PAPER

Offshore Wind Energy and the Mid-Atlantic Cold Pool: A Review of Potential Interactions

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ABSTRACT

The U.S. East Coast has 1.7 million acres of federal bottom under lease for the development of wind energy installations, with plans for more than 1,500 foundations to be placed. The scale of these wind farms has the potential to alter the unique and delicate oceanographic conditions along the expansive Atlantic continental shelf, a region characterized by a strong seasonal thermocline that overlies cold bottom water, known as the "Cold Pool." Strong seasonal stratification traps cold (typically less than 10°C) water above the ocean bottom sustaining a boreal fauna that represents vast fisheries, including the most lucrative shellfish fisheries in the United States. This paper reviews the existing literature and research pertaining to the ways in which offshore wind farms may alter processes that establish, maintain, and degrade stratification associated with the Cold Pool through vertical mixing in this seasonally dynamic system. Changes in stratification could have important consequences in Cold Pool setup and degradation, processes fundamental to high fishery productivity of the region. The potential for these multiple wind energy arrays to alter oceanographic processes and the biological systems that rely on them is possible; however, a great deal of uncertainty remains about the nature and scale of these interactions. Research should be prioritized that identifies stratification thresholds of influence, below which turbines and wind farm arrays may alter oceanographic processes. These should be examined within context of spatial and seasonal dynamics of the Cold Pool and offshore wind lease areas to identify potential areas of further study.
Keywords: offshore wind, ocean interactions, Mid-Atlantic Cold Pool

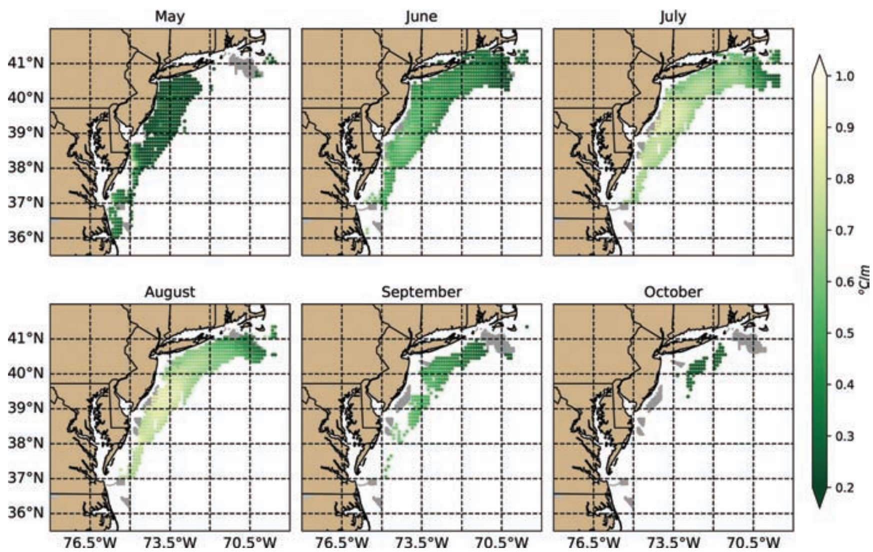
Introduction

Offshore wind development in the Mid-Atlantic has accelerated rapidly, with states stretching from Virginia to Massachusetts making firm commitments to solicit offshore wind and advance their renewable energy goals. These goals include an estimated 22 GW of cumulative installed wind capacity in the Mid-Atlantic Bight (MAB) in the next decade (Bureau of Ocean Energy Management, 2020). Due to these expectations, it is vital that the relationships between offshore wind and the Mid-Atlantic physical and ecological environment be thoroughly explored and understood, particularly how offshore wind development may influence the seasonal cycle of stratification in the region that leads to the formation, maintenance, and eventual breakdown of a Cold Pool of bottom water unique to the region.

