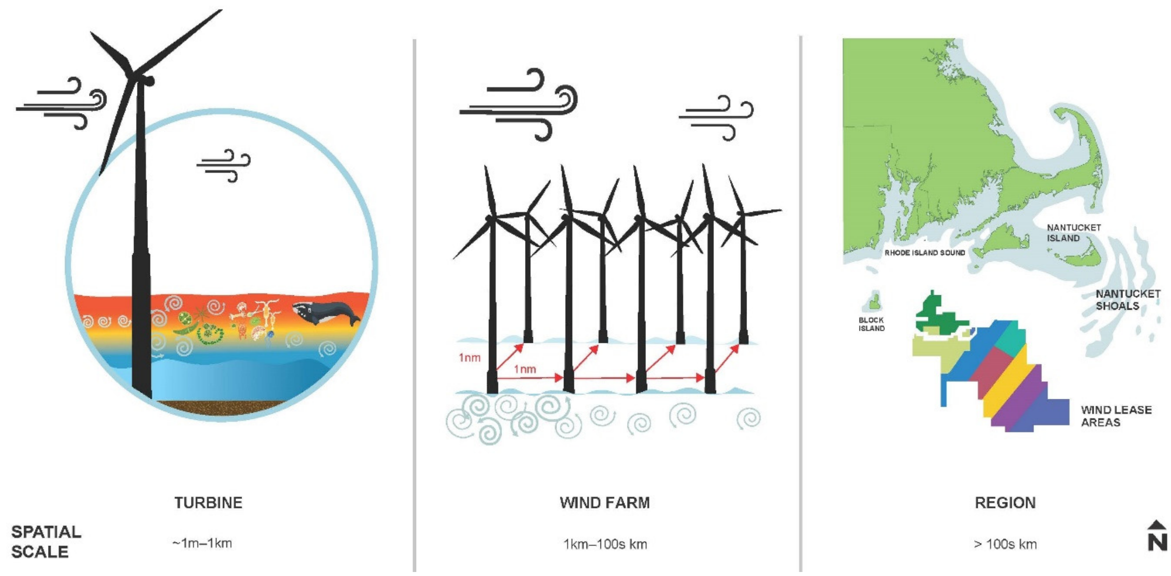

FIGURE 3.2 Effects on hydrodynamics at scales represented by an offshore wind turbine (left panel), an offshore wind farm (middle panel), and regional wind lease areas (right panel). Potential ecological effects at all scales extend from phytoplankton to whales (shown in the left panel), as discussed in Chapter 4.

The cumulative impact of multiple turbines on hydrodynamics is dependent on the relative scales of developed and undeveloped areas (Figure 3.2, middle and right panels). Using an unstructured grid model, Cazenave et al. (2016) expanded results for an idealized single turbine to an entire farm of turbines and found a localized weakening of stratification of about 5–15 percent of simulated seasonal stratification, consistent with previous results. Carpenter et al. (2016) extended these results to a larger geographic region and included advection estimates that restore seasonal stratification in the absence of turbines. This analysis showed that physical oceanographic forces can counteract the effect of wind farm–induced mixing when wind farm area coverage is small relative to the shelf region. Application of laboratory and modeling results from the North Sea to the Nantucket Shoals region must account for differences in the timing and intensity of site-specific ocean processes. These processes include differences in currents, winds, and tides; changes in surface density; and the influence of salt intrusions related to the presence of Gulf Stream warm core rings offshore as described in Chapter 2 (Nantucket Shoals region) and earlier in Chapter 3 (North Sea). Depending on the season and location of the study, ocean conditions within the Nantucket Shoals region are likely to vary from those conditions observed and modeled in the North Sea. Additionally, the impact of turbine-induced

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ocean wakes on stratification must be evaluated within the context of these shelf-wide physical forces specific to the Nantucket Shoals region that affect seasonal stratification. An important additional difference between results for the North Sea and the Nantucket Shoals region is the wider spacing of the turbine structures in the Nantucket Shoals. This is expected to result in a lower concentration of hydrodynamic impacts, other factors being equal (e.g., foundation structure geometry).

Atmospheric Effects

In addition to changes in mixing due to the physical presence of the turbine foundations (monopiles or jackets), wind-driven ocean circulation can potentially be affected via reductions in wind stress at the sea surface due to reduced wind speeds in the lee of a turbine. Since each turbine acts as a momentum sink and source of turbulence, energy extraction from the ambient wind field results in reduced wind speeds downstream of a turbine (Figure 3.1). The theoretical maximum efficiency of a turbine has been found to be ~59 percent (known as the Betz Limit; Betz, 1966), and modern offshore wind turbines extract ~50 percent of the energy from the wind that passes through the rotor area (DOE, 2015), subject to a cutoff wind speed above which wind energy extraction reaches a saturation limit. The maximum reduction in wind speeds is at hub height (in the range of 118 m to 152 m; Beiter et al., 2020), with a decay in the wind speed reductions above and below hub height. Xie and Archer (2015) modeled the horizontal and vertical structure of wind turbine wakes and found that while the largest reductions in wind speed are at hub height, the vertical extent of the region of wind speed reductions begins to extend down to the sea surface within a horizontal distance of 8 rotor diameters. Further, wind speed reductions at a height of 10 m above the sea surface become more pronounced with distance from the turbine. At the scale of an offshore wind farm, wakes have been observed over several tens of kilometers downstream of the wind farm under stable atmospheric stratification conditions (e.g., Christiansen and Hasager, 2005; Platis et al., 2018). Additionally, model studies of the atmosphere have generally reproduced (with respect to measurements) the wake effect several tens of kilometers downstream of a wind farm (Fischereit et al., 2021). The use of remote sensing techniques also offers the potential for additional validation exercises of modeled wind farm wakes (Djath and Schulz-Stellenfleth, 2019). In the North Sea, Duin (2019) examined wind stress reductions for a large offshore wind farm and reported that typical wind speeds at 10 m above the sea surface are reduced by up to 1 m/s, while other effects were observed on air temperature (increases and decreases at various locations around the wind farm), relative humidity (decreases above the wind farm), and shortwave radiation (decreases near the wind farm).

Ocean circulation processes such as upwelling or downwelling are influenced by wind stress at the sea surface when the spatial scales of wind forcing approach or exceed the internal Rossby radius of deformation (in the range of 7 km at the latitudes of Nantucket Shoals). Therefore, although the wake behind a single standalone turbine is unlikely to affect wind-driven circulation, wind stress changes from an offshore wind farm array could occur over spatial scales large enough that wind-driven ocean circulation (e.g., upwelling/downwelling) can be influenced (Figure 3.2).

Several studies have examined the effects of offshore turbines on wind-driven ocean circulation. Most of these studies have focused on the North Sea (see previous section), while studies with a reduced scope (atmospheric circulation, larval transport studies and upwelling

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circulation) have been executed on the U.S. East and West coasts. The effect of wind stress reductions on ocean circulation (upwelling/downwelling) were examined using an analytical framework that showed the presence of a wind stress curl-driven upwelling/downwelling dipole (Figure 3.3) in the lee of offshore turbines (Broström, 2008). The relation between coastal upwelling and wind farm size was examined by Paskyabi and Fer (2012), and Paskyabi (2015), who found that wakes increase the magnitude of pycnocline displacements, and in turn, upwelling/downwelling. A recent observational study conducted by Floeter et al. (2022) found the occasional presence of a curl-driven upwelling/downwelling dipole in the vicinity of a wind farm in the North Sea, similar to what was modeled for hypothetical wind farms in the California Current System by Raghukumar et al. (2023). A coupled physical–biological model implemented by Daewel et al. (2022) examined the effects of wind energy extraction by turbines in the southern North Sea and found changes in modeled primary production over a much larger area. While the appearance of an upwelling/downwelling dipole is justified by a clear, mechanistic understanding of the underlying physics, the appearance of changes (e.g., Daewel et al., 2022; Raghukumar et al., 2023) in other tracer fields, far from the wind farm areas requires further study, particularly from the point of view of understanding whether these changes are driven by numerical noise in instantaneous wind forcing or if there are indeed mechanistic processes that drive changes far from the wind farms.

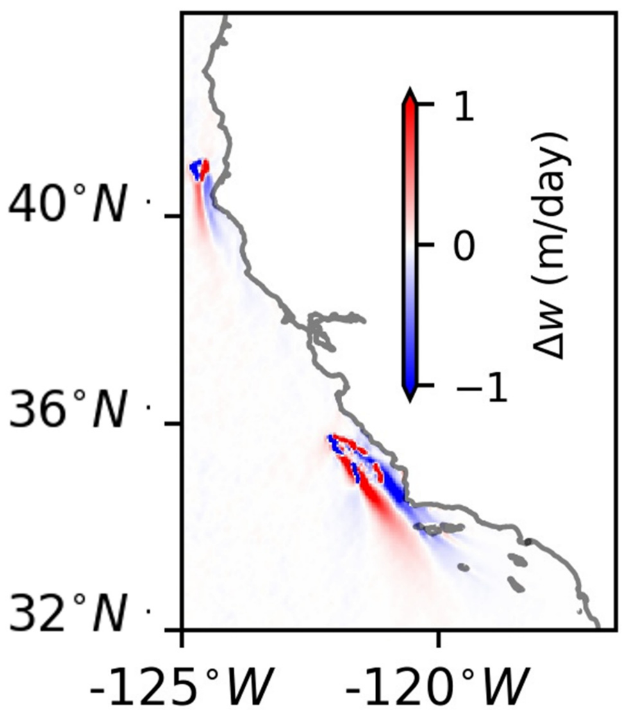

FIGURE 3.3 Example of upwelling/downwelling dipole, in terms of vertical velocity change (Δw) associated with curl-driven upwelling on the U.S. West Coast. SOURCE: Adapted from Raghukumar et al., 2023.

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ABILITY TO ACCURATELY AND PRECISELY ESTIMATE PERTURBATIONS CAUSED BY WIND TURBINE GENERATORS

In examining the potential hydrodynamic perturbations caused by offshore wind energy installations it is helpful to consider three natural length scales (Figure 3.2): (1) the turbine scale, which covers the near-field response of individual structures; (2) the wind farm scale, which is representative of individual farms where individual turbine-scale responses are expected to have either merged or are averaged into a scale that is comparable to the size of the farm; and (3) larger "regional" scales, which encompass the full extent of the perturbations as well as the regional-scale features of the oceanographic environment.

Turbine Scales

On the turbine scale, alterations in the hydrodynamics are produced through the generation of a turbulent wake as ocean currents flow past the turbine structure foundations (Figure 3.4). The wake is the hydrodynamic signature of the extraction of momentum by the drag force on the foundation structure, as well as the production of turbulence (i.e., turbulent kinetic energy [TKE]) through instabilities in the highly sheared viscous and turbulent boundary layers on the structures themselves. An approximate largest scale that defines the range of "turbine-scales" is on the order of 1 km, corresponding to the approximate turbine spacing in many existing farm layouts. This order of 1-km effect comes from observations of (a) sediment plumes (Vanhellemont and Ruddick, 2014; Förster, 2018), and (b) detectable alterations in stratification (Schultze et al., 2020), as well as turbulence-resolving (large eddy simulation [LES]) modeling of the stratification (Schultze et al., 2020). Defining a wake length is, however, dependent on the hydrodynamic quantity under consideration. For example, quantities that describe the turbulence, such as the dissipation rate of TKE or the turbulent buoyancy flux, represent localized wakes around the structures (Rennau et al., 2012; Schultze et al., 2020), with the wake signatures dissipating to the levels of background conditions within a couple hundred meters, compared to the 1-km and greater scales seen in the suspended sediment wakes (Vanhellemont and Rudick, 2014) and in the temperature wakes (Schultze et al., 2020). These differences arise from the different processes governing the dissipation of the wakes, such as turbulence decay versus sediment settling.

To evaluate the ability of existing approaches to accurately and precisely estimate turbine-scale wake perturbations, two methodologies can be applied: (1) a confident baseline can be identified, and each approach validated against it; or (2) two different and independent approaches can be compared against one another. The obvious choice for a confident baseline, identified in multiple studies (e.g., Rennau et al., 2012; Carpenter et al., 2016; Jensen et al., 2018; Schultze et al., 2020; Dorrell et al., 2022), is the classic drag law of a circular cylinder in a uniform, unstratified cross flow. This empirical "law" makes predictions for the extraction of momentum and the production of TKE that can be expected by a simple monopile structure in the idealized setting of an unstratified and uniform flow. Although both conditions are generally not satisfied in the coastal ocean, this drag law nonetheless represents a useful baseline. Despite the oversimplified formulation of the drag law for coastal ocean flows, it has been found to hold also in flows with current shear, a turbulent approach flow, and stratification, with drag coefficients within the classical range of variability (Schimmels, 2007; Jensen et al., 2018; Schultze et al., 2020). Values reported for the drag coefficient, obtained through LES modeling

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and laboratory experiments, are in the expected range (approximately 0.3–1.2) in the study of bridge piers with 0.3–0.8 (Jensen et al., 2018), and at 0.7 for a monopile in sheared, stratified flow (Schultze et al., 2020). However, not even the high resolutions of LES can be expected to consistently capture the physics of boundary-layer separation unless special care is taken close to the structure boundary (e.g., Janssen et al., 2018). The LES approach is therefore problematic when used as a strict test of the drag law. However, particularly in the case of turbine-scale modeling, comparison with the drag law provides a rough validation check that the turbulent momentum and energy fluxes are captured correctly (Rennau et al., 2012; Janssen et al., 2018; Schultze et al., 2020); a recommended step in the validation of the turbine-scale hydrodynamics. The drag coefficient is a function of Reynolds number and surface roughness (among other variables), and values above unity can also be expected (Carpenter et al., 2016), leading to a large range of variability.

Complications in applying the drag law directly to turbine-structure momentum and TKE sinks and sources do arise additionally from unknowns in the hydraulic response of the flow stratification (Dorrell et al., 2022; particularly when internal wave speeds are close to the speed of flow past the structure) as well as any possible biofouling on the structures themselves. The biofouling will likely play a similar role as an increased surface roughness, which has been found to increase drag coefficients on circular cylinders to the saturated high Reynolds number value of approximately unity. However, this correspondence of biofouling to surface roughness is not exact and almost certainly depends on the type of growth on the structures. Biofouling therefore contributes to the uncertainty in determining the drag coefficient. Additionally, some turbine structures have complex geometries that make application of the drag law problematic (e.g., Carpenter et al., 2016), and there are expected to be differences between monopile foundations and other foundation types in momentum extraction and turbulence production. These effects will enter through the changed frontal area of the structure (an input parameter to the drag law) and drag coefficient. To properly account for these effects, specifically designed experiments or simulations must be performed (e.g., Jensen et al., 2018, in the case of bridge piers).

