Oceanographic Effects of Offshore Wind Structures and Their Potential Impacts on the North Atlantic Right Whale and Their Prey

A White Paper Prepared for the American Clean Power Association

Prepared by:

AKRF RUTGERS Bigelow Laboratory for Ocean Sciences

October 2023

Oceanographic Effects of Offshore Wind Structures and Their Potential Impacts on the North Atlantic Right Whale and Their Prey

A White Paper Prepared for the American Clean Power Association

Authors and Affiliations:

AKRF

Joseph F. Brodie, Ph.D.
Rachael Manhard, Ph.D.
Justin Krebs, Ph.D.
Carlos Lozano
Laura Morales
Lesley Baggett, Ph.D.
Elizabeth Fuchs

Rutgers

Travis Miles, Ph.D.
Laura Nazzaro
Michael Crowley

Bigelow Laboratory for Ocean Sciences

David Fields, Ph.D.

Executive Summary

Development of offshore wind as a source of renewable energy is a key part of the strategy to achieve necessary reductions in carbon emissions, mitigate climate change, and achieve state and national goals for renewable energy. The presence of offshore wind structures on the Outer Continental Shelf is likely to have some impact on the hydrodynamics of the surrounding ocean as water moves past these structures. The level of impact is highly dependent on both local oceanography and wind farm characteristics (e.g., turbine size and spacing). The spatial extent and magnitude of hydrodynamic effects and the nature of any associated ecological impacts are less certain but are likely to be up to an order of magnitude less than changes due to natural variability and climate change.

This white paper presents a comprehensive and objective summary of the current state of knowledge on the effects of offshore wind structures on ocean circulation and stratification and their relationship to the distribution and density of copepods and the suitability of foraging habitat for the critically endangered North Atlantic right whale (NARW). Key takeaways reflecting the state of our knowledge from a comprehensive literature review on this topic are summarized in the inset box below and discussed in detail in this white paper. Following the completion of the literature review, an Expert Workshop was held to further discuss the state of the knowledge, to identify some of the critical knowledge gaps, and to establish some priorities for future research that would address these gaps. Recommendations for future research were developed from the scientific literature, from reports developed by experts from state, regional, and national science organizations, and through conversations with scientists and regulators familiar with these topics during the Workshop.

The topic of offshore wind and its effects on hydrodynamics and ecosystems is one that has been widely researched, with a well-established body of peer-reviewed literature, and with many research activities currently underway and anticipated to continue into the future. The current state of knowledge on this topic is summarized here from the results of published research on the oceanographic conditions, copepod distribution, and NARW distribution and habitat use in the Western North Atlantic. The topic of climate change and natural sources of environmental variability in the Western North Atlantic is summarized to provide context for understanding the potential hydrodynamic effects of offshore wind turbines, which are caused primarily by the wind wake effect in the atmosphere and induced mixing in the ocean. Our current understanding of these effects based on observational and modeling studies are summarized. Potential ecosystem impacts of hydrodynamic changes on primary and secondary productivity as a result of offshore wind farms are discussed.

State of the Knowledge

- The Western North Atlantic Ocean where the North Atlantic Right Whale (NARW) occurs is a highly dynamic physical environment consisting of three main oceanographic regions, each with a distinct oceanography: the Gulf of Maine, Mid-Atlantic Bight, and South Atlantic Bight.
- Recent shifts in NARW distribution and foraging habitat utilization within the Western North Atlantic have been observed and are believed to be associated with shifts in copepod prey distributions caused by warming sea surface temperatures related to climate change.
- Local or regional scale fragmentation of copepod aggregations has been observed and is projected to continue with subsequent declines in copepod abundance under future climate scenarios.
- Current foraging habitats may not support sufficient prey populations to allow growth of the NARW population based on the relatively low reproductive rate presently observed for NARW. As waters continue to warm due to climate change, current foraging areas may once again be abandoned as NARWs continue to shift their distribution in search of prey.
- Offshore wind farms can impact hydrodynamics in the surrounding ocean in two principal ways: 1) through an atmospheric wake effect that reduces wind speeds behind wind turbines that can reach the ocean surface, reducing surface wind stress and wind-induced currents, and 2) through subsurface mixing induced by the presence of the turbine substructure within the water column.
- Hydrodynamics and wind wake effects around offshore wind turbines are driven by physical ocean processes including tides, stratification, water depth, and wind-driven currents; and atmospheric processes such as turbulence and stability, all of which have significant natural variation.
- Changes in surface currents and sea surface temperatures caused by turbines in European windfarms (e.g., North Sea) are small enough that they can be difficult to isolate from other sources of natural variability.
- Although studies from the North Sea suggest that wind turbines could cause mixing and disrupt the stratification of ocean waters, wind turbines in the Mid-Atlantic Bight are unlikely to have much influence on summer stratification, which is significantly stronger than the weakly stratified waters of the North Sea.
- Due to the distinct oceanographic differences between the North Sea and the Western North Atlantic Ocean (and among regions therein), impacts of wind turbines in one region are not necessarily directly transferrable to other regions.
- Increased turbulent mixing caused by wind turbines may enhance nutrient mixing and stimulate primary production, in turn enhancing zooplankton abundance, including copepods. However, if turbulence levels are significant and cause sediment resuspension, primary production may decrease due to reduced light penetration.
- Hydrodynamic impacts are highly dependent on wind farm layout and wind turbine parameters, including turbine size (hub height and power capacity), type of foundation, turbine spacing within the wind farm, and the spacing between adjacent wind farms.
- Extensive build-out of offshore wind farms is likely necessary for these structures to have a significant hydrodynamic impact.
- Larger, more widely spaced turbines, such as those being planned for U.S. windfarms, are likely to have less hydrodynamic influence than the smaller, more closely spaced turbines currently in operation in Europe and other parts of the world.

Knowledge Gaps and Suggested Future Research Questions

While preparing this white paper, an Expert Workshop was convened to solicit input from thirteen scientific experts in physical oceanography, copepod biology, and marine mammal ecology. Experts represented the academic and private sectors, as well as federal agencies. Workshop participants provided valuable insight on recent and ongoing research and aided in identifying data and knowledge gaps that are vital to address moving forward (additional gaps are discussed in the white paper). These areas for expanded data collection to address knowledge gaps included:

- Collection of additional physical oceanography data, including water temperature and salinity. In particular, vertical profiles of physical parameters are needed to establish a baseline from which to document future impacts of offshore wind structures;
- Future modeling and model validation studies will need to consider the specific conditions present in the region being evaluated for potential offshore wind impacts, such as water depth, variability and magnitude of currents, strength of stratification, and wind farm parameters such as size and foundation type;
- Finer granularity on the distribution of the NARWs along the migration corridor and the environmental conditions associated with areas used by NARW throughout their range; and
- Physiological and behavioral effects to planktonic prey as a result of structure-induced changes to local physical oceanography.

Workshop participants also outlined several key questions to be addressed from ongoing and future research. These included:

- How can we disentangle the effects of offshore wind structures from other ongoing effects, including natural environmental variability and climate change?
- How should modelling results be used to predict hydrodynamic impacts of offshore wind structures, given the uncertainty in the models and the absence of observational data from the Western North Atlantic?
- Which driver of plankton movement is more significant, mixing or aggregation, and how will offshore wind structures affect these drivers?

Recommendations for Industry Support of Future Research and Monitoring

The offshore wind industry can continue the responsible development of offshore wind facilities along the Atlantic coast of the U.S. and elsewhere by contributing to research efforts, along with continuing meaningful engagement with all stakeholders. Additionally, the industry can help to improve the scientific understanding around the oceanographic and ecological impacts of wind farm development on NARW and their prey, and more broadly contribute to mitigating climate change and improving our collective understanding of ocean ecosystems.

Based on the literature review and insights from the Expert Workshop, this white paper recommends a number of key focal points for the offshore wind industry to consider as they decide how best to contribute to ongoing research efforts that will improve our understanding of offshore wind effects on NARW and their prey. These include:

- Providing funding for a retrospective analysis of existing data, particularly as it informs an understanding of baseline conditions prior to the buildout of offshore wind farms;
- Working with researchers to develop plans for utilizing offshore wind structures as stationary observation and data collection platforms;
- Continuing to engage with regional entities such as the Regional Wildlife Science Collaborative for Offshore Wind (RWSC), and considering contributions to a general research funding pool, possibly administered by RWSC or other similar entity, to provide independent and regional oversight of research funding; and
- Strategically developing monitoring plans to provide consistency among plans and to ensure the right data are collected to address the right issues.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

Acronym/Abbreviation	Definition
ACP	American Clean Power Association
BOEM	Bureau of Ocean Energy Management
°C	degree Celsius
CPR	Continuous Plankton Recorder
DFO	Fisheries and Oceans Canada
DOE	U.S. Department of Energy
E-TWG	Environmental Technical Working Group
EcoMon	Ecosystem Monitoring of the Northeast U.S. Continental Shelf
GOM	Gulf of Maine
GW	gigawatt (1,000 megawatts)
ICES	International Council for the Exploration of the Sea
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
m	meter
MAB	Mid-Atlantic Bight
MW	megawatt (1,000 kilowatts)
NAO	North Atlantic Oscillation
NARW	North Atlantic right whale
NCEI	National Centers for Environmental Information
NEFSC	Northeast Fisheries Science Center
NGO	Non-Governmental Organization
NJBPU	New Jersey Board of Public Utilities
NJDEP	New Jersey Department of Environmental Protection
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOWRDC	National Offshore Wind Research and Development Consortium
NYSERDA	New York State Energy Research and Development Authority
OCS	Outer Continental Shelf
OREC	Offshore Wind Renewable Energy Certificate
PAM	Passive Acoustic Monitoring
RMI	New Jersey Research and Monitoring Initiative
ROSA	Regional Offshore Science Alliance
RWSC	Regional Wildlife Science Collaborative for Offshore Wind
s	second
SAB	South Atlantic Bight
WEA	Wind Energy Area
WHOI	Woods Hole Oceanographic Institution
WREN	Working Together to Resolve Environmental Effects of Wind Energy
WOW	Wildlife and Offshore Wind

Author Statement

The authors of this technical white paper include subject matter experts from AKRF, the Rutgers University Center for Ocean Observing Leadership, and Bigelow Laboratory for Ocean Sciences. The paper has been prepared to provide a comprehensive and objective summary of the current state of knowledge on the effects of offshore wind structures on ocean circulation and stratification as it relates to NARWs and their prey and seeks to identify priorities for future research that would allow for more effective minimization and mitigation of these effects. The authors and Expert Workshop participants do not necessarily share the views or opinions of ACP. ACP is free to distribute, publicize, and reference this document without the permission or endorsement of the authors. The authors acknowledge that ACP provided financial support for the preparation of this white paper.

The authors would like to thank the participants of the Expert Workshop for their valuable time and insight. Expert Workshop participants were provided the opportunity to review and provide comment on this white paper prior to finalization.

1.0 Introduction

1.1 Purpose of the White Paper

The development of offshore wind will be fundamental to achieving the renewable energy goals established by many coastal states in the eastern U.S. Additionally, a federal goal of 30 gigawatts (GW, or 30,000 megawatts [MW]) of offshore wind by 2030 was established in 2021. In support of these goals, the Bureau of Ocean Energy Management (BOEM), the agency under the U.S. Department of the Interior that has jurisdiction over energy leases on the U.S. Outer Continental Shelf (OCS), has designated and leased 27 wind energy areas (WEAs) along the eastern seaboard from Massachusetts to South Carolina, with additional draft WEAs and call areas under consideration (see **Figure 1**). However, as of the time of this white paper, there are only 42 MW of installed offshore wind capacity, including the 30 MW Block Island Wind Farm and a 12 MW pilot project designated as Coastal Virginia Offshore Wind. Two larger-scale projects, the 130 MW South Fork Wind Farm and the 804 MW Vineyard Wind 1 project, are currently under construction south of Massachusetts and Rhode Island in the MA/RI WEAs. Several other projects are expected to begin construction during 2023-2025, including Revolution Wind and Sunrise Wind, both located in the MA/RI WEAs, and Empire Wind 1 and 2, Ocean Wind 1, and Atlantic Shores South, off the coast of New York and New Jersey. Several other lease areas are currently in development and proposing to begin construction during 2025-2028, including Atlantic Shores North, Ocean Wind 2, Beacon Wind, Commonwealth Wind, SouthCoast Wind, and Park City Wind.

Looking ahead, 18 of the 27 active commercial lease holders have submitted Construction and Operations Plans for offshore wind projects. BOEM has issued a Notice of Intent to conduct environmental review under the National Environmental Policy Act for ten of those projects. If BOEM completes another lease sale in the Central Atlantic, it is likely that three additional projects will initiate this process in the next few years to develop the three newly designated WEAs offshore of Delaware, Maryland, and Virginia. Additionally in the Gulf of Maine, BOEM has published an Environmental Assessment for a research lease, developed a Call Area, and published a Call for Information and Nominations for commercial lease issuance, indicating that research and/or commercial leases in this region are likely on the horizon. As construction of offshore windfarms has ramped up, concerns have been raised by both ocean users and the scientific community as to the potential environmental impacts of the deployment of offshore wind facilities. The offshore wind industry and the American Clean Power Association (ACP), which represents and advocates for offshore wind developers, understand these concerns and seek to support efforts to better understand the underlying science and approaches to avoid, minimize, and mitigate the environmental impacts of offshore wind development.

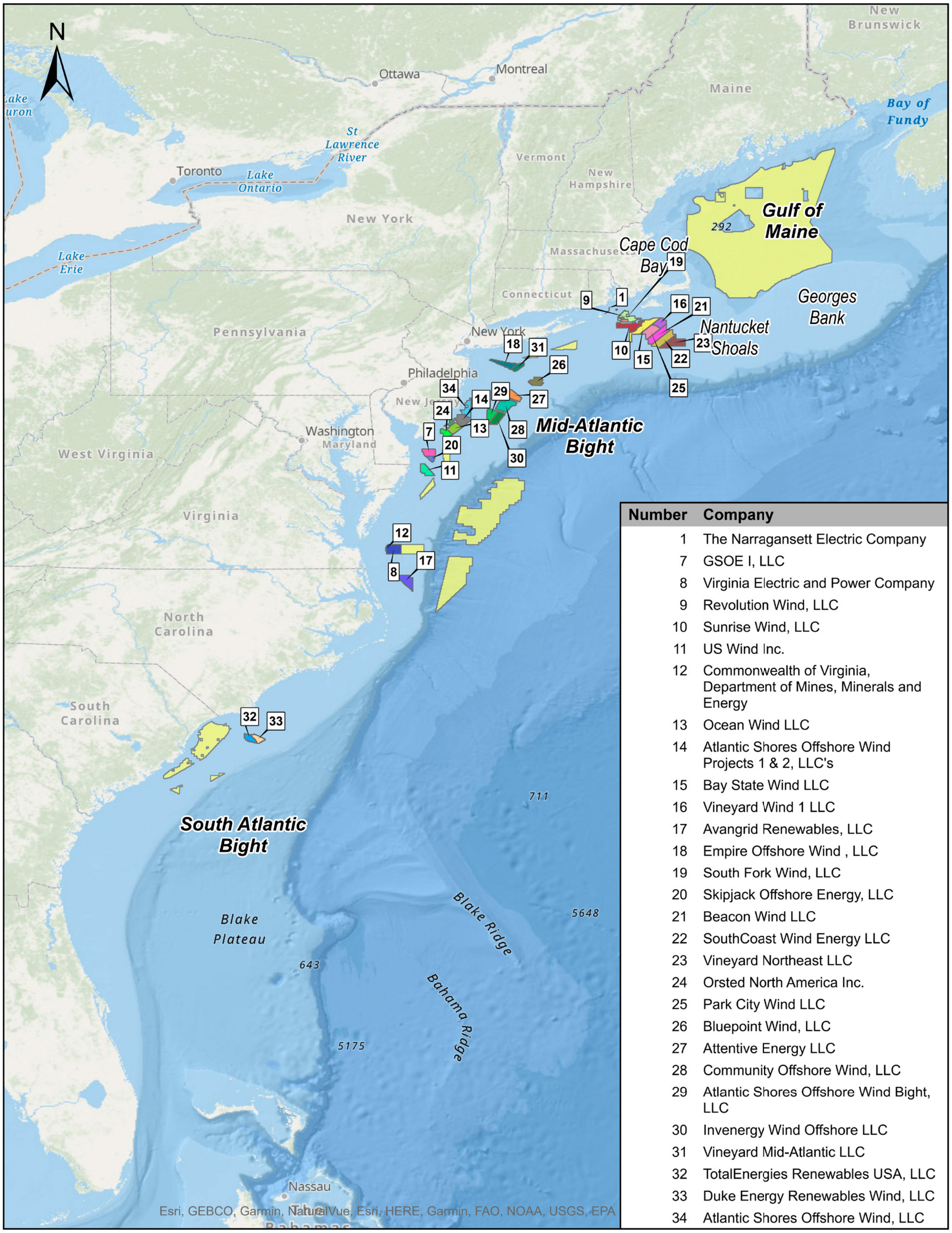


Figure 1.

Current U.S. wind energy leases (in multiple colors) and BOEM call areas (in light yellow) as of August 2023. Also shown are the broad geographic areas of the U.S. East Coast discussed in this white paper: the South Atlantic Bight, Mid-Atlantic Bight, and Gulf of Maine, as well as several other subregions discussed. Lease and call area shapefiles are available from BOEM at https://www.boem.gov/renewable-energy/mapping-and-data/renewable-energy-gis-data.

One area of interest, which is also the focus of this white paper, is the potential impact of the deployment of utility-scale offshore wind turbines on physical ocean processes. In particular, there is considerable interest in better understanding the hydrodynamic effect of such deployment given the complex atmospheric and oceanic processes in the coastal environment where installation of offshore wind structures is planned or ongoing, considering the expected duration of operations of 20 to 40 years. These physical processes may play a key role in influencing local ecosystem dynamics, which include both predator and prey species within the local marine food web and which sustain commercial and recreational fisheries.

One focal marine species is the critically endangered North Atlantic right whale (NARW; *Eubalaena glacialis*), and there is concern about how these physical processes may affect the abundance of copepods that are its preferred food source. The NARW was listed as endangered in 1970 under the precursor to the Endangered Species Act (USFWS 1970). From 2011 to 2020, the Western Atlantic NARW stock experienced a decline of approximately 30 percent, and its current abundance is estimated at approximately 340 individuals (Hayes et al. 2023). The NARW faces threats related to other ocean uses, particularly collision risk associated with vessel traffic and entanglement risk associated with fisheries and marine debris, as well as ongoing climate change and other sources of environmental variability that affect the physical and biological oceanography within its range. Given the species' low population size and current threats, there are concerns around how offshore wind development may affect the NARW. While offshore wind and other renewables play a key role in reducing the impacts of climate change by reducing the use of fossil fuels, there is concern around how the presence of wind turbine structures may alter the hydrodynamics that influence copepod aggregation, which may affect the availability of dense food patches and therefore foraging success of NARWs.

To support a detailed understanding of how the presence of wind turbine structures may alter hydrodynamics and provide guidance on how the offshore wind industry can best support research to understand and mitigate impacts, ACP sought to develop this white paper, which serves three key goals. First, it synthesizes the current state of the science on the hydrodynamic effects of offshore wind turbines, including recently published and ongoing research efforts. To support this synthesis, the white paper also presents an overview of the effects of climate change and natural environmental variability in the Western North Atlantic, providing context for ongoing and potential future changes in NARW distribution and habitat utilization. Second, the white paper outlines short- and long-term research questions and strategies to address those questions. Third, it describes how the offshore wind industry can be involved in addressing those questions to avoid, minimize, and mitigate potential impacts. This white paper is intended to serve as a useful public reference, and to complement efforts by other organizations and entities who share an interest in offshore wind's potential impacts on the surrounding environment, in particular, the ongoing efforts by the National Academies of Science, Engineering, and Medicine as part of their Committee on Evaluation of Hydrodynamic Modeling and Implications for Offshore Wind Development: Nantucket Shoals.[1] While the white paper does evaluate the state of the science and make recommendations for industry, it does not evaluate or make any recommendations on present or future policy decisions.

This review is structured to include a comprehensive literature review of the relevant science, found in Chapter 2. Known current and ongoing research efforts are briefly discussed in Chapter 3. Recognized knowledge gaps are identified, and recommendations for future research and the role of industry are outlined in Chapter 4. Finally, some conclusions on this effort are provided in Chapter 5.

---

1 Information on this committee can be found at *https://www.nationalacademies.org/our-work/evaluation-of-hydrodynamic-modeling-and-implications-for-offshore-wind-development-nantucket-shoals*.

1.2 Expert Workshop

A vital source of information for this white paper was the expert input from scientists performing work in this field, particularly those who have authored peer-reviewed literature relevant to the topics of oceanographic processes, copepod distribution, and the biology and ecology of the NARW. To that end, a virtual Expert Workshop was organized and held on July 13, 2023, following the compilation and review of much of the literature that was summarized to prepare the state of the science presented in this white paper.

The Expert Workshop was attended by 13 experts that spanned the spectrum of physical oceanography, copepod biology, and marine mammal biology with a particular focus on the NARW and have expertise on the hydrodynamic impacts from offshore wind. It included scientists from the academic and private sector, as well as representatives of BOEM and the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS).[2] Prior to meeting, experts were provided with the bibliography of studies compiled by the white paper authors and asked to review the bibliography and provide any additional studies relevant to the topic. During the Expert Workshop, experts were first asked to comment on recently published and currently ongoing research on the topic. The second, and largest, component of the Expert Workshop consisted of discussion around future questions that need to be addressed to more thoroughly understand the potential effects of offshore wind structures on ocean circulation, copepod distribution, and NARW foraging, and ways to address those questions. Finally, the experts were asked to weigh in on the role of the offshore wind industry in supporting research efforts. The PowerPoint slides shared at the Expert Workshop, which include all the questions posed to the attendees, can be found in the Appendix.

Detailed notes were taken of the discussion at the Expert Workshop, and these comments are included throughout this white paper. To encourage open discussion by participants, it was not recorded and was not attended by representatives of ACP or the offshore wind industry. All comments have been anonymized and synthesized.

2 Due to scheduling conflicts, NMFS representatives were unavailable to attend the Expert Workshop. However, the authors had a follow-up discussion with NMFS that included the same presentation and discussion topics, and their comments were incorporated into the comments from other workshop participants.

2.0 Scientific Overview and Literature Review

This chapter outlines the current state of the science around the potential for hydrodynamic changes due to the presence of offshore windfarms and the possibility for associated impacts on copepod prey for the NARW.

2.1 Baseline Oceanographic Conditions, Prey Distribution, and Foraging Ecology Throughout the Range of the North Atlantic Right Whale

Prior to evaluating the potential effects, we summarize the baseline oceanographic conditions (Section 2.1.1), current distribution of copepods (Section 2.1.2), and distribution and habitat use of NARW itself (Section 2.1.3).

2.1.1 Oceanography

Physical environmental conditions in the coastal ocean along the U.S. East Coast, and within the geographic range of the NARW, can be broadly separated into three primary regions. The Mid-Atlantic Bight (MAB), the epicenter of early offshore wind development in the U.S., is discussed first in Section 2.1.1.1. Further north, the Gulf of Maine (GOM) is discussed in Section 2.1.1.2. Finally, the South Atlantic Bight (SAB) is discussed in Section 2.1.1.3.

2.1.1.1. Mid-Atlantic Bight

The MAB extends from Cape Cod, MA to Cape Hatteras, NC, narrowing in width from 120 km at the northern extent to 40 km at the southern extent. Bathymetry is approximately parallel to the coast with the exception of the Hudson Shelf Valley and several much smaller shelf-break canyons. Its wide continental shelf, combined with reliable wind resources, has resulted in the MAB being the initial focus of offshore wind development in the United States. MAB shelf water originates from glacial melt off southern Greenland (Chapman and Beardsley 1989) and has an average downshelf (i.e., southward) flow that is strongest in fall and winter and weakest in the summer (Lentz 2008; Roarty et al. 2020), with additional variability introduced from changing winds, river discharge, frequent intrusions of Gulf Stream eddies, and mixing from storms (Roarty et al. 2020). Oceanographic conditions on the shelf are highly variable on timescales of days to decades. It is one of the most well-studied, observed, and modeled coastal ocean regions in the world with frequent research cruises, autonomous underwater gliders, remote sensing systems (e.g., high-frequency radar, satellites), moored systems, and regional hydrodynamic models.

The MAB experiences a dramatic seasonal cycle. Water is well-mixed and gradually cools through winter and spring. In late spring, cold glacial water moves downshelf and the winter/spring MAB water is isolated from a distinct surface layer by surface warming, river runoff, and weakening winds (Castelao et al. 2010; Chant et al. 2008; Miles et al. 2021). As regional stratification develops, the Mid-Atlantic Cold Pool (or simply Cold Pool, see **Figure 2**), a mass of deep cold water below 10°C that can span from Georges Bank to Cape Hatteras and from the coast to the 100-meter isobath, is formed (Houghton et al. 1982; Miles et al. 2021). Throughout the summer as surface heating intensifies and winds and ocean currents weaken, the thermocline strengthens and stabilizes the Cold Pool as it slowly migrates southward (Castelao et al. 2010; Lentz 2017). Persistent southwest winds that are common in the MAB during the summer can push the thin surface layer offshore, pull the Cold Pool closer to the coastline, and upwell the cold and nutrient-rich water to the surface at the shore (Glenn et al. 2004; Murphy et al. 2021). The warmest temperatures in the MAB are reached in the fall as stratification weakens due to decreased heating and increased strong wind events, ultimately breaking down into a well-mixed water column again (Castelao et al. 2010; Lentz 2017; Miles et al. 2021). The timing of the Cold Pool breakdown is highly variable and dependent on the occurrence and intensity of fall storms.