The MAB is bounded by Cape Cod, Massachusetts, to the north and Cape Hatteras, North Carolina, to the south and is intersected by the Hudson Shelf Valley extending from the mouth of the Hudson River out to the continental shelf break (Figure 1). The physical oceanography of this region is influenced by local topography, freshwater input from the large watersheds that empty through multiple rivers and estuaries, shelf-break canyons, large-scale atmospheric patterns over the North Atlantic, and tropical or winter coastal storm events. Ocean characteristics in this region undergo remarkable variability across time scales from days and weeks to seasons, years, and decades. As the United States embarks on the development of offshore wind energy installations with expected lifetimes of two to three decades on ~1.7 million acres of leased federal ocean bottom, these time scales of variability and the processes underlying them must be carefully considered. In this literature review, we detail the background oceanographic and ecosystem conditions of the MAB, with a particular focus on the seasonal Cold Pool and its stratification. We then review the state of the science on wind farm interactions with local oceanography, primarily focused on Europe where the majority of studies have been carried out. Finally, we provide context on how these previous studies relate to the local oceanography of the MAB, as well as Cold Pool setup, maintenance,

FIGURE 1

Average spatial extent of the Cold Pool by month, with currently leased offshore wind areas in gray. Plotted pixels indicate locations where bottom water is <10°C, and each pixel's maximum vertical thermal stratification (dT/dz) exceeds 0.2°C/m. Color saturation scales with more yellow colors indicate larger dT/dz or more vertical stratification. Data are the mean of 2005–2012 Northwest Atlantic Regional Climatology at 1/10° resolution accessed from the World Ocean Atlas.



and breakdown, ending with recommendations for future research.

Background

Regional Oceanography and Ecology

Seasonally, the Mid-Atlantic region experiences one of the largest transitions in stratification in our global ocean, from the cold well-mixed conditions in winter months to one of the largest top-to-bottom temperature differences in the world in summer (Castelao et al., 2010; Houghton et al., 1982). In late spring and early summer, a strong thermocline develops at ~20-m depth across the entire shelf, isolating a continuous mid-shelf "Cold Pool" of water that extends from Nantucket to Cape Hatteras (Houghton et al., 1982). Local river discharge can augment this thermal stratification across most of the shelf (Chant et al., 2008) and provides pulses of nutrients and other materials to the MAB. These riverine inputs are only a fraction of the supply from upstream sources delivered by a mean southwestward flow along the shelf (Fennel et al., 2006). In addition, upwelling along the coast occurs annually each summer. It is driven by southwest winds associated with the Bermuda High (Glenn & Schofield, 2003; Glenn et al., 2004). Local upwelling can transport Cold Pool water all the way inshore and to the surface near the coast (Glenn et al., 2004). This upwelled water can drive development of very large phytoplankton blooms that are advected offshore near the surface by wind (Shah et al., 2015). The Cold Pool is highly dynamic over its annual lifespan and among years (Chen & Curchitser, 2020), experiencing significant changes in stratification, with peak stratification occurring in summer and with weaker stratification occurring during its formation and breakdown in spring and fall. Additionally, the isolated volume of cold bottom water shifts location, predominately moving southwestward along the shelf as it slowly warms through the season (Houghton et al., 1982).

Seasonal Cold Pool evolution is central to structuring the MAB ecosystem. Intense ocean variability drives an equally variable ecosystem, from primary producers (Malone et al., 1988) to highly migratory fisheries throughout the region. The Cold Pool sustains a fauna whose range extends farther south than would be anticipated by its latitude and supports vast fisheries, including the most lucrative shellfish fisheries in the United States (Murray, 2016; National Marine Fisheries Service [NMFS], 2020). The region is highly productive, notably supporting the largest non-symbiotic clams on ocean shelves anywhere in the world and the second most lucrative single-species fishery, sea scallops, in the western Atlantic Ocean. The Cold Pool also regulates migratory behavior of fish that constitute the most important finfish fisheries in this region.

The shellfish resources that occupy the bottom along the Mid-Atlantic shelf are among the most important commercial fisheries in the United States, accounting for nearly 80% of the fisheries revenue in the Mid-Atlantic. Atlantic sea scallop (*Placopecten magellanicus*) is the second most valuable single-species fishery in the United States, worth over $523 million in 2018 (NMFS, 2020), and the Mid-Atlantic commercial clam fisheries for Atlantic surf clam (*Spisula solidissima*) and ocean quahog (*Arctica islandica*) are stable, year-round fisheries that land the second largest catch (by mass) in the region. Like many other species, these bivalve shellfish stocks are highly dependent on the unique oceanography of the Mid-Atlantic that is dominated by strong stratification and the Cold Pool.