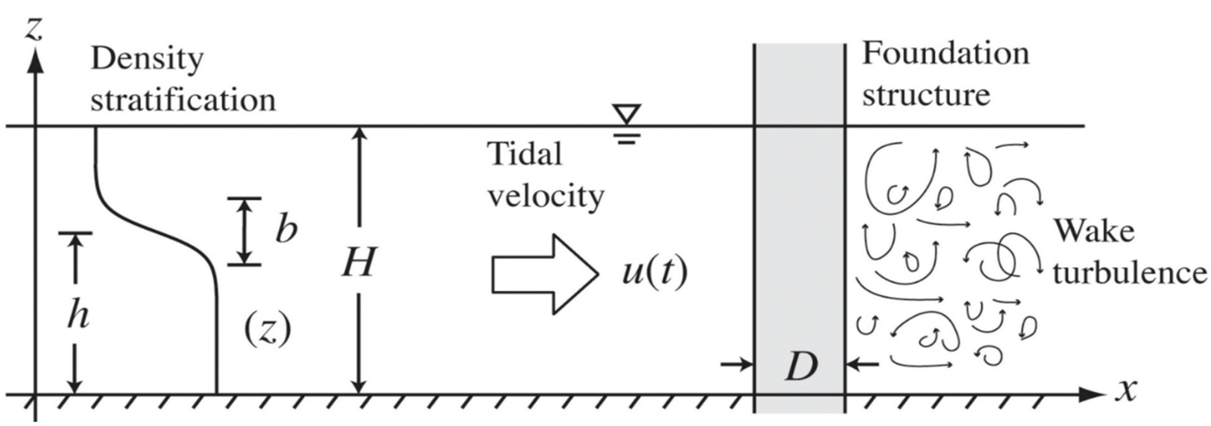

FIGURE 3.4 Schematic of the turbine-scale turbulent wake and relevant parameters for the mixing of stratification considered in the idealized model of Carpenter et al. (2016). The tidal current velocity, $u(t)$, is considered dominant in this North Sea application. The rate of turbine-scale mixing (indicated by swirls) is dependent on the structure and amplitude of currents, stratification (h, b determine pycnocline depth and thickness), and foundation structure geometry (D, diameter of foundation); H is the water depth. SOURCE: Carpenter et al. 2016.

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In addition to the use of LES modeling of the turbine-scale hydrodynamics, Reynolds-averaged Navier-Stokes (RANS) modeling of the wake has been performed (Schimmels, 2007; Rennau et al., 2012). This technique has the advantage of faster computation, allowing for a larger exploration of parameter space; however, larger inaccuracies can be expected due to the greater reliance on parameterizations of the structure-induced turbulence, with a potentially large difference in results (Schimmels, 2007). The highly localized scales of the turbine-scale wakes require careful attention to ensure a validated representation in regional-scale models.

When no established baseline, such as a drag law, is available, confidence in the accuracy of existing approaches can be estimated by a comparison of two independent methods. This was the approach taken by Schultze et al. (2020) in comparing the density structure of a single monopile wake both from observations of a towed chain of conductivity-temperature-depth (CTD) sensors and from LES modeling of the wake stratification. The comparison seemed to show qualitative agreement in the dependence of the wake on background stratification, and in the geometry of the wake; however, the comparison was limited by the difficulty in separating the observations of the wake from the natural background variability as well as the low confidence that necessarily accompanies a single observation of a turbulent flow. In conditions of stronger stratification, no wake could be identified from the observations (Schultze et al., 2020).

Significant uncertainties are associated with estimations of the hydrodynamic responses of the ocean wakes at the turbine scale. Process-based studies that are designed with narrowing of these uncertainties as an explicit objective are needed to accurately and precisely estimate hydrodynamic effects of turbines. There are also very few observational studies for "ground truthing" that can be used to verify turbine-scale wake behavior. Such observations will have to overcome the challenge of separating the turbine-structure effects from those of natural variability.

Wind Farm Scale

The wind farm scale represents the turbine arrays that are often constructed with a relatively tight (compared to the distance between adjacent arrays) spacing of turbine structures, and usually with identical foundation structure types (e.g., monopile) and geometries (e.g., hub heights). These areas can vary widely, but generally have length scales on the order of 10–100 km. Impacts of the turbine structures over the wind farm scale can arise through integrated local (turbine-scale) effects from the individual turbine structures arising from both the atmosphere and ocean wakes. Over this scale, the turbine wakes will possibly have merged with the background conditions to have created a coherent perturbation that may, or may not, be identifiable from the natural background environment. Such wind farm–scale effects identified in the literature include:

- A reduction in ocean current speeds resulting from the increased frictional drag within the wind farm area (Christiansen et al., 2022).
- A reduction in the stratification in a region roughly consistent with the wind farm area (Carpenter et al., 2016; Floeter et al., 2017; Christiansen et al., 2023).
- A "doming" of the pycnocline within the wind farm area, bringing it closer to the ocean surface (Floeter et al., 2017).

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- Ocean surface wind speed reductions focused closely within the wind farm (Golbazi et al., 2022).

Some of these effects may interact with one another. For example, it is important to be able to predict the advective transport of stratification by mean currents, and the possible alterations by ocean wake effects through reduced current speeds, in order to accurately predict impacts to the stratification. However, the evidence found for each of these effects is discussed independently below.

Current speed reductions, as well as altered current directions, represent one possible effect arising from the increased frictional drag forces within the wind farms. Christiansen et al. (2023) conducted a regional modeling study of such effects in the southern North Sea and found small changes in residual mean current speeds (i.e., after averaging out the dominant tidal currents) of approximately 2 mm/s, a speed that represents roughly 10 percent of natural mean currents in this area. This modeling study parameterized the additional friction through the drag law. An alternative approach that aimed at resolving the turbine-scale ocean wakes through a locally enhanced grid around the structures was found to be problematic and inaccurate. The wind farms were simply represented as uniform patches of increased friction and turbulence in accordance with the drag law formulation. Such estimates of alterations in mean residual (i.e., over longer timescales as tidal flows) currents due to ocean wake effects are fairly well supported and suffer uncertainty only in the uncertainty of the application of the drag law, as discussed for turbines in the previous section. Note, though, that there could be significant effects from altered wind speeds on the ocean currents that were not accounted for in the Christiansen et al. (2023) study. Another aspect of the dynamics that could play a role in the ability to estimate perturbations to currents is in the uncertain mixing of the stratification on the wind farm scale, which can lead to current changes through baroclinicity.

Using wind farm–scale observations obtained from a profiler towed through two different wind farms in the southern North Sea, Floeter et al. (2017) found the likely presence of stratification changes within the wind farm areas. A comparison to the predictions of the idealized ad hoc modeling of Carpenter et al. (2016) showed reasonable agreement but, because of uncertainties in the drag coefficient, have a range that differs by a factor of three (Floeter et al., 2017). However, separating the wind farm processes from the natural variability of the background environment was difficult, and a fortuitous transect through one of the same wind farms examined in the Floeter et al. (2017) study before the presence of turbine structures also showed a drop in stratification, albeit smaller than the drops after turbine installation. Christiansen et al. (2023) then used the Floeter et al. (2017) and Carpenter et al. (2016) studies as a benchmark for the regional modeling of stratification changes. Such a benchmark should not be considered a validation because of the large range of uncertainties as well as extremely limited coverage of the required relevant parameter space. The essential quantity required by the Christiansen et al. (2023) regional model is some measure of the bulk mixing efficiency, which expresses the amount of mixing (i.e., changes in the buoyancy field) for a given input of energy (called "production") to the turbulence of the wakes. The turbulence production is relatively well known through the drag law (with the complications discussed above), but the mixing efficiency is not. This crucial unknown mixing efficiency must come from turbine-scale, turbulence-resolving studies such as LES (Janssen et al., 2018; Schultze et al., 2020) or RANS (Schimmels, 2007; Rennau et al., 2012) simulations, or laboratory experiments (Janssen et al., 2018), or from field observation (likely together with one of the above types of studies, e.g., Schultze et al.,

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2020). Although the studies by Janssen et al. (2018) and Schultze et al. (2020) report similar values of the bulk mixing efficiency (ranging from 0.05–0.24 and 0.09–0.14, respectively), they cover a limited parameter range and an idealized uniform-approach flow. Much more work using more realistic coastal flows is needed to improve confidence in these estimates.

Floeter et al. (2017) also observed a "doming" of the pycnocline position within some of the wind farm observational transects, wherein the pycnocline stratification was drawn closer to the ocean surface. Although similar effects could be seen in the Christiansen et al. (2023) study, they were not consistently present. The doming effect remains to be explained and quantified, and it is unclear if it is a robust feature of the wind farm–scale hydrodynamic response.

Wind speed deficits have been found at hub height within wind farms through modeling and observational studies (Platis et al., 2018; Golbazi et al., 2022; Raghukumar et al., 2022). There has been considerable research on atmospheric wakes (e.g., the review by Stevens and Meneveau, 2017); however, the focus of this research has been on understanding flow features at the hub height. Extrapolating the atmospheric-wake flows to the ocean surface remains an uncertain exercise. Observations in the North Sea have shown that the atmospheric wakes can extend to the sea surface and be felt many tens of kilometers to the lee of the wind farms (Hasager et al., 2015; Platis et al., 2018). The horizontal extent of the wake at the sea surface was found to depend strongly on the atmospheric stability (Platis et al., 2018). Golbazi et al. (2022) considered larger hub heights (>100 m) and turbine rotor diameters (>170 m) and found that the wind speed deficit at the sea surface is at most 10 percent of the freestream value. This agrees with the parameterization used by Christiansen et al. (2022) for the lower-hub-height turbines in the North Sea (<100 m) with a maximum wind speed reduction of 8 percent.

Regional Scale

Perturbations to mesoscale circulation due to the presence of wind turbines (such as through changes to upwelling/downwelling and an increase/decrease in eddy kinetic energy within the wind farm areas) can potentially propagate to a regional scale through mechanisms that lead to offshore propagation of mesoscale eddies (Strub and James, 2000). The propagation of eddy variability is influenced by the mean background flow, shape of bottom topography, or energetic features such as coastal jets (Fu, 2009), all of which are prevalent in the Nantucket Shoals region. Most regional-scale models have the ability to propagate mesoscale and submesoscale eddy variability (e.g., Capet et al., 2008), once these are modeled within a smaller region. However, although it is theoretically conceivable that changes to ocean circulation within a wind farm region can potentially propagate out to regional scales, the difficulty arises in being able to quantitatively assess this regional-scale perturbation.

Perturbations due to turbines at the regional scale are more difficult to quantify because the processes responsible for significant environmental variability encompass short timescales of hours, days, and weeks to longer scales of seasons, years, and decades. These regional-scale processes, discussed in Chapter 2 and relevant to the Nantucket Shoals region, include

- Tidal currents that spatially vary and can drive spatially dependent mixing that leads to horizontal fronts.
- Seasonal changes in stratification that vary in timing and strength across the region.

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- Interactions with highly variable offshore Gulf Stream warm core rings that can shift the location of the shelf-break front and frequency and extent of mid-water salinity intrusions.
- Oceanic events that range in scale from the response of coastal and tropical storms to season-long oceanic heat waves.
- Decadal-scale trends in ocean warming, surface ocean freshening, and changes in ocean circulation.

Assessing offshore wind turbines' effects at a regional scale requires observations and analyses that can account for and isolate turbine-generated perturbations from those produced by regional-scale processes. Similarly, modeling studies with and without turbines must assess perturbations relative to the other sources of variability represented in the model. The ability of a particular analysis to properly quantify a regional-scale, turbine-induced perturbation requires an experimental design that properly accounts for the significant contribution of natural variability from event to multidecadal scales.

Finally, given the relatively small scale of perturbations relative to the background mean circulation, the effects of numerical noise in both oceanic and atmospheric circulation models must be considered and mitigation steps taken to ensure that there is no misinterpretation of results. One example of numerical noise has been documented in the atmospheric model, Weather Research and Forecasting (WRF; Ancell et al., 2018) with perturbation experiments that resulted in rapid propagation of errors into the model domain. When used in the absence and presence of wind farms to force an ocean circulation model, these small changes can potentially introduce spurious circulation effects that must be accounted for and mitigated against. Mitigation of numerical noise can be accomplished by averaging across long-time-duration simulations and by using sensitivity studies to determine adequate time durations over which to conduct model simulations.

APPLICABILITY OF HYDRODYNAMIC MODELS TO THE NANTUCKET SHOALS REGION

As detailed in Chapter 2, ocean circulation in the Nantucket Shoals region consists of complex processes that cascade from climatic forcing leading to a mesoscale/submesoscale response which in turn results in an ecosystem response. Mesoscale and submesoscale shelf-break processes in this region range from the presence of offshore warm core rings, wind-driven coastal jets, detachment and subsequent upwelling of the bottom boundary layer, subsurface intrusions, and the presence of a seasonal pycnocline, all of which are accompanied by mixing and nutrient exchange. Reliable predictions about any potential changes to hydrodynamic circulation from the presence of offshore wind farms requires that the range of shelf-break processes that drive nutrient delivery and exchange to the Nantucket Shoals region be accurately represented.

The differences obtained for the effects of turbines on hydrodynamics in the modeling studies by Chen et al. (2016, 2021) and Johnson et al. (2021) arise from differences in spatial scales, temporal resolutions, and wind farm build-out scenarios considered by each model. These differing results underscore the need for a baseline model (no turbines) that is capable of accurately representing and simulating

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1. The regime shift in shelf-break circulation starting in 2010 that coincides with right whale presence in the Nantucket Shoals region,
2. Seasonal and interannual variation of stratification on the shelf, and
3. Warm core ring water masses and the shelf-break front that lead to nutrient fluxes from offshore waters to the shelf.

All of these play an important role in driving nutrient fluxes and prey aggregations that can lead to right whale presence in the region.

Modeling of the regime shift in the shelf-break circulation is within the realm of commonly used regional-scale eddy-resolving models such as DHI-MIKE 3 Flexible Mesh (FM), Delft3D FM, Finite-Volume Community Ocean Model (FVCOM), and the Regional Ocean Modeling System (ROMS), described in more detail below. However, the representation of spatiotemporal variability in stratification requires inclusion of processes such as surface heating and cooling and flows along complex bathymetries that operate on multiple scales that have implications for subsurface nutrient exchange across the shelf break. The representation of mid-water slope water intrusions in any model needs careful consideration during model validation, particularly since the accuracy of this representation is sensitive to mixing parameterizations that can mix out the signal of the plume.

The choice of models is governed by the processes and scales that are of specific interest. The accurate representation of fine-scale, stratification-related processes is typically more suited to models that do not make the hydrostatic assumption, particularly when resolving hydrodynamic features in which the vertical momentum is of the same order as the horizontal momentum. Examples of these processes include convectively unstable buoyant overturns (*e.g.,* cooling of surface waters), short internal gravity waves, or eddies arising from shear instabilities. These processes affect the numerical results only when the model horizontal grid resolution is very small, that is, on the order of meters. The advantage of a nonhydrostatic model for simulating the fine-scale vertical structure is that it can potentially demonstrate the impacts of turbines on seasonal stratification. A disadvantage is that the accurate reproduction of the vertical structure of the flow requires extensive work to calibrate the vertical turbulence closure scheme as well as high computational cost.

Once a baseline hydrodynamic model has been calibrated, validated, and shown to reproduce key features associated with local and regional circulation (such as those listed above), turbines can be introduced into the simulation to study the effects of mixing around the turbine and from reduced wind stresses in the lee of the wind farm area. Modeling wind stress reductions can be achieved using various models with varying complexity and accuracy. Typically, wind stress reductions (i.e., the wind wake) are modeled using either a parameterized engineering model (e.g., PyWake; Pedersen et al., 2023), more complex atmospheric circulation models (e.g., WRF with wind farm parameterizations [Fitch et al. 2012; Volker et al., 2015]) or LESs (e.g., Simulator for Wind Farm Applications [SOWFA; Churchfield et al., 2012]). Modeled wind fields at 10-m height above the sea surface then provide surface-forcing fields for ocean circulation models. Each of the above models has its relative advantages and disadvantages, and their use depends on the specific processes and scales of interest. For example, PyWake is a computationally efficient method to obtain wake structures that has several wake models as options, including the ability to provide custom wake models, but lacks the ability to explicitly model wake interaction, as might occur in a wind farm. On the other hand, an LES might provide very-high-resolution wake structure (on the order of a meter or less) but can be computationally

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prohibitive to model wake structures on the scales of 100 km for input to a regional ocean circulation model. To date, the WRF model appears to be the most widely used (e.g., Daewal et al., 2022; Raghukumar et al., 2023) to provide surface forcing fields for ocean circulation models because of their ability to model wake structures (including wake interactions) at the mesoscale and has been validated performance against measurements (Fischereit et al., 2021). Atmospheric forcing fields for an ocean model can be provided as a one-way forcing field (i.e., the effect of varying ocean surface roughness on the lower atmospheric boundary layer is not explicitly modeled) or via a two-way fully coupled model (e.g., Alves et al., 2018). However, at this time, the need for two-way coupling for wind farm applications has not been specifically demonstrated.