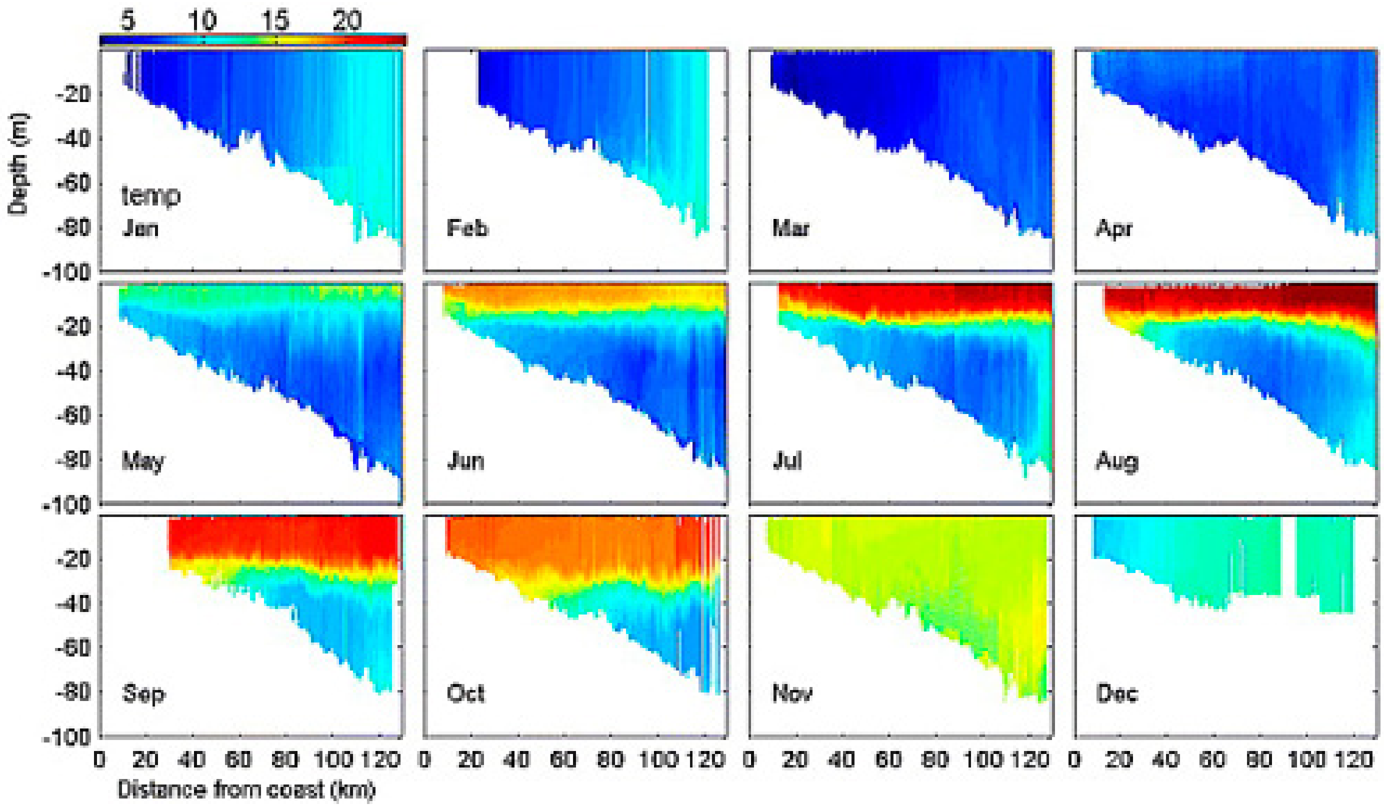


Figure 2.
Transect showing the vertical profile of temperature along the continental shelf taken by gliders throughout the year. The Mid-Atlantic Cold Pool is the colder water residing on the lower portion of the figures from May through October. Figure reproduced from Castelao et al. 2010.

The Nantucket Shoals are located at the northernmost end of the MAB and represent the boundary region between the rest of the Mid-Atlantic to the southwest and the GOM to the north. The oceanography of Nantucket Shoals is largely driven by strong tidal currents, the Gulf Stream, and the shelf break jet, which includes colder, fresher water inflow from the GOM via the Western Maine Coastal Current and the Outer Cape Coastal Current (e.g., Shcherbina and Gawarkiewicz 2008). A common feature of the Gulf Stream that influences the oceanography on Nantucket Shoals are "Gulf Stream meanders," which are instabilities in the flow of the Gulf Stream that can cause warm-core rings to break off from the Gulf Stream; these rings result in strong exchange of water across the continental shelf in this region, impacting the temperature, salinity, and available nutrients (e.g., Du et al. 2022). An example of this can be seen in **Figure 3**.

Unlike the rest of the MAB but more like regions of Europe's North Sea, Nantucket Shoals is generally well mixed due to strong tides (Wilkin 2006). The waters nearby can also be stratified during the summer months, much like the rest of the MAB. This unique oceanography provides for a dynamic and bountiful ecological environment.

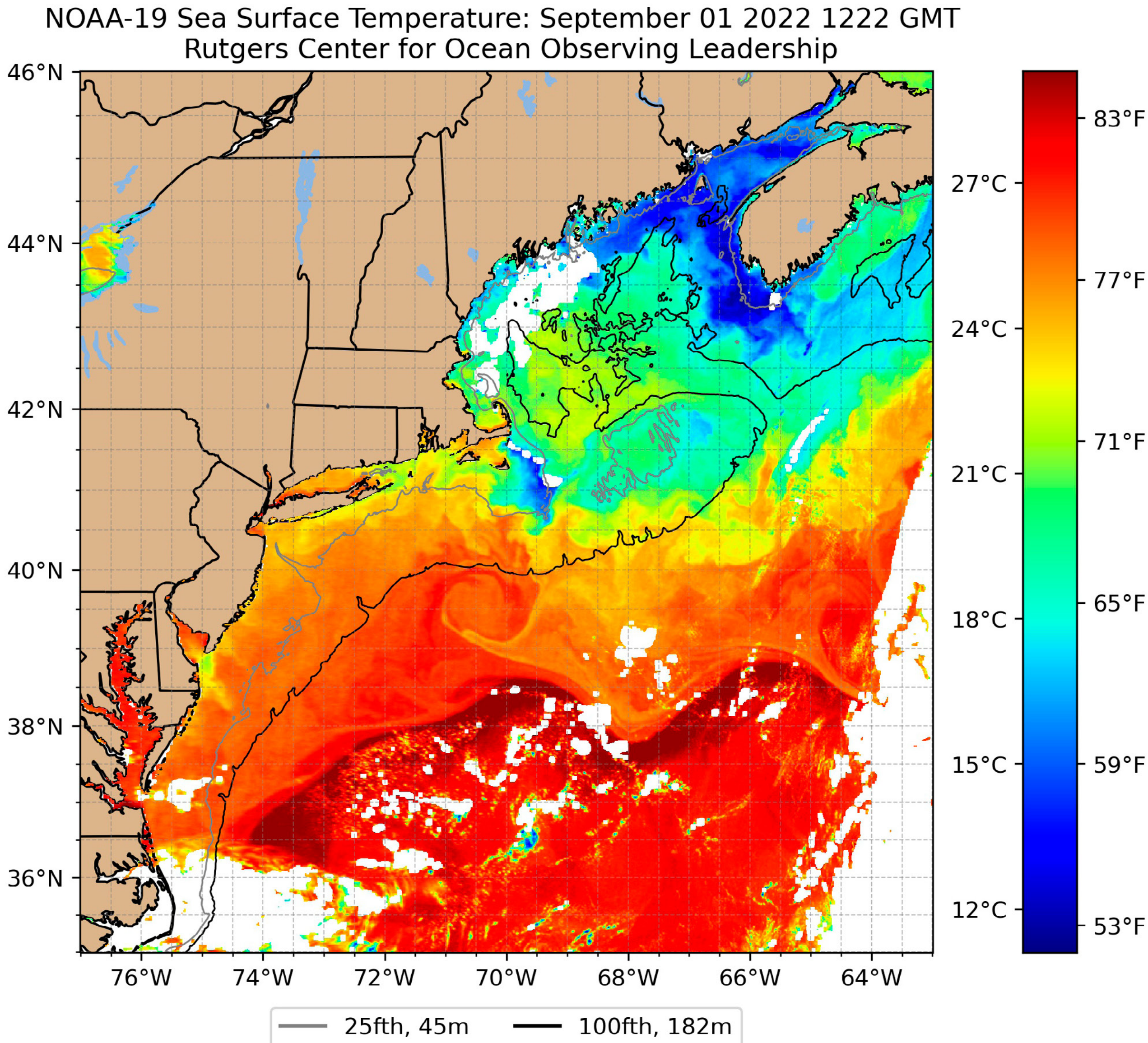


Figure 3.
Satellite image of sea surface temperature over the Mid-Atlantic Bight and Gulf of Maine. The Gulf Stream can be seen as the > 27°C water roughly below 38°N. A warm-core ring can be seen south of Cape Cod and east of New Jersey. Also shown is the cooler water over Nantucket Shoals and overall in the Gulf of Maine and Georges Bank region, with warmer water over much of the Mid-Atlantic. Satellite imagery is available at https://rucool.marine.rutgers.edu/data/satellites/.

2.1.1.2. Gulf of Maine

The GOM stretches from Cape Cod along the eastern coastline of New England and New Brunswick north to Nova Scotia. In contrast to the MAB, the GOM does not have a wide continental shelf, and the bathymetry there is much deeper closer to shore. It also does not form the strong temperature stratification that is present in the MAB during the summer months, remaining relatively cold year-round, as seen in **Figure 3**. However, flow within the GOM is driven by a complex combination of factors, including cold water traveling south from Nova Scotia (e.g., Townsend et al. 2015), freshwater inflow, and influx of warmer waters from the south over Nantucket Shoals and Georges Bank, including through water intrusion into the GOM driven by warm-core rings (Du et al. 2022). Additionally, tides play a significant role in circulation in the GOM. The Western Maine Coastal Current, which flows from north to south around the coastline, eventually flows south of Cape Cod and into the MAB and serves as a key source of water over Nantucket Shoals (Shcherbina and Gawarkiewicz 2008). Due to the water depths in the GOM, the conventional fixed-bottom wind turbine foundations that have been proposed for shallower lease areas in the MAB are not feasible, and instead, newer, floating foundation technology will be used for offshore wind farms that are constructed in these deeper areas. As described in Chapter 1, BOEM has developed a GOM Call Area and published a Call for Information and Nominations for the GOM, as well as issued a draft Environmental Assessment for a research lease. It is anticipated that BOEM will identify commercial WEAs before the end of 2023.

2.1.1.3. South Atlantic Bight

The SAB is the coastal region of the United States ranging from Cape Hatteras, NC to the southern tip of Florida. The continental shelf here is narrower than the portion of the shelf in the MAB, and extends 50 to 120 km from the Florida coastline to the shelf break (e.g., Xue et al. 2015). To date, there has been less focus on offshore wind within the SAB, although there are two existing leases and four call areas for potential future development. One of the dominant oceanographic features within the SAB is the Gulf Stream, which originates in the Gulf of Mexico and travels north along the coastline of the SAB before breaking away from the shelf break and moving offshore as it moves into the MAB north of Cape Hatteras, heading northeast towards Europe and influencing the waters off of New England as described above. The exact position of the Gulf Stream along the South Atlantic shelf varies on a number of timescales. As on the Nantucket Shoals, Gulf Stream meanders and eddies are common, and strongly influence the physical oceanographic conditions, overlying weather systems, and related ecosystems (Zeng and He 2016). These meanders are strongly influenced by the "Charleston Bump," which is a region around 31.5°N off of Charleston, SC, where a shallower portion of the shelf juts out into the deeper waters and can deflect the path of the Gulf Stream as it passes over (Zeng and He 2016). The ocean within the SAB is largely unstratified throughout much of the year, although it does experience stratification during the summer months, which is strongest over the outer part of the continental shelf (Atkinson et al. 1983). Subsurface cold water can also occasionally impinge onto the shelf.

2.1.2 Copepod Distribution

Copepods of the genus *Calanus* are the primary prey of NARWs within their feeding grounds between the GOM and MAB, with *Pseudocalanus* spp. and *Centropages typicus* serving as secondary prey taxa (Baumgartner and Mate 2003; Baumgartner et al. 2003; Kenney et al. 1986). *Calanus finmarchicus* is one of the dominant species in the mesozooplankton (i.e., planktonic animals that range in size between 0.2 and 20 millimeters and serve as an important trophic link between primary producers and carnivorous predators) community of the Northeast Atlantic (Sherman et al. 1983). Three copepod species, *C. finmarchichus, P. minutus* and *C. typicus*, account for seventy-five percent of the total mesozooplankton community (Sherman et al. 1983). Springtime peak copepod biomass is highest for *C. finmarchichus* compared to the other two copepod species in the GOM and Georges Bank (Sherman et al. 1983). In the MAB, *C. finmarchichus* ranks third in abundance to the other two copepod species with a peak abundance period from May to July (Sherman et al. 1983). Feeding activity of NARWs has been observed in close association with *C. finmarchicus* aggregations suggesting that the species is the principal prey supporting the population (Baumgartner and Mate 2003; Jiang et al. 2007; Mayo and Marx 1990). NARW feeding activity has been observed within prey aggregations with densities ranging from approximately fourteen hundred to forty thousand copepods per cubic meter (Record et al. 2019; Wishner et al. 1988).

The distribution and abundance of *C. finmarchicus* are subject to seasonal- and interannual-scale variability (Jiang et al. 2007; Plourde et al. 2001) and varies over the life cycle of the species. In the northwestern Atlantic, the abundance of *C. finmarchicus* in the upper water column is typically low in the winter (October-January), increases in early spring (February-March) to a maximum in late spring/early summer (April-June) and then declines in abundance during late summer/early autumn (July-September). During the onset of winter (September), late-stage pre-adult *C. finmarchicus* (the penultimate developmental stage [Stage V]), suspend development and enter into a state of diapause (Baumgartner and Tarrant 2017; Hirche 1996). During this stage they settle in deep waters (100 m+) where they are neutrally buoyant, to overwinter. It is during this stage that they form deep-water aggregations (at depths > 100 meters) at sizes that could support productive NARW feeding (Davies et al. 2014; Krumhansl et al. 2018). However, the probability of observing a NARW is very uncertain (Davies et al. 2014). Davies et al. (2014) suggested that insufficient survey effort contributes to this uncertainty, but NARWs may not regularly feed at such depths due to the energetic demand of such diving. NARW feeding during spring and summer has been observed near the surface (e.g., Beardsley et al. 1996); though, deep feeding dives have been observed (Baumgartner et al. 2017). During late winter of the following year, juvenile *C. finmarchicus* awake from diapause, molt to become adults and rise to near-surface layers where they begin to reproduce. Diapause is not an obligate stage in development and maturity. Multiple generations of copepods may mature within year or within season and reproduce prior to the diapause period (Melle et al. 2014; Ji et al. 2022a). The developmental rates of *C. finmarchicus* accelerate in warmer waters which could lead to spatiotemporal mismatches between phytoplankton production and *C. finmarchicus* peak abundances or their transition out of the diapause phase (Honda et al. 2023; Kvile et al. 2022; Payton et al. 2022). This has impacted the predators that rely on *C. finmarchicus* as a food source, including NARWs and the American lobster (*Homarus americanus*) (Carloni et al. 2018; Ganley et al. 2022). The concentration and duration of these high-density diapausing aggregations near the bottom are constrained by seasonal environmental conditions including warmer bottom temperatures (Krumhansl et al. 2018). Other mechanisms driving copepod prey aggregations are yet to be well defined (Sorochan et al. 2021a); however, evidence suggests that seasonal and spatial patterns in prey aggregations are responsive to ocean circulation processes that promote retention (Jiang et al. 2007). Shallow prey depth, supply, and aggregation contribute to suitable NARW foraging habitat (Sorochan et al. 2021b).

Variability in the location and abundance of copepods patches are also driven by physical oceanography, ocean circulation, and large-scale weather patterns (Davies et al. 2014; Plourde et al. 2001). Other environmental variables that may influence copepod aggregations include salinity, water temperature, and chlorophyll concentration which are all subject to climate change (Grieve et al. 2017). *C. finmarchicus* were captured in continuous plankton recorder (CPR) surveys at locations where temperature measurements (or estimates) ranged from 3.1°C to 28.1°C. From these surveys, the highest abundances were observed at water temperatures ranging from 7°C to 13°C, and the species was scarce at water temperatures above 21°C. As a result of the oceans warming, zooplankton populations have been moving poleward. Indeed, due to century long warming, *C. finmarchicus* has been shifting north at 8.1 km/decade in the North Atlantic and 16.5 km/decade in the Northeast Atlantic (Beaugrand et al. 2002). Shifts in the Northeast Atlantic were substantially higher (260 km/decade) for zooplankton assemblages in general (Beaugrand et al. 2002). These shifts in zooplankton species distributions are responsible for changes in species assemblages via replacement (Helaouët and Beaugrand 2007; Richardson 2008) or northward expansion by temperate species (Runge et al. 2023). Changes in species assemblages may result in shifts in the size structure of zooplankton communities with possible consequences to food webs (Runge et al. 2023). On the local or regional scale, *C. finmarchicus* aggregations may become fragmented due to climate change with potential direct consequences to NARW foraging (Pershing and Pendleton 2021; Pendleton et al. 2009). Runge et al. (2023) also documented the recovery of *Calanus* abundances in some years following declines. Decadal-scale stability of *Calanus* abundance in the western GOM has been documented and attributed to supply and transport as well as increased food availability promoting development and fecundity rates thereby regulating mortality rates (Ji et al. 2022a, 2022b; Runge et al. 2015).

Due to the ecological importance of *C. finmarchicus*, there have been multiple attempts to model its abundance. Under future climate scenarios in which emissions rates maintain their current trend or are reduced by approximately 2050, declines in *C. finmarchicus* abundance of twenty-one percent or greater may be realized by the 2081-2100 period (Grieve et al. 2017). Ecological niche models based on rising temperature projected *C. finmarchicus* will be functionally extirpated (probability of occurrence <0.1) south of the Gulf of St. Lawrence by 2050–2059 (Reygondeau and Beaugrand 2011).

Studies on impacts of offshore wind development on plankton communities are limited and not specific to copepod abundance and distribution (Daewel et al. 2022; Floeter et al. 2017; Paskyabi 2015); however, energy extraction by offshore wind farms, including due to wind wakes, could potentially impact local to regional ocean circulation and transport processes that are thought to influence copepod aggregations. Wind wakes may induce changes to primary productivity (i.e., phytoplankton that copepods feed on) including potential local increases, or decreases, and regional scale dispersion (Daewel et al. 2022). Fixed-bottom foundation structures from offshore wind development in the North Sea were found to impact oceanographic conditions including stratification resulting in bottom-up food web impacts such as increases in primary productivity and densities of larval echinoderms (Floeter et al. 2017). Increased primary productivity could provide improved grazing opportunities for *C. finmarchicus*, and increased densities of other larvae (e.g., echinoderm larvae) may improve prey opportunities while relieving predation pressure. On the other hand, changes in stratification and hydrology are likely to have negative impacts on copepod populations and, more specifically, on their densities. Modeled scenarios of impacts to regional hydrology in the MAB suggest that offshore wind development could impact transport of passive organisms (Johnson et al. 2021).

2.1.2.1. Mid-Atlantic Bight

In the MAB, *C. finmarchicus* is an important food source for larval stages of fish, pelagic fish stocks, and NARW (Bowman et al. 1984; Kane 1984). The abundance of *C. finmarchicus* shows significant interannual variation (Beare and McKenzie 1999; Kane 2005). CPR surveys show that the copepod's spatial and temporal abundance is linked to the climatic variability associated with the North Atlantic Oscillation (NAO) (Conversi et al. 2001; Fromentin and Planque 1996; Greene and Pershing 2000) most likely due to changes in ocean currents. Each year, the shelf populations are reestablished with animals that migrate up from local deepwater basins or are advected from other overwintering areas 'upstream' where prevailing circulation can transport awakened overwintering stocks into the area (Miller et al. 1998; Pershing et al. 2001). The latter source may be a major contributor (Lynch et al. 1998; Miller et al. 1998). Modeling studies indicate that the progeny of overwintering stocks in the GOM can be directly injected into the region or arrive there later after circulating all or part of the Georges Bank region. Since GOM overwintering stocks are likely derived from proximate slope water regions (Pershing et al. 2001), the interannual variability of the MAB *C. finmarchicus* population may be largely determined by events that affect the distant water stocks.

2.1.2.2. Gulf of Maine

Spatiotemporal dynamics of known NARW feeding areas in the northern extent of the MAB, sometimes referred as the southern New England subregion, Nantucket Shoals, and Georges Bank are closely associated with those in Cape Cod Bay and southern GOM (O'Brien et al. 2021; Leiter et al. 2017; Kane 2005; Thomas et al. 2003). The GOM is at the southern limit of the subarctic range of *C. finmarchicus* (Melle et al. 2014; Sundby 2000). South of this latitude, reproduction alone does not support high abundances, and the population requires passive advection to support high densities. Wilkinson Basin in the western GOM hosts some of the highest numbers (greater than 30,000 m^{-2}) of overwintering *C. finmarchicus* in the North Atlantic (Melle et al. 2014). These high concentrations are comparable to or higher than those observed in more northern coastal areas due to a combination of regional growth and advection (i.e., horizontal movement of a large mass) into the region from northern reservoirs (Melle et al. 2014; Maps et al. 2012). In spring and summer, *C. finmarchicus* can dominate both the biomass and abundance of zooplankton in coastal regions (Runge and Jones 2012; Manning and Bucklin 2005). High concentrations of chlorophyll A and NARW sightings and feeding activity in Cape Cod Bay from March to May suggest that *C. finmarchicus* is present in Cape Cod Bay during this time (Hlista et al. 2009), given that *C. finmarchicus* is a consumer of phytoplankton and NARW feeding is highly associated with high concentrations of copepod prey. Based on transport circulation modeling, *C. finmarchicus* is expected to be abundant in Cape Cod Bay during winter and spring in years with normal conditions when northwesterly winds prevail (Jiang et al. 2007). Interannual variability in prevailing winds lead to changes in *C. finmarchicus* abundance in Massachusetts and Cape Cod Bays (Jiang et al. 2007).

Georges Bank is thought to be a major spawning location for *C. finmarchicus* that are transported into the GOM via circulation patterns during winter (Lynch et al. 1998). These source generations of *C. finmarchicus* spawn and produce new generations after being advected into the GOM (Lynch 1998). Distributions of *C. finmarchicus* within the GOM are closely associated with spatiotemporal patterns in primary productivity (Lynch et al. 1998). Trends of warming sea surface temperatures are thought to result in increases of *C. finmarchicus* abundance in the GOM possibly due to local egg production during winter phytoplankton blooms and production and advection from the eastern GOM and the Scotian Shelf (Runge et al. 2015). Spring and summer amplification (i.e., reproduction and growth) likely further contributes to higher abundances of *C. finmarchicus* in the GOM under observed warming conditions (Ji et al. 2022a; Runge et al. 2015). Population dynamics (e.g., growth and mortality) differ among basins of the GOM leading to spatial differences in seasonal patterns of abundance (Ji et al. 2022b).

Due to northward shifts in *C. finmarchicus* distributions described in this section, foraging habitat of NARWs has expanded into the Gulf of St. Lawrence (Pershing and Pendleton 2021; Sorochan et al. 2019). New foraging habitats in the Gulf of St. Lawrence are fragmented compared to previous habitats (Pershing and Pendleton 2021). Retention of copepods in the Gulf of St. Lawrence may occur during spring and summer while export is likely during fall based on biophysical particle tracking modeling (Sorochan et al. 2021a; Brennan et al. 2019). Field samples of copepods in the Gulf of St. Lawrence confirmed that *C. finmarchicus* were the most abundant copepod species with other *Calanus* species also being abundant (Sorochan et al. 2023). The spatial distribution of copepods was widespread in the Gulf of St. Lawrence and exhibited diel patterns with daytime bottom concentrations being suitable for NARW feeding (Sorochan et al. 2023).

2.1.3 North Atlantic Right Whale Distribution and Habitat Utilization

NARWs in U.S. waters belong to the Western Atlantic stock. The range for this stock spans from the Atlantic coast of Florida northward into the Gulf of St. Lawrence (see **Figure 4**) with occasional sightings east of Canadian waters. Though this stock generally travels between summer foraging grounds off New England and Canada and calving and wintering grounds off the southeastern U.S., NARWs may be found throughout their range year-round, particularly north of Cape Hatteras, indicating that a portion of the population does not move to the southern calving grounds to give birth or overwinter every year (Davis et al. 2017). Historically (i.e., prior to 2010), there were five major concentration areas recognized for the species: the southeastern U.S. along the North Florida-Georgia coastline; eastern Cape Cod Bay and Massachusetts Bay; the Great South Channel (the deep-water area separating Nantucket Shoals and Georges Bank) and the northern portion of Georges Bank; the Bay of Fundy; and the southeastern Scotian Shelf (NMFS 2022) (see **Figure 5**). Calving and overwintering grounds are found within the North Florida-Georgia coastline concentration area, while foraging habitat has historically occurred within the other four pre-2010 concentration areas. These historical foraging areas utilized prior to the recent shift in NARW distribution are described in Section 2.1.3.1. The post-2010 distribution shift and current foraging areas are described in Section 2.2.3. Current calving and overwintering grounds for the species are described in Sections 2.1.3.2 and 2.1.3.3, respectively.