Analysis by the NMFS Climate Vulnerability Assessment ranked sea scallops, surf clams, and ocean quahogs particularly high in terms of overall climate vulnerability in the face of anticipated future changes in temperature, ocean acidification (OA), and benthic habitat (Hare et al., 2016). The fisheries for these three stocks have likewise been identified as being the most vulnerable to loss due to user conflicts with offshore wind energy development (Kirkpatrick et al., 2017). Atlantic sea scallop habitat may be vulnerable on two fronts; summer maximum bottom temperature limits their inshore distribution, and the offshore extent of the distribution is probably limited by high recruit predation by sea stars (*Astropecten americanus*) (Hart, 2006). Sea stars exist in deep water, and their onshore distribution is limited by winter minimum bottom temperatures (Hart, 2006). Under this scenario, increased water temperatures by way of reductions in size and/or warming of the Cold Pool itself would result in a contraction of sea scallop habitat in the MAB with summer maxima isotherms moving offshore and winter minima isotherms moving inshore. This situation could have reverberating consequences to this highly valuable commercial resource. Changing bottom water conditions and consequent thermal stress have already been linked to observed changes in the fishable range of surf clams over the past two to three decades (Munroe et al., 2016; Narváez et al., 2015). Any future changes in timing, duration, or location of the Cold Pool, whether due to changing climate or by interactions with offshore wind farms, could have critical consequences for these important shellfish stocks (Kirkpatrick et al., 2017).

Commercially and recreationally important demersal fish species also use Cold Pool habitat in various parts of their life history. Yellowtail flounder (*Limanda ferruginea*), winter flounder (*Pseudopleuronectes americanus*), summer flounder (*Paralichthys dentatus*), windowpane (*Scophthalmus aquosus*), witch flounder (*Glyptocephalus cynoglossus*), fourspot flounder (*Paralichthys oblongus*), black sea bass (*Centropristis striata*), tautog (*Tautoga onitis*), goosefish (aka monkfish, *Lophius americanus*), spiny dogfish (*Squalus acanthias*), and several skate species (*Rajidae*) are all economically important species that depend on bottom water conditions that are often linked to the Cold Pool. Summer flounder use bottom habitats for feeding and spawning during winter. The species is important as a commercial fishery and is critical to the small boat and shore-based recreational fishery (Morson et al., 2017; Terceiro, 2016). They make cross-shelf migrations out to spawning grounds and back to estuaries annually, the timing of which varies and is tightly linked to local weather and water temperature events (Sackett et al., 2007, 2008). Winter flounder exhibit an inverse migration to that of summer flounder, largely spawning in coastal estuaries in winter. Yet, a small part of the population remains on the shelf to spawn, and that contingent is becoming increasingly important to reproduction as water temperature shifts (Able et al., 2014; Coleman, 2015). Yellowtail flounder, winter flounder, summer flounder, fourspot flounder, and windowpane are all found on sandy bottom in scallop beds (Grothues et al., 2017). The scallop beds, especially those in the region of the Cold Pool, are important nursery grounds for yellowtail flounder juveniles. The overall distribution of yellowtail flounder can vary greatly in response to the presence and strength of the Cold Pool (Sullivan et al., 2000, 2003, 2005, 2006).

The tight coupling between the Cold Pool ocean conditions and the behaviors, distribution, and habitat preference of so many commercially and recreationally targeted species highlights the fundamental importance of this unique oceanography to the ecology of this region. Given the spatial overlap of this essential habitat feature and a number of offshore wind energy lease areas (Figure 1), careful consideration must be given to the ways that turbine array fields may interact with seasonal processes underlying Cold Pool formation, maintenance, and breakdown. The potential for these vast offshore wind energy arrays to alter these oceanographic processes and the biological systems that rely on them exists; however, a great deal of uncertainty remains about the nature and scale of these interactions. The goal of this review is to identify what is known about the potential for wind arrays to alter the Mid-Atlantic Cold Pool and to outline key gaps in knowledge about the mechanisms by which wind farms may alter associated oceanographic and ecological processes.