HYDRODYNAMIC MODELS FOR SHELF AND COASTAL OCEANOGRAPHY

Most of the existing three-dimensional (3D) hydrodynamic models implemented to simulate large-scale oceanographic processes in coastal and shelf regions are based on the same governing equations, the RANS equations for an incompressible flow under the assumptions of hydrostatic pressure and Boussinesq approximation. Vertical acceleration due to the fluid motion is thus neglected in the vertical momentum equation. Turbulence closure schemes are required to determine the eddy viscosity for the Reynolds stresses in the RANS equations. Turbulence-induced vertical mixing of horizontal momentum, mass, and heat is modeled by vertical eddy viscosity and eddy diffusivity coefficients. Assumptions are made to relate the magnitude of the coefficients to the scales of velocity and mixing length as determined by various turbulence closure schemes. Although nonhydrostatic ocean models have been developed (e.g., Fringer et al., 2006; Kanarska et al., 2007; Lai et al., 2010), typical applications are limited to surface waves and internal waves or rapid-varying flows with large hydrodynamic or bathymetric gradients.

Examples of RANS models include DHI-MIKE 3 FM, Delft3D FM, FVCOM, and ROMS (Table 3.1). The first three models have been used in BOEM-funded environmental impact statement (EIS) analyses or studies in conjunction with U.S. Atlantic WEAs that include the Nantucket Shoals region; ROMS has been used in a variety of research and operational regional-scale model implementations on the U.S. Northeast North Atlantic Continental Shelf (He and Wilkin, 2006; Wilkin, 2006; Chen and He, 2010) and elsewhere. Nonhydrostatic versions of FVCOM, DHI-MIKE, Delft3D, and ROMS are available, although none have been used in BOEM-funded EIS studies for WEAs. The key relevant hydrodynamic processes simulated or parameterized by these RANS regional ocean models are listed in Table 3.1. The characteristics of ROMS are provided as a comparison.

The ability of RANS models to simulate the multiscale hydrodynamic processes of offshore wind farms depends on a number of factors that include (1) proper parameterizations of the drag force resulting from the ocean wake induced by turbine foundations at the turbine scale, (2) correct representation of the atmospheric wake caused by wind turbine effects on the wind stress that is applied at the ocean surface, and (3) adequate spatial and temporal resolution of the regional-scale model with appropriate open boundary conditions and atmospheric forcing.

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TABLE 3.1 Characteristics of RANS Models Compared to Characteristics of the Regional Ocean Modeling System

Physical Process	FVCOM	DHI-MIKE	Delft3D FM	ROMS
Turbine scale: turbine foundation-induced ocean wake	Subregion model resolving each turbine foundation (Chen et al., 2016; Cazenave et al., 2016)	Parameterized as a drag force (Johnson et al., 2021)	Parameterized as a drag force	Parameterized as a drag force
Horizontal mixing	Smagorinsky formulation of 2D subgrid scale	Smagorinsky formulation of 2D subgrid scale	2D subgrid scale and 3D turbulence computed by a closure scheme	Horizontal Laplacian and biharmonic viscosity and diffusion
Vertical mixing	General Ocean Turbulence Model (GOTM) with a k/ε formulation from Umlauf and Burchard (2005)	Eddy viscosity determined from the k/ε turbulence scheme	Eddy viscosity determined from a 3D turbulence closure scheme	Vertical harmonic viscosity and diffusion computed by turbulence closure schemes
Bottom friction	Drag coefficient determined by spatially varying bottom roughness length in a logarithmic bottom layer	Drag coefficient determined by a Nikurades equivalent roughness length of 0.001 m (Johnson et al., 2021)	Drag coefficient determined by the law of the wall	Drag coefficient determined by the law of the wall
Strong stratification	Using a hybrid vertical coordinate derived from a generalized terrain-following coordinate and data assimilation (Li et al., 2015)		Applying a background vertical eddy viscosity; using the k/ε turbulence scheme; using Z-grid	
Regional scale	Tide-, wind-, wave-, and density-driven flows; transport of conservative variables	Tide-, wind-, wave-, and density-driven flows; transport of conservative variables	Tide-, wind-, wave-, and density-driven flows; transport of conservative variables	Tide-, wind-, wave-, and density-driven flows; transport of conservative variables
Coupling of physical and ecological processes	Coupled with the FVCOM Generalized Ecosystem Module, which divides lower trophic food web processes into seven state variable groups, and the FVCOM Water Quality Module based on the EPA Water Quality Analysis Simulation Program	Coupled with MIKE ECO Lab for complex ecosystems and MIKE ABM Lab for agent-based modeling of coral spawn, eelgrass succession, or other species migration patterns	Coupled with the D-Water Quality module, including chemical composition of a water system and biological components up to the level of primary producers and some secondary producers	Coupled with the North Pacific Ecosystem Model for Understanding Regional Oceanography (Kishi et al., 2007), including 11 state variables (Zang et al. 2020).

NOTES: The first three models, FVCOM, DHI-MIKE and Delft3D FM, have been used in BOEM-funded environmental impact studies to assess the effects of offshore wind energy installations in U.S. east coast continental shelf waters. The Regional Ocean Modeling System (ROMS) characteristics are provided for comparison.

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The typical horizontal resolution used in implementations of RANS regional ocean models varies from 10 m to 10 km (e.g., Chen et al., 2016), which does not allow for resolving the turbine-scale ocean wakes that occur at meter to submeter scales and require nonhydrostatic pressure dynamics and LES of unresolved subgrid turbulence (Table 3.2). Thus, parameterizations of the turbine ocean wake effects as a momentum sink term in the horizontal momentum equations in the form of a drag and inertial force acting on the fluid by the turbine foundation have been implemented into these RANS models (Johnson et al., 2021). The turbulence closure schemes have also been modified to account for the drag force, and the skill of such parameterizations depends on the choice of the drag coefficient. Studies have shown that the drag coefficient is a function of the Reynolds number, varying over a large range. Although the relationship of the drag coefficient and Reynolds number for an unstratified flow around a vertical cylinder in the water column is well understood, uncertainties exist in complex stratified ocean circulation in the shelf and coastal regions. It is crucial to calibrate and validate the RANS models with appropriate drag coefficient values.

TABLE 3.2 Hierarchy of Scales Resolved by Various Models

Scale of Effects	Resolution	Idealized	LES	Non-hydrostatic Models	RANS Models
Turbine O(1)m – O(1)km	Millimeters to meters	🔵	🟢	◖ (green)	◖ (orange)
WEA O(1) km – O(10-100)km	Meters to 10s of meters	🔵	🟠	🟢	🟢
Region >O(100)km	10s-1000s of meters	🔵	🟠	🟢	🟢

🔵 Only assess key processes at these scales
🟢 Support predictions at specified resolution
◖ (green) Some versions can support an unstructured grid
🟠 Full range of process at these scales is constrained by computational capacity
◖ (orange) Can assess specific processes at these scales and requires parameterization

The flexibility provided by unstructured meshes, such as used in FVCOM, supports implementation of subregion models that cover the wind farm scale and explicitly resolve individual turbine foundations with a spatial resolution of 1.3 m (or 2.5 m) along the circumference (15.7 m) of a monopole (Cazenave et al., 2016; Chen et al., 2016). Compared with the drag-force parameterization approach, these subregion models, in theory, include the blockage effects of turbine foundations on the continuity or mass conservation of the flow, as well as the form drag due to flow separation around a turbine foundation (Chen et al., 2016), and

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thereby are intended to eliminate the need for an empirical drag coefficient. However, there are potential drawbacks to this approach. First, the turbulence parameterization must be carefully chosen to be capable of representing rapidly varying separated bluff-body turbulent flows that are naturally nonhydrostatic (Schimmels, 2007). Second, this approach results in a significant increase in computational cost, especially as the number of turbines increases (Cazenave et al., 2016) and does not resolve the effects of nonhydrostatic pressure and the boundary layer at each turbine foundation. The pros and cons of turbine-resolved and turbine-parameterized RANS models for complex ocean circulation are not well understood. It is recommended that a comparative study of the two approaches be carried out using a validated LES model as a reference (e.g., Schultze et al., 2020) as a part of inter-model comparisons.

There is robust literature on modeling the hydrodynamic impact of wetland vegetation on flows and surface waves in coastal areas. Vegetation stems were treated as cylinders of small diameter and parameterized as a drag force in the momentum equations in RANS and nonhydrostatic flow models (Morison et al., 1950; Ma et al., 2013; Chen et al., 2018). RANS models with such parameterizations were successfully used to simulate the hydrodynamics in wetlands (in analogy to the warm farm scale) under extreme weather conditions (Hu et al., 2015) and normal tidal conditions (Ge et al., 2021). Wind surface stress reduction due to the presence of vegetation was also considered in the wind forcing of coastal storms for RANS-type models. It can be concluded that RANS models incorporating proper parameterizations of vegetation-induced drag on the flow and wind stress reduction due to the increase in surface roughness are capable of modeling the cumulative impact of wetland vegetation on coastal hydrodynamics. This lends some confidence in the ability of commonly used RANS models to simulate the cumulative impact of turbines on the hydrodynamics at the scale of a wind farm if the turbine-scale ocean wakes and atmospheric wakes are properly parameterized in the models. It is recommended, however, that care be taken to determine the suitable drag coefficient through comparison with measurements and/or results from high-fidelity LES modeling (e.g., Chakrabarti et al., 2016; Jensen et al., 2018; Schultze et al., 2020).

Effects of offshore wind turbines on wind waves at a regional scale have been studied using spectral wave models based on the wave action balance equation (Chen et al., 2016; Johnson et al., 2021). Model results show potential reduction of wave energy at the wind farm scale and beyond due to the modeled reduction of wind forcing in the atmospheric wake of turbines. Interaction of wind waves with turbines can contribute to ocean wake but it is mainly limited to the upper water column or near the free surface (Chakrabarti et al., 2016). LES and nonhydrostatic models are suitable for quantifying the effects of wave-induced turbulence around a turbine foundation. Wind wave effects have yet to be parameterized and implemented into RANS models to simulate the potential impact on ocean mixing at the wind farm and regional scales.

The regional-scale oceanographic processes in the Nantucket Shoals area are complex, as discussed in Chapter 2. The RANS models listed in Table 3.1 were designed to simulate tide-, wind-, wave-, and density-driven flows, and the transport of conservative variables (heat, salt etc.). The model skill, however, depends on various factors, including (1) the open boundary conditions of a regional model domain, (2) the accuracy of the bathymetry and geometry of coastlines, (3) the momentum fluxes applied on the seabed and the ocean surface, (4) the parameterizations of turbulent mixing or the accuracy of the turbulence closure schemes, and (5) the temporal and spatial resolution of a model (e.g., Tian and Chen, 2006; Chen et al., 2011; Sun et al., 2016). For example, comparing the model results from the Northeast Coastal Ocean

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Forecast System, which is based on FVCOM, with the CODAR-derived surface currents in Block Island Sound over 8 years showed that tidal currents were overestimated because of inaccuracies in local bathymetry and bottom roughness (Sun et al., 2016). Modeled tidal elevations are sensitive to tidal forcing specified at the open boundary of the computational domain. Stratification has limited impact on tidal elevation, but it can significantly affect the tidal-current profile in the water column and can interact with the steep bottom topography, resulting in energetic internal waves (Chen et al., 2011). With sufficient spatiotemporal resolution as well as realistic open boundary and atmospheric forcing, RANS models such as ROMS are capable of simulating the interaction of Gulf Stream warm core rings and shelf-break circulation (e.g., Chen and He, 2010; Chen et al., 2014).

The errors in simulated temperature and salinity obtained from RANS models (Table 3.1) can be reduced through assimilation of data that include, but are not limited to, satellite sea surface height (SSH), sea surface temperature (SST), and other remotely sensed oceanographic data (Medina-Lopez et al., 2021), in-situ temperature, and salinity profiles measured by different methods, such as expendable bathythermograph, Argo floats, shipboard CTD casts, and glider transects (Chen et al., 2014b). With multidecadal, high-resolution, data-assimilated simulations, RANS models such as FVCOM can capture the significant seasonal and interannual variability of stratification in the Northeast Atlantic Continental Shelf (Li et al., 2015).

In addition to tide- and wind-driven circulation on the continental shelf, the hydrodynamic models implemented for the Nantucket Shoals region must include seasonal progression of stratification and capability to simulate interannual variability scenarios as well as the effects of long-term surface densification, onshore advection of warm core rings, and onshore migration of shelf-break front. Accurate representation of these complex oceanographic processes is difficult and made even more so because of inevitable errors in the open boundary and atmospheric forcing, as well as the imperfect parameterizations of turbulent mixing and turbine-induced oceanic and atmospheric wakes. It is recommended that adequate model calibration and validation against field observations and inter-model comparison of key processes be implemented to evaluate model skill in predicting key metrics such as seasonal variability of stratification and atmospheric wake effects. A related recommendation is to identify key metrics that can be used to evaluate skill of individual models and across models.

Model calibration, verification, and validation should take a hierarchical modeling approach, starting with idealized simulations that address key physical processes at scales ranging from individual turbine, wind farm area with planned or built offshore wind farms, and regional area encompassing the wind farms (Table 3.2). The idealized simulations are particularly useful for the turbine-scale processes because much fewer turbine-scale observations are available compared to those at the regional scale. In the absence of field measurements near a turbine, high-fidelity models, such as LES models (e.g., Schultze et al., 2020), should be employed to produce reference results for idealized simulations to calibrate and verify the parameterizations of oceanic and atmospheric wake effects in regional RANS models. It is also highly desirable to develop reference results using high-fidelity models at the wind farm scale for idealized simulations. In addition to comparison with LES model results, idealized simulations at hierarchical scales should test the sensitivity of RANS model results to the spatiotemporal resolution. Such convergence tests should consider the realistic bathymetric and open boundary conditions, albeit simplified, to capture the key oceanographic processes. Moreover, it is necessary to consider the need for fine spatial resolution in zooplankton modeling when designing the computational mesh for hydrodynamic modeling. Studies have shown that spatial

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resolution of hydrodynamic models for coastal and shelf circulation can significantly influence the modeled transport and dispersal patterns of marine organisms in their early-life stages (Ward et al., 2023).