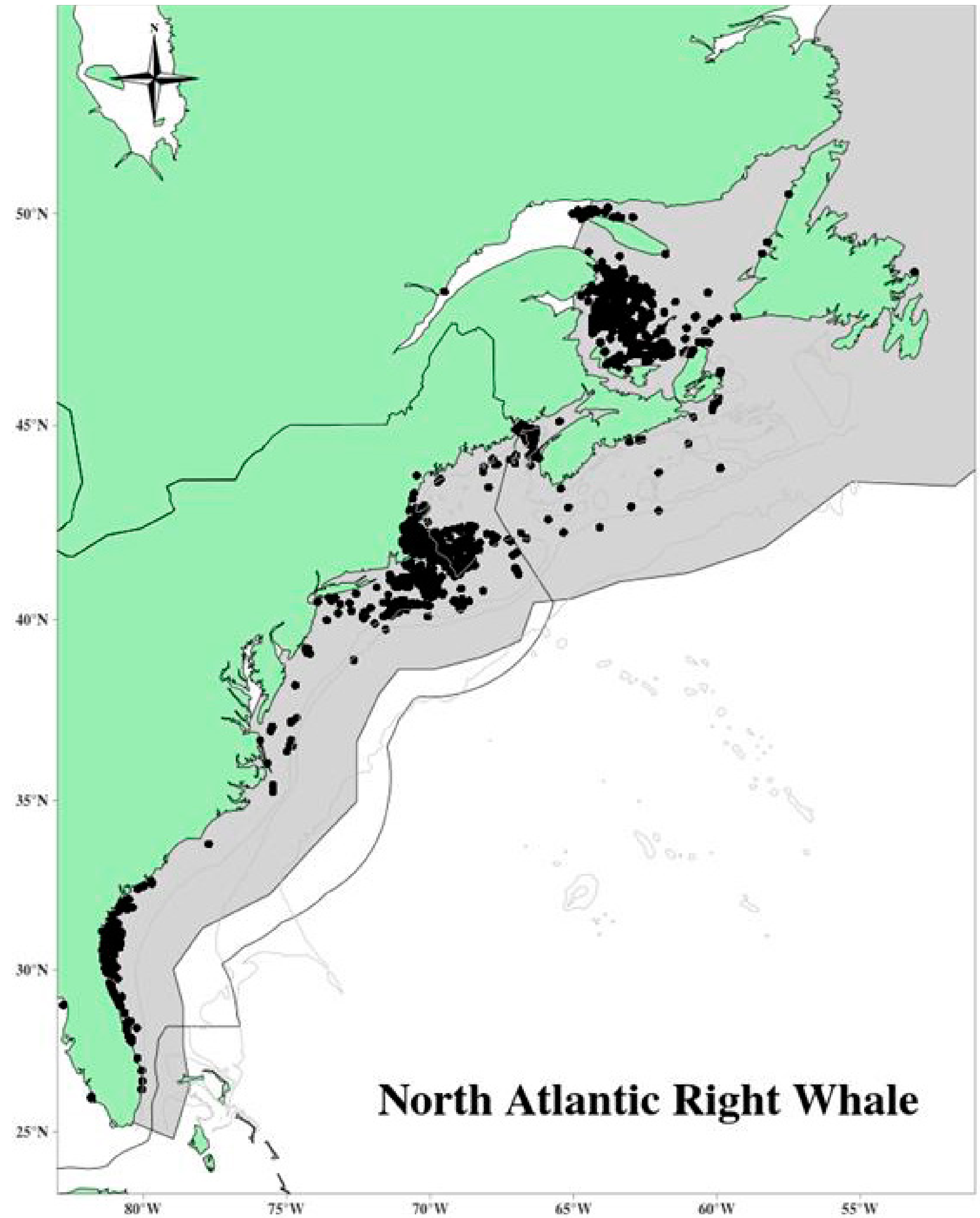


Figure 4.
Habitat range (shaded in gray) of the Western Atlantic stock of North Atlantic right whales with known sightings of North Atlantic right whales (dots) from 2016 to 2020. Figure reproduced from Hayes et al. 2023.

2.1.3.1. Historical Foraging Areas

As noted above, NARWs have historically concentrated on foraging grounds off the northeastern U.S. and Canada, generally traveling from one foraging area to another as the feeding season progressed from spring to fall. Historical NARW movements between foraging habitats was likely driven by abundance and concentration of their copepod prey.

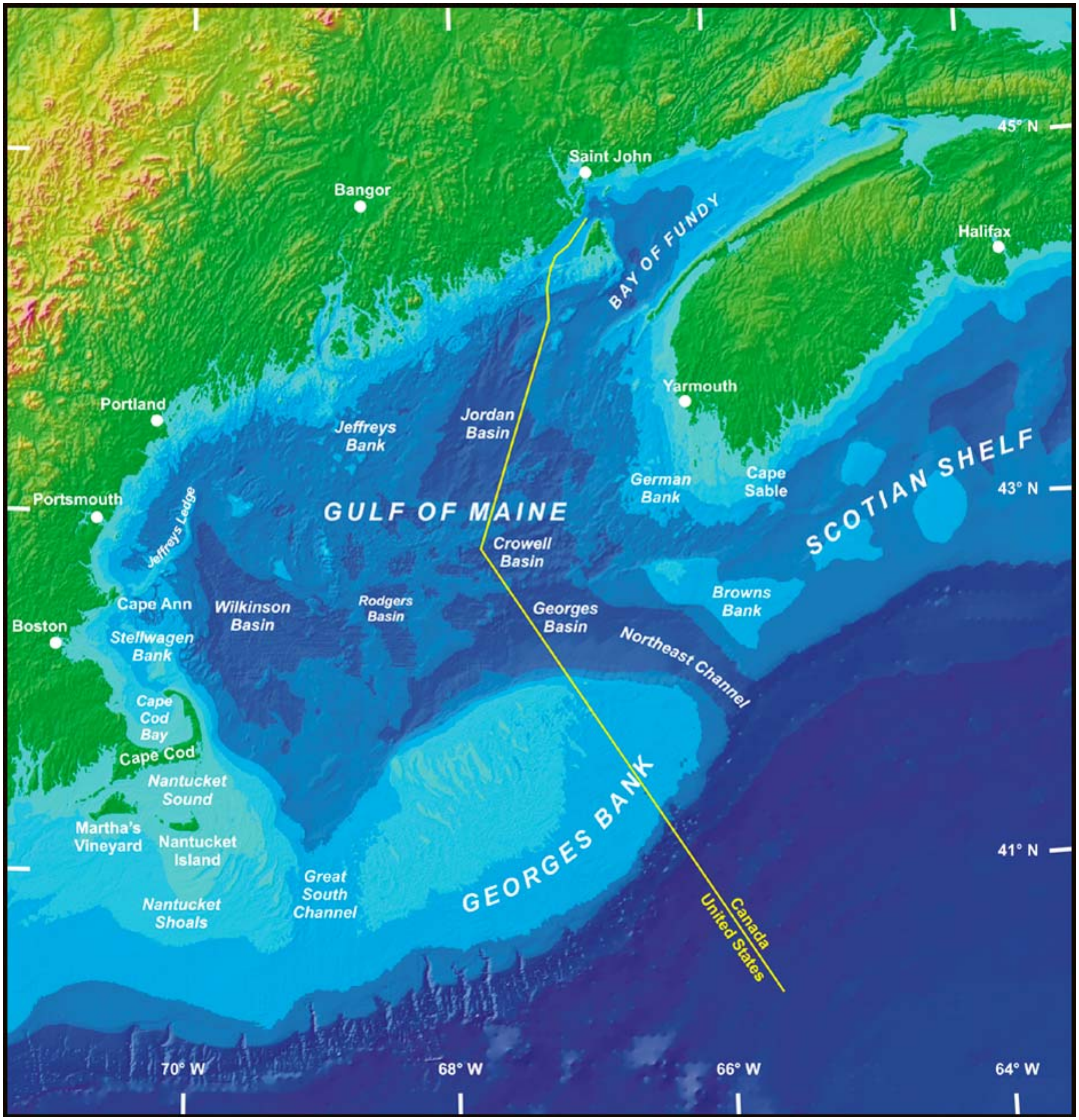


Figure 5.
Map of the Gulf of Maine and Georges Bank region showing historical foraging areas for NARW. Figure reproduced from NMFS 2015.

NARWs are ram feeders, swimming through the water with an open mouth to collect prey, and rely on dense concentrations of copepods to forage efficiently. They forage in areas where *C. finmarchicus*, their preferred prey species, aggregates in dense layers (Baumgartner and Mate 2003; Beardsley et al. 1996). Modeling has been used to estimate the density of *C. finmarchicus* necessary to support the daily metabolic demands of NARWs (Baumgartner and Mate 2003; Kenney et al. 1986), and tagging and observational studies have shown that NARWs require above-average *C. finmarchicus* densities to forage but will forage at densities lower than those required to support metabolic demands (Baumgartner and Mate 2003; Beardsley et al. 1996; Pendleton et al. 2009). Tagging studies have also shown that NARWs exhibit potential searching behavior when in areas with lower-density aggregations (Baumgartner and Mate 2003), indicating that they will ignore copepod patches with densities below a certain threshold in favor of locating higher-density aggregations.

Studies of NARW diving behavior show that the species' dive profile is optimized to feed on dense layers of copepods, with a rapid descent and ascent, maximizing the duration at foraging depth (Baumgartner and Mate 2003). Though NARWs may exhibit low variability in foraging dive depth in a given foraging habitat (Baumgartner and Mate 2003), dive depth varies between foraging habitats with a strong correlation between dive depth and the depth of maximum *C. finmarchicus* concentration (Baumgartner and Mate 2003; Baumgartner et al. 2017). This variation is indicative of exploiting *C. finmarchicus* aggregations as this species' vertical distribution varies across the foraging season and exploiting aggregations of other copepods (e.g., *Pseudocalanus* spp. and *C. typicus*) at times or locations when/where *C. finmarchicus* is not available at sufficient densities to support NARW foraging.

In spring, NARWs have historically foraged along the western edge of the GOM in Cape Cod Bay and Massachusetts Bay (Meyer-Gutbrod et al. 2015) with the greatest abundance observed in Cape Cod Bay in April (Pendleton et al. 2009). Through mid-spring, *C. finmarchicus* is generally not available. For that reason, NARWs in Cape Cod Bay in early to mid-spring likely forage on less energy dense copepod species (e.g., *Pseudocalanus* spp. and *C. typicus*) (Baumgartner et al. 2017; Pendleton et al. 2009).

From Cape Cod Bay and Massachusetts Bay, NARWs have historically moved to the central GOM and Great South Channel to forage from mid-spring into the summer (Meyer-Gutbrod et al. 2015). In mid- to late-spring, *C. finmarchicus* occur in the upper water column but also exhibit diel vertical migration during this period. Due to this vertical migration, NARWs have been observed foraging on *C. finmarchicus* concentrations at both shallow and deep depths in spring at the Great South Channel (Baumgartner et al. 2017; Beardsley et al. 1996). Spring *C. finmarchicus* abundance in the GOM has been previously identified as an important factor that allows reproductively viable females to transition from resting to pregnant states due to its influence on nutritional condition, which affects the ability to conceive (Meyer-Gutbrod et al. 2015).

In late summer, NARWs have historically transitioned to the Bay of Fundy at the northeastern end of the GOM and Roseway Basin on the Scotian Shelf to forage through the fall (Meyer-Gutbrod et al. 2015). During summer, *C. finmarchicus* moves deeper into the water column, resulting in more consistent foraging dive depths during this time period corresponding to copepod aggregations in mid-water layers (Baumgartner et al. 2017). The Bay of Fundy may have served as an important foraging area for pregnant females, which may rely on high summer abundance of *C. finmarchicus* to sustain a pregnancy (Meyer-Gutbrod et al. 2015).

2.1.3.2. Calving Grounds

During winter, pregnant females, as well as some juveniles, non-reproductive adult females, and adult males, travel to the NARW calving grounds off the southeastern U.S., generally off the coast of Georgia and northern Florida (Gowan et al. 2019; Kenney et al. 2001). This winter movement to the calving grounds has remained unchanged over the past three decades (Meyer-Gutbrod et al. 2022).

2.1.3.3. Overwintering Grounds

The overwintering habitat for the portion of the NARW population that does not travel to the calving grounds for the winter season is generally undefined (Kenney et al. 2001). NARWs have been observed foraging on copepod aggregations near the sea floor in the western GOM in December (Baumgartner et al. 2017), and there have been anecdotal observations of NARWs in Cape Cod Bay in the same month (Ganley et al. 2019). The western and central GOM, including Cape Cod Bay, may serve as mating grounds during the overwintering period (Bort et al. 2015; Cole et al. 2013; Mayo et al. 2018). Individuals have also been sighted in winter (i.e., December through February) south of Rhode Island and Massachusetts with a relatively high abundance of sightings south of Martha's Vineyard and Nantucket (Leiter et al. 2017). Southern New England, particularly waters south of Martha's Vineyard and Nantucket, currently supports a substantial portion of the population during the winter (O'Brien et al. 2022). Passive acoustic monitoring (PAM) equipment has detected NARWs in the southern Gulf of St. Lawrence in December and January (DFO 2020) and in the New York Bight between December and February (Muirhead et al. 2018).

2.2 Climate Change, Environmental Variability, and Shifting Distribution of the NARW in the Western North Atlantic

The environment in which NARWs live is a highly dynamic physical environment, experiencing extensive variability and ongoing change on a variety of timescales ranging from hours to centuries. This includes both variability caused by the influence of anthropogenic climate change (Section 2.2.1) and natural variability (Section 2.2.2). Climate change and large-scale environmental variation have likely driven a shift in NARW distribution, as described in Section 2.2.3.

2.2.1 Background on Current Trends in Climate Change

Climate change is occurring on a global scale. Just this year, temperature records have been broken around the world. On July 6, 2023, the average daily global temperature reached 17.08°C and exceeded the hottest measurement on record,[3] breaking the previous record set in August 2016.[4] This comes on the heels of June 2023 being the hottest June on record,[5] and prior to July 2023 being recorded as not only the hottest July, but also the hottest month ever recorded on Earth and perhaps in at least 120,000 years.[6] These changes are also being experienced in the Earth's oceans, with **Figure 6** showing how anomalously warm the global average sea surface temperature has been in 2023. Globally, marine heatwaves, which like their terrestrial counterparts are periods of anomalously warm temperatures, have increased in frequency by 34 percent and in duration by 17 percent from 1925 through 2016, which is reflected in a 54 percent increase in global marine heatwave days each year (Oliver et al. 2018).

In its most recent assessment report that was finalized between August 2021 and March 2023, the United Nations Intergovernmental Panel on Climate Change (IPCC)[7] concluded that "it is unequivocal that human influence has warmed the atmosphere, ocean and land," (IPCC 2021, 2023). This report goes on to state that under all emissions scenarios, the global surface temperature will continue to climb, at least until the middle of the 21st century, exceeding at least 1.5°C of warming globally unless there are significant and meaningful reductions in greenhouse gas emissions (IPCC 2021, 2023).

---

3 *https://climate.copernicus.eu/july-2023-sees-multiple-global-temperature-records-broken*

4 *https://public.wmo.int/en/media/press-release/july-2023-set-be-hottest-month-record*

5 *https://climate.nasa.gov/news/3276/nasa-finds-june-2023-hottest-on-record*/

6 *https://www.washingtonpost.com/weather/2023/08/02/july-hottest-month-global-temperatures/*

7 The IPCC (*https://www.ipcc.ch/*) is composed of three Working Groups that focus on physical science, impacts, and mitigation. The IPCC compiles work being done by scientists around the globe as part of Assessment and Synthesis Reports that are released approximately every six to seven years.

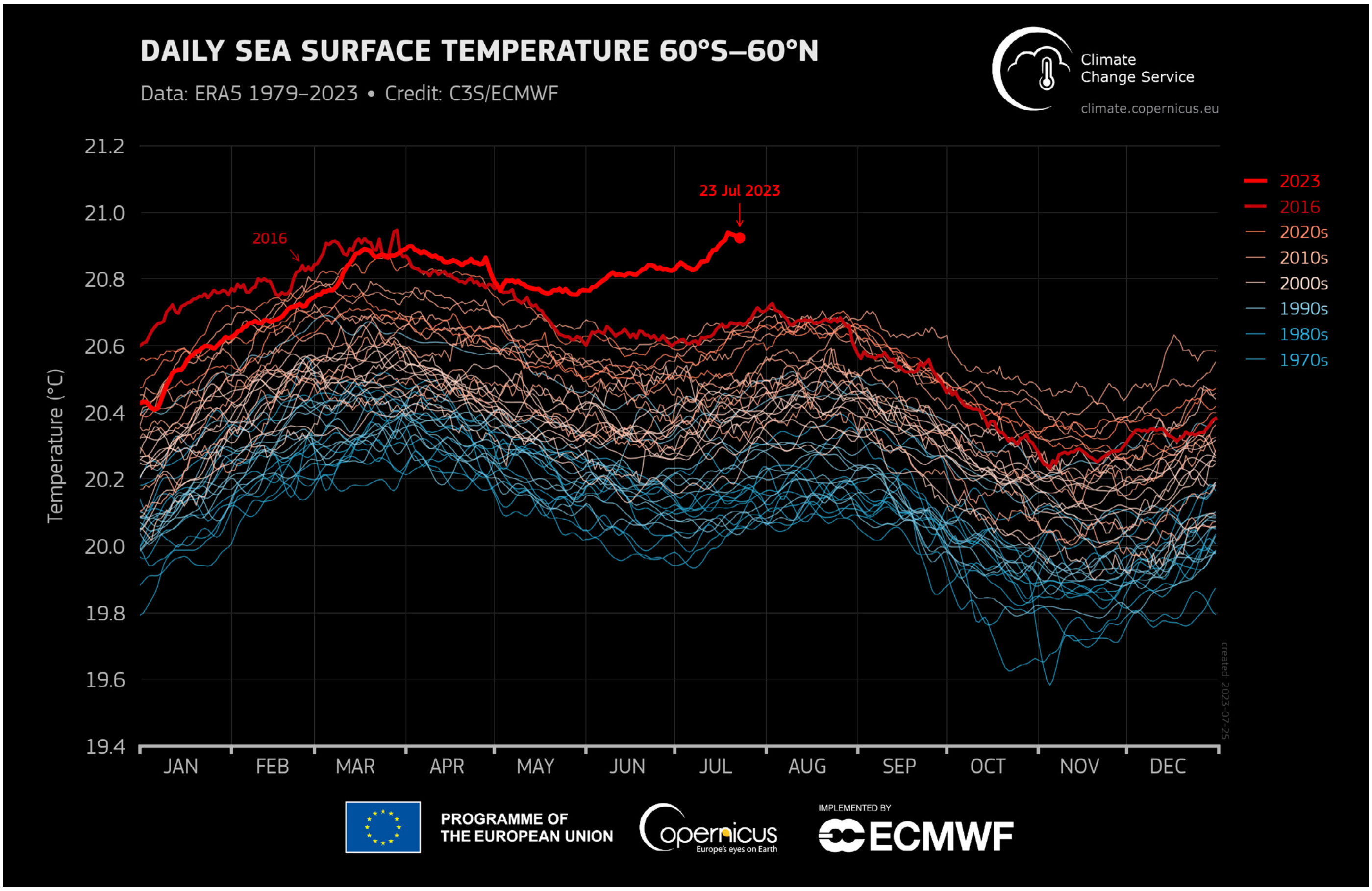


Figure 6.

Daily global sea surface temperature (°C) averaged over the 60°S-60°N domain plotted as a time series for each year from January 1, 1979 to July 23, 2023. The years 2023 and 2016 are shown with thick lines shaded in bright red and dark red, respectively. Other years are shown with thin lines and shaded according to the decade, from blue (1970s) to brick red (2020s). Figure credit: Copernicus Climate Change Service/European Centre for Medium-Range Weather Forecasts , with data from ERA5 climate reanalysis.

2.2.1.1. Regional Climate Change

The shelf waters of the GOM and MAB are one of the fastest warming ecosystems worldwide, with temperatures increasing at a rate of 0.25°C per decade since the mid to late 1900s (Friedland et al. 2020, 2022; Saba et al. 2016). This warming is especially prominent in the autumn, and the rate of warming has increased during recent years, sometimes exceeding 1.0°C per decade, a trend that is expected to continue (Friedland et al. 2020; Pershing et al. 2015; Saba et al. 2016). There is evidence that the regional warming is not a steady increase in temperature but instead may include several regime shifts, especially during the fall (Friedland et al. 2020). Fall surface temperatures, especially over Georges Bank and the GOM, exhibited regime shifts in 1999 and 2011 that were likely related to oceanic effects, while any trends and possible regime shifts in spring were weaker and likely due to atmospheric effects (Chen et al. 2018; Friedland et al. 2020). Trends in spring bottom temperature are similarly weak. However, fall bottom temperatures across the shelf have shown significant warming with a strong regime shift in 2008 likely due to Gulf Stream effects on the Labrador flow changing the advection of Labrador slope water into the region (Brickman et al. 2018; Friedland et al. 2020). This has caused warming of the deeper waters of the Cold Pool, as well as a decrease in size and persistence of the Cold Pool, during the summer and fall of the past several decades (Chen and Curchitser 2020; Friedland et al. 2022; Miller et al. 2016), with a notable increase in temperature and decrease in Cold Pool volume observed during the 2008 regime shift (Friedland et al. 2022).

Warming is also being experienced in the GOM and the area around Nantucket Shoals. During the period of 1977 through 2016, warming there was seen to be about half as strong as that seen in the MAB during the same time period (Wallace et al. 2018). The region near Nantucket Shoals, including the northern MAB and Georges Bank to the east of the shoals, was also seen to experience significant reduction in salinity during that period (Wallace et al. 2018). These changes in temperature and salinity are driving changes in overall stratification in the GOM, as they are in the MAB. Marine heatwaves have increased considerably since 2012, showing at their extremes temperatures 3°C above normal at the surface and up to 7°C above normal at 100 m depth (Großelindemann et al. 2022). Additionally, the frequency of Gulf Stream meanders has been increasing, with a near doubling of warm core rings observed since 2000 (Andres 2016). These regional changes due to global climate change are connected to the ecosystems which inhabit these ocean spaces and are likely to continue to intensify into the future.

2.2.1.2. Wind Energy's Role in Mitigating Climate Change

One of the key motivations behind the development of wind energy is the fact that it produces substantially less equivalent carbon dioxide emissions per generated unit of power than a conventional fossil fuel-powered plant.[8] While wind turbines themselves do not produce any emissions during normal operations, there are emissions associated with the construction, operation and maintenance, and decommissioning of wind projects. However, these emissions are at least an order of magnitude less than the emissions generated by the burning of fossil fuels to produce an equivalent amount of electricity (NREL 2021). Additionally, as sources of emissions related to offshore wind continue to be reduced by new technologies and developments, such as blade recycling and vessel modernization, further reductions in emissions can be achieved. Replacing fossil fuel-powered plants with renewable energy plants, such as wind energy, will reduce the overall emissions associated with electricity generation, and play a role in reducing warming associated with climate change.

While offshore wind development plays a key role in the transition away from fossil fuels and is an essential component to meeting carbon reduction targets, it is only one element of climate change mitigation. Other aspects include the ongoing and continued development of other renewable technologies, such as solar and onshore wind, as well as other less carbon-intensive energy sources, including some that are still being developed. New technologies continue to be developed that can further mitigate the effects of climate change, such as carbon capture and storage, green hydrogen, and additional technologies that may come along in the future.

2.2.2 Natural Sources of Environmental Variability in the Western North Atlantic

Additional sources of environmental variation within foraging habitats of NARW include the ongoing regime shift in the Arctic climate system and the NAO, as detailed in the following sections. Natural variability cycles such as these are also impacted by ongoing climate change.

2.2.2.1. Arctic Regime Shift

Regime shifts are large, sudden changes in ecosystems that persist for a substantial duration (Biggs et al. 2009). Arctic regime shifts affect circulation in the Arctic Ocean, which affects freshwater export out of the Arctic (Greene et al. 2008). When freshwater export out of the Arctic Ocean is high, salinities are reduced in the North Atlantic. Reduced salinities can alter the timing and extent of stratification in the water column, which in turn affects abundance and seasonality of phytoplankton and zooplankton (e.g., copepods) (Greene et al. 2008). One such Arctic regime shift resulted in increased freshwater export out of the Arctic and led to the Great Salinity Anomaly of the 1990s (Meyer-Gutbrod and Greene 2014). The low-salinity waters, and associated changes in stratification, led to a significant decline in abundance of *C. finmarchicus*. The decline in abundance of its primary copepod prey resulted in a decline in calf production by NARW in the following years (Meyer-Gutbrod and Greene 2014). In the late 1990s,

8 For more details, see "Life Cycle Assessment Harmonization," available at https://www.nrel.gov/analysis/life-cycle-assessment.html.

another Arctic regime shift occurred that favored freshwater retention in the Arctic Ocean. With the reduction in freshwater export, salinities in the North Atlantic rose, and the abundance of *C. finmarchicus* increased. This rebound in the copepod abundance resulted in a sharp increase in annual calf production of NARWs in the first decade of the 2000s (Meyer-Gutbrod and Greene 2014).

2.2.2.2. North Atlantic Oscillation

The NAO is a variation in surface pressure between two regions of the North Atlantic: a low-pressure area around Iceland (i.e., the sub-polar low) and a high-pressure area around the Azores Islands (i.e., the subtropical high). The NAO Index, which is based on the difference in pressure between the sub-polar low and subtropical high, is used to track this oscillation. When the NAO Index is positive (i.e., there is a large pressure difference between the regions), the U.S. East Coast generally experiences warm conditions; when the NAO Index is negative, the U.S. East Coast generally experiences cold conditions (NOAA 2009).