Cold Pool Processes and Seasonality

The Cold Pool is historically defined as the 8°C–10°C or colder bottom water occupied between the 0- and 100-m isobaths from Georges Bank to Cape Hatteras beneath the seasonal thermocline. On average, it is about 35 m thick, representing 30% of the total volume of MAB shelf water (Glenn et al., 2004; Houghton et al., 1982; Pacheco, 1988; Voynova et al., 2013). Although typically defined as a pool of 10°C water, the Cold Pool gradually warms from about 7°C in May to 10°C in September, presumably due to heat fluxes through its surface and lateral boundaries (Lentz, 2017). The Cold Pool develops in the spring of each year, reaches peak volume in early summer (Chen et al., 2018), and is eroded in early fall of each year (Figure 2). Mechanisms proposed for the formation and maintenance of the Cold Pool by Bigelow (1933) and Houghton et al. (1982) suggest that the Cold Pool forms as remnant well-mixed winter water over the shelf, capped by stratification, fresh water runoff, and reduced wind mixing in spring (Lentz et al., 2003). Given these generalizations, the Cold Pool is a highly dynamic feature that varies in size and location within and among years (Figure 1), depending on a variety of oceanographic processes (Chen & Curchitser, 2020).

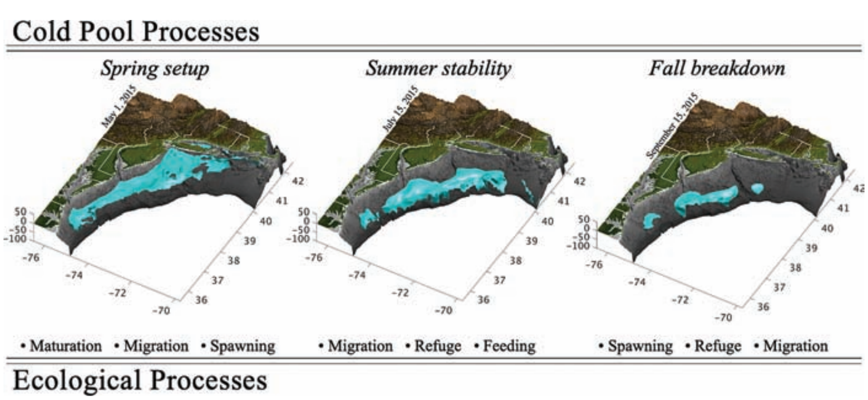
Spring Setup

In winter, MAB shelf water cools, reaching its lowest temperature in late February or early March (Pacheco, 1988). Winter water is well mixed with a weak horizontal gradient towards warmer offshore water, and any weak vertical stratification is due entirely to salinity driven by freshwater input from estuaries along the coast (Castelao et al., 2010). An additional upstream source of MAB shelf water originates in the Northern Labrador Sea and continually transforms as it transits south through the Gulf of Maine before entering the MAB (Chapman & Beardsley, 1989; Fairbanks, 1982; Smith, 1983; Mountain & Manning, 1994; Wallace et al., 2018). As these waters move south over Nantucket shoals, strong tides cause vigorous mixing before this cold denser bottom water spreads south into the MAB along the midshelf at approximately 2 cm/s (Chen et al., 2018). Additional studies indicate this remote supply of cold bottom water from the north helps to maintain and enhance MAB stratification throughout spring and into summer (Brown et al., 2015; Chen et al., 2018; Chen & Curchitser, 2020; Fairbanks, 1982). Throughout the spring setup, the Cold Pool interacts with adjacent water masses including the warmer and saltier Gulf Stream water along the offshore edge (Fogarty et al., 2007; Wallace et al., 2018).

The Cold Pool forms between late March and May as surface heat fluxes increase and wind mixing from storm activity is reduced (Bigelow, 1933; Castelao et al., 2010; Houghton et al., 1982). During this time, a stratified water column develops with a warm and shallow near-surface layer that caps off the cold bottom water (Chen & Curchitser, 2020). The onset of vernal warming is irregular across the MAB and can be complicated by the cold and warm water intrusions summarized above (Pacheco, 1988). Nearly half of the annual freshwater runoff in the MAB occurs in spring, which can further intensify the development of stratification (Castelao et al., 2010; Houghton et al., 1982; Pacheco, 1988). At its offshore edge, the Cold Pool is bounded by warmer, saltier slope water and the shelf-break jet, a narrow southward-flowing current along the edge of the continental shelf (Flagg et al., 2006; Lentz, 2017; Linder & Gawarkiewicz, 1998).