To capture the natural variability of oceanographic processes, multiyear simulations with long-term scalability should be conducted as opposed to considering only extreme weather events (Chen et al., 2016) or a single year (Johnson et al., 2021). The regional model domain needs to be large enough to include relevant open boundary fluxes from the Gulf Stream and the upstream region (Chen et al., 2014; Tian et al., 2014) because the interaction of the warm core rings and shelf-break circulation is one of the key physical processes in the Nantucket Shoals region. For model calibration and validation, observations from satellites, shore-based remote sensing platforms, in situ sensors, and airborne and shipborne sensing must be synthesized and utilized (Medina-Lopez et al., 2021). It is important to include model uncertainty estimates as part of the validation processes. The conclusion of a hydrodynamic modeling study on the environmental impact of offshore wind farms should be drawn in the context of model uncertainties, natural variability, and marine ecology.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion: Knowledge of the effects of offshore wind turbine structures on hydrodynamics is limited and primarily based on modeling studies. At the turbine scale, there are few observations that can be used to verify turbine-scale wake behavior, and coverage of parameter space is limited in modeling studies. At the wind farm scale, the potential impacts include reduction in ocean current speeds, reduction in the stratification, reduction in ocean surface wind speed, and deflection of the pycnocline. At the regional scale, perturbations due to turbines are difficult to quantify because of the natural processes that drive significant environmental variability across the region.

Understanding Hydrodynamic Effects

Conclusion: There are significant uncertainties in the hydrodynamic response of the wind and ocean wakes and of hydrodynamic effects of turbines.

Conclusion: Impacts of offshore wind development in the Nantucket Shoals region on the regional hydrodynamics are uncertain and will be difficult to isolate from the much larger magnitude of variability introduced by natural and anthropogenic sources (including climate change) in this dynamic and evolving oceanographic system.

Conclusion: More hydrodynamic observations are available at the regional scale than at the wind farm and turbine scales. Existing oceanographic monitoring programs historically have, and should continue to provide, important baseline data at the regional scale; new smaller-scale observational studies are encouraged and are a priority.

> **Recommendation**: The Bureau of Ocean Energy Management, National Oceanic Atmospheric Administration, and others should promote, and where possible, require observational studies within wind farms during all phases of wind energy development—

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surveying, construction, operation, and decommissioning—that target processes at the relevant turbine to wind farm scales to isolate, quantify, and characterize the hydrodynamic effects. Studies at Block Island, Dominion, Vineyard Wind I, and South Fork should be considered as case study sites given their varying numbers of turbines, types of foundation, and sizes of spacing of turbines.

Modeling Capability and Validation

Conclusion: The hydrodynamics of the Nantucket Shoals region are driven by complex interactions among shelf-break processes, seasonal stratification, annual variability, bottom friction, tides, and flows over complex bathymetry. In addition to these processes, models should also represent the variability associated with region-specific processes such as long-term surface densification, onshore advection of warm core rings, onshore displacement of shelf-break front, and interdecadal variability in circulation.

Conclusion: The structure and magnitude of the wind wakes from offshore wind turbines at the sea surface are poorly understood since most measurement and modeling efforts have focused on wind speed reductions at hub height. Further, the effect of the lower boundary layer (ocean surface roughness) and atmospheric stability on wind stress reductions at the sea surface is also poorly understood.

Conclusion: There is a hierarchy of important modeling approaches that assess hydrodynamic impacts, from small-scale idealized simulations and LES that resolve individual turbines to larger-scale, fully dynamic models at the regional scale.

Conclusion: Hydrodynamic modeling studies funded by BOEM (MIKE/DHI, FVCOM, Delft3D) differ in their parameterization and/or representation of turbines and wind farm areas, which likely have contributed to differences in simulated hydrodynamic wind and ocean wake impacts.

Conclusion: Model errors and uncertainty propagate through to the predictions and introduce associated uncertainty in assessing hydrodynamic and ecological impacts.

Recommendation: The Bureau of Ocean Energy Management, 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. These studies should

- Evaluate the ability of the model to represent the physical complexity of the processes specific to the questions asked (from small-scale idealized and large eddy simulation models to fully dynamic models at the regional scale).
- Evaluate the model sensitivity to selection of model configuration, parameterization, and/or turbine representation.
- Quantify the uncertainty in the simulated output and implications for interpretation of results.

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- Evaluate model performance through intercomparisons with other models and, once available, data from observational studies at the turbine and wind farm scales.
- Make parameterizations, model configurations, and solutions publicly available to encourage engagement by the broader community to assess model predictions of offshore wind turbine impacts.

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4
Potential Ecological Impacts of Offshore Wind Turbines

STATE OF UNDERSTANDING

The presence of wind turbines has the potential to impact hydrodynamic processes, though the magnitude and direction of any potential impacts remain poorly understood and difficult to parameterize, as discussed in Chapter 3. If present, significant impact(s) to hydrodynamic processes may in turn impact primary production as well as upper-trophic-level consumers (Figure 4.1). In the Nantucket Shoals region, potential changes to the supply, abundance, and aggregation of zooplankton may, in turn, affect the critically endangered North Atlantic right whale, which has recently been observed foraging in this habitat. As described in Chapter 2, copepods are the primary prey of right whales, particularly *Calanus finmarchicus*. Although these zooplankters are capable of swimming (Hirche, 1987), they are advected and aggregated by various physical forcing mechanisms and regimes (Sorochan et al., 2021). The presence of copepod concentrations in sufficient density to allow for profitable feeding in right whales (reviewed in Ross et al., 2023, table 2) is the product of several factors, which mirror the three scales of interest for offshore wind energy development: turbine, wind farm, and regional. At the largest scale, a supply of copepods must be produced that are available in sufficient quantities to support reproduction and maintenance of right whale populations (Fortune et al., 2013), and this supply must be delivered to the region where right whales are able to find and access these prey. At the scale of the wind farms, the processes and conditions that support copepod growth, produce aggregations, and influence where copepods are found in significant concentration(s) are important. Finally, at the scale of the turbine, combinations of water mass movements, bathymetry, and submesoscale circulation patterns are important for aggregating copepods. Changes in prey availability can have important conservation implications by directly affecting right whale reproduction rates (Meyer-Gutbrod et al., 2015) and/or triggering distribution shifts that reduce the efficacy of protective policies (Davies and Brillant, 2019; Meyer-Gutbrod et al., 2018). This chapter reviews what is known about the impacts of wind turbines on surrounding ecosystems and assesses what is known about how these mechanisms may affect the ecosystem of the Nantucket Shoals region, with a focus on how these influence right whales.

Ability to Accurately and Precisely Estimate Potential Effects on Ecosystems

Most relevant studies of the ecological effects of wind turbines and wind farms have been done for installations in the North Sea and are summarized in the following sections. These studies represent potential ecological effects that may occur in the Nantucket Shoals region, but the magnitude and degree of impact may differ from the North Sea, especially in terms of potential impact on zooplankton and right whales.

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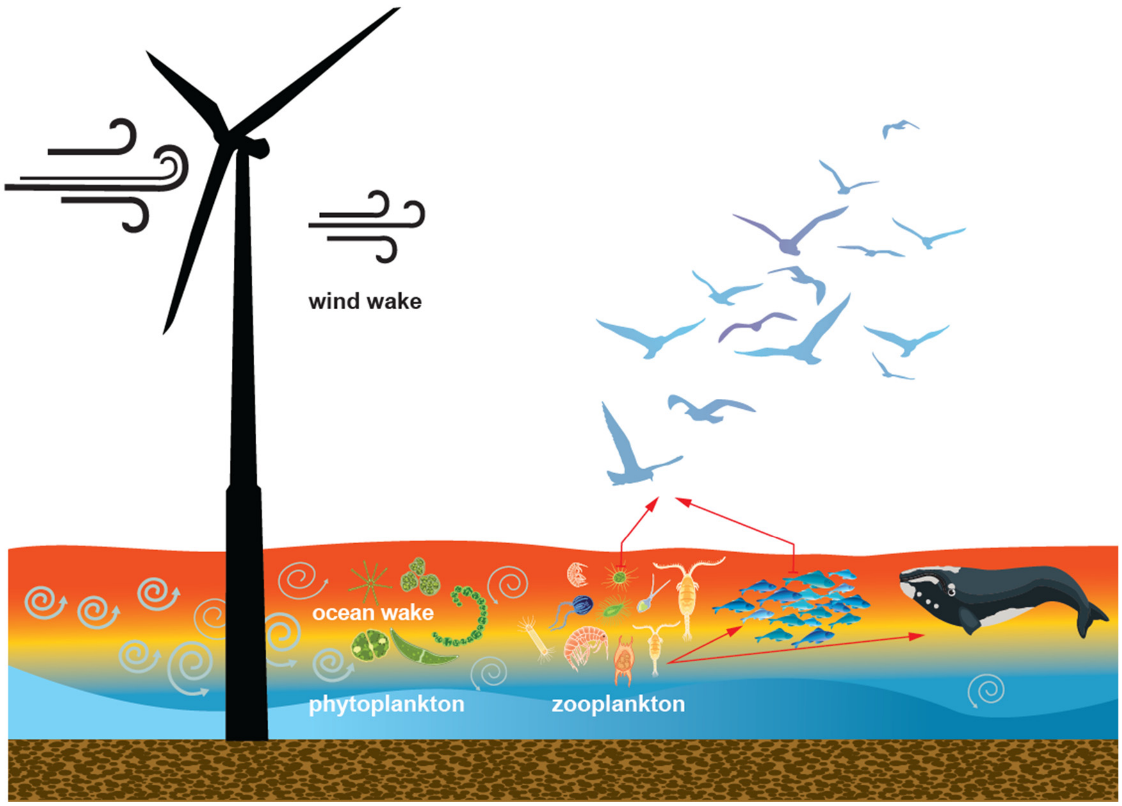

FIGURE 4.1 Schematic of potential ecological effects of a wind turbine that extend from phytoplankton to whales. The wind, blowing from left to right, decreases in energy as it moves across the turbine. Ocean circulation, flowing from left to right, becomes more turbulent (shown by increased swirls) as it flows past the turbine, with potential effects on water column stratification (gradient shading, red to blue representing transition from low-density surface water to more dense water at depth). The turbine, phytoplankton, zooplankton, and higher-trophic-level organisms are not shown to scale.

Turbine Scale

The turbine structure provides a hard substrate (artificial reef) that creates habitat for rapid colonization by many species (e.g., Degraer et al., 2020). The habitat gain provided by wind turbines can enhance abundances of local species, alter local biodiversity, and create new feeding areas for many species (Bergström et al., 2014). The turbine provides vertical substrates as well as a range of horizontal habitats that are defined by foundation type (Degraer et al., 2020). Species that live on and attach to the turbine structure form a new community that can affect the benthic community beneath a turbine and the local pelagic food web. Many of the species that attach to the hard surface of the turbine are suspension feeders that can represent over 95 percent of the biomass on artificial structures (Coolen et al., 2018). These suspension feeders have the potential to reduce local concentrations of phytoplankton, microzooplankton, and mesozooplankton (e.g., Degraer et al., 2020), increase the supply of pelagic food to the benthos (Slavik et al., 2019), and enrich the organic matter content of sediments around turbines (Maar et al., 2009).

Removal of phytoplankton biomass via filtration has the potential to alter pelagic primary production which in turn can alter the local food web and biogeochemical cycling (Slavik et al.,

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2019; Degraer et al., 2020). As an example, the blue mussel (*Mytilus edulis*) is a dominant colonizing suspension feeding species on wind turbines. In addition to affecting the pelagic food web via filtration and the benthic community via organic matter deposition, this species has the potential to modify ecosystem structure in the local vicinity of turbines via reef-building on the surrounding sediments, as has been observed around turbines in the North Sea (Lefaible et al., 2019) and Block Island (Hutchison et al., 2020a,b). Increased availability of hard substrates can facilitate the establishment of non-native species by creating new dispersal pathways that support migrations into new regions (Adams et al., 2014), thereby altering local biodiversity. For example, in the North Sea, the barnacle *Balanus perforatus* expanded farther north using the offshore wind farm habitat (Glasby et al., 2007; De Mesel et al., 2015). The scour protection materials around wind turbine pilings (e.g., concrete mattresses or rocks) also increase the availability of hard substrate, creating new benthic habitat. The observed ecological effects of turbine scour protection include shifts in community composition, modified biomass abundances, changes in biodiversity, and introduction of new species (Hutchison et al., 2020b; Wilson and Elliott, 2009; Ter Hofstede et al., 2022). Burkhard et al. (2011) implemented an integrated modeling framework that linked circulation, ecosystem, and food web models to assess the impacts of wind farms on trophic levels, biotic diversity, and energy transfer, with a focus on the effect of additional hard substrate provided by piles. This analysis showed small changes in total system biomass before and after wind farm construction, suggesting that the artificial reef effect from the piles would not have a significant impact on the structure and energy flow of the local ecosystem.

A review of several studies of the local ecosystem impacts of wind turbines showed that the primary effect of the additional hard substrate was to increase aggregations and locally increase abundances of pelagic and benthic species (e.g., Bergström et al., 2014). Studies of ecosystem changes resulting from the artificial reef effect on higher trophic levels have shown changes in feeding behavior of specific fish species, aggregation behavior around wind turbines (Reubens et al., 2014), and site fidelity (Reubens et al., 2013). Sampling at sites before and after construction, operation, or presence phase of offshore wind farms (Before-After-Control-Impact design; Green, 1979) has been used to detect changes in fish species or fish groups (Methratta et al., 2020, table 2 and references). The changes detected by these observational studies include increased fish assemblages around foundations over short and long times, increased biomass of certain species (e.g., crabs, lobsters), and increased biodiversity (Methratta et al., 2020; Perry and Heyman, 2020). However, differentiating avoidance and attraction effects of offshore wind turbines on various species from seasonal and weather effects was difficult. These studies showed inconsistent or weak effects of offshore wind turbines on fish, with the implication that the disturbance from these structures is small relative to natural variability (e.g., van Hal et al., 2017; Methratta et al., 2020).

Observational assessments of the impacts of wind turbines, including wake effects, on local zooplankton assemblages, production, and aggregation are limited. A study of zooplankton in a wind farm in coastal waters off China showed no significant difference in the spatial distribution of zooplankton within and outside of the wind turbines, a change in the relative abundance of zooplankton species after wind turbine construction, increased microzooplankton abundance, and decreased macrozooplankton abundance (Wang et al., 2018). The decrease in macrozooplankton biomass was correlated with suspended sediment concentration, which may be related to turbine effects on local flow (Wang et al., 2018).

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Wind Farm Scale

Simulations obtained from a coupled hydrodynamic–ecosystem model were used by Daewel et al. (2022) to project the effects of increasing offshore wind generation capacity in the North Sea on the ecosystem. Simulations showed that increasing the amount of future offshore wind farm installations relative to current capacity will alter the wind field, resulting in a shoaling of the mixed-layer depth, modifications to the vertically averaged horizontal velocities, and production of an upwelling/downwelling dipole in the wind farm region of the southern and central North Sea. Daewel et al. (2022) showed about a 10 percent increase/decrease in simulated net primary production inside the offshore wind farm region, which was attributed to modified nutrient supply from the upwelling/downwelling circulation. The increased phytoplankton biomass resulted in about a 12 percent increase in zooplankton biomass, suggesting that grazing control on the local ecosystem could be enhanced by wind farms. The increased zooplankton production could be consumed by higher trophic levels with implications for ecosystem structure (Daewel et al., 2022). Consequently, the changes in primary production at wind farm scales were considered to be potentially important for ecosystem productivity and ecosystem structure (Daewel et al., 2022). Moreover, changes in current velocities modified bottom stress, resulting in reduced resuspension of organic matter, thereby increasing local sediment carbon by 6 percent to 10 percent, potentially enriching the benthos (Daewel et al., 2022).