In 1996, the NAO Index exhibited the largest drop in the 20th century. Following this drop there was a large-scale change in circulation patterns over the continental shelf and the continental slope of the Northwest Atlantic (Greene and Pershing 2003). This change in circulation was likely a significant factor in the further decline in *C. finmarchicus* abundance, which was already reduced following the Arctic regime shift in the early 1990s (Greene and Pershing 2004; Meyer-Gutbrod and Greene 2014). After the abundance of *C. finmarchicus* declined in 1998, NARWs experienced a reproductive failure in 1999 and 2000 (Meyer-Gutbrod and Greene 2014).

While the 10-year cycles in NARW productivity from the 1980s to the 2000s appear to be largely explained by the NAO and its effect on prey species, by 2010, the data suggested that climatic warming was driving a regime shift in the GOM and Western Scotian shelf. The prominent driver of this shift is hypothesized to be the weakening of the Atlantic meridional overturning circulation during the early 2000s. This has increased the frequency of warm core ring shedding, which injects warm, high saline waters onto the shelf of the MAB and Georges Bank. The advection of this warm slope water through the deep channels of the GOM, in combination with the decrease in the cold, fresher Labrador Current water coming in from the north, is driving the decade-long warming trend recorded in the GOM. Coinciding with the regime shift in 2010, annual *C. finmarchicus* abundance declined significantly in the GOM (Sorochan et al. 2019). While the higher temperatures are not lethal for *C. finmarchicus*, the increase in temperature directly impacts their population by increasing their metabolism (thus requiring more food), decreasing their body size, and lowering their lipid content, making them energetically less valuable as a food source for the NARW (Fields et al. 2023).

2.2.3 Shifting Distribution of North Atlantic Right Whale

Movement patterns of NARWs are more closely tied to environmental physical processes compared to other baleen whales in the North Atlantic, potentially due to their feeding on lower trophic levels (Pendleton et al. 2022). Based on these close ties, environmental changes associated with climate change (Section 2.2.1) and other sources of variability (Section 2.2.2) are likely significant drivers in the shifting NARW distribution. NARWs are sensitive to temperature variability and may use temperature as a migratory cue (Ganley et al. 2022; Pendleton et al. 2022). Warming water temperatures associated with climate change may be causing earlier migration cues and driving the extended utilization period in some foraging habitats (Ganley et al. 2022). There is also evidence that the shift in the distribution of NARWs is driven by changes in prey availability associated with climate change (Davies et al. 2019). Diapausing *C. finmarchicus* prefer temperatures below 5°C (Gavrilchuk et al. 2021). As the waters of the GOM and the Scotian Shelf warm, they become less suitable for *C. finmarchicus*, and NARWs may have to travel further north seeking cooler waters that support adequate concentrations of *C. finmarchicus* for their metabolic demands (Pershing and Pendleton 2021).

Since 2010, sightings of NARWs on historical foraging grounds (Section 2.1.3.1), particularly in the GOM and Bay of Fundy, have declined significantly (Davies et al. 2019; Meyer-Gutbrod et al. 2021; Pershing et al. 2021). Foraging habitats utilized by NARWs from 2010 to 2014 are largely unknown (Meyer-Gutbrod et al. 2021), suggesting that the population was dispersed (Davies et al. 2019) or utilizing previously unknown habitats not covered by annual surveys during this period. Following the decline in sightings on historical foraging grounds, sightings during the foraging season increased in Cape Cod Bay (Ganley et al. 2019; Mayo et al. 2018) and in previously unidentified concentration areas, including the central MAB (Davis et al. 2017), southern New England (Meyer-Gutbrod et al. 2022 O'Brien et al. 2022; Quintana-Rizzo et al. 2021), and the Gulf of St. Lawrence (Bishop et al. 2022).

2.2.3.1. Cape Cod Bay

Cape Cod Bay was historically utilized for early spring foraging (Section 2.1.3.1) and has been consistently utilized as an early spring foraging habitat since 2010 (Meyer-Gutbrod et al. 2022). However, a greater proportion of the NARW population now utilizes Cape Cod Bay, and the duration of utilization has increased, beginning in the winter and extending into late spring (Ganley et al. 2019; Mayo et al. 2018; Meyer-Gutbrod et al. 2022; O'Brien et al. 2022; Pendleton et al. 2022). This area is now recognized as an important NARW habitat for foraging, socialization, and nursing calves, as evidenced by the increasing proportion of cow/calf pairs that utilize Cape Cod Bay (Ganley et al. 2019; Mayo et al. 2018). Cape Cod Bay may also serve as a holding area where NARWs can forage as *C. finmarchicus* densities increase in foraging areas further north (Pendleton et al. 2022). Peak seasonal abundance in Cape Cod Bay currently occurs in March (Ganley et al. 2019).

2.2.3.2. Central Mid-Atlantic Bight

As sightings in the GOM and Bay of Fundy have decreased since 2010, sightings in the MAB have increased (Davis et al. 2017). NARW have been detected during PAM off Long Island and New York Harbor in the spring, fall, and winter, with the greatest presence in spring (Muirhead et al. 2018). The extended utilization of this habitat suggests that some NARWs may be resident in the New York Bight waters stretching from Cape May, NJ to Montauk, NY within the MAB year-round (Muirhead et al. 2018).

2.2.3.3. Southern New England

Southern New England is another area where NARW have been observed foraging since the utilization of historical foraging habitats decreased (Meyer-Gutbrod et al. 2022). There has been a significant increase in NARW abundance in the region and an extension in the period of occurrence (O'Brien et al. 2022). Historically, NARW presence peaked in southern New England in winter and spring (O'Brien et al. 2022), and foraging was observed in the region in early spring (Leiter et al. 2017). NARWs were once absent from June through October, but since 2017 they have been observed in low numbers in summer and fall (Meyer-Gutbrod et al. 2022; O'Brien et al. 2022; Quintana-Rizzo et al. 2021). Usage of foraging habitat in southern New England has also increased in the spring (Meyer-Gutbrod et al. 2022). This region now serves as a year-round habitat and supports a substantial proportion of the NARW population during winter and spring (Estabrook et al. 2022; O'Brien et al. 2022). Nantucket Shoals in Southern New England has been identified as a potential hotspot for NARW and is utilized by the species throughout much of the year, concentrating particularly in the winter in recent years (Quintana-Rizzo et al. 2021).

2.2.3.4. Gulf of St. Lawrence

The Gulf of St. Lawrence has also become an important summer foraging habitat for NARWs in recent years (Bishop et al. 2022; Meyer-Gutbrod et al. 2021, 2022; O'Brien et al. 2022; Pershing and Pendleton 2021), particularly the western and southern portions of the gulf (Bishop et al. 2022; DFO 2020; Gavrilchuk et al. 2021). The Gulf of St. Lawrence, particularly the southern gulf, may be a more favorable foraging habitat than other areas based on its physical oceanography (Gavrilchuk et al. 2021). Specifically, the broad, shallow shelf in the southern Gulf of St. Lawrence receives *Calanus* copepods that are transported from deeper waters, and these copepods are compressed against the seafloor of the shelf, resulting in high prey concentrations at relatively shallow depths, requiring less time and energy to reach (Gavrikchuk et al. 2021). NARWs are present in the Gulf of St. Lawrence from May through November (DFO 2020), with the greatest abundance during the peak foraging season (i.e., June through October) (Bishop et al. 2022; Crowe et al. 2021). The Gulf of St. Lawrence is now utilized by a substantial proportion of the NARW population (DFO 2022) and serves as an important foraging habitat for female NARWs, as indicated by the greater reproductive success of females utilizing this habitat (Bishop et al. 2022).

The new summer foraging grounds in the Gulf of St. Lawrence are approximately 1,000 km north of the historical summer foraging areas (Bishop et al. 2022), resulting in higher costs, in terms of both energy and time, to reach these grounds from calving and overwintering areas (Meyer-Gutbrod and Greene 2018). Higher energetic demands may in turn affect calving rates for the population (Meyer-Gutbrod and Greene 2018). Calving rates are also influenced by abundance of copepod prey (Meyer-Gutbrod and Greene 2018; Pershing and Pendleton 2021). With warmer water temperatures resulting in both earlier migratory cues, and therefore extended residence times in spring foraging areas, and reduced prey abundance in spring foraging habitats, NARWs may be experiencing a predator-prey mismatch (Ganley et al. 2022). NARW may also be experiencing a climate deficit, which results from experiencing sub-optimal foraging conditions in both historical foraging areas and new foraging habitats (Pershing and Pendleton 2021). The reduction in fitness associated with a predator-prey mismatch and/or a climate deficit may have a negative impact on reproductive rate for the NARW population.

2.3 Potential Hydrodynamic Effects of Wind Turbines

The presence of wind turbine structures in the offshore environment can impact the physical conditions of the atmosphere/ocean system in two principal ways. The first is the atmospheric wind wake effect, whereby the wind speeds behind the turbines are reduced by the extraction of energy from the wind, which is discussed in Section 2.3.1. The second is through additional mixing that occurs from water flowing around the turbine's foundation structure below the waterline and the potential subsequent effect on thermal stratification, discussed in Section 2.3.2. Efforts to study both of these effects through coupled modeling is discussed in Section 2.3.3, followed by a discussion of potential ecosystem impacts in Section 2.3.4.

2.3.1 Wind Wake Effect

Wind turbines operate by converting kinetic energy from the movement of air passing through the turbine's rotor (wind) into electricity with a generator. The act of converting this kinetic energy to electrical energy results in less kinetic energy in the atmosphere, resulting in a localized reduction in wind speed behind the turbine rotor. This reduction in wind speed is known as a "wake." The wakes originate directly behind each turbine, and propagate in the direction of the wind, expanding and weakening as they do so, before eventually dissipating in the surrounding airflow (e.g., Ainslee 1988). Wakes from adjacent turbines interact with each other as they propagate downstream, resulting in wake pattern for the full wind farm. These wakes vary in both intensity and dimensions, and are highly dependent on a variety of factors, such as wind speed, turbine size, and layout (i.e., direction and spacing) of the wind turbine array (e.g., Barthelmie et al. 2010).

Key among these factors is atmospheric stability (Ghaisas et al. 2017; Hansen et al. 2012), which is a measure of how easily the atmosphere mixes due to vertical motions. An unstable atmosphere is typified by warmer air below cooler air: since warm air rises, it will start to rise and cool. Provided it remains warmer than the surrounding air as it does so, it will continue to rise; unstable atmospheres are perhaps best exemplified by the vast vertical extent and power of a thunderstorm. A stable atmosphere, on the other hand, is typified by cooler air below warmer air: the cooler air will not rise above warmer air naturally without some sort of external force. Stable atmospheres are exemplified by morning fog layers over a lake that is cooler than the surrounding air, or when smoke remains close to the surface after leaving a chimney. Stable conditions can be commonly found in northeastern coastal waters during certain times of day, particularly during the summer months when the air moving over the ocean from land is commonly warmer than the ocean's surface (e.g., Dicopoulos et al. 2021; Golbazi et al. 2022). However, the frequency of stable versus unstable conditions can vary considerably by location and season (Archer et al. 2016).

Within existing wind farms, stable atmospheric conditions have been demonstrated to result in longer wake propagation (e.g., Christiansen et al. 2022a; Ghaisas et al. 2017; Golbazi et al. 2022) due to the reduced amount of vertical mixing present in the ambient air that serves to mix wakes into the surrounding air when the atmosphere is unstable. As the wakes propagate downwind, they expand, potentially reaching the surface. Modeling studies in the North Sea have shown wind speed reductions at the surface due to these wakes on the order of 0.1 to 0.5 m/s, depending on the season and density of wind turbines (Akhtar et al. 2021; Christiansen et al. 2022a). This reduction in wind speed at the surface is "felt" by the ocean as a reduction in surface wind stress. In the North Sea, modeling studies have shown that the reductions in surface winds and wind stress can be seen over several tens of kilometers downwind from groups of wind turbines, and do not necessarily fully return to ambient conditions in between closely adjacent wind farms within that range (Christiansen et al. 2022a). More details on the oceanic impacts of atmospheric wakes are discussed in Section 2.3.3.

As wind turbine technology has advanced, wind turbines have continued to grow in size, having larger rotors and larger hub heights, which positions the rotors higher above the surface of the ocean. Recent research has explored the role of these changes in wind turbine design on wakes. Golbazi et al. (2022) modeled 2,252 "extreme scale" (hub heights >100 m, rotor diameters >150 m, with a rated capacity >10 MW) turbines hypothetically constructed in the New York Bight to include wind turbines fully installed in all existing lease areas. The study found that these larger turbines that are consistent with those planned for construction in the U.S. have less impact on the ocean's surface than the smaller scale turbines commonly found presently in Europe. The authors note that atmospheric warming, which takes place in the wake due to mixing, does not reach the surface for these larger turbines, and as a result there is no increase in sea surface temperature due to the wake.

2.3.2 Induced Underwater Mixing Effect

Offshore wind turbines are attached to the ocean floor by one of several methods, divided into two broad types: fixed-bottom foundations and floating foundations. Fixed-bottom foundations are by far the most prevalent to date (both in the United States and globally), and the only type being deployed in the current tranche of offshore wind farms along the U.S. East Coast. They consist of a rigid subsurface structure, usually a single pole (monopile) or several legs (jacket), though gravity-based structures are also under consideration. The presence of this foundational structure can alter the flow of water that is pushed through the offshore wind farm by currents and can affect thermal stratification of the water. This impact is highly dependent on the flow conditions already present, and the types of currents that drive the flow. These can be characterized into flows that have stronger currents (order of magnitude of 0.5-1.0 m/s), often strongly influenced by tides, such as in the North Sea or on Nantucket Shoals; and flows that are generally weaker (order of magnitude of 0.1 m/s), often strongly influenced by wind-driven currents, such as in the MAB (e.g., Miles et al. 2021). It should be noted that the overall currents experienced in a particular area are a combination of various forces, and the magnitude of these forces can vary between locations. Additionally, the strength of thermal stratification present in an area is dependent on the types of currents and the source water of those currents (e.g., fresh v. salty), as well as factors such as solar insolation which varies by season and weather conditions.

Floating foundations are types where the turbine is floating on the surface of the ocean with some type of floating substructure (such as a spar or platform) and anchored to the ocean floor with anchoring chains. These types of foundations are less common as of the writing of this white paper but are rapidly developing in order to allow for offshore wind deployment in deeper waters than fixed-bottom technologies allow. The induced underwater effect of floating turbines has not been extensively studied to date, but due to the fact that the anchoring chains present much less surface area for the current flow to interact with, the impacts are expected to be less than those with fixed-bottom foundations.

2.3.2.1. Thermal Stratification

As discussed in Section 2.1.1, stratification plays a key role in the oceanography of regions inhabited by NARW and is highly seasonal. Typically, where thermal stratification takes place (such as the MAB, GOM, and Europe's North Sea), stratification is strongest in the summer months, while spring is associated with the setup of the stratification after a well-mixed winter, and autumn is associated with the eventual breakdown of stratification leading into the well-mixed winter months. In a modeling study of the North Sea, the strongest changes to stratification from offshore wind were shown to take place during the formation months of May and June, and the breakdown months of August and September, with autumnal changes being five to ten times stronger than the other months (Christiansen et al. 2022a). This indicates that the presence of offshore wind in the MAB is more likely to influence the setup or breakdown of the Cold Pool in spring and fall, respectively, but is unlikely to have much influence on the very strong summer stratification, which is significantly stronger (30 percent or more) than the stratification experienced in the German Bight (Miles et al. 2021). It should be noted that the Cold Pool already experiences extensive variability in the timing and intensity of the setup and breakdown seasons (e.g., Chen et al. 2018).

2.3.2.2. Stronger Flows

The currents in some coastal waters can be largely driven by the influence of diurnal tides. This is particularly true in the regions of the North Sea where there have been a large number of wind farms built to date, as well as along Nantucket Shoals (see Section 2.1.1.1). Due to many of the existing studies of hydrodynamic influences of offshore wind being conducted in the North Sea, much of this work is particularly relevant to tidally driven flows.

Carpenter et al. (2016) aimed to calculate order-of-magnitude assessments of two time scales that drove mixing of stratification in the North Sea: the mixing time scale, which is a measure of how long it takes to completely mix the stratified conditions; and the advective time scale, which is a measure of how long a particular water parcel takes to move through the enhanced mixing area of underwater wind farm structures. To do so, available in situ observations were utilized, as well as modeling, and wind farm parameters such as the monopile frontal area, monopile drag coefficient, and monopile spacing, plus parameters of the water column such as density, overall depth, depth of the pycnocline, current speed, and a measurement of stratification were included. The mixing time scale was estimated to be larger than, but comparable to, the total time period of summer stratification in the North Sea, indicating that the induced mixing from offshore wind could be significant. This time scale was sensitive to both stratification strength and the foundation structural drag (Carpenter et al. 2016).

While the mixing time scale serves as an indicator of how much the turbine structures may induce mixing, the advective time scale indicates whether or not the moving water spends enough time under the influence of the wind farm to have that effect. Carpenter et al. (2016) estimated that water parcels are unlikely to spend much time in the enhanced mixing area of a wind farm of finite size, and so extensive regions of the North Sea would likely need to be covered with wind turbines in order for there to be a significant impact on stratification. They also stated that the use of floating or semi-submerged offshore wind platforms could help to minimize any effects (Carpenter et al. 2016).

A modeling study in the Irish Sea which evaluated in-water wakes around turbine monopiles saw localized reductions in current speeds of up to 5 cm/s (approximately 5 percent of the background tidal current of about 1 m/s) extending about 1.25 km behind each monopile. The monopiles also enhanced local vertical mixing within 20 m of the monopile (Cazenave et al. 2016). Modeling studies in the North Sea which combined the impacts of tides with the wind wake effect showed mean changes over the 48-hour modeled time period to be very small, showing little effect on mean horizontal flow (Christiansen et al. 2022b). This was due to the positive velocity changes from tidally-induced countercurrents (that change direction diurnally), which counteracted the negative changes from aligned currents and prevented the development of a consistent surface velocity reduction. In terms of vertical velocity changes, in deeper waters of the North Sea, any changes were similar both with and without tides; in shallow waters, tidal mixing mitigated any secondary wake effects, with the mean temperature stratification being about 50 percent weaker with tides (Christiansen et al. 2022b).

2.3.2.3. Weaker Flows

To date, much of the construction of offshore wind in the North Sea has taken place in waters that are more tidally driven and have stronger overall currents relative to other areas of the North Sea. However, ongoing expansion of the offshore wind industry in the North Sea will move into areas with weaker tidal influence and weaker overall currents, which may experience greater wake effects than areas with strong tides (Christiansen et al. 2022b). Additionally, while some regions in the U.S. expecting to have offshore wind development have strong tidal currents, other regions have much weaker currents, like the MAB (Roarty et al. 2020).

Shultze et al. (2020) evaluated field observations of stratification within the wake of a single offshore wind turbine for the first time and combined these data with high-resolution large eddy simulation modeling of four different stratification strengths. They found that the turbulent wake from a monopile foundation is narrow and highly energetic in the first 100 m behind the substructure, adding about 7-10 percent additional mixing to the bottom mixed layer. While they found that the effect of a single turbine is fairly low, they state that large-scale offshore wind farms could significantly alter the vertical structure of a weakly stratified water column (Shultze et al. 2020).

Shultze et al. (2020) further updated the mixing time scale from Carpenter et al. (2016) using these results, and calculated the time scale to be 55 days, which is close to the typical timescale of stratification formation of 60 days. This indicated that mixing induced by offshore wind farms could be significant in the stratification process, but it is reliant on the stratified water column spending significant time within the offshore wind farm (the advective time scale). Floeter et al. (2017) estimates that the advective time scale for a typical 9 km wide offshore wind farm is about 7 to10 days; this indicates that the reduction of stratification within a wind farm could be about 13-18 percent, and a wind farm on the scale of 100 km wide would be needed to prevent stratification (Shultze et al. 2020). The authors emphasized that future studies should also include both wind and tidal effects to better understand this process.

2.3.3 Coupled Modeling of Atmospheric and Oceanic Effects

The physical processes taking place in offshore wind farms occur in a highly coupled physical environment, where the atmosphere and ocean both have their own internal processes, while also interacting with each other at the air/sea interface. As such, it is important to understand both systems individually, but also how they act as a combined system. As an example, despite the strong tidal influence in the North Sea, the general circulation there is still largely wind-driven, and so a reduction in wind stress could result in changes in circulation, accompanied by attenuated momentum flux and less transfer of energy from the atmosphere to the ocean. This could result in potential changes in wave formation, horizontal surface current velocity, and could reduce surface layer turbulence and thereby impact stratification (Christiansen et al. 2022a).

Wind turbine wakes in the North Sea were shown to change the surface velocity by about 5 percent of the mean surface residual velocity, which is about 10 to 15 percent of the interannual and decadal surface velocity variability (Christiansen et al. 2022a). This indicates that it can be challenging to isolate changes to surface current velocity from the presence of the wind farm from other sources of variability. Furthermore, studies have found that changes in sea surface temperatures in the wake of North Sea offshore wind farms can be up to 0.1°C, which is an order of magnitude less than the average perturbations from climate change, and up to 10 percent of the typical interannual variability of 1 to 1.5°C (Christiansen et al. 2022a; Daewel and Schrum 2017; Schrum et al. 2016).

One of the key findings in studies such as Christiansen et al. (2022a) was the presence of large-scale dipole changes (see **Figure 7**) in sea surface elevation in the North Sea, which serve as a main driver of wake-related processes in the ocean. These dipoles drive large-scale structural changes in stratification strength and unanticipated spatial variability in mean currents. However, the magnitude of changes is small compared to overall long-term variability of temperature and salinity in the region, and they are difficult to distinguish from the existing interannual variability. As a result, "severe" impacts of wakes on the ocean's thermodynamic processes are not expected (Christiansen et al. 2022a).

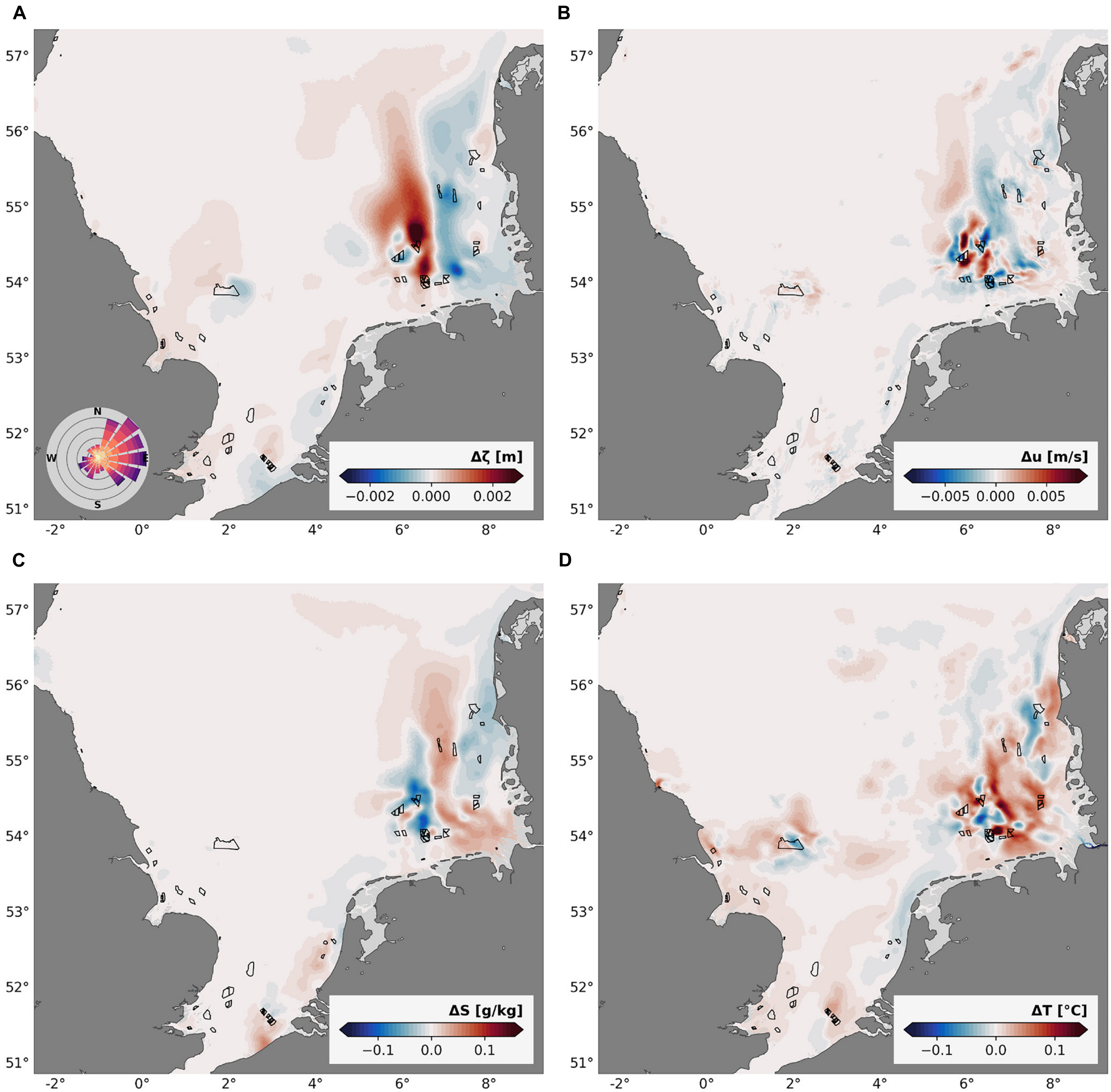


Figure 7.

Mean modeled changes in sea surface elevation (A), depth-averaged velocity (B), sea surface salinity (C), and sea surface temperature (D) for the month of August 2013. Black polygons indicate offshore wind farms. The wind rose indicates the direction in which the wind blew (color range between 1 and 12 m/s). Reproduced from Figure 7 in Christiansen et al. 2022a.