FIGURE 2

A schematic representation of the seasonal stages of the MAB Cold Pool and examples of the timing of local ecological processes. Three-dimensional representations of the Cold Pool were derived by extracting the 12°C isotherm from the Regional Ocean Modeling System (ROMS) DOPPIO domain (López et al., 2020).



Peak Summer Stability

Through summer, the thermocline strengthens as a result of surface heating and freshwater runoff, reaching a seasonal peak in July or August (Castelao et al., 2010). At this peak, the average density difference across the pycnocline is as large as 4 kg/m^3 (Castelao et al., 2010), and surface-to-bottom temperature differences reach approximately 10°C (Lentz, 2017). From July to October, rapid warming of the Cold Pool occurs over Georges Bank, and more gradual warming occurs in central and southern MAB (Bigelow & Schroeder, 1953; Houghton et al., 1982; Lentz, 2017) due to heat fluxes across its surface and lateral boundaries (Benway & Jossi, 1998; Chen, 2018; Lentz, 2017). Near the 60-m isobath, maximum bottom temperatures are not reached until mid-November; however, warming is faster in shallower water due to a vertical turbulent heat flux from the thermocline to the Cold Pool (Lentz, 2017). Here, seasonal heating extends to the bottom, and maximum bottom temperatures can be reached in September. In general, the northern extent of the Cold Pool retreats 2.6 times faster than the southern extent due to horizontal advection of upstream warm water in Georges Bank and downstream advection at the southern edge (Chen, 2018).

Throughout this stable summer Cold Pool peak, it is repeatedly acted on by wind events, gulf stream rings, bathymetric features, convective and advective mechanisms, and seasonal and interannual variations (Pacheco, 1988). Under this extreme summer stratification, the Cold Pool is a relatively slow-moving feature with a long-term average flow in a season of 1–3 cm/s southwestward in the alongshore direction. Throughout this slow migration down the shelf, the Cold Pool position varies in response to surface wind forcing. This movement can lead to seasonal ocean events along the coast. As an example, along shore winds will force the Cold Pool to slosh back and forth between the coast and shelf break. Movement toward the coast is called upwelling (driven by southwesterly winds), and movement away from the coast toward the shelf break is called downwelling (driven by northeasterly winds). Typical summer winds are either from the northeast (downwelling favorable) or southwest (upwelling favorable.). During summertime periods of persistent upwelling favorable wind conditions, the Cold Pool is advected towards the coast as the surface layer moves offshore. In addition to being low temperature, these subsurface Cold Pool waters are nutrient enriched (Voynova et al., 2013). Their advection coastward stimulates rapid phytoplankton growth as nutrient-rich waters upwell toward the surface and are exposed to sunlight sustaining high primary production. The shoreward edge of the Cold Pool during the oscillations between upwelling and downwelling winds in the summer moves the onshore edge of the Cold Pool from the coast to as far as 75 km offshore on time scales of days to weeks (Glenn et al., 2004). The occurrence of upwelling events is modulated by wind forcing, the location of the Cold Pool, the strength of coastal river plumes, and the occurrence of downwelling favorable winds during summer storms. In addition, following colder winters, the most significant upwelling events have been observed suggesting severe cooling may result in a larger and/or colder Cold Pool (Glenn et al., 2004).

Fall Breakdown

During the fall, an increase in the frequency of strong wind events and decreasing surface heat over increasingly shorter daily daylight hours shifts the balance between heat input and vertical mixing, resulting in a reduction in stratification, ultimately breaking down the Cold Pool (Bigelow, 1933; Castelao et al., 2010; Gong et al., 2010; Lentz, 2017; Lentz et al., 2003). In late summer, the thermocline deepens near the coast and begins mixing downward, increasing bottom temperatures (Pacheco, 1988). Reductions in stratification can also be induced through internal wave breaking in the region of the pycnocline (Lentz et al., 2003; MacKinnon & Gregg, 2005). Each successive storm weakens thermal stratification, reducing stability and allowing for more mixing until it becomes vertically uniform at 10°C–15°C and the seasonal Cold Pool disappears. This breakdown typically occurs within ~1 month after surface temperatures reach a maximum near the end of summer (Ketchum & Corwin, 1964). Recent work has identified the importance of fall transition storms that can rapidly mix the water column. Late-season tropical storms or extra-tropical cyclones, often referred to as fall transition storms, can lead to abrupt erosion of the Cold Pool over a few days or even hours depending on storm strength and remaining water column stability (Glenn et al., 2016; Seroka et al., 2016). Therefore, timing of Cold Pool breakdown varies significantly each year and has been documented to occur anytime from mid-September to November (Bigelow, 1933; Chen, 2018; Lentz, 2017; Lentz et al., 2003; Pacheco, 1988).