Slavik et al. (2019) assessed the sensitivity of pelagic primary productivity to increased abundance and distribution of *M. edulis* in North Sea wind farms. This analysis used a coupled circulation–ecosystem model that included an empirically based filtration model to simulate removal of phytoplankton carbon by *M. edulis*. Simulation scenarios assessed the effects of only epibenthic mussels versus the effects of additional epistructural *M. edulis* at the wind farms. The simulations showed that the increased presence of *M. edulis* in wind farms can reduce phytoplankton productivity by up to 8 percent but with considerable variability in the magnitude of the change over the 11 years (2003–2013) included in the simulation, with some years showing little to no change. The differences in simulated productivity may reflect natural annual variability in the patterns of phytoplankton productivity in the regions included in the simulation (Slavik et al., 2019). The presence of *M. edulis* also changed the magnitude and timing of delivery of organic matter to the sediment which has implications for biogeochemical cycling (Slavik et al., 2019; De Borger et al., 2021).

Regional Scale

The effects of offshore wind turbines on ecosystem structure and production at the regional scale are difficult to quantify because of the complexity of potential responses that encompass a wide range of time and space scales. Daewel et al. (2022) found changes in net primary production that extended outside of offshore wind farms, but when integrated over the regional scale of the North Sea, the positive and negative changes tended to cancel. Regional averages of net primary production for the whole North Sea and surrounding regions showed reductions of −0.5 percent, which is within natural variability. Sediment carbon showed only about a 0.2 percent increase when averaged over the North Sea, again within natural variability.

Simulations of the epistructural filtration from increased abundances of *M. edulis* showed that potential ecosystem effects extend beyond the local wind farm to regional scales (Slavik et al., 2019). The simulations showed decreased phytoplankton carbon within 20 km of an offshore

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wind farm and an increase up to 50 km outside the wind farm area, changes that were attributed to *M. edulis* filtration. These regional effects arise from complex ecosystem interactions that control nutrient, phytoplankton. and zooplankton production. Slavik et al. (2019) conclude that the increased abundance of *M. edulis* associated with offshore wind farms only moderately affects ecosystem functioning via modifying net primary production but suggest that the effect on benthic structure (reef building) and as prey for higher trophic levels may be more important.

Assessing the regional-scale ecosystem effects of turbines requires observations, analyses, and models that can account for and isolate turbine-generated perturbations from those produced by regional-scale ecosystem processes, including climate change–driven alterations in those processes. The modeling studies done to date focus on identifying effects on nutrient cycling, primary production, and secondary production. Quantitative studies of the effects on regional-scale species distribution and diversity are needed, especially for higher trophic levels, to isolate species-specific effects of offshore wind farms from natural variability.

Importance of Linking Ecological and Hydrodynamic Models

Baleen whales, such as the endangered North Atlantic right whale, rely on dense aggregations of their zooplankton prey for successful foraging (Fortune et al., 2013; van der Hoop et al., 2019). To meet energetic demands, right whales typically target the lipid-rich late copepodite and adult stages of *C. finmarchicus* (Figure 2.4; Wishner et al., 1995; DeLorenzo Costa et al., 2006) in densities of 1,000–10,000 individuals/m^3 (Baumgartner and Mate, 2003; Fortune et al., 2013). Energetic demands of lactating females are even higher, requiring them to target late-stage *C. finmarchicus* median densities >15,000 individuals/m^3 (Gavrilchuk et al., 2021). Nutritional variability within a given copepod life stage varies with environmental parameters and may also impact right whale foraging success (DeLorenzo Costa et al., 2006; Michaud and Taggart, 2007; McKinstry et al., 2013). Right whales forage on relatively shallow (hundreds of meters or less) aggregations of *C. finmarchicus* and thus concentrate their feeding on the continental shelf (Baumgartner et al., 2003, 2017; Plourde et al., 2019). Hydrodynamic processes impact the production, growth, and advection of right whales' zooplankton prey within a region, as well as the concentrating mechanisms that govern the density of zooplankton within an aggregation (Figure 4.2, reviewed in Sorochan et al., 2021).

Hydrodynamic Impacts on Zooplankton Abundance and Density

Hydrodynamics influence zooplankton at a range of spatial scales, from large-scale circulation patterns that supply or remove zooplankton to fine-scale physics that contribute to the formation of high-density patches (Prairie et al., 2012, fig. 3). The most important physical processes will depend on the time of year, location, and behavior and life history of the species in question. Although late-stage *C. finmarchicus* is the primary prey, right whales also feed on other *Calanus* stages and other zooplankton species, such as *Pseudocalanus* spp., *Centropages* spp. and barnacle larvae (Mayo and Marx, 1990; Hudak et al., 2023). These different species have varied interactions with the physical environment.

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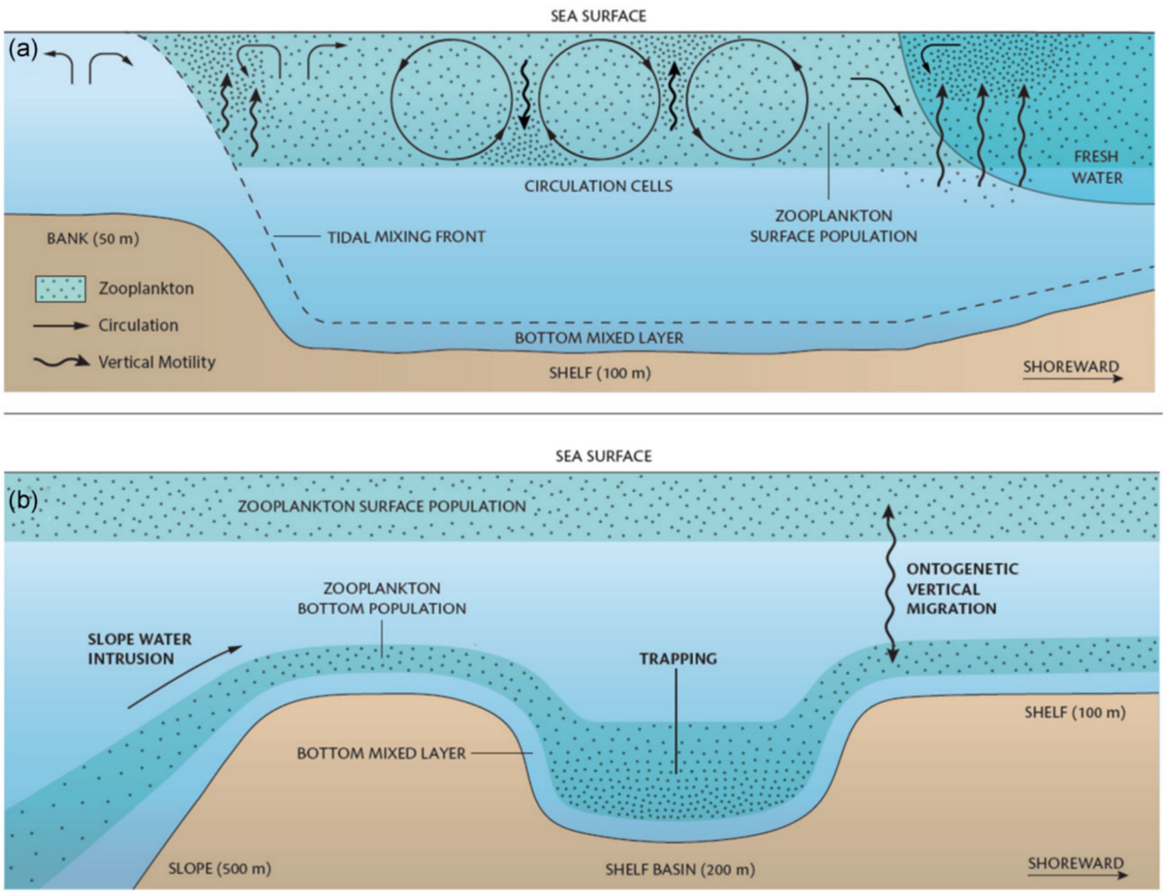

FIGURE 4.2 Summary of processes that influence dynamics of *Calanus* spp. in (a) only the active phase (upper water column) in a shelf-bank environment; (b) active and diapause phases at a slope–shelf interface and shelf basin. SOURCE: Sorochan et al., 2021.

Climate-driven changes to ocean temperatures and circulation have significant potential to reduce the spatial extent and density of *C. finmarchicus*, a critical species in the Northwest Atlantic food web (Reygondeau and Beaugrand, 2011; Grieve et al., 2017; Chust et al., 2014). Abundance of *C. finmarchicus* is highly sensitive to oceanographic and ecological conditions, due to trophic and demographic impacts at the local scale (Frank et al., 2005; Ji et al., 2022; Wiebe et al., 2022), fluctuations in temperature and salinity driven by shifting water masses (MERCINA Working Group, 2012; Davies et al., 2014; Meyer-Gutbrod et al., 2021), and changes in advective patterns that impact *C. finmarchicus* downstream supply (Ji et al., 2017; Greene and Pershing, 2000; MERCINA Working Group, 2004; Ji et al., 2022). For example, in the coastal amplification of supply and transport (CAST) hypothesis, biologically productive coastal waters support the rapid reproduction and growth of *C. finmarchicus* individuals that may then be advected to boost the population in the Wilkinson Basin, just upstream of the Nantucket Shoals (Figure 2.2; Ji et al., 2017). However, modeling of advective transport is complex because it operates differently depending on the life stage of the individual copepod; naupliar life stages and reproductive adults are affected by surface currents, and diapausing copepodites in ocean basins are affected by deeper currents and bathymetry (Figures 4.3 and 4.4; Ji et al., 2022).

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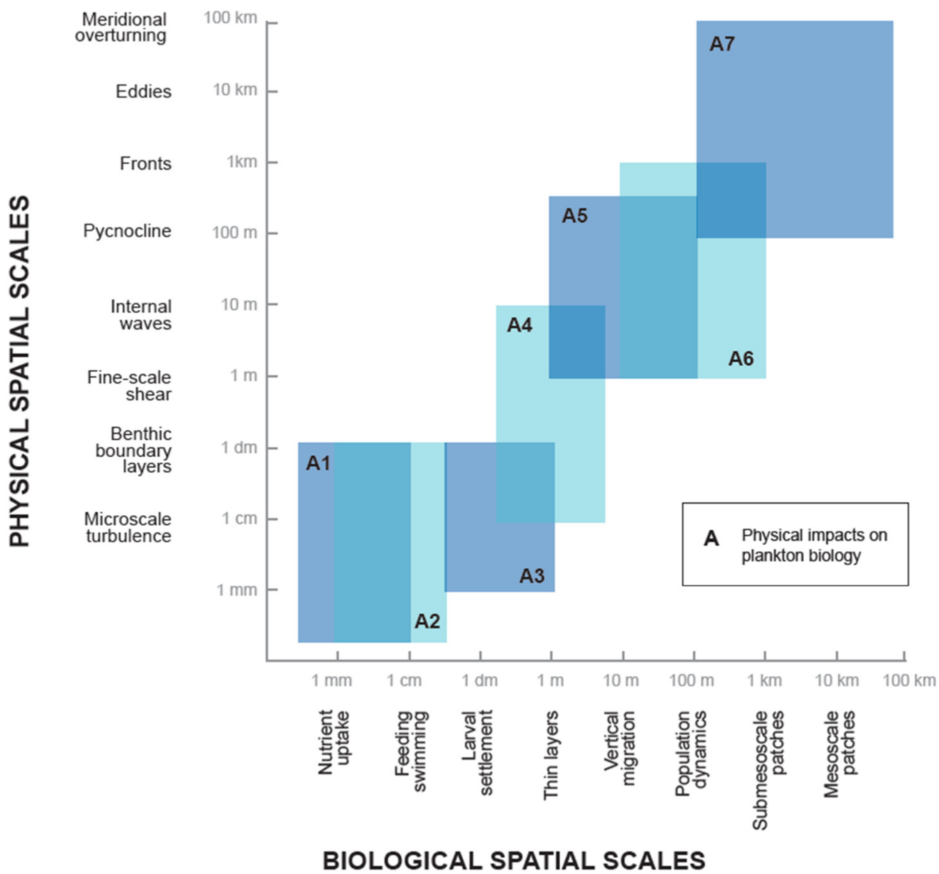

FIGURE 4.3 Scales of interactions and overlap between biological and physical processes relevant to plankton ecology. Boxes represent physical processes that affect plankton dynamics or distributions: A1, effect of turbulence on plankton growth and community composition; A2, turbulence and plankton encounter rates; A3, impact of benthic boundary layers on plankton dynamics and distributions; A4, plankton thin layers; A5, horizontal plankton patchiness induced by internal waves; A6, planktonic interactions with coastal flow; A7, fronts and submesoscale to mesoscale plankton patchiness. SOURCE; Adapted from Prairie et al., 2012.

Local factors also contribute to the production, growth, advection, and aggregation of *C. finmarchicus,* and thus contribute to the suitability of a habitat for right whale foraging. Oceanographic processes that increase local stratification, including freshwater transport from the Arctic Ocean and incursions of warm Gulf Stream water have been linked to declines in *C. finmarchicus* (MERCINA Working Group, 2012; Greene et al., 2013; Meyer-Gutbrod et al., 2021), and this may be caused by an ecological shift to smaller zooplankton taxa during highly stratified, summer-like, water column conditions (Pershing and Kemberling, 2023). As an income breeder, *C. finmarchicus* production is strongly associated with seasonal variability in the phytoplankton and microzooplankton available for adult females to consume (Durbin et al., 2003; Runge et al., 2006). For effective foraging, right whales target high-density patches of prey (3,000–15,000 copepods/m^3; Wishner et al., 1988; Baumgartner and Mate, 2003) that have been aggregated by copepod behavior and/or local physical concentrating processes. Aggregation density of late-stage *C. finmarchicus* is spatially and temporally heterogeneous but is difficult to capture in models (Ross et al., 2023). The processes that lead to zooplankton patch formation

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vary across the different foraging habitats and depend on circulation features, bathymetry, and water mass structure (reviewed in Sorochan et al., 2021). In areas with complex bathymetry, tidal currents can interact with steep bathymetric gradients to form dense patches of diapausing *C. finmarchicus* (Davies et al., 2013), and these patches have been associated with fine-scale water mass features within a single basin (Davies et al., 2014).

The supply, transport, and aggregation of late-stage *C. finmarchicus* also responds to oceanographic processes across a range of temporal scales. Natural and anthropogenic climate processes have been linked to reductions in *C. finmarchicus* supply to right whale foraging habitats on decadal scales, with reductions in prey availability demonstrated in the 1990s (Greene et al. 2013; Meyer-Gutbrod and Greene, 2014) and 2010s (Record et al., 2019; Sorochan et al., 2019; Meyer-Gutbrod et al., 2021, 2022). Interannual variability in abundance can depend on the direction and strength of winds and coastal currents and their contribution to particle retention (Jiang et al., 2007). Individual copepod lipid content also varies annually, perhaps due to fluctuations in temperature or phytoplankton abundance (Sorochan et al., 2019; McKinstry et al., 2013). There is strong seasonal variability in the relative proportion of adult-stage *C. finmarchicus* (Meise and O'Reilly, 1996; Ji et al., 2022) and their individual lipid content (Michaud and Taggart, 2007; DeLorenzo Costa et al., 2006). Patch formation and persistence is highly ephemeral and can vary at the scale of hours (Baumgartner et al., 2003).

For smaller copepod species that may contribute to right whale diets in southern New England, life history and behavior can interact with physics to determine the spatiotemporal abundance patterns. For example, for genera such as *Pseudocalanus* and *Centropages*, vertical migration, cannibalism, and spawning strategies interact with circulation patterns to shape distributions in and around the Gulf of Maine (Ji et al., 2009; Stegert et al., 2011).