Tidal currents were found to deflect or even invert wake-induced processes, with the alignment between the wind and ocean currents determining the magnitude of the wake effect. Inclusion of tides indicated that the mean sea level change from the dipole pattern is half as large (Christiansen et al. 2022b). Wake related changes in stratification are a function of local stratification strength, which is governed by tidal mixing in this region. Weakly stratified waters result in weaker secondary wake effects, while stronger stratification results in stronger secondary wake effects. The authors state that local stratification strength can be used to help evaluate the expected impacts of secondary wake effects; they further emphasize that tides, water depth, and stratification regimes are all important factors in the overall impacts of offshore wind farms and their wake effects; atmospheric conditions are not the only factor (Christiansen et al. 2022b). Connecting this back to U.S. waters, this balance between a reduction in surface mixing due to the wind turbine wakes and the increase in mixing due to the presence of the underwater structures would need to be evaluated on a project specific basis for local geographies and wind turbine parameters including their size and hub height, due to significant differences in these factors between the U.S. and Europe (Golbazi et al. 2022; Miles et al. 2021). Local geographic differences between the U.S. and the North Sea include current strength and patterns including differences in tides, water depths, stratification strength, and general topography. This serves to emphasize the importance of understanding the entire coupled atmosphere/ ocean system in order to fully understand offshore wind impacts on local hydrodynamics.

2.3.4 Potential Ecosystem Impacts of Hydrodynamic Effects

The ocean ecosystem is tightly coupled to the physical oceanography, as the physics dictate the background conditions present for organisms such as *C. finmarchicus* and other copepod taxa, including the presence, absence, and movement of nutrients, as well as habitat temperature, salinity, and water chemistry. Any potential hydrodynamic changes from offshore wind could therefore interact with the surrounding ecosystem. These could include changes in primary productivity (Section 2.3.4.1) and secondary changes that might take place as a result (Section 2.3.4.2). This is a key area for research and is of particular interest to interdisciplinary scientific teams.

2.3.4.1. Primary Productivity

The primary productivity in an area is largely a function of the local nutrient availability and the availability of sunlight. In turn, nutrient availability in a given location is tightly connected to the physical ocean conditions, influenced not just by the conditions at the location, but also how the water is flowing through the area. The specific effects of offshore wind farms on primary production and water stratification can vary based on factors such as the size, location, design, and local environmental conditions of the wind farm. In shallow waters (<30 m), the construction and operation of offshore wind farms can create regional turbulence and high sediment loading in the water column. While construction is a more intense activity on the sea floor, it is also of relatively short duration. However, satellite imagery has shown suspended sediment in the wakes of wind farms in the UK (Vanhellemont and Ruddick 2014). Through the use of simple idealized numerical modeling, Broström (2008) suggested that wake-induced temperature differences could be related to regional nutrient availability in the North Sea. Additionally, Christiansen et al. (2022a) stated that changes to the mixed layer depth seen in their physical modeling of the North Sea could impact nutrient intrusion, which would impact primary production. Floeter et al. (2017) found that there were increases in primary productivity attributed to the presence of wind farms in the North Sea which resulted in a 20 percent decrease in light availability during tow transects. Increased turbulence may enhance nutrient mixing and stimulate primary production. However, if the turbulence levels are significant and cause bottom sediment resuspension, primary production may decrease due to shallowing of the euphotic zone and the decreased onset of stratification. It is important to consider the balance between turbulence and its effects on nutrient availability, light penetration, and phytoplankton response when assessing the impact of increased turbulence on primary productivity. Local conditions, including the baseline nutrient concentrations, the types of nutrients available, and the specific characteristics of the marine ecosystem, will all play a role in determining how turbulence influences primary productivity.

2.3.4.2. Secondary Impacts

Since primary producers like phytoplankton serve as the base of the oceanic food web, any changes in primary productivity can have secondary impacts on organisms in higher trophic levels, which feed on primary producers (e.g., copepods), on up to the complex, large organisms which feed on them (e.g., whales). Additionally, changes in populations of higher-level organisms can impact the availability of primary producers. In the North Sea, Slavik et al. (2019) found that the increased abundance of mussels through attaching to wind turbine foundations impacted pelagic primary productivity at the local scale. Additionally, Floeter et al. (2017) suggested that high densities of sand habitat-dwelling echinoderm larvae near two offshore wind farms could have resulted from increased prey resources from the additional benthic habitat found within the wind farms. Around Nantucket Shoals, White and Veit (2020) identified high densities of sea ducks that were feeding on prey congregations associated with the tidal front that intersects with the Massachusetts WEAs. Research on these potential ecosystem impacts is continuing to be done; some details on the ongoing research efforts are discussed in Chapter 3.

2.4 Scientific Takeaways and State of the Knowledge

This chapter discusses the currently available science on the status of the NARW's habitat, both physically and biologically, as well as the natural and anthropogenic changes already occurring. It also discusses the currently available information on the evolving science around potential hydrodynamic effects of offshore wind development, and potential ecosystem impacts that could affect the NARW. This section outlines some general conclusions and key points from the details outlined in previous sections.

- The Western North Atlantic Ocean where the NARW occurs is a highly dynamic physical environment consisting of three main oceanographic regions, each with a distinct oceanography: the Gulf of Maine, Mid-Atlantic Bight, and South Atlantic Bight.
- Recent shifts in NARW distribution and foraging habitat utilization within the Western North Atlantic have been observed and are believed to be associated with shifts in copepod prey distributions caused by warming sea surface temperatures related to climate change.
- Local or regional scale fragmentation of copepod aggregations has been observed and is projected to continue with subsequent declines in copepod abundance under future climate scenarios.
- Current foraging habitats may not support sufficient prey populations to allow growth of the NARW population based on the relatively low reproductive rate presently observed for NARW. As waters continue to warm due to climate change, current foraging areas may once again be abandoned as NARWs continue to shift their distribution in search of prey.
- Offshore wind farms can impact hydrodynamics in the surrounding ocean in two principal ways: 1) through an atmospheric wake effect that reduces wind speeds behind wind turbines that can reach the ocean surface, reducing surface wind stress and wind-induced currents, and 2) through subsurface mixing induced by the presence of the turbine substructure within the water column.
- Hydrodynamics and wind wake effects around offshore wind turbines are driven by physical ocean processes including tides, stratification, water depth, and wind-driven currents; and atmospheric processes such as turbulence and stability, all of which have significant natural variation.
- Changes in surface currents and sea surface temperatures caused by turbines in European windfarms (e.g., North Sea) are small enough that they can be difficult to isolate from other sources of natural variability.

- Although studies from the North Sea suggest that wind turbines could cause mixing and disrupt the stratification of ocean waters, wind turbines in the Mid-Atlantic Bight are unlikely to have much influence on summer stratification, which is significantly stronger than the weakly stratified waters of the North Sea.
- Due to the distinct oceanographic differences between the North Sea and the Western North Atlantic Ocean (and among regions therein), impacts of wind turbines in one region are not necessarily directly transferrable to other regions.
- Increased turbulent mixing caused by wind turbines may enhance nutrient mixing and stimulate primary production, in turn enhancing zooplankton abundance, including copepods. However, if turbulence levels are significant and cause sediment resuspension, primary production may decrease due to reduced light penetration.
- Hydrodynamic impacts are highly dependent on wind farm layout and wind turbine parameters, including turbine size (hub height and power capacity), type of foundation, turbine spacing within the wind farm, and the spacing between adjacent wind farms.
- Extensive build-out of offshore wind farms is likely necessary for these structures to have a significant hydrodynamic impact.
- Larger, more widely spaced turbines, such as those being planned for U.S. windfarms, are likely to have less hydrodynamic influence than the smaller, more closely spaced turbines currently in operation in Europe and other parts of the world.

3.0 Review of Ongoing Research Efforts

This chapter outlines current ongoing research efforts that pertain to the hydrodynamic impacts of offshore wind and their potential effects on copepods and NARW. There is extensive work being done on these topics; this chapter is intended to provide a snapshot of known research being conducted at present, and provide useful sources for the latest available information on the evolving science. National and regional efforts are discussed in Section 3.1; state efforts in Section 3.2; and additional efforts in Section 3.3. This chapter likely does not capture all efforts being undertaken; however, it does provide many useful sources for learning more about ongoing research, many of which are frequently updated.

3.1 National and Regional Efforts

The research efforts outlined in this section are being led by national or regional organizations, including federally-funded research of broad scope as well as regional or national research coalitions.

3.1.1 Department of Energy

The U.S. Department of Energy (DOE) has multiple offices and laboratories that contribute to research efforts around the topic of offshore wind, including the Energy Efficiency and Renewable Energy office. Its network of 17 national laboratories lead and collaborate on a number of research efforts related to offshore wind. A couple key efforts are discussed below. Additionally, DOE is a key supporter of the National Offshore Wind Research and Development Consortium (NOWRDC), which is discussed in Section 3.1.4.

3.1.1.1. Working Together to Resolve Environmental Effects of Wind Energy

One effort being coordinated by DOE is Task 34 of the International Energy Agency (IEA) Wind Committee, Working Together to Resolve Environmental Effects of Wind Energy (WREN).[9] It includes a team composed of DOE's Wind Energy Technologies Office, the National Renewable Energy Laboratory, and the Pacific Northwest National Laboratory. The effort was established in 2012, and is currently in its third phase, which runs through 2024. In this phase, the three primary goals are to identify further research priorities related to the environmental effects of wind energy development; to collect and distribute information on the global state of the science on these issues; and to assess the technical readiness and effectiveness of technological solutions. This effort, while being led here in the United States, includes a large number of international partners, and has published a number of papers and fact sheets since its inception. WREN has also significantly contributed to the widely used Tethys database,[10] which includes a knowledge base and map viewer, among other features, all focused on the environmental effects of wind energy. Many of the studies and datasets featured in this white paper can also be found on Tethys.

3.1.1.2. Wildlife and Offshore Wind (Project WOW)

A key study of high relevance to the ongoing research associated with the impacts of offshore wind on NARW is "Wildlife and Offshore Wind (WOW): A Systems Approach to Research and Risk Assessment for Offshore Wind

9 WREN: https://tethys.pnnl.gov/about-wren.

10 Tethys: https://tethys.pnnl.gov/

Development."[11] This project, jointly funded by DOE and the U.S. Department of the Interior (through BOEM), aims to create a comprehensive system for evaluating the potential effects of offshore wind development on marine wildlife. WOW is a large-scale study being led by Duke University, along with multiple academic, industry, and environmental Non-Governmental Organization (NGO) partners, and includes collaboration with the Regional Wildlife Science Collaborative for Offshore Wind (RWSC, see Section 3.1.5). It also features an external advisory board consisting of state and federal agencies and labs, offshore wind developers, and additional environmental NGOs.

The project has two key objectives: a gap analysis and risk assessment leading to a research framework; and a targeted data collection and technology validation campaign. It aims to provide all stakeholders, including developers and regulators, with a unified framework for the assessment of environmental impacts from offshore wind at both regional and site-specific scales, to enable the responsible design, development, and management of offshore wind farms.

3.1.2 Bureau of Ocean Energy Management

As part of its mission to manage development of U.S. OCS energy and mineral resources in an environmentally and economically responsible way, BOEM funds a number of research efforts as part of its renewable energy program in order to provide scientific research to inform its decision-making process.[12] Information on completed and ongoing studies is available through their website, as is information on their planning for future studies. BOEM also hosts or co-hosts periodic conferences, workshops, and public meetings where the latest research is shared and discussed. Several ongoing studies[13] related to this white paper are described in the following sections.

3.1.2.1. Environmental Studies Program

As of the writing of this white paper, there are three ongoing BOEM-supported studies focused on large-scale environmental monitoring. One of these, Project WOW, is described in Section 3.1.1.2. The second, the "Ecological Baseline Study of the U.S. Outer Continental Shelf Off Maine," is led by the Biodiversity Research Institute and HiDef Aerial Surveying and aims to retrieve baseline information on the distribution and abundance of marine mammals, birds, and sea turtles in the GOM. This is being done to assist with the environmental review process associated with offshore wind development in the GOM. The third study, "Standardizing Integrated Ecosystem-Based Assessment Nationally," led by the Blue World Research Institute, aims to benefit BOEM's environmental assessment process by creating tools for synthesizing diverse data sources and being able to assess trade-offs between multiple ocean users, species, and jurisdictions. The study aims to minimize potential conflicts, while improving opportunities for advancement. A fourth, recently completed study, "Sustained Monitoring of Zooplankton Populations at the Coastal Maine Time Series and Wilkinson Basin Time Series Stations in the Western Gulf of Maine" was mentioned during the Expert Workshop. The results of this study have been included in this white paper (Runge et al. 2023).

3.1.2.2. Marine Mammal-Focused Studies

As of the writing of this white paper, there are currently 12 ongoing, BOEM-supported studies on marine mammals. Of these, 8 are either directly related to NARW, or more broadly relevant to other marine mammals that includes NARW. These studies are listed in **Table 1** below.

11 Wildlife and Offshore Wind (Project WOW): *https://offshorewind.env.duke.edu/*.

12 BOEM Renewable Energy Research: *https://www.boem.gov/environment/environmental-studies/renewable-energy-research*.

13 BOEM Ongoing Studies: *https://www.boem.gov/environment/environmental-studies/renewable-energy-research-ongoing-studies*.

Table 1.
Ongoing research funded by BOEM related to NARW.

Project Title	Project Lead
Assessing Population Effects of Offshore Wind Development on North Atlantic Right Whales	University of St. Andrews
Atlantic Marine Assessment Program for Protected Species (AMAPPS) – Photogrammetric Aerial Surveys to Improve Detection and Classification of Seabirds, Cetaceans, and Sea Turtles	U.S. Fish and Wildlife Service
Atlantic Marine Assessment Program for Protected Species III	NMFS
Comparative Study of Aerial Survey Techniques	NMFS Northeast Fisheries Science Center
Investigating Persistent Super Aggregations of Right Whales and Their Prey in Lease Areas in the North Atlantic	NMFS
Marine Mammal and Sea Turtle Field Surveys and Marine Resource Characterization for Offshore Wind Energy Planning Offshore Rhode Island and Massachusetts	Massachusetts Clean Energy Center and New England Aquarium
Passive Acoustic Monitoring in the Massachusetts and Rhode Island Wind Energy Areas in Support of the Partnership for an Offshore Wind Energy Regional Observation Network (POWERON)	LGL Ecological Research Associates
Protected Species Database and Information Management	Mysticetus

Additional details on these, and other, ongoing BOEM-funded studies are available online at: *https://www.boem.gov/environment/environmental-studies/renewable-energy-research-ongoing-studies*.

3.1.2.3. Physical Environment Studies

There are two physical environment studies currently being funded by BOEM as of the time of the writing of this white paper; one of which is related to oceanographic process that may influence copepods and NARW. This study, "Offshore Wind Impacts on Oceanographic Processes: North Carolina to New York," is being led by DHI Water & Environment and RPS Group. The study uses hydrodynamic and particle-tracking models to understand the potential impacts to the physical oceanography and transport processes related to large-scale offshore wind development. This is a follow-up study to the completed BOEM OCS Study 2021-049, "Hydrodynamic Modeling, Particle Tracking and Agent-Based Modeling of Larvae in the U.S. Mid-Atlantic Bight," (Johnson et al. 2021).

3.1.3 National Oceanic and Atmospheric Administration

The National Oceanic and Atmospheric Administration (NOAA) is the federal agency responsible for ecosystem management and protection in U.S. coastal waters, among other responsibilities including national weather data collection and forecasting through the National Weather Service. NOAA performs its mission to conserve and manage coastal and marine ecosystems and resources including management of protected species and fisheries, in part through its NMFS regional offices and regional science centers, such as the Northeast Fisheries Science Center (NEFSC). Some of NOAA's research efforts related to hydrodynamics, copepods, and NARW are listed below; this is by no means an exhaustive list, but rather a snapshot of several activities being led by NOAA, as highlighted during the Expert Workshop.

3.1.3.1. COPEPOD: Coastal & Oceanic Plankton Ecology, Production, and Observation Database

The COPEPOD[14] project provides researchers with a global integrated dataset containing information on plankton distribution and associated environmental data (e.g., biological, chemical, meteorological, and hydrographic). Since

14 NOAA COPEPOD: *https://www.st.nmfs.noaa.gov/copepod/*

its debut in 2004, the database has compiled more than 400,000 observations of phytoplankton, zooplankton, and microbial plankton taxa with support from NOAA, NMFS, and COPEPOD database users. The COPEPOD project consists of the following four components: 1) the global plankton database (COPEPOD), 2) a global time-series directory and time-series analysis toolkit (COPEPODITE), 3) ecosystems data products and visual tools (NAUPLIUS), and 4) taxonomic information, photos, and biometric data (COPEPEDIA). New content is added to the COPEPOD database monthly, with the full database of content and method summaries released every two to five years. The COPEPOD Interactive Time-series Explorer (COPEPODITE) consists of the METABASE, a global directory of plankton and environmental time-series data, as well as a Time Series Toolkit, which allows users to perform various analyses and create visualization plots of their own uploaded data. The Numerical Analysis, Uniform Plotting & Integration of User-selected Subregions (NAUPLIUS) is composed of two sub-elements, The NAUPLIUS Spatiotemporal Data Toolkit and the NAUPLIUS Gridded Fields Explorer. The Spatiotemporal Data Toolkit provides users with personalized data sets, summaries, and graphics for their selected location, whereas the Gridded Fields Explorer is a collection of pre-prepared regional summaries of environmental variables including model-based mixed-layer depth, sea surface temperature, satellite-observed chlorophyll, and satellite-observed wind. COPEPEDIA is a database of plankton taxa, and includes photographs, taxa morphology and genetic markers, and distribution maps. This database is a collaborative effort by the NOAA Fisheries COPEPOD Project, the International Council for Exploration of the Sea (ICES) Working Group on Integrated Morphological and Molecular Taxonomy, the ICES Working Group on Zooplankton Ecology, and the ICES Working Group on Phytoplankton and Microbial Ecology and is currently in the development stage.

3.1.3.2. Ecosystem Monitoring of the Northeast U.S. Continental Shelf (EcoMon)

Through the EcoMon[15] program, NOAA aims to conduct scientific surveys six times a year at 120 randomly selected stations and 35 fixed stations across the continental shelf and slope of four regions: GOM, Southern New England, Georges Bank, and the MAB. These surveys collect information on the distribution and abundance of zooplankton and larval fish, as well as on physical variables such as salinity, water temperature, pH, total alkalinity, dissolved inorganic carbon, and nutrients. Observational data on marine mammals, sea turtles, and birds are also collected during the surveys. Archival plankton data collected during surveys performed from 1977 to 2021 are publicly available online through the National Centers for Environmental Information (NCEI). Time-series plots and summaries of EcoMon data are also available through the METABASE Explorer of the COPEPOD project.

3.1.3.3. Plankton Energy Density Studies

A NOAA-funded study conducted by researchers from the Bigelow Laboratory for Ocean Sciences, the University of Maine, and Duke University (Ross et al. 2023) used MARMAP/EcoMon data to model environmental factors associated with *Calanus finmarchicus* patch densities above the feeding threshold (τ) for the NARW. Ross et al. (2023) evaluated models using a range of τ values from earlier energy density studies. The study also evaluated models using life stage-structured or -unstructured abundance data. Major outcomes of the study include that spatial patterns are more pronounced at higher values of τ, *C. finmarchicus* τ patches are possible in areas with higher sea surface temperatures than previously reported, and using energy rich higher life stages of copepods in models do not improve model performance. Results from this study provide updated information on prey distributions that can be used as a decision-making tool in NARW management. NOAA also collaborates with Fisheries and Oceans Canada (DFO) on *Calanus* spp. density and modeling studies, with observational data publicly available through DFO,[16] as well as supporting additional energy density studies currently underway with the University of Massachusetts Dartmouth.

---

15 NOAA EcoMon: https://www.fisheries.noaa.gov/new-england-mid-atlantic/ecosystems/monitoring-ecosystem-northeast

16 *Calanus* spp. size and lipid content metrics in North Atlantic, 1977-2019: https://open.canada.ca/data/en/dataset/72e6d3a1-06e7-4f41-acec-e0f1474b555b.

3.1.3.4. Passive Acoustic Monitoring

Since 2006, NEFSC's Passive Acoustic Research group has performed PAM of underwater sounds (natural physical and biological noise, as well as anthropogenic noise) in the northwest Atlantic Ocean. Recordings obtained from this monitoring are used to study distribution and migration patterns of marine mammals such as baleen whales and beaked whales, as well as marine mammal vocalizations and related behaviors. Information gained from this research can be used to identify shifts in marine mammal distributions, examine the impacts of anthropogenic noise on marine mammals, and inform management efforts for the NARW. Data are available through a Google Cloud Platform and through an interactive Passive Acoustic Cetacean Map.

3.1.4 National Offshore Wind Research and Development Consortium

NOWRDC[17] is a non-profit organization with national focus that works to prioritize research and development activities that reduce the levelized cost of energy of offshore wind while also improving social and economic benefits. It was initially funded through support from the DOE and New York State Energy Research and Development Authority (NYSERDA) but has secured additional funding support from various state members include California, Maine, Maryland, Massachusetts, New Jersey, and Virginia. Their current research goals are laid out in Version 4.0 of their Roadmap.[18] They also maintain an online database[19] of all of their funded research projects. The projects listed below in **Table 2** are highlighted due to their relevance to the topics of this white paper.

Table 2.
NOWRDC-funded research projects related to potential offshore wind impacts to NARW.

Project Title	Project Lead/Awardee
Technology Development Priorities for Scientifically Robust and Operationally Compatible Wildlife Monitoring and Adaptive Management	Advisian
Right Wind: Resolving Protected Species Space-Use Conflicts in Wind Energy Areas	Cornell University
Renewable Powered, Uncrewed Mobile Assets to Monitor Protected Marine Mammals	SAILDRONE Inc.

Additional details on these, and other, research studies funded by NOWRDC is available on their website at: https://nationaloffshorewind.org/project-database/.

3.1.5 Regional Wildlife Science Collaborative for Offshore Wind

RWSC was organized in 2021 in order to "collaboratively and effectively conduct and coordinate relevant, credible, and efficient regional monitoring and research of wildlife and marine ecosystems that supports the advancement of environmentally responsible and cost-efficient offshore wind power development activities in U.S. Atlantic Waters."[20] It includes a steering committee made up of representatives from the federal government, state agencies, environmental NGOs, and the offshore wind industry. Structurally, RWSC has six technical subcommittees composed of volunteer experts on: sea turtles; habitats and ecosystems; marine mammals; birds and bats; protected fish species; and technology. The organization is hosted by the Northeast Regional Ocean Council and the Mid-Atlantic Regional Council on the Ocean.

17 National Offshore Wind Research and Development Consortium: https://nationaloffshorewind.org/.

18 NOWRDC R&D Roadmap 4.0: https://nationaloffshorewind.org/wp-content/uploads/NOWRDC-Research-Development-Roadmap-4.0.pdf.

19 NOWRDC Project Database: https://nationaloffshorewind.org/project-database/.

20 Regional Wildlife Science Collaborative for Offshore Wind: https://rwsc.org/.

A key initiative of RWSC is the development of an "Integrated Science Plan for Wildlife, Habitat, and Offshore Wind Energy in the U.S. Atlantic," referred to as the Science Plan. During the Expert Workshop, it was discussed that RWSC has issued a draft of the Science Plan for comment on July 1, 2023. It was available for public comment through September 30, 2023, and is intended to be a living and evolving document as both the science and the offshore wind industry continue to evolve. The draft Science Plan includes a section for marine mammals as well as two sections related to habitat and ecosystem oceanography and seafloor.

Another product of the RWSC is an offshore wind and wildlife research database,[21] which includes research projects and data collection activities that the RWSC has learned about from steering and subcommittee members or through public sources. It should be noted that since this is a public and ever-evolving resource, it is subject to new additions at any time. New projects can be submitted directly on the database webpage.

3.1.6 Responsible Offshore Science Alliance

The Responsible Offshore Science Alliance (ROSA) is a collaboration between the commercial fishing and offshore wind industries, as well as fisheries scientists from federal and state agencies, academic institutions, and NGOs. ROSA's focus is the advancement of research and monitoring necessary to understand the potential impacts of offshore wind on the fishing industry and fisheries.[22] While ROSA's efforts are focused on commercial and recreational fisheries, their efforts in supporting research on ecosystem impacts from offshore wind are complementary to those of other organizations, such as RWSC. In 2022, ROSA worked to assemble the "Fish FORWRD" database,[23] which compiles research around fisheries and offshore wind taking place along the U.S. East Coast. The database is accompanied by a report which also describes current gaps in these research areas to help inform future research efforts.

3.2 State Efforts

The research efforts outlined here include efforts that are being led by state organizations, including state government-sponsored research.

3.2.1 New York State Energy Research and Development Authority

NYSERDA has several initiatives to further offshore wind development while considering the potential environmental impacts and developing ways to mitigate those impacts.[24] The New York State Offshore Wind Master Plan[25] included 20 studies, including one on marine mammals and sea turtles. The Master Plan also led to the creation of the Environmental Technical Working Group (E-TWG),[26] which serves as an advisory body to the State of New York focusing on offshore wind and wildlife issues. The E-TWG formed a Regional Synthesis Workgroup in 2021

21 RWSC Research Database: *https://database.rwsc.org/*.

22 Responsible Offshore Science Alliance: *https://www.rosascience.org/*.

23 ROSA Fish FORWRD Database and Report: *https://www.rosascience.org/resources/regional-framework-databases/*.

24 NYSERDA Protecting the Dynamic Ocean: *https://www.nyserda.ny.gov/All-Programs/Offshore-Wind/Focus-Areas/Ocean-Environment*.