Ecological Links to the Seasons of the Cold Pool

These Cold Pool "seasons" of spring setup, summer stability, and fall breakdown are themselves associated with and drivers of important biological and ecological processes that support key species of commercial and recreational importance. As an example, surf clam growth is not uniform over the year, and their growth and survival are tied to sustained periods of Cold Pool stability through the summer. Mortality events in surf clams have been linked to earlier-than-normal breakdown of the Cold Pool, which mixed warm water to the bottom (Narváez et al., 2015). In ocean quahogs, reproductive condition increases from early summer through fall, with heaviest spawning coinciding with Cold Pool breakdown in the fall (Jones, 1981; Mann, 1982). Altered timing of mixing and Cold Pool breakdown could lead to changes in spawning timing for this species and possible larval match-mismatch conditions (Toupoint et al., 2012).

Interannual and Decadal Variability

The Cold Pool exhibits significant variability year to year in persistence, time, volume, temperature, spatial distribution, and southward progression (Chen, 2018). The Cold Pool typically reaches its minimum temperature in early spring to early summer depending on its geographic location (Pacheco, 1988). Off southern New England, the Cold Pool minimum is 1.1°C–3.3°C in mid-March and the maximum is 11.6°C–13°C in November, for a difference of ~13°C. Off New York, the minimum is 3.8°C–4.7°C in early June and the maximum is ~13°C in November, for a difference of ~9°C (Chen, 2018). Interannual temperature variability is driven by differences in warming/cooling from the initial temperature in the spring and horizontal advection during the summer. At its maximum, this variability can lead to a Cold Pool that persists from April to October and has a colder minimum temperature, and the core travels further south at a faster rate (2.1 m/s) (Chen, 2018). Conversely, in years with warm initial temperatures and low southward cold water advection, the feature persists from early April through August, the volume is a third of the size of a peak year, the minimum temperature is 2°C warmer, and the core travels at a slower rate (1.5 cm/s) (Chen, 2018).

There is also evidence of interannual variability in the seasonal duration of the Cold Pool. Maximum bottom temperatures are reached when vertical stratification is destroyed, and the Cold Pool breaks down in the fall. The rate of surface cooling during autumn varies locally and with the strength of the wind and roughness of the sea (Pacheco, 1988). Additionally, during Cold Pool setup in spring, vernal warming is spatially non-uniform, begins in late February or early March, and can be complicated by cold and warm water intrusions. For example, in 1979, steady warming persisted until the end of October when onshore movement of warmer slope water warmed the near-bottom shelf water leading to a slower Cold Pool formation in the spring (Wright, 1983). In 1996, on September 6, Hurricane Edouard resulted in vertical mixing throughout the water column leading to an early Cold Pool breakdown (Dickey et al., 1998; Lentz et al., 2003; Williams et al., 2001).

Over longer time scales of variability, global climate models predict the North-West Atlantic continental shelf will have a general warming trend (Intergovernmental Panel on Climate Change [IPCC] fifth assessment; Saba et al., 2016), suggesting substantial changes to the structure of the MAB ecosystem (Chen, 2018). MAB water column warming is primarily driven by the atmosphere, both of which have experienced accelerated warming since the 1970s (Wallace et al., 2018). Over four decades, Wallace and colleagues observed MAB warming rates of 0.57°C per decade during the winter and spring (January to April) and 0.47°C per decade during the fall and winter (September through December) (Wallace et al., 2018). More significant temperature increases were observed in the winter and spring in the southern MAB from 1977 to 1999. Higher overall rates of warming were experienced for MAB waters than shelf waters due to offshore heat flux. The MAB water column experienced greater warming compared to atmospheric warming possibly due to advection of warmer water into the MAB from upstream locations, which experienced amplified atmospheric temperature increase. The warming experienced in the Gulf of Maine and Georges Bank was half the rate of the MAB. From 1977 to 2013, Forsyth et al. (2015) found that depth-averaged shelf temperature off New Jersey increased at 0.26°C ± 0.01°C per decade with accelerated warming in the last decade. Mountain (2003) observed that shelf water of the MAB in the 1990s was approximately 1°C warmer, 0.25 PSU fresher, and 1,000 km^3 more abundant than during the 1977–1987 period. Long-term changes in the physical state of the MAB Cold Pool and surrounding regions will impact marine ecosystems along the east coast as there is growing evidence of interannual to decadal shifts in both MAB ecology associated in part with thermal habitat preference and systematic changes in temperature (Lentz, 2017; Wallace et al., 2018)