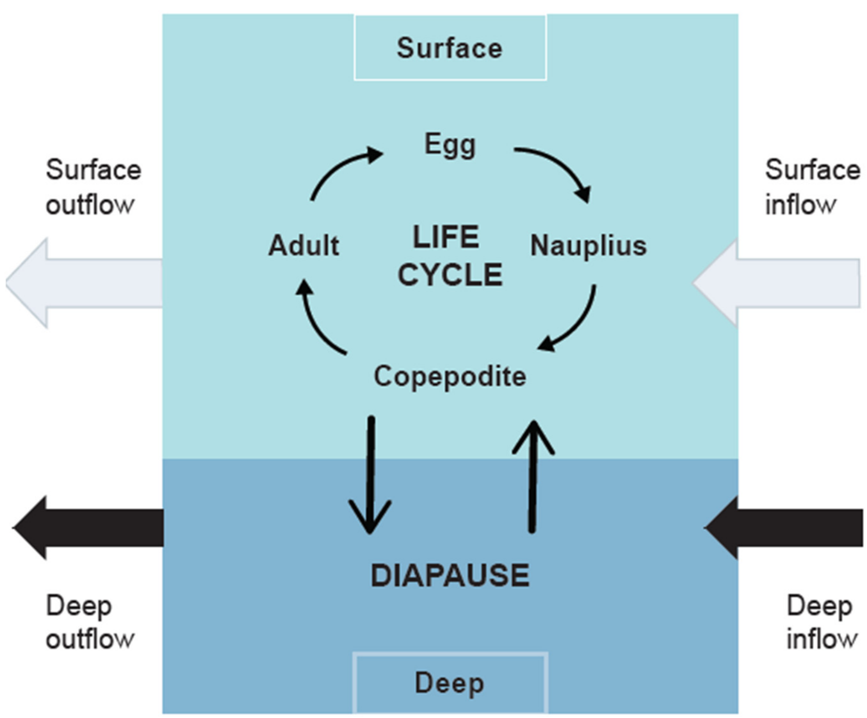

FIGURE 4.4 Conceptual illustration of the life cycle and external exchange of *C. finmarchicus* population in the Gulf of Maine. SOURCE: Adapted from Ji et al., 2022.

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Effects of Zooplankton on Right Whale Distribution and Demography

Oceanographic processes governing the North Atlantic over the past 40 years explain considerable variation in late-stage *C. finmarchicus* abundance in the Gulf of Maine region (Greene et al., 2013) and have been shown to directly affect right whale demography and distribution (Pendleton et al., 2009; Meyer-Gutbrod et al., 2021, 2022). For example, in spring 1992, right whales were not seen in their typical foraging area in the Great South Channel, likely corresponding to a shift in the zooplankton community which occurred in conjunction with unusually low salinity (Kenney et al., 2001). From 1993 to 1997, Roseway Basin on the western Scotian Shelf was abandoned by the right whales, again in response to low prey densities (Patrician and Kenney, 2010; Davies et al., 2015). Because of the high energy demand of reproduction (Fortune et al., 2013), these periods of low prey availability decreased calving rates and thus directly affected population growth (Greene and Pershing, 2004; Meyer-Gutbrod et al., 2015).

During a later decade (2010–2019), the Gulf of Maine/western Scotian Shelf region warmed more rapidly than most of the global ocean (Pershing et al., 2015). Associated reductions in late-stage *C. finmarchicus* in these regions again led to poor foraging conditions and declines in right whale calving rates (Record et al., 2019; Meyer-Gutbrod et al., 2021). Right whale use of the Gulf of Maine, Bay of Fundy, and Scotian Shelf regions also declined substantially during this period while a large portion of the population began to utilize the southern Gulf of St. Lawrence during spring, summer, and autumn (Davis et al., 2017; Davies et al., 2019; Record et al., 2019; Simard et al., 2019; Crowe et al., 2021; Meyer-Gutbrod et al., 2021, 2022). Concurrently, right whale abundance increased, and timing of habitat use shifted almost 3 weeks over 21 years in Cape Cod Bay (Ganley et al., 2019; Pendleton et al., 2022), while right whales repatriated historic whaling grounds south of Cape Cod (O'Brien et al., 2022).

Increased use of Cape Cod Bay and southern New England may be driven by spatiotemporal inconsistencies in the patterns of *C. finmarchicus* abundance in the previous decade. Although late-stage *C. finmarchicus* declined in the central and eastern portions of the Gulf of Maine, primarily in the late summer and fall, abundance increased in the southeastern portion of the Gulf, paralleling spring increases in Cape Cod Bay and Wilkinson Basin (Ji et al., 2017; Record et al., 2019; Meyer-Gutbrod et al., 2022). This regional increase in zooplankton could supply the downstream Nantucket Shoals region, potentially explaining the recent increase in right whale foraging in this area (Quintana-Rizzo et al., 2021; O'Brien et al., 2022). Prior to the shift, Pendleton et al. (2012) predicted favorable foraging habitat in this region at this time of year based on copepod abundance patterns. In the Cape Cod Bay region, and thus in the downstream Nantucket Shoals region, smaller zooplankton species such as earlier stages of *C. finmarchicus*, the *Pseudocalanus* complex, *Centropages* spp. and barnacle larvae may also be important to right whale diets (Pendleton et al., 2009; O'Brien et al., 2022; Hudak et al., 2023). However, the nutritional value of these smaller zooplankton prey is significantly less than late-stage *C. finmarchicus* due to smaller individual body mass and reduced lipid stores (Table 4.1; DeLorenzo Costa et al., 2006), thus most research on right whale prey dynamics is focused on late-stage *C. finmarchicus*. Although research on these smaller taxa is limited, recent fluctuations in their abundance and aggregation may be a driving factor in right whale foraging in this region.

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TABLE 4.1 Variability in the nutritional value of the major copepod species in Cape Cod Bay (Massachusetts, USA)

		number of samples				
species	stage	regular stations	whale stations	% C	mg-C individual^{-1}	C/N ratio
Centropages	female	64	6	39.5	14.2 ± 1.5	3.7 ± 0.07
	male	63	6	40	12.1 ± 1.4	3.7 ± 0.09
	V	64	3	39.7	6.4 ± 0.6	3.9 ± 0.11
	all	191	15	39.7	11.0 ± 0.2	3.8 ± 0.01
Pseudocalanus	female	83	4	45.7	20.6 ± 3.7	4.4 ± 0.39
	V	76	3	49.6	15.6 ± 3.3	5.5 ± 0.55
	all	159	7	47.6	18.2 ± 0.3	5.0 ± 0.06
Calanus	female	52	19	48.3	148.6 ± 35.7	5.0 ± 0.87
	male	5	5	57.5	190.7 ± 21.3	7.6 ± 0.66
	V	116	28	58.1	169.3 ± 43.0	8.2 ± 0.86
	IV	87	16	52.1	54.6 ± 17.0	6.3 ± 1.03
	III	50	10	43.9	13.6 ± 5.0	4.4 ± 0.72
	II	14	0	36.4	3.9 ± 0.3	3.5 ± 0.05
	all	324	78	52.4	109.9 ± 3.6	6.5 ± 0.09

SOURCE: DeLorenzo Costa et al., 2006.

As right whale distributions change, policies to effectively mitigate anthropogenic impacts have become more challenging. The rapid shift in distribution and phenology in the 2010s has likely contributed to the species' unusual mortality event as they became more vulnerable to ship strikes and entanglements in unprotected waters. With reduced reproduction and elevated mortality rates, the right whale population began to decline around 2015 for the first time since post-whaling demographic data became available during the early 1980s (Pettis et al., 2021; Meyer-Gutbrod et al., 2021). During this past decade, total population size has declined an estimated 26 percent, with the U.S. Endangered Species Act classifying the species as *endangered* and the International Union for Conservation of Nature reclassifying the species' status from *endangered* to *critically endangered*.

EFFECTS OF HYDRODYNAMIC PERTURBATIONS ON ECOSYSTEM DYNAMICS IN THE NANTUCKET SHOALS REGION

As detailed in Chapter 2, the Nantucket Shoals region is characterized by dynamic ocean processes supporting a complex marine ecosystem. Its dominant hydrodynamic features include significant southwestward currents and strong seasonal stratification of the water column from June through September with waters well mixed the remainder of the year. This stratification is influenced by significant tidal mixing around the actual Nantucket Shoals and south of Martha's Vineyard with tidal effects declining to the west. Advection is driven by the westward coastal currents along the shelf with transport from both the Gulf of Maine through the Great South Channel and over Nantucket Shoals, and over the mid shelf by transport from Georges Bank.

This historical character of the Nantucket Shoals region is now influenced by major changes that have occurred in its oceanography since 2000. A change point occurred in 2010–2011 when both surface and bottom temperatures began to dramatically increase (Friedland et al., 2020; Chen et al., 2021). This was followed by distinct ocean heat waves in 2012 and 2017 that have been attributed to atmospheric forcing and Gulf Stream warm core rings (Chen et al.,

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2014; Gawarkiewicz et al., 2019). Gulf Stream meanders have moved progressively northward and westward (Saba et al., 2016; Seidov et al., 2021) with increasing frequency of the intrusion of warm core rings onto the shelf. These intrusions have moved farther inshore into the tidal mixed area (Gawarkiewicz et al., 2022). Multiple intrusions are apparent in some summer depth profiles, which could produce multiple layers of zooplankton. Up to 50 percent of the profiles now show intrusions in summer, and 70 percent of the intrusions occurred in proximity to warm core rings (Silver et al., 2023). As a result, the shelf-break front is moving farther inshore. Seasonal stratification is thus changing and extending further into the fall. Effects on the spring are unclear.

This flux in the physical oceanography of the Nantucket Shoals region affects the Nantucket Shoals marine ecosystem at all levels and could account for its current characterization as a major foraging area for the right whales during winter–spring. The shift of right whales' residency into the area appears to have occurred after the 2010–2011 change point in the Nantucket Shoals region (Quintana-Rizzo et. al., 2021). However, recent increases in use of the Nantucket Shoals region by right whales may also be driven by declines in prey availability elsewhere. Thus, the distribution patterns of right whales cannot be predicted exclusively with local or regional ecosystem dynamics (e.g., Meyer-Gutbrod et al., 2022).

Hydrodynamic perturbations resulting from individual turbines, wind farm projects, and regional-scale concentration of projects will be overlaid on the Nantucket Shoals regional oceanography, which is already a highly dynamic and changing marine system. The major hydrodynamic impact of this activity could be on stratification and advection (i.e., drift). However, the scale of the hydrodynamic impacts of these activities are likely to be small compared to the ongoing climate-induced changes that are occurring in the Nantucket Shoals region (see Chapter 3). The ability to disentangle hydrodynamic impacts of wind development on the local ecosystem from large-scale climate dynamics will require the continuation of long-term ecological monitoring programs, the execution of fine-scale observational efforts to support ecological process studies, and the development of robust coupled hydrological–ecological models.

POTENTIAL IMPACTS TO THE PREY FIELD OF THE NORTH ATLANTIC RIGHT WHALE

Given the state of understanding of the effects of hydrodynamics on zooplankton supply, abundance, and aggregation, as well as uncertainties regarding how turbines will affect the hydrodynamics of the Nantucket Shoals region, it is unclear how wind development will affect right whale prey availability in this region. There are mechanisms that could support an increase, a decrease, or no measurable change in right whale prey availability. Future research supporting observational studies and model development are needed to support accurate predictions.

Some studies show mechanisms that could cause turbines to increase zooplankton productivity and/or aggregate zooplankton into high-density patches to support right whale foraging. Reductions in wind stress at the air–sea interface caused by extraction of wind-driven kinetic energy at the turbine can cause an upwelling/downwelling dipole downstream of turbines that may change local primary productivity (Broström, 2008; Floeter et al., 2022; Raghukumar et al., 2023). Increases in turbulent mixing caused by currents flowing around individual monopiles may break down stratification and boost primary productivity (Carpenter et al., 2016; Cazenave et al., 2016). Reduced stratification may be associated with a community shift that is less

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favorable for smaller zooplankton taxa and more favorable for late-stage *C. finmarchicus* (Pershing and Kemberling, 2023). Because *C. finmarchicus* is an income breeder, increased concentrations of phytoplankton and microzooplankton may contribute to higher rates of egg production (Durbin et al., 2003; Runge et al., 2006). However, this potential mechanism is complex to connect to right whale foraging success in the area because right whales rely on adult stages of *C. finmarchicus*, and in the weeks required for *C. finmarchicus* to mature to adult stages (Marshall and Orr, 1972), the juvenile stages may be advected to a different region, boosting downstream abundances of right whale prey. High primary productivity may also contribute to feeding success of individual *C. finmarchicus and* increases in the lipid stores of individual zooplankton will increase the overall nutritional value of the right whale foraging area (McKinstry et al., 2013).

Wind turbines also have the potential to decrease zooplankton productivity and/or reduce the potential for high-density aggregations, thus potentially reducing foraging opportunities for right whales in the region. Sediment plumes caused by bottom disturbance at the turbine site may increase water turbidity, thus decreasing rates of primary productivity in the area (Vanhellemont and Ruddick, 2014). With less food available for *C. finmarchicus*, survival and reproduction may decline (Durbin et al., 2003; Runge et al., 2006). Increases in fish and invertebrate abundances and diversity have been detected around turbines, due to either attraction or production (e.g., Methratta et al., 2020; Perry and Heyman, 2020), which could expose late-stage *C. finmarchicus* to higher levels of predation. Reductions in current speeds at the scale of the wind farm (e.g., Christiansen et al., 2023) could potentially modify local zooplankton supply. Local increases in turbulent mixing resulting from drag forces downstream of the monopile (e.g., Rennau et al., 2012; Schultze et al., 2020) could disrupt zooplankton aggregations or induce avoidance behavior, thus reducing high-density patches of right whale prey (Incze et al., 2001; Visser et al. 2001). However, it is unknown whether any of these potential mechanisms for decreasing zooplankton abundance and aggregation could occur at a scale that affects right whale foraging efficacy.

A third possibility is that wind farm development will have no appreciable impact on right whale foraging dynamics. This may occur because the potential mechanisms to increase and decrease zooplankton abundance and aggregation are mild and do not significantly alter prey availability, or these mechanisms may cancel each other out or be insignificant compared to ongoing climate-induced changes in the ecosystem. Coupled physical–biological processes, unrelated to wind energy development, may reduce or increase the abundance and density of right whale prey in the region.

Right whale use of this region as a foraging area is heterogeneous on seasonal, annual, and decadal scales, and although right whales have been foraging in the Nantucket Shoals region over the past decade, it is difficult to predict their future use of this area. Oceanographic and ecological processes may change the supply of zooplankton to the area, especially *C. finmarchicus* which is primarily advected into the region. Because right whales forage over a vast geographic area, their use of any particular region may be partially driven by conditions in distant regions, such as alternative foraging habitats. It is plausible that zooplankton abundances in historical high-use foraging areas such as the Bay of Fundy and Roseway Basin will rebound, or right whales will increase occupancy in a different region (as recently done in the Gulf of St. Lawrence); thus, right whales may shift away from the Nantucket Shoals region to forage in these more northern areas. Alternatively, declines in prey availability in remote foraging areas could cause right whales to increase their use of the Nantucket Shoals region. Climate change is

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responsible for shifting baselines in zooplankton abundance and right whale habitat use; thus, it will be difficult to disentangle the impacts of wind energy development from other anthropogenic and natural factors that affect right whale prey.