25 New York State Offshore Wind Master Plan: *https://www.nyserda.ny.gov/All-Programs/Offshore-Wind/About-Offshore-Wind/Master-Plan*.

26 Environmental Technical Working Group: *https://www.nyetwg.com/*.

with the goal of informing and providing guidance on regional-scale research and monitoring for the dynamic relationship between offshore wind development and wildlife in the eastern U.S., which is discussed in Section 4.4.3. Additionally, NYSERDA requires offshore wind developers to make funding commitments to environmental research as part of their solicitations for Offshore Wind Renewable Energy Certificates (ORECs).

NYSERDA also funds its own research projects at the interface of the environment and offshore wind: one such highlighted project related to this white paper is "Ecosystem Dynamics: An Examination of the Relationships Between Environmental Process, Primary Productivity, and Distribution of Species at Higher Trophic Levels."[27] They also deployed two floating metocean buoys in the New York Bight over a period of two years which included a lidar system to record vertical profiles of wind data, along with measurements of waves, currents, and other environmental and wildlife data. The data collected during this metocean buoy campaign are publicly available online.[28]

In 2021, NYSERDA announced[29] the availability of nearly $1.3 million in support of acoustic and oceanographic data collection in the New York Bight. The survey would provide data to quantify marine mammal presence, habitat use, distribution, and seasonal movement, as well as collecting oceanographic covariate data associated with the Cold Pool. They sought to include both autonomous vehicles and a network of bottom-mounted PAM sensors. The study commenced in 2022 and includes a research team composed of researchers from Rutgers University, Stony Brook University, and Woods Hole Oceanographic Institution.[30] The study runs through December 2024.

3.2.2 New Jersey Research and Monitoring Initiative

The New Jersey Research and Monitoring Initiative (RMI)[31] is jointly administered by the New Jersey Department of Environmental Protection (NJDEP) and New Jersey Board of Public Utilities (NJBPU). It is meant to address needs for regional research and monitoring of the marine environment associated with offshore wind development and is funded by offshore wind developers as part of their OREC solicitation awards in New Jersey. While funding is provided by the developers, NJDEP and NJBPU administer the funding.

RMI has provided funding to the Woods Hole Oceanographic Institution (WHOI) to deploy a buoy off Atlantic City to perform acoustic monitoring for whales in near real-time. As part of the project, WHOI will examine the best ways to use collected data for management, stakeholder education, and to foster dialogue on implementation of these types of systems into offshore wind development.

Additionally, RMI has funded autonomous underwater gliders with Rutgers University to characterize environmental conditions and how these conditions might impact the distribution of marine organisms on timescales from weeks to years. This effort is being done to aid with future efforts of assessing and attributing impacts from both ongoing climate change and offshore wind. The gliders include sensors to monitor physical oceanographic conditions (e.g., temperature, salinity, density), sensors to monitor phytoplankton and dissolved organic matter, a sensor to monitor dissolved oxygen, a fish telemetry receiver, a passive acoustic sensor for marine mammals, and an Acoustic Zooplankton Fish Profiler for active acoustic detection of various pelagic organisms.

---

27 NYSERDA Ongoing Environmental Research: *https://www.nyserda.ny.gov/All-Programs/Offshore-Wind/Focus-Areas/Ocean-Environment/Ongoing-Environmental-Research*.

28 The physical metocean data are available at: *https://oswbuoysny.resourcepanorama.dnv.com/*, while wildlife data analysis is available at: *https://remote.normandeau.com/nys_overview.php*.

29 Press Release: *https://www.nyserda.ny.gov/About/Newsroom/2021-Announcements/2021-12-08-NYSERDA-Announces-Predevelopment-Data-Collection*.

30 GLIDE: Glider based ecological and oceanographic surveys of the NY Bight: *https://rowlrs.marine.rutgers.edu/research/new-york-state-energy-research-and-development-authority-nyserda/*.

31 NJ Research and Monitoring Initiative: *https://dep.nj.gov/offshorewind/rmi/*.

3.3 Additional Research Efforts

There are additional research efforts that are led by industry or independent organizations, and efforts with an international focus. These efforts can also often include support from the previously discussed organizations, but since they aren't directly supported by only one primary organization, they are considered below.

Several offshore wind developers are funding PAM efforts, either independently or as a result of requirements of their project approvals from BOEM and NOAA, or through commitments through their OREC contracts. These efforts typically include acoustic monitoring buoys and occasionally mobile platforms, meant to listen for the signatures of vocalizing marine mammals, along with other sound sources such as vessel traffic or pile driving. These data are typically being made publicly available and are often fed into platforms such as Whale Alert, to improve awareness of the presence of marine mammals for vessel operators in the area. In addition to the acoustic data, many developers are also making other collected data publicly available, including some physical oceanographic and wind data. These data can be incredibly valuable to the research community and the general public.

As an example of a data clearinghouse for the wide array of ongoing PAM efforts, a team of researchers led by WHOI operates a fleet of PAM systems deployed on both autonomous mobile platforms and moored buoys for detecting and classifying marine mammal vocalizations, including NARW. These platforms use the Digital Acoustic Monitoring Instrument developed at WHOI (e.g., Baumgartner et al. 2019, 2021) combined with shore-based acoustic analysts to validate potential detections of NARW, and are sponsored by a number of organizations including government agencies and the offshore wind industry. Several of the efforts outlined elsewhere in this white paper are part of the Robots4Whales collaboration. The detections made using platforms in the Robots4Whales network are made available to the public through the website,[32] and detections are fed into systems such as Whale Alert.

Finally, as highlighted throughout this chapter, a significant portion of the literature focusing on the hydrodynamic impacts of offshore wind have been conducted in Europe, largely due to the fact that the offshore wind industry there has been in existence for several decades, and so the availability of observations in existing large-scale offshore wind farms makes this a research epicenter. It is anticipated that research in Europe around these topics will continue into the future. In particular, during the Expert Workshop, it was discussed that there will likely be a number of studies based in the Baltic Sea being published in the next few years.

32 Robots4Whales Website: *http://robots4whales.whoi.edu/*.

4.0 Identification of Knowledge Gaps and Recommendations for Future Research

This chapter summarizes knowledge gaps related to hydrodynamic impacts of the construction and operation of offshore wind farms and the potential associated effects on NARW. These knowledge gaps were identified through a review of the existing literature and discussion during the Expert Workshop. Additionally, this chapter discusses future research, monitoring, and mitigation efforts centered around the hydrodynamic impacts of offshore wind and the NARW. This includes a discussion on existing recommendations from other entities and those presented within the literature. Finally, recommendations that emerged during the Expert Workshop are discussed, as well as recommendations for industry involvement in funding and executing future research efforts.

4.1 Observational Studies and Modeling Efforts

The lack of observational studies on the U.S. East Coast represents a significant knowledge gap for our understanding of how hydrodynamic impacts of offshore wind structures may affect NARW. Given that most of the available observational studies have been conducted in Europe, a discussion topic for the Expert Workshop was how international experience and research could best be applied to predict impacts and effects on the U.S. East Coast. There was agreement among participants that while some of the general physics are similar between the U.S. East Coast and the North Sea, where many observational studies and modeling efforts have been conducted, there are still significant differences between the two locations, including bathymetry and large-scale circulation patterns. Given the identified similarities, it may be appropriate to apply certain findings from international studies related to general physics to regions of the U.S. East Coast. However, differences in the physical environment and the use of new technologies (floating vs. fixed units) and turbine designs (e.g., larger and taller turbines, different spacing, different foundation types) limit the broad applicability of study and modeling results from other locations like the North Sea to the U.S. East Coast. It was emphasized that results from international studies cannot be used as direct predictors for effects on the U.S. East Coast because of these differences.

Another difference limiting the applicability of international observational study and modeling results to the U.S. East Coast identified by Expert Workshop participants is the design of the windfarms themselves. The existing turbines in European windfarms are smaller, with lower hub heights, lower rated capacity, and relatively close spacing; the windfarms planned or under construction off the U.S. East Coast have larger turbines, and the individual turbines are spaced further apart. For example, though European studies have shown that atmospheric wind wakes result in reduced wind speed and stress, which affects turbulence and mixing in the water downstream of the turbines (e.g., Christiansen et al. 2022a), the significantly greater hub height of the turbines off the U.S. East Coast may reduce surface impacts associated with atmospheric wind wakes (Golbazi et al. 2022). It would be possible to address this knowledge gap using scalable modeling, but site-specific data should be collected and analyzed as well.

4.2 Data Gaps

During the Expert Workshop, participants discussed a number of data gaps or limitations in data availability. These gaps and availability issues concerned both physical oceanography data and information on NARW distribution.

– Physical oceanography data, including water temperature and salinity

Temperature and salinity data are widely collected but under published. Existing retrospective studies have evaluated a subset of the available data, but there are likely additional decades worth of data that could be used to strengthen the baseline and improve our ability to detect changes due to the installation of offshore wind structures.

– Vertical profiles of physical parameters are needed to establish a baseline from which to document future impacts of offshore wind structures

During the Expert Workshop there was discussion around the availability of a suitable amount of vertical profile data. Some participants felt that the current datasets are insufficient, but others indicated that there has been a sufficient amount of data collected but much of it is not publicly available and awareness of these data is limited. Vertical profiles allow the establishment of baseline conditions in three dimensions, improving our understanding of the buildup and breakdown of stratification. This three-dimensional baseline would improve our ability to evaluate potential impacts on mixing or stratification associated with offshore wind structures.

– Future modeling and model validation studies will need to consider the specific conditions present in the region being evaluated for offshore wind impacts

Participants at the Expert Workshop discussed the role of modeling for an improved understanding of the hydrodynamics of offshore wind as it continues to be developed along the Atlantic Coast of the U.S. Future studies need to consider the local conditions, such as water depth, variability and magnitude of currents, strength of stratification, and wind farm parameters such as size and foundation type. It will be important to capture relevant physical oceanographic data after wind farms are built as well to inform research on how the different physical characteristics of wind farms in the U.S. compare to what's been observed in European waters.

– Finer granularity on the distribution of NARWs along the migration corridor and the environmental conditions associated with areas used by NARW during migration

To better understand NARW distribution, there have been extensive surveys completed in the GOM and Canadian waters, specifically the Gulf of St Lawrence. However, Expert Workshop participants acknowledged that a majority of their large migration corridor has not been studied closely (e.g., Meyer-Gutbrod et al. 2022). Participants discussed the need to know more about where NARWs occur throughout the year as it is critical to understand distribution patterns to accurately assess potential effects on this species associated with hydrodynamic impacts of offshore wind structures.

– Physiological and behavioral effects to planktonic prey as a result of structure-induced changes to local physical oceanography

While there was a lot of focus on oceanographic processes and parameters during the Expert Workshop, participants also raised concerns about the potential effects of offshore wind structures on the plankton prey of NARW. In particular, knowledge of the short-term physiological responses, energetic content, and changes in feeding behavior of plankton prey as a result of the presence of structures needs to be more fully understood before the implications for NARW foraging can be addressed.

4.3 Key Questions

During the Expert Workshop, participants were asked to identify the most critical questions that need to be answered to evaluate the effects of hydrodynamic impacts associated with offshore wind structures on NARWs. Key questions identified included:

- How can we disentangle the effects of offshore wind structures from other ongoing effects, including climate change?
- How should modelling results be used to predict hydrodynamic impacts of offshore wind structures, given the uncertainty in the models and the absence of observational data from the U.S. Atlantic Coast?
- Which driver of plankton movement is more significant, mixing or aggregation, and how will offshore wind structures affect these drivers?

4.4 Review of Existing Recommendations

4.4.1 Regional Wildlife Science Collaborative for Offshore Wind

As discussed in Section 3.1.5, RWSC has issued a draft Science Plan for public comment.[33] The draft Science Plan is broadly organized into chapters based on specific wildlife taxa, including marine mammals. There are also chapters focused on data, technology, and oceanography as it relates to habitats and ecosystems. One element of each relevant chapter is a discussion of work needed to help address current research needs and to begin addressing new research questions.

The draft marine mammal chapter, completed by the RWSC Marine Mammal Subcommittee, lists 21 research topics grouped into 5 broad research themes, and makes specific recommendations on each of these topics. Research themes include mitigation of negative impacts that are likely to take place as a result of offshore wind activities or are considered to result in potentially severe impacts; detecting and quantifying any changes to wildlife or habitats; understanding the full environmental context around these changes; determining causality of these changes; and enhanced data sharing and access. Of particular note for specific research topics, both under "understanding environmental context," are recommendations to work with the RWSC Habitat and Ecosystem Subcommittee to ensure key oceanographic and habitat data are collected and made available, as well as working to determine how wind turbine structures may alter hydrodynamics, including stratification and mixing. Implementation of

33 RWSC Science Plan: *https://rwsc.org/science-plan/*.

RWSC's Science Plan could provide the appropriate mechanism by which to address the data gaps identified above (Section 4.2) related to physical oceanography.

Note that as of the writing of this white paper, the Science Plan is in draft form, and so it is subject to change when it is finalized. The draft Science Plan was open for public comment from July 1 through September 30, 2023. Readers are strongly encouraged to consult the RWSC website for the latest information on the Science Plan and other topics of interest.

4.4.2 Workshop on Marine Mammal Research Priorities

In 2018, several organizations, including the Massachusetts Clean Energy Center, BOEM, and the New England Aquarium hosted a workshop on setting research priorities around marine mammals and offshore wind.[34] Key focal points for future research included both short- and long-term displacement studies; behavioral studies around short-term disturbances; and physiological stressor studies. Of particular note centered around the topics of this white paper, they mention plankton studies as being of particular importance when determining potential cause and effect relationships from offshore wind. This also included a recommendation for modeling studies, which could be informative in terms of providing information on bounding unknowns, given the physical processes that drive prey patch formation are not fully understood. Similar to recommendations elsewhere, they also emphasized the importance of data transparency, availability, and consistency. Full details on the workshop and their recommendations can be found in the report (Kraus et al. 2019).

4.4.3 Environmental Technical Working Group

As discussed in Section 3.2.1, the New York State E-TWG Regional Synthesis Workgroup[35] is developing two key products:

- Identification of research needs and data gaps from existing sources, and assembly into an online database; and
- Making interim recommendations on regional-scale research that would complement the database.

The recommendations document makes recommendations on the design of regional studies to answer ecological questions effectively, as well as recommendations on collaboration and data consistency and transparency (Regional Synthesis Workgroup of the E-TWG 2023). The database was placed online through Tethys,[36] and includes approximately 220 synthesized research recommendations from a dataset of over 800 recommendations from over 60 sources. The database is sortable by stressor/topic (e.g., habitat change, technology development, etc.), receptor (e.g., marine mammals, ecosystem/oceanographic processes, etc.), and offshore wind development stage. In addition to providing the synthesized recommendations, the database includes links to relevant citations to allow the user to investigate more on the sources of that recommendation.

As an example of some of the recommendations available in this database, **Table 3** includes a list of the synthesized recommendations that include both "marine mammals" and "ecosystem/oceanographic processes" as receptors, representing the overlap between the two topics. More detail on specific actions on and receptors for these recommendations is available through the database and the citations contained therein.

---

34 Information on this workshop, including the final report and proceedings, is available at *https://www.masscec.com/resources/related-wildlife-analyses*.

35 More information on the Regional Synthesis Workgroup is available at *https://www.nyetwg.com/regional-synthesis-workgroup*.

36 This database is available at *https://tethys.pnnl.gov/atlantic-offshore-wind-environmental-research-recommendations*.

Table 3.

Synthesized research recommendations from the NY E-TWG Regional Synthesis Workgroup database that included both marine mammals and ecosystem/oceanographic processes as receptors.

Research Recommendation	Stressor/Topic
Adapt study design for OSW farm presence	Technology/Methods Development
Assess the demographic consequences of OSW development	Cumulative Impacts Population Dynamics
Collect baseline diet information	Baseline Diet and Food Web Dynamics
Collect baseline information about habitat use through different life stages	Baseline Habitat Change
Coordinate research and monitoring	Data Management
Develop a centralized data repository for OSW-related ecological data	Data Management
Develop guidance for research, monitoring, and mitigation	Technology/Methods Development
Develop methods for estimating cumulative impacts	Technology/Methods Development Cumulative Impacts
Develop methods to translate individual effects to population-level consequences	Technology/Methods Development Cumulative Impacts
Develop or improve mitigation approaches	Technology/Methods Development
Examine factors influencing displacement, attraction, avoidance	Avoidance Displacement Ecological Drivers
Examine influence of wind farm characteristics on level of effect	Technology/Methods Development
Incorporate long-term OSW studies into marine spatial planning	Technology/Methods Development
Investigate tradeoffs of decommissioning strategies	Habitat Change
Make all ecological data publicly available/accessible	Data Management
Monitor primary productivity	Baseline Diet and Food Web Dynamics
Review existing mitigation technologies and methods	Technology/Methods Development
Standardize data collection, QA/QC, and reporting	Data Management

More information is available in the full database, which is available at *https://tethys.pnnl.gov/atlantic-offshore-wind-environmental-research-recommendations*.

4.4.4 Existing Literature

Through the literature reviewed throughout Chapter 2 of this white paper, a number of recommendations for future research emerged. Some of the most relevant recommendations from this literature are summarized below:

- Shultze et al. (2020) indicated that future modeling work should include both wind and tidal effects, assess a variety of foundation types and stratification conditions, and study possible effects of enhanced scalar fluxes on primary productivity and biological activity.
- Miles et al. (2021) discussed that the balance between a reduction in surface mixing due to the wind turbine wakes and the increase in mixing due to the presence of the underwater structures must be further assessed for local geographies and wind turbine parameters in order to better understand impacts in the U.S. versus those in European waters.
- Christiansen et al. (2022a) concluded that further studies beyond the physical modeling studies are required to understand the impacts on marine ecosystems and organisms, as changes in mixed layer depth indicated by the modeling studies can impact nutrient intrusion, which could impact primary production.
- Christiansen et al (2022b) stated that regional model simulations are needed to determine actual response in various environments, and must capture the effects of tides, water depths, and stratification regimes in addition to the atmospheric conditions and wakes.
- Golbazi et al. (2022) indicated that atmospheric modeling studies evaluating wake effects must include enough vertical resolution to capture the movement of the wake in enough detail for large-scale, modern wind turbines.
- Daewel et al. (2022) modeled hydrodynamic impacts of energy loss from wind turbine wakes showing potential changes in primary productivity and declines in dissolved oxygen levels that could result in food web and ecosystem impacts. The need for future research leading to better understanding of the consequences to higher trophic levels is implied and studies on changes to species distributions are directly recommended.
- Meyer-Gutbrod et al. (2022) stated that further efforts are needed to understand changes in NARW seasonal patterns in habitat use to improve effectiveness of management of this endangered species. Expanded monitoring and predictive modeling will be needed to address this knowledge gap.
- Ganley et al. (2022) suggested that causal models need to be combined with species distribution models to better understand long-term changes in NARW distribution in response to climate change.
- Sorochan et al. (2021b) identified the need for identification of zooplankton concentration mechanisms, which is a significant information gap related to the impacts of environmental changes on NARW foraging. Additionally, further quantification of the vertical distribution and motility of NARW prey and zooplankton monitoring are needed.

4.5 Expert Workshop Recommendations

During the Expert Workshop, participants proposed a number of recommendations to address knowledge gaps and improve our ability to assess hydrodynamic impacts of offshore wind structures and how these impacts may affect NARWs. Recommendations from participants included (in no particular order):

- To better understand the ability to apply observational study and modeling results to other areas (e.g., from the North Sea to Western Atlantic Outer Continental Shelf), a collaborative study or international review paper on general ocean physics should be undertaken.
- Republishing and/or reanalyzing/repurposing decades worth of previously uncharacterized physical and biological oceanographic data could provide the scientific community with a better baseline under a universal metric.

- To improve the aerial coverage of sampling data the use of unmanned vehicles for data collection should be increased rather than only relying on the typical method of collecting data from large ships deployed on research cruises. Unmanned vehicles can be used to collect data along programmed transect lines that could then be put together in a more complete data set that captures temporal and spatial variability and would be better suited for modeling applications.
- There are opportunities to outfit existing structures and other data-collecting platforms with additional sensors (e.g., hydrophones, acoustic receivers) to broaden monitoring efforts and increase data collection at a relatively small cost.
- Continue to hire fishermen and fishing vessels to assist with monitoring and data collection efforts prior to and during offshore wind farm construction and operation. The utilization of the fishing industry increases involvement of these stakeholders with the offshore wind industry, and the extensive local knowledge provided by the fishing community is highly valuable.
- Baseline data from existing NARW studies should be evaluated holistically to identify areas that are commonly used by NARW historically, while also considering the dynamic nature of the ocean environment and the use of that environment by NARW as habitat use shifts over time. In order to do so, existing data need to be compiled in a standardized format and made more accessible.
- Continue organizing a coordinated effort among developers to create strategic monitoring programs that provide secondary benefits (e.g., allow research questions to be addressed) rather than simply complying with the monitoring requirements of project permits.
- Developers should continue to contribute to a general research funding pool and recommendations regarding research and monitoring efforts should be developed to ensure the funding is allocated to the most significant research topics. These efforts could be coordinated by an organization like RWSC.
- The research community should revisit existing studies on sediment transport around wind turbine foundations (e.g., resuspension models) as a means by which to evaluate broader hydrodynamic effects.
- Though difficult to collect, there is a need for synoptic data to further our understanding and make more accurate predictions related to hydrodynamic impacts of offshore wind structures.
- Thought needs to be given on how to continue existing, often long-running, survey campaigns whose sampling strategy or the technology used for performing the sampling may need to change once structures are in the water.
- New data collected should follow established standards to enable comparison with existing data and studies. Some cited data standards included NOAA's NCEI and RWSC data standards for passive acoustic monitoring of marine mammals.
- Oceanographic modeling within U.S. wind farm areas is key to investigating how the ocean may respond to offshore wind development. When different models provide different results, context is important to understand the applicability of those different results, particularly when used for regulatory decisions. A multi-model approach is key to improved understanding.

4.6 Recommendations for the Industry

Based on the literature reviewed and input received during the Expert Workshop, this white paper aims to make several recommendations as to how ACP and the offshore wind industry as a whole can support ongoing efforts in this area. First, recommendations on what the role of industry in research could be is presented in Section 4.6.1; finally, some recommendations on next steps and focus areas for industry to consider pursuing are provided in Section 4.6.2.

4.6.1 Role of Industry

During the Expert Workshop there was frequent mention of industry and their current and potential involvement in research and monitoring efforts. Overall, a lot was discussed about the joint industry program for oil and gas and how that could provide a model for a similar program for the offshore wind industry. Additionally, participants were asked "What role should developers play in needed research (e.g., funding, technical guidance, data sharing)?" Continued data sharing and transparency will be critical to the success of industry participation in research and monitoring efforts. To support impartiality, one potential approach would be to fund independent research organizations via "blind" contributions. This would provide guardrails for industry involvement and make the research more "trusted" to people who do not understand the processes and/or maintain particular biases. Industry research efforts should also include extensive stakeholder involvement, as well as incorporation of valuable traditional/local knowledge. Finally, products of these research efforts should be made available to the public, including both data and publication of results in open-source literature.

Participants were also asked "What are some vital guideposts to ensure independence of research, if funding/guidance is to be provided by the developers?" Again, participants referred to the oil and gas industry as a good model for data sharing and data transparency. Similarly, it was suggested that independent third parties could be used to collect funds and distribute Requests for Proposals and review protocols. It is also important to note that existing entities, such as RWSC, have been working on guidance documents and best practices, and the conversation for improved data integration and research strategies is underway and continues to evolve.

4.6.2 Key Industry Focal Points

Several focus areas emerged as items that are of vital importance for next steps. As such, this white paper recommends that ACP and the offshore wind industry consider the following when deciding on ways to focus their contributions to research efforts.

- **Providing funding for a retrospective analysis of existing data, particularly as it informs an understanding of baseline conditions prior to the buildout of offshore wind farms.** One topic that was discussed in detail during the Expert Workshop is the fact that there is already a large amount of existing data that hasn't been analyzed in ways that are useful to explore questions related to hydrodynamic impacts and NARW. As such, a key recommendation that emerged was that there needs to be a large-scale study that examines past data to determine what is already available as a baseline and what further data collection should be done. It would also provide key insight into the next level of questions that need to be asked and answered as research advances.

- **Work with researchers to develop plans for utilizing offshore wind structures as observation and data collection platforms.** The presence of hundreds or thousands of offshore wind turbine structures provides a unique opportunity to collect additional oceanographic and biological data from a long-term stable platform.

The cost of collecting scientific data at sea can be very high and limits the amount of data that can be collected. If offshore wind platforms were to include basic instrumentation, such as sea surface temperature, bottom temperature and salinity, it could provide a wealth of information to the scientific community to benefit research around not only offshore wind impacts on hydrodynamics and ecosystems, but many other avenues of research, (e.g., weather forecasting, particularly for severe storms). However, the ability to instrument these platforms is limited by factors such as engineering and safe access. Continued dialog between industry and Federal, State and local governments on what is possible, along with independent researchers about what is needed, would provide oceanographic and biological data to the communities that manage marine resources. Additionally, such systems can be part of a broad spectrum of additional monitoring technologies, including autonomous mobile platforms that are continuing to develop.

- **Continue to engage with regional entities such as RWSC, and consider contributing to a general research funding pool, possibly administered by RWSC or another similar entity, to provide independent and regional oversight of research funding.** While it is vitally important for the offshore wind industry to be part of research efforts to better quantify the potential for hydrodynamic impacts of the turbines, the independence of the scientific process must be protected. Engaging with an independent third-party, like RWSC, can help to ensure scientific independence, minimizing concerns around or perceptions of conflicts-of-interest when research is funded by the private sector. Given that many recognized scientific experts serve on entities such as these, they can also help ensure both the quality of the research, and make sure that the most important questions are being addressed. These entities also continue to evolve as the science does, allowing their focus to shift to the most relevant needs as they arise into the future.