Interactions Among Wind Farms and Ocean Physics

The effects of offshore wind turbines on near–sea-surface winds and on the underlying ocean have been observed from both satellite remote sensing and in-situ measurements. Though limited in their ability to capture both temporal and spatial variability or the full range of ocean and atmospheric conditions, they have identified that turbines induce downstream impacts on ocean velocities, turbulence, and stratification. Satellite remote sensing from synthetic aperture radar (SAR) has revealed near–sea-surface wind speed deficits (Christiansen & Hasager, 2005; C. Li et al., 2013; Hasager et al., 2015) ranging from 8% to 24.4% within 5–20 km from turbines under some wind conditions. Satellite remote sensing observations have additionally been used to identify sediment resuspension in wind farm wakes near the Thames Estuary (Vanhellemont & Ruddick, 2014), with enhanced suspended particulate matter concentrations within a few kilometers of a series of offshore wind farms. A study of drifter releases (Callies et al., 2019) within a wind farm in the German Bight showed an increase in horizontal dispersion of drifter pairs within the wind farm area, though the numbers released were too limited to draw clear conclusions on the impact of the foundations compared to other coincident factors. A study by Floeter et al. (2017), also in the German Bight, included in-situ surveys with a towed research platform. They found indications of "doming" of isotherms and weaker stratification within the offshore wind farm suggesting enhanced mixing; however, similar conditions were observed prior to turbine installation, highlighting the difficulty in disentangling complex circulation and seasonal patterns from wind farm impacts. A recent study by Schultze et al. (2020) included both in-situ observations of monopile wake effects and numerical modeling. Their in-situ measurements identified a disturbed region 70 m wide and 300 m long in the wake of a single turbine during weak stratification (0.5°C surface-to-bottom temperature difference). During stronger thermal stratification (~3°C surface-to-bottom temperature difference), no clear turbulent wake or disruption to stratification was detected.

While still limited, there is an increasing body of research focused on the specific processes that describe the interaction between offshore wind turbines and underlying ocean conditions, at scales ranging from individual turbines to entire wind farms. These studies generally fall into three categories, including (1) turbulence generated by turbine foundations, (2) wind extraction reducing surface wind stress and altering water column turbulence, and (3) wind farm wake-driven divergence and convergence driving upwelling and downwelling. All of these categories of impact, discussed further in the following paragraphs, could influence ocean mixing and, in turn, stratification that is a key characteristic of the MAB Cold Pool. The net impact of offshore wind farms on ocean stratification is dependent on the relative contribution of these three processes and potentially other currently unknown processes in a particular wind farm facility.

Several laboratory (Miles et al., 2017a) and numerical modeling (Carpenter et al., 2016; Cazenave et al., 2016; Schultze et al., 2020) studies have been carried out to investigate the influence of turbines on ocean turbulence and stratification. Generally, these studies have focused on monopile structures and shown decreased ocean velocities and increased turbulence extending a few hundred meters from the structure. The amount of increased turbulence, and its extent, is highly dependent on ocean currents with faster ambient velocities resulting in more intense turbulence extending further from the foundation.