Given the uncertainty in the impacts of turbines on right whale prey availability, and thus right whale behavior, distribution, and demography, an important starting point is robust monitoring in order to understand the sign of potential impacts on this critically endangered marine mammal and to mitigate negative impacts. In addition to monitoring, modeling programs that couple the fine-scale physics with copepod biology and behavior are needed to better understand the processes of prey patch formation. Modeling will be challenging, because the processes necessary for patch formation span a wide range of scales, from supply (hundreds of kilometers) to fine-scale physics and behavior (1 cm to 10 m). There have been modeling studies that couple some of these processes at a variety scales (e.g., Pershing et al., 2009; Record et al., 2010; Ji et al. 2012; Bandara at al., 2018; Ross et al., 2023), as well as cross-scale observational studies of zooplankton patches (Robinson et al., 2021). Assembling the various modeling and monitoring components to address patch formation and dynamics around turbines will be challenging but should be feasible. These threats can be mitigated with a robust set of conservation measures designed to support NOAA's existing network of visual and real-time acoustic monitoring for right whale presence in the region year-round. These observations support NOAA's existing dynamic management policy framework to slow vessel speeds and potentially re-route vessel traffic when right whales are in the region. Continued and robust monitoring of right whales' presence and behavior, using multiple sampling modes and implemented across broad spatial scales, will be critical for regularly assessing these mitigation efforts (BOEM and NOAA, 2022; Silber et al., 2023). This is especially important as right whale use of the Nantucket Shoals region evolves due to oceanographic changes and/or the activities and conditions relevant to wind farms.

Individual wind farm projects are also responsible for limited monitoring of the project's impacts on right whales. For example, the Record of Decision and the Construction and Operations Plans for Vineyard Wind and South Fork Wind include a series of conservation measures related to potential interactions between right whales and wind farm activities. This provides for at least 3 years of deployment during and after construction of passive acoustic monitoring devices to monitor for the presence of right whales, stationing trained protected species observers on industry vessels, restricting vessel speeds to 10 kts (5 m/s) during times when right whales may be present in the wind farm areas, scheduling construction activities to occur only in summer and outside of the times when right whales are normally present in the wind farm areas, and scheduling regular inspections and cleanup around turbines to prevent the accumulation of lines and other debris around monopiles. Recent studies suggest that right whale distributions continue to evolve in this region (Quintana-Rizzo et al., 2021), which has implications for mitigating risk during construction and operation.

In a scenario where turbines increase the abundance and/or aggregation of right whale prey, increased right whale foraging in the Nantucket Shoals region may subject animals to increased risk of exposure to vessel strikes, entanglement in regional fishing gear, including gear that may aggregate around the base of the monopile, and anthropogenic noise. Alternatively, in a scenario where right whale use of the Nantucket Shoals region declines in response to turbine construction and operation, understanding of shifts in right whale foraging behaviors is essential for guiding future wind farm construction in other areas and predicting right whale use of alternative foraging grounds. In either scenario, visual monitoring and passive acoustic

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monitoring will be critical for characterizing the changes in habitat use and understanding the drivers of right whale decision making to search for and occupy foraging refugia. Although changes to the prey field are not likely to be significant enough to drive annual reductions in foraging success that decrease calving rates, understanding of foraging dynamics in this first large-scale wind energy site will provide critical information for planning future wind energy development to avoid population-level impacts.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion: The paucity of observations and uncertainty of the modeled hydrodynamic effects of wind energy development at the turbine, wind farm, and regional scales make potential ecological impacts of turbines difficult to predict and/or detect.

Conclusion: The hydrodynamic impacts from offshore wind development in the Nantucket Shoals region on zooplankton will be difficult to isolate from the much larger magnitude of variability introduced by natural and other anthropogenic sources (including climate change) in this dynamic and evolving oceanographic and ecological system.

Observations

Conclusion: Long-term zooplankton and whale monitoring programs have provided valuable information about right whale ecology and distribution.

Conclusion: The mechanisms that supply, transport, and aggregate right whale prey such as *C. finmarchicus* into suitable foraging habitat vary at temporal scales that range from hours to decades and spatial scales that range from the millimeter-scale size of the copepod to the size of an ocean basin.

Conclusion: There is a gap in understanding of foraging by North Atlantic right whales in the Nantucket Shoals region. This includes the very basic question of which zooplankton taxa right whales are feeding on in the region, and how this changes seasonally. Surveys of zooplankton associated with foraging right whales as well as simultaneous collection of ecosystem-level information about foraging whales would improve this understanding.

Conclusion: The spatiotemporal coverage of studies concentrated at wind farm areas does not adequately capture broad-scale right whale use of the Nantucket Shoals region and potential impacts from offshore wind turbines.

> **Recommendation**: The Bureau of Ocean Energy Management, 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

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of the Nantucket Shoals region continues to evolve due to oceanographic changes and/or the activities and conditions relevant to offshore wind turbines. Observations should

- Include concurrent measures of relevant physical processes and ecological effects through upper trophic levels at the turbine, wind farm, and regional scales.
- Be expanded to identify the links and relevant processes between zooplankton supply, abundance, and aggregation and right whale habitat use in the Nantucket Shoals region.
- Use combined observational and modeling studies to isolate potential effects of wind farms from those resulting from natural and/or other anthropogenic drivers, recognizing that this will take dedicated long-term studies.
- Sample zooplankton at the appropriate spatiotemporal scales necessary to characterize right whale prey availability, including zooplankton life history and behavior.
- Monitor right whale habitat use within and outside of wind energy areas.
- Maintain existing long-term monitoring programs to provide insight on regional and ocean-basin scale changes to right whales and their prey.

Modeling

Conclusion: Right whale distribution and demography has been shown to depend on the distribution and density of late-stage *C. finmarchicus*, both through prey-dependent reproduction rates as well as increases in the rates of anthropogenic-related mortality that occur with rapid prey-driven distribution shifts.

Conclusion: Right whale spatial distribution and demography are directly related to the distribution and density of their zooplankton prey including late-stage *C. finmarchicus*. However, studies focusing on the links between right whale habitat use and zooplankton in the Nantucket Shoals region are limited.

Conclusion: The supply of zooplankton to Nantucket Shoals is dependent on regional circulation, but aggregation is presumably dependent on local physical processes and zooplankton behavior.

Conclusion: There is currently a lack of robust (coupled physical–biological) models that can effectively incorporate the supply of zooplankton, their behavior, and the physical oceanographic processes that aggregate the zooplankton in the Nantucket Shoals region in sufficient densities for right whale foraging. Given this lack of models, it will be difficult to predict whether wind farm projects will have an impact on right whales.

Recommendation: The Bureau of Ocean Energy Management, 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

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whales and improve predictions of ecological impacts from wind development at other lease sites. This modeling should

- Include zooplankton life history and behavior modeled at appropriate scales.
- Identify and model the mechanisms that drive supply, abundance, and aggregation of zooplankton.
- Utilize improved hydrodynamic models that represent the mechanisms that drive regional transport, supply, and local aggregation processes.
- Be expanded to identify and incorporate the link between zooplankton supply, abundance, and aggregation and right whale habitat use in the Nantucket Shoals region.
- Be conducted at the appropriate spatiotemporal scales necessary to isolate effects driven by wind turbines from those resulting from natural and/or other anthropogenic drivers.
- Incorporate physical and ecological information pertinent to right whale foraging outside of the Nantucket Shoals Region, because right whale foraging in this region may depend on the availability of alternative foraging areas.

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Potential Hydrodynamic Impacts of Offshore Wind Energy on Nantucket Shoals Regional Ecology: An Evaluation from Wind to Whales

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Appendix A
Committee Biographies

Eileen Hofmann, *Chair*, is a professor and eminent scholar in the Department of Ocean and Earth Sciences and a member of the Center for Coastal Physical Oceanography at Old Dominion University. Her research interests are in the areas of physical–biological interactions in marine ecosystems, environmental control and transmission of marine diseases, and descriptive physical oceanography. Her research has focused on a variety of marine environments that include the Ross Sea and the western Antarctic Peninsula, Delaware and Chesapeake Bays, and the Mid-Atlantic Bight (MAB) continental shelf. Hofmann's current research is focused on understanding and quantifying interactions between offshore wind energy development in the MAB and commercial shellfish species. She is the co-chair of the Southern Ocean Observing System. Her contributions to modeling physical-biological interactions in marine systems were recognized by her election as a fellow of the American Geophysical Union. Hofmann received a B.S. in biology from Chestnut Hill College and an M.S. in physical oceanography and Ph.D. in marine sciences and engineering from North Carolina State University. She is a member of the National Academies of Sciences, Engineering. and Medicine's Understanding Gulf Ocean Systems Standing Committee and was previously a member of the Ocean Studies Board and Committee on Fisheries Research and Monitoring for Atlantic Offshore Development: A Workshop.

Jeffrey Carpenter is a physical oceanographer who leads the Small-Scale Physics and Turbulence Group at the Institute for Coastal Ocean Dynamics at the Helmholtz-Zentrum Hereon in Geesthacht, Germany. His work focuses on the fluid mechanics of physical processes in oceans and lakes, and his research interests include turbulent mixing in stable-density stratification, shear-flow instability and the transition to turbulence, double-diffusive convection flows, Arctic oceanography, the use of autonomous vehicles in studying ocean processes, and the impacts of offshore wind farms on coastal seas. He is the recipient of the Alexander Graham Bell Canada Graduate Scholarship as well as a European Research Council Consolidator Grant. Carpenter received a Ph.D. in civil engineering from the University of British Columbia, Canada, and completed postdoctoral training at Yale University and the Swiss Federal Institute of Aquatic Science and Technology.

Qin Jim Chen is a professor of civil and environmental engineering and marine and environmental sciences at Northeastern University. Prior to joining Northeastern University in 2018, he was a professor of coastal engineering at Louisiana State University. He specializes in the development and application of numerical models for coastal dynamics, including ocean waves, storm surges, estuarine circulation, fluid–structure interaction, sediment transport, and deltaic morphodynamics, as well as field observations of nearshore extreme events. Chen's research program is focused on the integration of computer modeling with field observations and application of high-performance computing and machine learning technologies for coastal resilience and sustainability. He is a recipient of the National Science Foundation CAREER award, the Best Paper Award of the Louisiana Association of Professional Biologists, and the James M. Todd Technological Accomplishment Medal. Chen received a Ph.D. in civil engineering from Old Dominion University in collaboration with the Danish Hydraulic Institute

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and completed postdoctoral training in the Center for Applied Coastal Research at the University of Delaware.

Josh Kohut is a professor in the Department of Marine and Coastal Sciences at Rutgers University. Using networks of ocean observing technologies, his research and extension programs focus on the ocean processes that structure marine ecosystems. He is involved in many research programs that range in scope from storm intensity, offshore wind, local water quality, regional fisheries, and environmental studies of polar ecosystems in the coastal waters surrounding Antarctica. In the Mid-Atlantic Bight, Kohut is engaged in multiple research efforts to both monitor and understand the dynamic ocean relative to movements of marine mammals and their prey in the context of planned offshore wind development. His research is collaborative, and he works with multiple stakeholder groups to ensure that his work is relevant to management of ocean resources. Kohut received a B.S. in physics from the College of Charleston and a Ph.D. in physical oceanography from Rutgers University.

Kohut's research has been partially funded by offshore wind development companies. He also currently serves as a member of the New Jersey Department of Environmental Protection (NJDEP) Science Advisory Board, Water Quality and Quantity Standing Committee. NJDEP has recently made public statements about whale strandings along the New York and New Jersey coasts.

Richard Merrick is retired from the National Oceanic and Atmospheric Administration (NOAA) Fisheries. Post-retirement he has become involved with committees and boards related to marine conservation, including the Marine Mammal Protection Act's Atlantic Scientific Review Group and the New England Fishery Management Council's Scientific and Statistical Committee. During his last 5 years of service with NOAA Fisheries, he was the director of Scientific Programs where he formulated and directed NOAA's biological and social science research for fish, marine mammal, and turtle species in the United States. In this role, Merrick provided science policy advice to NOAA leadership, Congress, and other stakeholders. Previously, he led Northeast and Alaska regional NOAA Fishery's programs focused on conservation of U.S. living marine resources. He received the Presidential Distinguished Rank Award, NOAA's Distinguished Career Award, and a variety of others awards during his career. He is a member of Sigma Xi and Phi Kappa Phi, and a charter member of the Society for Marine Mammalogy. Merrick received an M.S. in biological oceanography and marine resource management from Oregon State University and a Ph.D. in fisheries from the University of Washington. He was previously a member of the National Academies of Sciences, Engineering, and Medicine's Committee on Assessment and Advancement of Science in the Bureau of Ocean Energy Management's Environmental Studies Program.

Erin Meyer-Gutbrod is an assistant professor in the School of the Earth, Ocean, and Environment at the University of South Carolina. She is a quantitative marine ecologist who uses statistical, demographic, and spatial models to understand how marine species respond to environmental processes. Many of Meyer-Gutbrod's research projects focus on human impacts to threatened or economically valuable species. She serves on the Justice, Equity, Diversity & Inclusion (JEDI) committee for the Oceanography Society and edits a quarterly JEDI column in *Oceanography* magazine. Meyer-Gutbrod received a B.S. in physics from the University of

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Notre Dame and a Ph.D. in earth and atmospheric science from Cornell University. Meyer-Gutbrod submitted public comments on the National Oceanic and Atmospheric Administration's proposed North Atlantic Right Whale Vessel Strike Reduction Rule.

Douglas Nowacek is a professor at the Nicholas School of the Environment and Pratt School of Engineering at Duke University. His research is focused on the link between acoustic and motor behavior in marine mammals, primarily cetaceans and manatees, specifically, how they use sound in ecological processes. Other research interests include offshore renewable energy and the effect(s) of anthropogenic noise on marine mammals. Nowacek received a B.A in zoology from Ohio Wesleyan University and a Ph.D. in biological oceanography/engineering from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program. He served as a compensated member of a review panel for Orsted's Offshore Wind Research Plan in 2021.

Kaustubha Raghukumar is a consultant in marine sciences at Integral Consulting Inc., an international environmental sciences and engineering company headquartered in Seattle, Washington. Prior to joining Integral, he was a research associate at the Naval Postgraduate School in Monterey, California, and a postdoctoral scholar at the University of California, Santa Cruz. Raghukumar is an oceanographer with a background in physical oceanography, ocean acoustics, and wave propagation physics. He has 16 years of experience in modeling and at-sea measurements of hydrodynamic processes and in underwater acoustics. He is currently involved in modeling efforts to understand the effects of offshore wind development on coastal circulation and to examine the potential environmental effects of marine renewable energy installations. Raghukumar received a Ph.D. in oceanography from the Scripps Institution of Oceanography.

Integral Consulting's portfolio has been partially funded by offshore wind development companies.

Nicholas Record is a senior research scientist at Bigelow Laboratory for Ocean Sciences. He is the director of the Tandy Center for Ocean Forecasting, which works with partners to build forecasting tools for ocean systems. His expertise is in ocean ecosystem modeling, machine learning, and climate adaptation. He works at the intersection of computational oceanography and social sciences, partnering with global stakeholders, to calculate paths forward for the ocean and the communities that depend on it. He also directs the Sea Change Semester Program for undergraduates at Bigelow Laboratory. Record received a B.A. and M.A. in mathematics from the University of Rochester, an M.S. in physical oceanography from the Memorial University of Newfoundland, and a Ph.D. in oceanography from the University of Maine.