- **Strategically develop monitoring plans to provide consistency among plans and to ensure the right data are collected to address the right issues.** Another item of consensus during the Expert Workshop was the need for industry to be strategic in their data collection to meet their monitoring requirements. Through the careful development of monitoring protocols, data will be more useful for the evaluation of impacts and provide a greater contribution to the understanding of impacts across the region. Engagement with a third-party entity (e.g., RWSC) during development of protocols to standardize data collection methods and data formats is recommended. Additionally, data transparency and broad public availability is key, when possible.

5.0 Conclusions

The development of offshore wind as a source of renewable energy is a key part of the strategy to achieve necessary reductions in carbon emissions, mitigate climate change, and achieve state and national goals for renewable energy. The presence of offshore wind structures on the OCS is likely to have some impact on the hydrodynamics of the ocean as the air and water moves past these structures and through wind turbine arrays. However, the potential ecological effects of those hydrodynamic changes are unclear. This white paper presents a comprehensive and objective summary of the current state of knowledge on the effects of offshore wind structures on ocean circulation and stratification and its their relationship to the distribution and density of copepods, which is a key factor in the suitability of foraging habitat for the critically endangered NARW. Additionally, it identifies some of the critical knowledge gaps and priorities for future research that would address these gaps and allow for more effective minimization and mitigation of potential effects. Recommendations were developed from the scientific literature, experts from state, regional, and national science organizations, and through conversations with experts during an Expert Workshop.

The coastal ocean, like the rest of Earth, is undergoing significant changes due to global climate change, leading to warmer waters and in many cases, even more dynamic oceanographic conditions. Meanwhile, zooplankton populations, including the NARW's preferred copepod prey species *Calanus finmarchicus* are shifting northward due to ocean warming associated with climate change. This shift can also drive shifts in the distribution of species such as NARW that consume planktonic prey. Since 2010, NARW sightings have declined in many historically important foraging areas, particularly the GOM and Bay of Fundy. Coincident with this decline, sightings have increased in Cape Cod Bay and other previously unidentified foraging areas, including the central MAB, southern New England, and the Gulf of St. Lawrence. As the marine environment continues to change with climate change, NARW distribution may continue to shift as prey species distributions shift.

Offshore wind farms can impact the hydrodynamics of the surrounding ocean in two principal ways: through an atmospheric wake effect that reduces wind speeds behind wind turbines, and through additional subsurface mixing within the water column induced by the presence of the turbine substructure itself. The reduction in wind speed due to the atmospheric wake effect can reach the ocean surface, reducing surface wind stress and the wind-induced current. However, as turbines continue to grow larger, operate at greater heights above the sea surface, and are placed further apart, such as those slated for construction in the U.S., the atmospheric and oceanographic effects may likely be reduced.

Much of the research regarding underwater impacts from the turbine foundation structure have taken place in Europe's North Sea. These studies have shown that while turbines can and do induce additional mixing within the water column which impacts stratification, the effects are highly dependent on the regional conditions and the factors that are included in the modeling study. Most have concluded that extensive build-out of offshore wind would be required to have a significant impact when compared to existing sources of variability. While studies from the North Sea are highly informative, it's critical to note that the underlying oceanography of the GOM, MAB, and SAB is quite different, and future studies need to consider the specific conditions present in the region (e.g., water depth, variability and magnitude of currents, strength of stratification, and wind farm parameters such as size, foundation type, and spacing) being evaluated for potential offshore wind impacts. Nevertheless, it is an important question for further study, given the tight connections between local hydrodynamics and the local ecology.

Valuable insight provided by scientific experts in physical oceanography, copepod biology, and marine mammal biology at the Expert Workshop identified recently completed and ongoing research, and aided in identifying data and knowledge gaps that are vital to more fully understand this topic. These included the need for expanded physical oceanographic data, particularly full vertical profiles; considerations for future modeling and model validation studies; improved granularity of NARW distribution and movement patterns and the concurrent environmental conditions in important foraging habitats and along migratory routes; and quantification of the physiological/energetic and behavioral effects of hydrodynamic changes to copepods as a result of the presence of offshore wind structures. Experts also provided a number of recommendations for the industry to consider as they seek to improve the understanding of hydrodynamic impacts of offshore wind and the potential effects on NARW. These included recommendations on research topics, methods, and data transparency/sharing; ways for the industry to guide and provide independent funding mechanisms for research to advance the understanding of the topic; and guidance on maintaining the independence and objectivity of scientific research.

Finally, based on the literature and the insights of the Expert Workshop, this white paper recommends a number of key focal points for the offshore wind industry to consider as it decides how best to contribute to ongoing research efforts. These include providing funding for a retrospective analysis of existing data on oceanographic parameters, zooplankton distribution, and NARW distribution and movement patterns; collaborating with researchers to develop oceanographic and biological monitoring plans that utilize offshore wind structures as data collection platforms; continued engagement with regional entities, such as RWSC, that are acting to coordinate research and monitoring efforts and to identify data standards and research priorities within the industry; and strategic development of monitoring plans to ensure relevant information is gathered and shared. The offshore wind industry can continue the responsible development of offshore wind facilities along the Atlantic coast of the U.S. and elsewhere through these efforts, along with continued meaningful engagement with all stakeholders. Additionally, the industry can continue to help improve the scientific understanding around the oceanographic and ecological impacts of wind farm development on NARW and their prey, while more broadly contributing to mitigating climate change and improving our collective understanding of ocean ecosystems.

References

Ainslie, J. F. 1988. Calculating the flowfield in the wake of wind turbines. *Journal of Wind Engineering and Industrial Aerodynamics* 27:213-224.

Akhtar, N., B. Geyer, B. Rockel, P. S. Sommer, and C. Schrum. 2021. Accelerating deployment of offshore wind energy alter wind climate and reduce future power generation potentials. *Scientific Reports* 11:11826.

Andres, M. 2016. On the recent destabilization of the Gulf Stream path downstream of Cape Hatteras. *Geophysical Research Letters* 43:9836-9842.

Archer, C. L., B. A. Colle, D. L. Veron, F. Veron, and M. J. Sienkiewicz. 2016. On the predominance of unstable atmospheric conditions in the marine boundary layer offshore of the U.S. northeastern coast. Journal of Geophysical Research: Atmospheres 121:8869-8885.

Atkinson, L. P., T. N. Lee, J. O. Blanton, and W. S. Chandler. 1983. Climatology of the Southeastern United States Continental Shelf Waters. *Journal of Geophysical Research: Oceans* 88:4705-4718.

Barthelmie, R. J., S. C. Pryor, S. T. Frandsen, K. S. Hansen, J. G. Schepers, K. Rados, W. Schlez, A. Neubert, L. E. Jensen, and S. Neckelmann. 2010. Quantifying the impact of wind turbine wakes on power output at offshore wind farms. *Journal of Atmospheric and Oceanic Technology* 27:1302-1317.

Baumgartner, M. F., and B. R. Mate. 2003. Summertime foraging ecology of North Atlantic right whales. *Marine Ecology Progress Series* 264:123-135.

Baumgartner, M. F., and A. M. Tarrant. 2017. Physiology and ecology of diapause in marine copepods. *Annual Reviews in Marine Science* 9:387-411.

Baumgartner, M. F., K. Ball, J. Partan, L. P. Pelletier, J. Bonnell, C. Hotchkin, P. J. Corkeron, and S. M. Van Parijs. 2021. Near real-time detection of low-frequency baleen whale calls from an autonomous surface vehicle: Implementation, evaluation, and remaining challenges. *Journal of the Acoustical Society of America* 149:2950-2962.

Baumgartner, M. F., J. Bonnell, S. M. Van Parijs, P. J. Corkeron, C. Hotchkin, K. Ball, L. P. Pelletier, J. Partan, D. Peters, J. Kemp, J. Pietro, K. Newhall, A. Stokes, T. V. N. Cole, E. Quintana, and S. D. Kraus. 2019. Persistent near real-time passive acoustic monitoring for baleen whales from a moored buoy: System description and evaluation. *Methods in Ecology and Evolution* 10:1476-1489.

Baumgartner, M. F., T. V. N. Cole, R. G. Campbell, G. J. Teegarden, and E. G. Durbin. 2003. Associations between North Atlantic right whales and their prey, *Calanus finmarchicus*, over diel and tidal time scales. *Marine Ecology Progress Series* 264:155-166.

Baumgartner, M. F., F. W. Wenzel, N. S. J. Lysiak, and M. R. Patrician. 2017. North Atlantic right whale foraging ecology and its role in human-caused mortality. *Marine Ecology Progress Series* 581:165-181.

Beardsley, R. C., A. W. Epstein, C. Chen, K. F. Wishner, M. C. Macaulay, and R. D. Kenney. 1996. Spatial variability in zooplankton abundance near feeding right whales in the Great South Channel. *Deep-Sea Research II* 43:1601-1625.

Beare, D. J., and E. McKenzie. 1999. Temporal patterns in the surface abundance of *Calanus finmarchicus* and *C. helgolandicus* in the northern North Sea (1958-1996) inferred from continuous plankton recorder data. *Marine Ecology Progress Series* 190:241-251.

Beaugrand, G., P. C. Reid, F. Ibeñez, J. A. Lindley, and M. Edwards. 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* 296:1692-1694.

Biggs, R., S. R. Carpenter, and W. A. Brock. 2009. Turning back from the brink: Detecting an impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences* 106:826-831.

Bishop, A. L., L. M. Crowe, P. K. Hamilton, and E. L. Meyer-Gutbrod. 2022. Maternal lineage and habitat use patterns explain variation in the fecundity of a critically endangered baleen whale. *Frontiers in Marine Science* 9:880910.

Bort, J., S. M. Van Parijs, P. T. Stevick, E. Summers, and S. Todd. 2015. North Atlantic right whale *Eubalaena glacialis* vocalization patterns in the central Gulf of Maine from October 2009 through October 2010. *Endangered Species Research* 26:271-280.

Bowman, R. W., J. Warzocha, and T. Morris. 1984. Trophic relationships between Atlantic mackerel and American sand lance. *ICES CM* 1984/H:H27.

Brennan, C. E., F. Maps, W. C. Gentleman, S. Plourde, D. Lavoie, J. Chassé, C. Lehoux, K. A. Krumhansl, and C. L. Johnson. 2019. How transport shapes copepod distributions in relation to whale feeding habitat: Demonstration of a new modelling framework. *Progress in Oceanography* 171:1-21.

Brickman, D., D. Hebert, and Z. Wang. 2018. Mechanism for the recent ocean warming events on the Scotian Shelf of eastern Canada. *Continental Shelf Research* 156:11-22.

Broström, G. 2008. On the influence of large wind farms on the upper ocean circulation. *Journal of Marine Systems* 74:585-591.

Carloni, J. T., R. Wahle, P. Geoghegan, and E. Bjorkstedt. 2018. Bridging the spawner-recruit disconnect: Trends in American lobster recruitment linked to the pelagic food web. *Bulletin of Marine Science* 94:719-735.

Carpenter, J. R., L. Merckelbach, U. Callies, S. Clark, L. Gaslikova, and B. Baschek. 2016. Potential Impacts of Offshore Wind Farms on North Sea Stratification. *PLoS ONE* 11:e0160830.

Castelao, R., S. Glenn, and O. Schofield. 2010. Temperature, salinity, and density variability in the central Middle Atlantic Bight. *Journal of Geophysical Research* 115:C10005.

Cazenave, P. W., R. Torres, and J. I. Allen. 2016. Unstructured grid modelling of offshore wind farm impacts on seasonally stratified shelf seas. *Progress in Oceanography* 145:25-41.

Chant, R. J., S. M. Glenn, E. Hunter, J. Kohut, R. F. Chen, R. W. Houghton, J. Bosch, and O. Schofield. 2008. Bulge formation of a buoyant river outflow. *Journal of Geophysical Research* 113:C01017.

Chapman, D. C., and R. C. Beardsley. 1989. On the origin of shelf water in the Middle Atlantic Bight. *Journal of Physical Oceanography* 19:384-391.

Chen, Z., and E. N. Curchitser. 2020. Interannual variability of the Mid-Atlantic Bight cold pool. *Journal of Geophysical Research: Oceans* 125: e2020JC016445.

Chen, Z.., E. N. Curchitser, R. Chant, and D. Kang. 2018. Seasonal variability of the cold pool over the Mid-Atlantic Bight continental shelf. *Journal of Geophysical Research: Oceans* 123:8203-8226.

Christiansen, N., U. Daewel, B. Djath, and C. Schrum. 2022a. Emergence of large-scale hydrodynamic structures due to atmospheric offshore wind farm wakes. *Frontiers in Marine Science* 9:818501.

Christiansen, N., U. Daewel, and C. Schrum. 2022b. Tidal mitigation of offshore wind wake effects in coastal seas. *Frontiers in Marine Science* 9:1006647.

Cole, T. V. N., P. Hamilton, A. G. Henry, P. Duley, R. M. Pace, B. N. White, and T. Frasier. 2013. Evidence of a North Atlantic right whale *Eubalaena glacialis* mating ground. *Endangered Species Research* 21:55-64.

Conversi, A., S. Piontkovski, and S. Hameed. 2001. Seasonal and interannual dynamics of *Calanus finmarchicus* in the Gulf of Maine (Northeastern US shelf) with reference to the North Atlantic Oscillation. *Deep-Sea Research II* 48:519-520.

Crowe, L. M., M. W. Brown, P. J. Corkeron, P. K. Hamilton, C. Ramp, S. Ratelle, A. S. M. Vanderlaan, and T. V. N. Cole. 2021. In plane sight: A mark-recapture analysis of North Atlantic right whales in the Gulf of St. Lawrence. *Endangered Species Research* 46:227-251.

Daewel, U., and C. Schrum. 2017. Low-frequency variability in North Sea and Baltic Sea identified through simulations with the 3-D coupled physical-biogeochemical model ECOSMO. *Earth System Dynamics* 8:801-815.

Daewel, U., N. Akhtar, N. Christiansen, and C. Schrum. 2022. Offshore wind farms are projects to impact primary production and bottom water deoxygenation in the North Sea. *Communications Earth & Environment* 3:292.

Davies, K. T. A., M. W. Brown, P. K. Hamilton, A. R. Knowlton, C. T. Taggert, A. S. M. Vanderlaan. 2019. Variation in North Atlantic right whale *Eubalaena glacialis* occurrence in the Bay of Fundy, Canada, over three decades. *Endangered Species Research* 39:159-171.

Davies, K. T. A., C. T. Taggart, and R. K. Smedbol. 2014. Water mass structure defines the diapausing copepod distribution in a right whale habitat on the Scotian Shelf. *Marine Ecology Progress Series* 497:69-85.

Davis, G. E., M. F. Baumgartner, J. M. Bonnell, J. Bell, C. Berchok, J. B. Thornton, S. Brault, G. Buchanon, R. A. Charif, D. Cholewiak, C. W. Clark, P. Corkeron, J. Delarue, K. Dudzinski, L. Hatch, J. Hildebrand, L. Hodge, H. Klinck, S. Kraus, B. Martin, D. K. Mellinger, H. Moors-Murphy, S. Nieukirk, D. P. Nowacek, S. Parks, A. J. Read, A. N. Rice, D. Risch, A. Sirovic, M. Soldevilla, K. Stafford, J. E. Stanistreet, E. Summers, S. Todd, A. Warde, and S. M. Van Parijs. 2017. Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. *Scientific Reports* 7:13460.

Dicopoulos, J., J. F. Brodie, S. Glenn, J. Kohut, T. Miles, G. Seroka, R. Dunk, and E. Fredj. 2021. Weather Research and Forecasting model validation with NREL specifications over the New York/New Jersey Bight for offshore wind development. In OCEANS 2021: *San Diego – Porto,* San Diego, CA, USA. pp. 1-7.

Division of Fisheries and Oceans (DFO). 2020. Updated information on the distribution of North Atlantic right whale in Canadian waters. *Science Advisory Report* 2020/037.

Du, J., W. Zhang, and Y. Li. 2022. Impact of Gulf Stream warm-core rings on slope water intrusion into the Gulf of Maine. *Journal of Physical Oceanography* 52:1797-1815.

Estabrook, B. J., J. T. Tielens, A. Rahaman, D. W. Ponirakis, C. W. Clark, and A. N. Rice. 2022. Dynamic spatiotemporal acoustic occurrence of North Atlantic right whales in the offshore Rhode Island and Massachusetts Wind Energy Areas. *Endangered Species Research* 49:115-133.

Fields, D. M., J. A. Runge, C. R. S. Thompson, C. M. F. Durif, S. D. Shema, R. M. Bjelland, M. Niemisto, M. T. Arts, A. B. Skiftesvik, and H. I. Browman. 2023. A positive temperature-dependent effect of elevated CO2 on growth and lipid accumulation in the planktonic copepod, *Calanus finmarchicus*. *Limnology and Oceanography* 68: S87-S100.

Floeter, J., J. E. van Beusekom, D. Auch, U. Callies, J. Carpenter, T. Dudeck, S. Eberle, A. Eckhardt, D. Gloe, K. Haenselmann, M. Hufnagl, S. Janssen, H. Lenhart, K. O. Moeller, R. P. North, T. Phlmann, R. Riethmueller, S. Schulz, S. Spreizenbarth, A. Temming, B. Walter, O. Zielsinski, and C. Moellmann. 2017. Pelagic effects of offshore wind farm foundations in the stratified North Sea. *Progress in Oceanography* 156:154-173.

Friedland, K. D., T. Miles, A. G. Goode, E. N. Powell, and D. C. Brady. 2022. The Middle Atlantic Bight Cold Pool is warming and shrinking: Indices from in situ autumn seafloor temperatures. *Fisheries Oceanography* 31:217-223.

Friedland, K. D., R. E. Morse, J. P. Manning, D. C. Melrose, T. Miles, A. G. Goode, D. C. Brady, J. T. Kohut, and E. N. Powell. 2020. Trends and change points in surface and bottom thermal environments of the US Northeast Continental Shelf Ecosystem. *Fisheries Oceanography* 29:396-414.

Fromentin, J. M., and B. Planque. 1996. *Calanus* and environment in the eastern North Atlantic. II. Influence of the North Atlantic Oscillation on *C. finmarchicus* and *C. helgolandicus*. *Marine Ecology Progress Series* 134:111-118.

Ganley, L. C., S. Brault, and C. A. Mayo. 2019. What we see is not what there is: Estimating North Atlantic right whale *Eubalaena glacialis* local abundance. *Endangered Species Research* 38:101-113.

Ganley, L. C., J. Byrnes, D. E. Pendleton, C. A. Mayo, K. D. Friedland, J. V. Redfern, J. T. Turner, and S. Brault. 2022. Effects of changing temperature phenology on the abundance of a critically endangered baleen whale. *Global Ecology and Conservation* 38:e02193.

Gavrilchuk, K., V. Lesage, S. M. E. Fortune, A. W. Trites, and S. Plourde. 2021. Foraging habitat of the North Atlantic right whales has declined in the Gulf of St. Lawrence, Canada, and may be insufficient for successful reproduction. *Endangered Species Research* 44:113-136.

Ghaisas, N. S., C. L. Archer, S. Xie, S. Wu, and E. Maguire. 2017. Evaluation of layout and atmospheric stability effects in wind farm using large-eddy simulation. *Wind Energy* 20:1227-1240.

Glenn, S., R. Arnone, T. Bergmann, W. P. Bissett, M. Crowley, J. Cullen, J. Gryzemski, D. Haidvogel, J. Kohut, M. Moline, M. Oliver, C. Orrico, R. Sherrell, T. Song, A. Weidemann, R. Chant, and O. Schofield. 2004. Biogeochemical impact of summertime coastal upwelling on the New Jersey Shelf. J*ournal of Geophysical Research* 109:C12S02

Golbazi, M., C. L. Archer, and S. Alessandrini. 2022. Surface impacts of large offshore wind farms. *Environmental Research Letters* 17:064021.

Gowan, T. A., J. G. Ortega-Ortiz, J. A. Hostetler, P. K. Hamilton, A. R. Knowlton, K. A. Jackson, R. C. George, C. R. Taylor, and P. J. Naessig. 2019. Temporal and demographic variation in partial migration of the North Atlantic right whale. *Scientific Reports* 9:353.

Greene, C. H., and A. J. Pershing. 2000. The response of *Calanus finmarchicus* populations to climate variability in the Northwest Atlantic: Basin-scale forcing associated with the North Atlantic Oscillation. *ICES Journal of Marine Science* 57:1536-1544.

Greene, C. H., and A. J. Pershing. 2003. The flip-side of the North Atlantic Oscillation and modal shifts in slope-water circulation patterns. *Limnology and Oceanography* 48:319-322.

Greene, C. H., and A. J. Pershing. 2004. Climate and the conservation biology of North Atlantic right whales: The right whale at the wrong time? *Frontiers in Ecology and the Environment* 2:29-34.

Greene, C. H., A. J. Pershing, T. M. Cronin, and N. Ceci. 2008. Arctic climate change and its impacts on the ecology of the North Atlantic. *Ecology* 89:S24-S38.

Grieve, B. D., J. A. Hare, and V. S. Saba. 2017. Projecting the effects of climate change on *Calanus finmarchicus* distribution within the U.S. Northeast Continental Shelf. *Scientific Reports* 7:s41598-017-06524-1.

Großelindemann, H., S. Ryan, C. C. Ummenhofer, T. Martin, and A. Biastoch. 2022. Marine heatwaves and their depth structures on the northeast U.S. continental shelf. *Frontiers in Climate* 4:857937.

Hansen, K., R. Barthelmie, L. Jensen, and A. Sommer. 2012. The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm. *Wind Ener*gy 15:183-196.

Hayes, S. A., E. Josephson, K. Maze-Foley, P. E. Rosel, J. McCordic, and J. Wallace. 2023. U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments 2022. NOAA Tech. Memo. NMFS-NE-304.

Helaouët, P., and G. Beaugrand. 2007. Macroecology of *Calanus finmarchicus* and *C. helgolandicus* in the North Atlantic Ocean and adjacent seas. *Marine Ecology Progress Series* 345:147-165.

Hirche, H. J. 1996. Diapause in the marine copepod, *Calanus finmarchicus* – A review. *Ophelia* 44:129-143.

Hlista, B. L., H. M. Sosik, L. V. Martin Traykovski, R. D. Kenney, and M. J. Moore. 2009. Seasonal and interannual correlations between right-whale distribution and calving success and chlorophyll concentrations in the Gulf of Maine, USA. *Marine Ecology Progress Series* 394:289-302.

Honda, I. A., R. Ji, and A. R. Solow. 2023. Spatially varying plankton synchrony patterns at seasonal and interannual scales in a well-connected shelf sea. *Limnology and Oceanography Letters.* DOI: 10.1002/lol2.10348.

Houghton, R. W., R. Schlitz, R. C. Beardsley, B. Buttman, and J. L. Chamberlin. 1982. The Middle Atlantic Bight Cold Pool: Evolution of the temperature structure during summer 1979. *Journal of Physical Oceanography* 12:1019-1029

Intergovernmental Panel on Climate Change (IPCC). 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfeld, O. Yelekçi, R. Yu, and B. Zhou (eds.)].

Intergovernmental Panel on Climate Change IPCC). 2023. Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Lee, H., and J. Romero (eds.)].

Ji, R., Z. Feng, B. T. Jones, C. Thompson, C. Chen, N. R. Record, and J. A. Runge. 2022a. Coastal amplification of supply and transport (CAST): A new hypothesis about the persistence of *Calanus finmarchicus* in the Gulf of Maine. *ICES Journal of Marine Science* 74:1865-1874.

Ji, R., J. A. Runge, C. A. Davis, and P. H. Wiebe. 2022b. Drivers of variability of *Calanus finmarchicus* in the Gulf of Maine: Roles of internal production and external exchange. *ICES Journal of Marine Science* 79:775-784.

Jiang, M., M. W. Brown, J. T. Turner, R. D. Kenney, C. A. Mayo, Z. Zhang, and M. Zhou. 2007. Springtime transport and retention of *Calanus finmarchicus* in Massachusetts and Cap Code Bays, USA, and implications for right whale foraging. *Marine Ecology Progress Series* 349:183-197.

Johnson, T. L., J. J. van Berkel, L. O. Mortensen, M. A. Bell, I. Tiong, B. Hernandez, D. B. Snyder, F. Thomsen, and O. S. Petersen. 2021. *Hydrodynamic Modeling, Particle Tracking and Agent-Based Modeling of Larvae in the U.S. Mid-Atlantic Bight*. OCS Study BOEM 2021-049. 232 pp.

Kane, J. 1984. The feeding habits of co-occurring cod and haddock larvae from Georges Bank. *Marine Ecology Progress Series* 16:9-20.

Kane, J. 2005. The demography of *Calanus finmarchicus* (Copepoda: Calanoida) in the Middle Atlantic Bight, USA, 1977-2001. *Journal of Plankton Research* 27:401-414.

Kenney, R. D., M. A. M. Hyman, R. E. Owen, G. P. Scott, and H. E. Winn. 1986. Estimation of prey densities required by western North Atlantic right whales. *Marine Mammal Science* 2:1-13.

Kenney, R. D., C. A. Mayo, and H. E. Winn. 2001. Migration and foraging strategies at varying spatial scales in western North Atlantic right whales: A review of hypotheses. *Journal of Cetacean Research and Management* 2:251-260.

Kraus, S. D., R. D. Kenney, and L. Thomas. 2019. A Framework for Studying the Effects of Offshore Wind Development on Marine Mammals and Turtles. Report prepared for the Massachusetts Clean Energy Center and Bureau of Ocean Energy Management.