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Appendix B
Public Meeting Agendas

COMMITTEE ON EVALUATION OF HYDRODYNAMIC MODELING AND IMPLICATIONS FOR OFFSHORE WIND DEVELOPMENT: NANTUCKET SHOALS

The Keck Center, 500 Fifth Street, NW
Washington, DC 20001

APRIL 25, 2023
VIRTUAL

12:15-1:15 Sponsor Briefing
Mary Boatman, BOEM
Sean Hayes, NOAA

June 01, 2023
ROOM 101

9:00-9:15 Welcome, Introductions, and Statement of Task
Kelly Oskvig, Study Director
Eileen Hofmann, Committee Chair

9:15-10:00 Oceanography of the Nantucket Shoals
Glen Gawarkiewicz, Woods Hole Oceanographic Institution

10:00-10:45 Potential Changes in Ecosystems Dynamics/Prey Field from Offshore Wind Turbine in the Nantucket Shoals Region
Jeffrey Runge, University of Maine

10:45-11:15 Break

11:15-12:30 European Perspective on Offshore Wind Turbine Effects on Hydrodynamics and Associated Ecosystems Changes
Göran Broström, University of Gothenburg
Ute Daewel, Helmholtz-Zentrum Hereon
Ariana Zampollo, University of Aberdeen

12:30-1:15 Lunch

1:15-3:15 Hydrodynamic Models (How Do Methods, Assumptions, and Conclusions Translate to the Nantucket Shoals Region)
FVCOM, **Changsheng Chen**, University of Massachusetts Dartmouth
MIKE/DHI, **Ole Petersen** and **Thomas Johnson**,

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	Danish Hydraulic Institute Delft3D, **Yorick Broekema**, Deltares
3:15-3:30	Break
3:30-4:15	Atmospheric Modeling for Wind Turbines—Wind Turbine Effects on Wind Stress **Cristina Archer**, University of Delaware
4:15-5:30	Industry Perspective on the Committee's Task **Ruth Perry**, Shell Renewable and Energy Solutions **Seth Kaplan**, Ocean Winds **Laura Morse**
5:30	Meeting Adjourns

June 27, 2023
VIRTUAL

3:00-3:10	Welcome and Introductions **Kelly Oskvig**, Study Director **Eileen Hofmann**, Committee Chair
3:10-3:35	Presentation on Zooplankton Dynamics in the NW Atlantic **Andrew Pershing**, Director of Climate Science at Climate Central
3:35-4:00	Q&A

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Appendix C

TABLE C-1 Commercially and ecologically important fish and invertebrates found in the Nantucket Shoals Region

Species	Scientific Name	Essential Fish Habitat Listing	Endangered Species Act Status	Commercial - Recreational (·) or Ecological (E) Importance	Habitat Association
Acadian Redfish	*Sebastes fasciatus*			·	Demersal
Alewife	*Alosa pseudoharengus*		Candidate/ Species of Concern	·/E	Pelagic
American Lobster	*Homarus americanus*			·	Benthic
American Sand Lance	*Ammodytes americanus*			E	Demersal
Atlantic Albacore Tuna	*Thunnus alalonga*	·		·	Pelagic
Atlantic Bluefin Tuna	*Thunnus thynnus*	·	Species of Concern	·	Pelagic
Atlantic Butterfish	*Peprilus triacanthus*	·		·/E	Demersal / Pelagic
Atlantic Cod	*Gadus morhua*	·		·	Demersal
Atlantic halibut	*Hippoglossus hipposglosus*		Species of Concern	·	Demersal
Atlantic Mackerel	*Scomber scombrus*	·		·	Pelagic
Atlantic menhaden	*Brevoortia tyeannus*			·/E	Pelagic
Atlantic salmon	*Salmo salar*		Endangered		
Atlantic Sea Herring	*Clupea harengus*	·		·/E	Pelagic
Atlantic Sea Scallop	*Placopecten magellanicus*			·	Benthic
Atlantic sturgeon	*Acipenser oxyrinchus*		Endangered or Threatened		Benthic
Atlantic Surf Clam	*Spisula solidissima*	·		·	Benthic
Atlantic Yellowfin Tuna	*Thunnus albacares*	·		·	Pelagic
Atlantic wolfish	*Anarhichas lupus*	·	Species of Concern		Demersal
Basking Shark	*Cetorhinus maximus*	·	Candidate		Pelagic
Bay Scallops	*Argopecten irradians*			·	Benthic
Black Sea Bass	*Centropristis striata*			·	Demersal
Blue Shark	*Prionace glauca*	·			Pelagic
Bluefin Tuna	*Thunnus thynnus*			·	Pelagic
Bluefish	*Pomatomus saltatrix*	·		·	Pelagic
Cobia	*Rachycentron canadum*	·		·	Pelagic
Common Thresher Shark	*Alopias vulpinus*	·			Pelagic

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Species	Scientific Name	Essential Fish Habitat Listing	Endangered Species Act Status	Commercial - Recreational (·) or Ecological (E) Importance	Habitat Association
Cusk	*Brosme brosme*		Candidate/ Species of Concern	·	Demersal
Dusky Shark	*Carcharhinus obscurus*	·	Species of Concern		Pelagic
Golden Tilefish	*Lopholatilus chamaeleonticeps*			·	Demersal
Haddock	*Melanogrammus aeglefinus*	·		·	Demersal
Jonah Crab	*Cancer borealis*			·	Benthic
King Mackerel	*Scomberomorus cavalla*	·		·	Pelagic
Little Skate	*Leucoraja erinacea*	·		·	Demersal
Long-Finned Squid	*Loligo pealeii,*	·		·/E	Pelagic
Monkfish	*Lophius americanus*	·		·	Demersal
Northern Quahog	*Mercenaria mercenaria*			·	Benthic
Ocean Pout	*Macrozoarces americanus*	·			Demersal
Ocean Quahog	*Artica islandica*	·		·	Benthic
Pollock	*Pollachius pollachius*	·		·	Demersal
Porbeagle Shark	*Lamna nasus*	·	Species of Concern	·	Pelagic
Red Hake	*Urophycis chuss*	·		·	Demersal
Sand Tiger Shark	*Carcharias taurus*	·	Species of Concern		Pelagic
Sandbar Shark	*Carcharhinus plumbeus*	·			Pelagic
Scup	*Stenotomus chrysops*	·		·	Demersal/ Pelagic
Shortfin Mako	*Isurus oxyrinchus*	·		·	Pelagic
Short-Finned Squid	*Illex illecebrosus*	·		·/E	Pelagic
Shortnose sturgeon	*Acipenser brevirostrum*		Endangered		Benthic
Silver Hake	*Merluccius bilinearis*	·		·	Demersal
Spanish Mackerel	*Scomberomorus maculatus*	·		·	Pelagic
Spiny Dogfish	*Squalus acanthias*			·	Demersal
Striped Bass	*Morone saxatilis*			·	Pelagic
Summer Flounder	*Paralichthys dentatus*	·		·	Demersal
Swordfish	*Xiphias gladius*	·		·	Pelagic
Tautog	*Tautoga onitis*			·	Demersal
Tiger Shark	*Galeocerdo cuvier*			·	Pelagic
White Hake	*Urophycis tenuis*	·		·	Demersal
Weakfish	*Cynoscion regalis*			·	Demersal

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Species	Scientific Name	Essential Fish Habitat Listing	Endangered Species Act Status	Commercial - Recreational (·) or Ecological (E) Importance	Habitat Association
Windowpane Flounder	*Scopthalmus aquosus*	·		·	Demersal
Winter Flounder	*Pseudopleuronectes americanus*	·		·	Demersal
Winter Skate	*Leucoraja ocellata*	·		·	Demersal
Witch Flounder	*Glyptocephalus cynoglossus*	·		·	Demersal
Yellowtail Flounder	*Limanda ferruginea*	·		·	Demersal

SOURCE: BOEM, 2014.

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Appendix D

TABLE D-1 Marine mammals that may occur within the Nantucket Shoals Region

Species	Scientific Name	Stock	Best Range wide Population Estimate	Endangered Species Act Status	Occurrence within Offshore Project Area
North Atlantic Right Whale	*Eubalaena glacialis*	Western North Atlantic	338	Endangered	Common
Humpback Whale	*Megaptera novaeangliae*	Gulf of Maine	1,396	None	Common
Fin Whale	*Balaenoptera physalus*	Western North Atlantic	6,802	Endangered	Common
Sei Whale	*Balaenoptera borealis*	Nova Scotia	6,292	Endangered	Common but less common than other common baleen whales)
Minke Whale	*Balaenoptera acutorostrata*	Canadian east coast	21,968	None	Common
Blue Whale	*Balaenoptera musculus*	Western North Atlantic	Unknown	Endangered	Rare
Sperm Whale	*Physeter macrocephalus*	North Atlantic	4,349	Endangered	Uncommon
Dwarf and Pygmy Sperm Whale	*Kogia sima and K. breviceps*	Western North Atlantic	7,750	None	Rare
Cuvier's Beaked Whale	*Ziphius cavirostris*	Western North Atlantic	5,744	None	Rare
Mesoplodont Beaked Whales (Blainville's, Gervais', True's, Sowerby's)	*Mesoplodon spp.*	Western North Atlantic	10,107	None	Rare
Risso's Dolphin	*Grampus griesus*	Western North Atlantic	35,215	None	Uncommon
Pilot Whale, Long-Finned	*Globicephalus melas*	Western North Atlantic	39,215	None	Uncommon
Pilot Whale, Short-Finned	*Globicephalus macrorhynchus*	Western North Atlantic	28,924	None	Rare
White-Sided Dolphin	*Lagenorhynchus acutus*	Western North Atlantic	536,016	None	Common
Short-Beaked Common Dolphin	*Delphinus delphis*	Western North Atlantic	172,974	None	Common
Atlantic Spotted Dolphin	*Stenella frontalis*	Western North Atlantic	39,921	None	Rare
Striped Dolphin	*Stenella coeruleoalba*	Western North Atlantic	67,306	None	Rare

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Species	Scientific Name	Stock	Best Range wide Population Estimate	Endangered Species Act Status	Occurrence within Offshore Project Area
Common Bottlenose Dolphin*	*Tursiops truncatus*	Western North Atlantic, offshore	62,851	None	Common
Common Bottlenose Dolphin*	*Tursiops truncatus*	Western North Atlantic, northern migratory coastal	6,639	None	Rare
Harbor Porpoise	*Phocoena phocoena*	Gulf of Maine/Bay of Fundy	95,543	None	Common
Harbor Seal	*Phoca vitulina*	Western North Atlantic	61,336	None	Common
Gray Seal	*Halichoerus grypus*	Western North Atlantic	27,300	None	Common
Harp Seal	*Pagophilus groenlandicus*	Western North Atlantic	7.6M	None	Uncommon

SOURCE: Hayes et al., 2023.

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Appendix E

TABLE E.1 Marine birds that may occur within the Nantucket Shoals region (Epsilon, 2020)

Species	Scientific Name	Regional Presence	Distribution	Feeding Habitat	Diet
Loons & Grebes					
Common Loon	*Gavia immer*	winter	pelagic	mid-water	fish, inverts
Red-throated Loon	*Gavia stellata*	winter	inshore	mid-water	fish, inverts
Horned Grebe	*Podiceps auritus*	winter	coastal	surf-mid	fish, inverts
Red-necked Grebe	*Podiceps grisegena*	winter	coastal	surface	fish, inverts
Seaducks					
King Eider	*Somateria spectabilis*	winter	coastal	benthos	inverts
Common Eider	*Somateria mollissima*	year-round	coastal	benthos	inverts
Surf Scoter	*Melanitta perspicillata*	winter	coastal	benthos	inverts
White-winged Scoter	*Melanitta fusca*	winter	coastal	benthos	inverts
Black Scoter	*Melanitta nigra*	winter	coastal	benthos	inverts
Long-tailed Duck	*Clangula hyemalis*	winter	coastal	benth-mid	inverts
Shearwaters, Petrels & Storm-Petrels					
Northern Fulmar	*Fulmarus glacialis*	winter	pelagic	surface	fish, squid
Cory's Shearwater	*Calonectris diomedea*	summer	pelagic	surface	fish, inverts
Great Shearwater	*Puffinus gravis*	summer	pelagic	surface	fish, inverts
Sooty Shearwater	*Puffinus griseus*	summer	pelagic	surface	fish, inverts
Manx Shearwater	*Puffinus*	summer	pelagic	surface	fish, inverts
Audubon's Shearwater	*Puffinus lherminier*	summer	pelagic	surface	fish, inverts
Wilson's Storm-Petrel	*Oceanites oceanicus*	summer	pelagic	surface	plankton
Leach's Storm-Petrel	*Oceanodroma leucorhoa*	summer	pelagic	surface	plankton
Gannets & Cormorants					
Northern Gannet	*Morus bassanus*	winter	coast-pelagic	mid-water	fish
Double-crested Cormorant	*Phalacrocorax auritus*	year-round	coast-inland	mid-water	fish
Great Cormorant	*Phalacrocorax carbo*	year-round	coast-inland	benthos	fish
Gulls & Jaegers					
Black-legged Kittiwake	*Rissa tridactyla*	winter	pelagic	surface	fish, inverts
Bonaparte's Gull	*Larus philadelphia*	winter	pelagic	surface	fish, inverts
Black-headed Gull	*Chroicocephalus ridibundus*	rare	coastal	surface	fish, inverts
Little Gull	*Hydrocoloeus minutus*	rare	coastal	surface	fish, inverts

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Species	Scientific Name	Regional Presence	Distribution	Feeding Habitat	Diet
Laughing Gull	*Larus atricilla*	summer	coastal	surface	fish, inverts
Ring-billed Gull	*Larus delawarensis*	year-round	coastal	surface	fish, inverts
Herring Gull	*Larus argentatus*	year-round	coastal	opportunistic	
Icelandic Gull	*Larus glaucoides*	winter	coastal	opportunistic	
Lesser Black-backed Gull	*Larus fuscus*	rare	coastal	opportunistic	
Glaucous Gull	*Larus hyperboreaus*	winter	coastal	opportunistic	
Great Black-backed Gull	*Larus marinus*	year-round	coastal	opportunistic	
Pomarine Jaeger	*Stercorarius pomarinus*	passage	pelagic	surface	fish, inverts
Parasitic Jaeger	*Stercorarius parasiticus*	passage	pelagic	surface	fish, inverts
Long-tailed Jaeger	*Stercorarius longicaudus*	passage	pelagic	surface	fish, inverts
Least Tern	*Sternula antillarum*	summer	coastal	surface	fish, inverts
Caspian Tern	*Sterna caspia*	summer	coastal	surface	fish, inverts
Black Tern	*Chlidonias niger*	passage	coastal	surface	inverts, fish
Roseate Tern	*Sterna dougalli*	summer	coastal	surface	fish, inverts
Common Tern	*Sterna hirundo*	summer	coastal	surface	fish, inverts
Arctic Tern	*Sterna paradisae*	passage	coastal	surface	fish, inverts
Forster's Tern	*Sterna forsteri*	summer	coastal	surface	fish, inverts
Royal Tern	*Sterna maxima*	summer	coastal	surface	fish, inverts
Auks					
Dovekie	*Alle alle*	winter	pelagic	mid-water	plankton
Common Murre	*Uria aalge*	winter	pelagic	mid-water	fish, inverts
Thick-billed Murre	*Uria lomvia*	winter	pelagic	mid-water	fish, inverts
Razorbill	*Alca torda*	winter	pelagic	mid-water	fish, inverts
Black Guillemot	*Cepphus grylle*	year-round	coastal	benth-mid	fish, inverts
Atlantic Puffin	*Fratercula artica*	winter	pelagic	mid-water	fish
Shorebirds					
Red-necked Phalarope	*Phalaropus lobatus*	passage	pelagic	surface	plankton
Red Phalarope	*Phalaropus fulicarius*	passage	pelagic	surface	plankton

SOURCE: NOAA NBDC, 2017.

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