Krumhansl, K. A., E. J. H. Head, P. Pepin, S. Plourde, N. R. Record, J. A. Runge, and C. L. Johnson. 2018. Environmental drivers of vertical distribution in diapausing *Calanus* copepods in the Northwest Atlantic. *Progress in Oceanography* 162:202-222.

Kvile, K. Ø., I. P. Prokopchuk, and L. C. Stige. 2022. Environmental effects on *Calanus finmarchicus* abundance and depth distribution in the Barents Sea. *ICES Journal of Marine Science* 79:815-828.

Leiter, S. M., K. M. Stone, J. L. Thompson, C. M. Accardo, B. C. Wilkgren, M. A. Zani, T. V. N. Cole, R. D. Kenney, C. A. Mayo, S. D. Kraus. 2017. North Atlantic right whale *Eubalaena glacialis* occurrence in offshore wind energy areas near Massachusetts and Rhode Island, USA. *Endangered Species Research* 34:45-59.

Lentz, S. J. 2008. Observations and a model of the mean circulation over the Middle Atlantic Bight Continental Shelf. *Journal of Physical Oceanography* 38:1203-1221.

Lentz, S. J. 2017. Seasonal warming of the Middle Atlantic Bight Cold Pool. *Journal of Geophysical Research: Oceans* 122:941-954

Lynch, D. R., W. C. Gentleman, D. J. McGillicuddy, Jr., and C. S. Davis. 1998. Biological/physical simulations of *Calanus finmarchicus* population dynamics in the Gulf of Maine. *Marine Ecology Progress Series* 169:189-210.

Manning, C. A., and A. Bucklin. 2005. Multivariate analysis of the copepod community of near-shore waters in the western Gulf of Maine. *Marine Ecology Progress Series* 292:233-249.

Maps, F., J. A. Runge, A. Leising, A. J. Pershing, N. R. Record, S. Plourde, and J. J. Pierson. 2012. Modelling the timing and duration of dormancy in populations of *Calanus finmarchicus* from the Northwest Atlantic shelf. *Journal of Plankton Research* 34:36-54.

Mayo, C A., and M. K. Marx. 1990. Surface foraging behaviour of the North Atlantic right whale, *Eubalaena glacialis*, and associated zooplankton characteristics. *Canadian Journal of Zoology* 68:2214-2220.

Mayo, C. A., L. Ganley, C. A. Hudak, S. Brault, M. K. Marx, E. Burke, and M. W. Brown. 2018. Distribution, demography, and behavior of North Atlantic right whales (*Eubalaena glacialis*) in Cape Cod Bay, Massachusetts, 1998-2013. *Marine Mammal Science* 34:979-996.

Melle, W., J. Runge, E. Head, S. Plourde, C. Castellani, P. Licandro, J. Pierson, S. Jonasdottir, C. Johnson, C. Broms, H. Debes, T. Falkengaug, E. Gaard, A. Gislason, M. Heath, B. Niehoff, T. Gissel Nielsen, P. Pepin, E. Kaare Stenevik, and G. Chust. 2014. The North Atlantic Ocean as habitat for *Calanus finmarchicus*: Environmental factors and life history traits. *Progress in Oceanography* 129:244-284.

Meyer-Gutbrod, E. L., and C. H. Greene. 2014. Climate-associated regime shifts drive decadal-scale variability in recovery of North Atlantic right whale population. *Oceanography* 27:148-153.

Meyer-Gutbrod, E. L., and C. H. Greene. 2018. Uncertain recovery of the North Atlantic right whale in a changing ocean. *Global Change Biology* 24:455-464.

Meyer-Gutbrod, E. L., K. T. A. Davies, C. L. Johnson, S. Plourde, K. A. Sorochan, R. D. Kenney, C. Ramp, J. Gosselin, J. W. Lawson, and C. H. Greene. 2022. Redefining North Atlantic right whale habitat-use patterns under climate change. *Limnology and Oceanography*. DOI: 10.1002/lno.12242.

Meyer-Gutbrod, E. L., C. H. Greene, K. T. A. Davies, and D. G. Johns. 2021. Ocean regime shift is driving collapse of the North Atlantic right whale population. *Oceanography* 34:22-31.

Meyer-Gutbrod, E. L., C. H. Greene, P. J. Sullivan, and A. J. Pershing. 2015. Climate-associated changes in prey availability drive reproductive dynamics of the North Atlantic right whale population. *Marine Ecology Progress Series* 535:243-258.

Miles, T., S. Murphy, J. Kohut, S. Borsetti, and D. Munroe. 2021. Offshore wind energy and the Mid-Atlantic Cold Pool: A review of potential interactions. *Marine Technology Society Journal* 55:72-87.

Miller, C. B., D. R. Lynch, F. Carlotti, W. C. Gentleman, and C. Lewis. 1998. Coupling of an individual-based population dynamical model for stocks of *Calanus finmarchicus* with a circulation model for the Georges Bank region. *Fisheries Oceanography* 8:219-234.

Miller, T. J., J. A. Hare, and L. A. Alade. 2016. A state-space approach to incorporating environmental effects on recruitment in an age-structured assessment model with an application to southern New England yellowtail flounder. *Canadian Journal of Fisheries and Aquatic Sciences* 73:1261-1270.

Muirhead, C. A., A. M. Warde, I. S. Biedron, A. N. Mihnovets, C. W. Clark, and A. N. Rice. 2018. Seasonal acoustic occurrence of blue, fin, and North Atlantic right whales in the New York Bight. *Aquatic Conservation: Marine and Freshwater Ecosystems* 28:744-753.

Murphy, S., L. Nazzaro, J. Simkins, M. Oliver, J. Kohut, M. Crowley, and T. Miles. 2021. Persistent upwelling in the Mid-Atlantic Bight detected using gap-filled, high-resolution satellite SST. *Remote Sensing of Environment* 262:112487.

National Marine Fisheries Service (NMFS). 2015. North Atlantic right whale (*Eubalaena glacialis*) source document for critical habitat designation. 177 pp.

National Marine Fisheries Service (NMFS). 2022. North Atlantic right whale (*Eubalaena glacialis*) 5-year review: Summary and evaluation. 55 pp.

National Oceanic and Atmospheric Administration (NOAA). 2009. Climate variability: North Atlantic Oscillation. Available: https://www.climate.gov/news-features/understanding-climate/climate-variability-north-atlantic-oscillation. Accessed: August 2023.

National Renewable Energy Laboratory (NREL). 2021. Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update. Golden, CO: National Renewable Energy Laboratory. NREL/FS-6A50-80580.

O'Brien, O., K. McKenna, D. Pendleton, and J. Redfern. 2021.Megafauna Aerial Surveys in the Wind Energy Areas of Massachusetts and Rhode Island with Emphasis on Large Whales: Interim Report Campaign 6A, 2020. OCS Study BOEM 2021-054. 41 pp.

O'Brien, O., D. E. Pendleton, L. C. Ganley, K. R. McKenna, R. D. Kenney, E. Quintana-Rizzo, C. A. Mayo, S. D. Kraus, and J. V. Redfern. 2022. Repatriation of a historical North Atlantic right whale habitat during an era of rapid climate change. *Scientific Reports* 12:12407.

Oliver, E. C. J., M. G. Donat, M. T. Burrows, P. J. Moore, D. A. Smale, L. V. Alexander, J. A. Benthuysen, M. Feng, A. S. Gupta, A. J. Hobday, N. J. Holbrook, S. E. Perkins. 2018. Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9:1324.

Paskyabi, M. B. 2015. Offshore wind farm wake effect on stratification and coastal upwelling. *Energy Procedia* 80:131-140.

Payton, L., C. Noirot, K. S. Last, J. Grigor, L. Hüppe, D. V. P. Conway, M. Dannemeyer, A. Suin, and B. Meyer. 2022. Annual transcriptome of a key zooplankton species, the copepod *Calanus finmarchichus*. *Ecology and Evolution* 12:e8605.

Pendleton, D. E., A. J. Pershing, M. W. Brown, C. A. Mayo, R. D. Kenney, N. R. Record, and T. V. N. Cole. 2009. Regional-scale mean copepod concentration indicates relative abundance of North Atlantic right whales. *Marine Ecology Progress Series* 378:211-225.

Pendleton, D. E., M. W. Tingley, L. C. Ganley, K. D. Friedland, C. Mayo, M. W. Brown, B. E. McKenna, A. Jordaan, and M. D. Staudinger. 2022. Decadal-scale phenology and seasonal climate drivers of migratory baleen whales in a rapidly warming marine ecosystem. *Global Change Biology* 28:4989-5005.

Pershing, A. J., and D. E. Pendleton. 2021. Can right whales out-swim climate change? Can we? *Oceanography* 34:19-21.

Pershing, A. J., M. A. Alexander, C. M. Hernandez, L. A. Kerr, A. Le Bris, K. E. Mills, J. A. Nye, N. R. Record, H. A. Scannell, J. D. Scott, G. D. Sherwood, and A. C. Thomas. 2015. Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science* 350:2369-2391.

Pershing, A. J., C. H. Greene, C. G. Hannah, D. Sameoto, E. J. H. Head, D. G. Mountain, J. W. Jossi, M. C. Benfield, P. C. Reid, and T. Durbin. 2001. Oceanographic responses to climate in the Northwest Atlantic. *Oceanography* 14:76-82.

Plourde, S., P. Joly, J. A. Runge, B. Zakardjian, and J. J. Dodson. 2001. Life cycle of *Calanus finmarchicus* in the lower St. Lawrence Estuary: The imprint of circulation and late timing of the spring phytoplankton bloom. *Canadian Journal of Fisheries and Aquatic Sciences* 58:647-658.

Quintana-Rizzo, E., S. Leiter, T. V. N. Cole, M. N. Hagbloom, A. R. Knowlton, P. Nagelkirk, O. O'Brien, C. B. Kahn, A. G. Henry, P. A. Duley, L. M. Crowe, C. A. Mayo, and S. D. Kraus. 2021. Residency, demographics, and movement patterns of North Atlantic right whales *Eubalaena glacialis* in an offshore wind energy development area in southern New England, USA. *Endangered Species Research* 45:251-268.

Record, N. R., J. A. Runge, D. E. Pendleton, W. M. Balch, K. T. A. Davies, A. J. Pershing, C. L. Johnson, K. Stamieszkin, R. Ji, Z. Feng, S. D. Kraus, R. D. Kenney, C. A. Hudak, C. A. Mayo, C. Chen, J. E. Salisbury, and C. R. S. Thompson. 2019. Rapid climate-driven circulation changes threaten conservation of endangered North Atlantic right whales. *Oceanography* 32:162-169.

Regional Synthesis Workgroup of the Environmental Technical Working Group. 2023. Responsible Practices for Regional Wildlife Monitoring and Research in Relation to Offshore Wind Energy Development. 44 pp. Available: https://www.nyetwg.com/regional-synthesis-workgroup. Accessed: September 2023.

Reygondeau, G., and G. Beaugrand. 2011. Future climate-driven shifts in distribution of *Calanus finmarchicus*. *Global Change Biology* 17:756-766.

Richardson, A. J. 2008. In hot water: Zooplankton and climate change. *ICES Journal of Marine Science* 65:279-295.

Roarty, H., S. Glenn, J. Brodie, L. Nazzaro, M. Smith, E. Handel, J. Kohut, T. Updyke, L. Atkinson, W. Boicourt, W. Brown, H. Seim, M. Muglia, H. Wang, and D. Gong. 2020. Annual and seasonal surface circulation over the Mid-Atlantic Bight Continental Shelf derived from a decade of high frequency radar observations. *Journal of Geophysical Research: Oceans* 10.1029/2020JC016368.

Ross, C. H., J. A. Runge, J. J. Roberts, D. C. Brady, B. Tupper, and N. R. Record. 2023. Estimating North Atlantic right whale prey based on *Calanus finmarchicus* thresholds. *Marine Ecology Progress Series* 703:1-16.

Runge, J. A., and R. J. Jones. 2012. Results of a collaborative project to observe coastal zooplankton and ichthyoplankton abundance and diversity in the Western Gulf of Maine: 2003-2008. *American Fisheries Society Symposium* 79.

Runge, J. A., R. Ji, C. R. S. Thompson, N. R. Record, C. Chen, D. C. Vandemark, J. E. Salisbury, and F. Maps. 2015. Persistence of *Calanus finmarchicus* in the western Gulf of Maine during recent extreme warming. *Journal of Plankton Research* 37:221-232.

Runge, J., L. Karp Boss, E. Dullaert, R. Ji, J. Motyka, R. Young-Morse, D. Pugh, S. Shellito, and D. Vandemark. 2023. Sustained monitoring of zooplankton populations at the Coastal Maine Time Series (CMTS) and Wilkinson Basin Time Series (WBTS) stations in the western Gulf of Maine: Results from 2005-2022. OCS Study BOEM 2023-015. 40 pp.

Saba, V. S., S. M. Griffies, W. G. Anderson, M. Winton, M. A., Alexander, T. L. Delworth, J. A. Hare, M. J. Harrison, A. Rosati, G. A. Vecchi, and R. Zhang. 2016. Enhanced warming of the Northwest Atlantic Ocean under climate change. *Journal of Geophysical Research: Oceans* 121:118-132.

Schrum, C., J. Lowe, H. E. M. Meier, I. Grabemann, J. Holt, and M. Mathis. 2016. Projected Change - North Sea. In *North Sea Region Climate Change Assessment* [M. Quante and F. Colijn (eds.)] pp. 175–217.

Schultze, L. K. P., L. M. Merckelbach, J. Horstmann, S. Raasch, and J. R. Carpenter. 2020. Increased mixing and turbulence in the wake of offshore wind farm foundations. *Journal of Geophysical Research: Oceans* 125:e2019JC015858.

Shcherbina, A. Y., and G. G. Gawarkiewicz. 2008. A coastal current in winter: Autonomous underwater vehicle observations of the coastal current east of Cape Cod. *Journal of Geophysical Research* 113:C07030.

Sherman, K., J. R. Green, J. R. Goulet, and L. Ejsymont. 1983. Coherence in zooplankton of a large Northwest Atlantic ecosystem. *Fishery Bulletin* 55:730-738.

Slavik, K., C. Lemmen, W. Zhang, O. Kerimoglu, K. Klingbeil, K. W. Wirtz. 2019. The large-scale impact of offshore wind structures on pelagic primary productivity in the southern North Sea. *Hydrobiologia* 845:35-53.

Sorochan, K. A., C. E. Brennan, S. Plourde, and C. L. Johnson. 2021a. Spatial variation and transport of abundant copepod taxa in the southern Gulf of St. Lawrence in autumn. *Journal of Plankton Research* 43:908-926.

Sorochan, K. A., S. Plourde, M. F. Baumgartner, and C. L. Johnson. 2021b. Availability, supply, and aggregation of prey (*Calanus* spp.) in foraging areas of the North Atlantic right whale (*Eubalaena glacialis*). *ICES Journal of Marine Science* 78:3498-3520.

Sorochan, K. A., S. Plourde, and C. L. Johnson. 2023. Near-bottom aggregations of *Calanus* spp. copepods in the southern Gulf of St. Lawrence in summer: Significance for the North Atlantic right whale foraging. *ICES Journal of Marine Science* 80:787-802.

Sorochan, K. A., S. Plourde, R. Morse, P. Pepin, J. Runge, C. Thompson, and C. L. Johnson. 2019. North Atlantic right whale (*Eubalaena glacialis*) and its food: (II) Interannual variations in biomass of *Calanus* spp. on western North Atlantic shelves. *Journal of Plankton Research* 41:687-708.

Sundby, S. 2000. Recruitment of Atlantic cod stocks in relation to temperature and advection of copepod populations. *Sarsia* 85:277-298.

Thomas, A. C., D. W. Townsend, and R. Weatherbee. 2003. Satellite-measured phytoplankton variability in the Gulf of Maine. *Continental Shelf Research* 23:971-989.

Townsend, D.W., N.R. Pettigrew, M.A. Thomas, M.G. Neary, D.J. McGillicuddy, and J. O'Donnell. 2015. Water masses and nutrient sources to the Gulf of Maine. *Journal of Marine Research* 73:3-4.

U.S. Fish and Wildlife Service (USFWS). 1970. List of endangered foreign fish and wildlife. 35 FR 18319.

Vanhellemont, Q., and K. Ruddick. 2014. Turbid wakes associated with offshore wind turbines observed with Landsat 8. Remote Sensing of Environment 145:105-115.

Wallace, E. J., L. V. Looney, and D. Gong. 2018. Multi-decadal trends and variability in temperature and salinity in the Mid-Atlantic Bight, Georges Bank, and Gulf of Maine. *Journal of Marine Research* 76:163-215.

White, T. P. and R. R. Veit. 2020. Spatial ecology of long-tailed ducks and white-winged scoters wintering on Nantucket Shoals. *Ecosphere* 11:e03002.

Wilkin, J. L. 2006. The summertime heat budget and circulation of southeast New England shelf waters. *Journal of Physical Oceanography* 36:1997-2011.

Wishner, K., E. Durbin, A. Durbin, M. Macaulay, H. Winn, and R. Kenney. 1988. Copepod patches and right whales in the Great South Channel off New England. *Bulletin of Marine Science* 43:825-844.

Xue, Z., J. Zambon, Z. Yao, Y. Liu, and R. He. 2015. An integrated ocean circulation, wave, atmosphere, and marine ecosystem prediction system for the South Atlantic Bight and Gulf of Mexico. *Journal of Operational Oceanography* 8:80-91.

Zeng, X. and R. He. 2016. Gulf Stream variability and a triggering mechanism of its large meander in the South Atlantic Bight. *Journal of Geophysical Research: Oceans* 121:8021-8038.

Appendix: Expert Workshop Slides

AKRF
Environmental, Engineering, and Planning Consultants

Rutgers

Bigelow | Laboratory for Ocean Sciences

Oceanographic Effects of Offshore Wind Structures and Their Impacts on the North Atlantic Right Whale and Their Prey

Expert Workshop | July 13, 2023

Introductions

White Paper Team:

AKRF

RUTGERS

Bigelow | Laboratory for Ocean Sciences

White Paper Goals

- Understand the latest science on interactions between NARW and the oceanographic impacts of both climate change and the presence of structures associated with large-scale deployment of OSW in the US
- Review recent and ongoing research efforts in this area
- Identify knowledge gaps and make recommendations for future research, monitoring, and mitigation for the industry
- Serve as a useful public reference
- Complement efforts by other organizations and entities

White Paper Literature Review

- Baseline Conditions
  - Oceanography
  - Copepod Distribution
  - NARW Distribution and Habitat Utilization
- Climate Change in Eastern Coastal Waters
  - Background on Climate Change
  - Shifting NARW Distributions
  - Wind Energy's Role in Climate Change Mitigation
- Potential Hydrodynamic Effects of Wind Turbines
  - Wind-Wake Effect
  - Induced Underwater Mixing Effect
  - Combining Atmospheric and Oceanic Effects
  - Potential Ecosystem Impacts of Hydrodynamic Effects

Mid-Atlantic Cold Pool

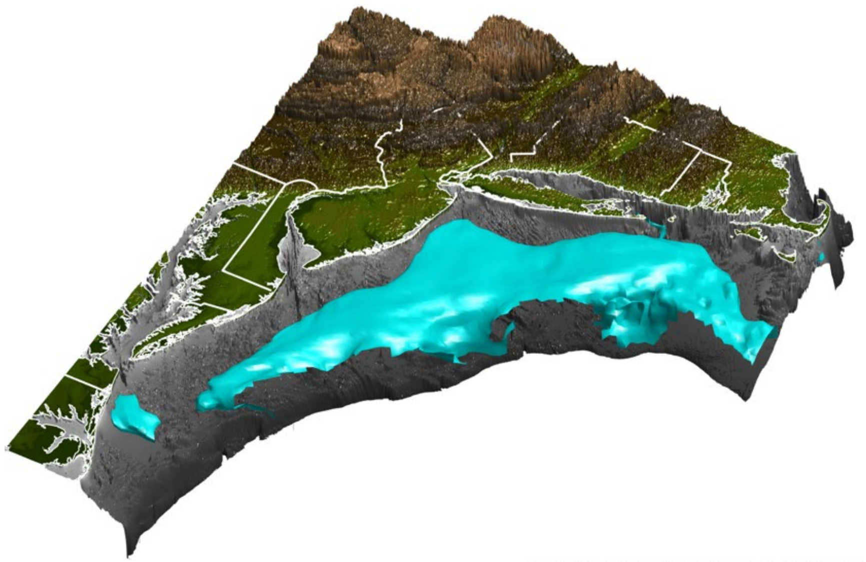
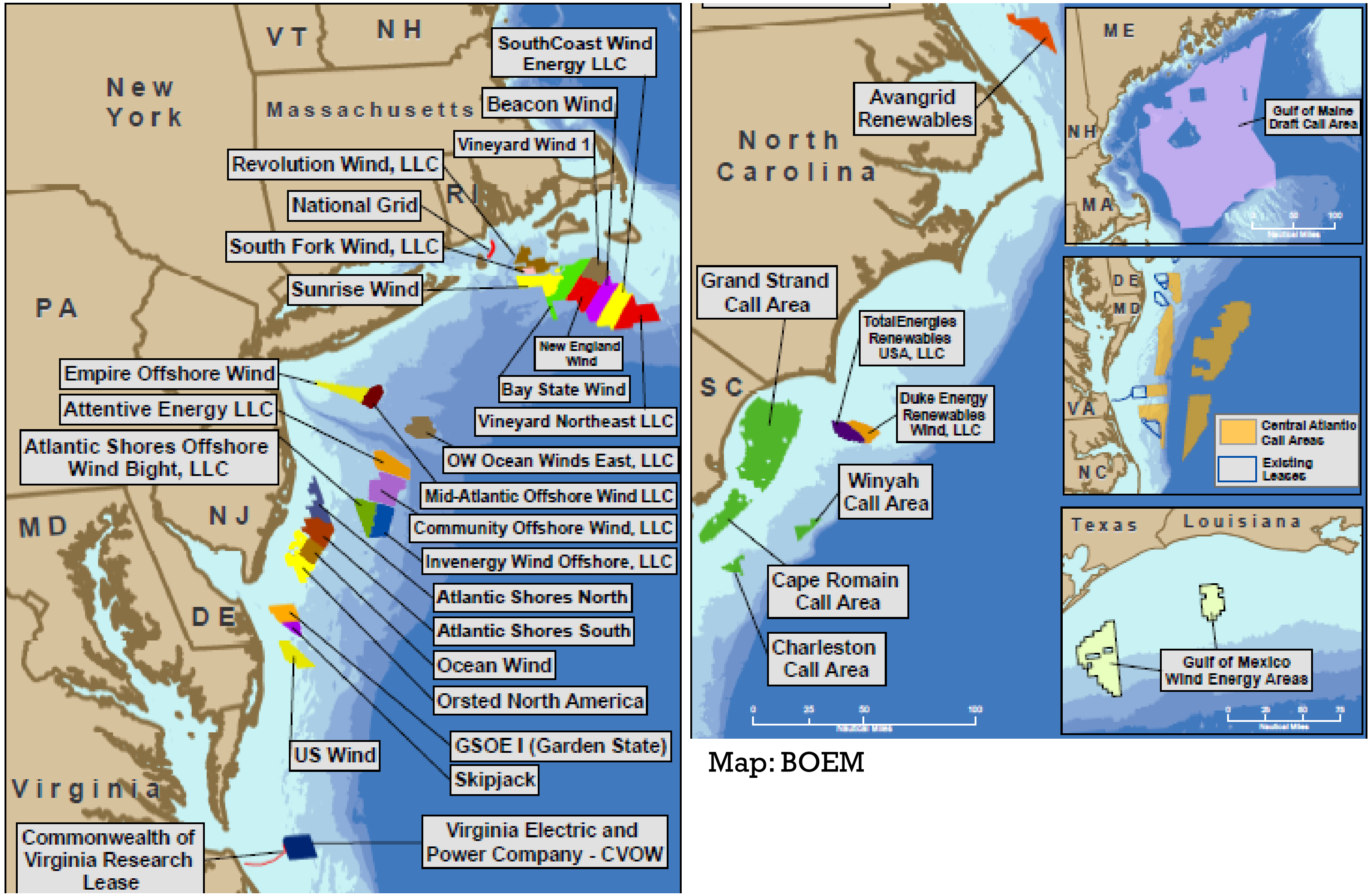


Figure: RUCOOL

Review of Focus Areas

Current Lease Areas



Map: BOEM

NARW Migration

Figure: Smithsonian

Workshop Goals

- Solicit input on the current state of the research
- Explore future research needs and objectives
- Understand the role of industry in achieving these research needs
- No statements will be attributed to individuals; all participant comments will be anonymized

Discussion Topic: Recent and Ongoing Research

- Are there any previously-published studies not accounted for in the current literature list?
- Are there current projects focused on this topic that not yet published?
- How should international experience and research be best applied to the US East Coast?

Discussion Topic: Future Questions

- What are the most critical questions that need to be answered or data gaps that need to be addressed?

- Are there monitoring efforts anticipated for other purposes (e.g., fisheries monitoring) that could be leveraged to inform NARW impacts?

- What is the role of monitoring equipment deployed within the first OSW projects?

Discussion Topic: Future Questions

- How will we differentiate changes that are resulting from OSW development vs. other ongoing changes (e.g., climate change)?

- How do we best utilize resources and avoid unnecessary duplicative efforts?

- What is the role of ongoing modeling as in-situ data becomes available with deployed projects?

Discussion Topic: Industry Involvement

- What role should developers play in needed research? (e.g. funding, technical guidance, data sharing)

- What are some vital guideposts to ensure the independence of research, if funding/guidance is to be provided by developers?

- What is the role of university v. private research organizations for scientific independence?

Other Topics/Concerns

- Any other discussion items?
- Any additional concerns?
- Any further questions?

Thank You!

Questions?

AKRF
Environmental, Engineering,
and Planning Consultants