A laboratory study by Miles et al. (2017b) showed a peak in turbulence within 1 monopile diameter and that downstream effects (more than 5% of background) persisted for 8–10 monopile diameters. Schultze et al. (2020) utilized highly resolved large Eddy simulations (LESs) to study impacts of wind turbines on turbulence under a variety of stratification conditions. They found turbulent effects were concentrated within the first 100 m in the wake of the turbine for all cases and impacts on ocean temperatures and stratification varied across cases. Similar to their observed field results discussed above, more ocean cooling and vertical mixing were observed under weak stratification than under strong stratification cases. Overall, they indicate that turbine-induced mixing may locally account for an additional 7%–10% mixing above typical bottom boundary layer mixing processes for their application. Carpenter et al. (2016) take an alternate approach with a simplified monopile mixing parameterization to estimate the impact on the duration of typical North Sea seasonal stratification if only turbine-induced processes were present. They show that adjusting a variety of parameters in their model setup can lead to seasonal stratification duration ranging from 37 to 688 days. Stratification durations in the North Sea are typically near 80 days, highlighting the large uncertainty between findings of significant versus limited impacts based on model assumptions. Additionally, Carpenter et al. (2016) assume that wind farms fill the entire sea and 1-dimensional mixing processes are felt everywhere rather than focusing on a single limited wind farm area. When they include advection estimates that would replenish stratification, they find that these replenishing forces can occur on timescales of ~4 days, effectively counteracting the effect of mixing when wind farm areal coverage remains small relative to the shelf region. Cazenave et al. (2016) attempt to bridge the gap between single-turbine simulations and wind farm scale models. To do this, they used an unstructured grid model (Finite Volume Community Ocean Model [FVCOM]) in both idealized and realistic configurations with refined resolution near turbine monopiles. Cazenave et al. (2016) found similar results to the above studies (Carpenter et al., 2016; Miles et al., 2017a; Schultze et al., 2020) when focusing on single turbines and, when scaled up to a realistic wind farm in the Irish Sea, found localized reductions in stratification of between 5% and 15%.

A significant body of research exists focused on wind speed deficits and turbulence within wind turbine wakes from near the ocean surface up to turbine hub height. Observations from satellite SAR (Christiansen & Hasager, 2005; Hasager et al., 2015; X. Li et al., 2014) have identified near–sea-surface wind speed deficits behind turbines up to 25% within 20 km of turbines for select time periods under stable atmospheric boundary layers. Aircraft-based measurements with scanning lidar (Platis et al., 2018) identified reductions in wind speed typically within 10 km of the turbine. However, maximums of 40% reductions in wind speed up to 70 km from the turbine were observed. These observations were taken during moderate wind conditions with a stable boundary layer over the German Bight. Ground-based measurements from dual-Doppler instruments showed wind wakes extending 17 km off the coast of the United Kingdom (Nygaard & Newcombe, 2018). An in-situ observational study of an offshore wind turbine wake was published by Barthelmie et al. (2003). They observed velocity deficits of between 10% and 30% at a height of 40 m over the course of 36 surveys with measurement distances of over 7 rotor diameters. While these studies, among others, have captured wind turbine wake-induced deficit in wind velocity, few have captured the impact on the underlying ocean and its vertical stratification.

Numerical modeling studies on this topic have used idealized ocean and atmospheric models to simulate impacts of wind turbines' (individual) and farms' (collective) wind deficits on the ocean environment. Along with observational studies, findings are that wind turbines will reduce wind speeds and resultant wind stresses at the sea surface. These reduced sea surface stresses can reduce vertical ocean mixing and lead to a more stable water column (Afsharian & Taylor, 2019). However, additional impacts on the underlying ocean have been simulated. A study by Nagel et al. (2018) showed that wind turbines can generate eddies that disturb the underlying sediment during unstratified conditions. Paskyabi (2015) showed that coastal upwelling dynamics can be modified by wind farm wakes due to changes in horizontal pressure gradients. A series of papers (Broström, 2008; Ludwig et al., 2015; Paskyabi & Fer, 2012) have also simulated impacts of increased horizontal wind shear, due to local reductions in surface wind stress. In their model simulations, increased wind shear alters the wind stress curl and can induce a significant (10s of meters per day) upwelling and downwelling on either side of the wind wake, respectively. However, this dipole effect is found in simulations of large wind farms with a singular farm-scale wake but has not been observed in the field, and results are less clear when simulations are performed at higher resolutions with individual turbine wakes. A study by Segtnan and Konstantinos (2015) performed a sensitivity test with two different wind farm designs for a potential wind farm off Havasu, Norway, showing enhanced upwelling and downwelling in a region that already experiences strong topographically driven upwelling and downwelling during a strong wind event.

The studies detailed above provide evidence of disturbances to both atmosphere and ocean processes from a combination of wind farm turbines and foundations. Some impacts may increase mixing, and other may limit mixing. These impacts have been captured in a variety of field observations as well as realistic and idealized numerical modeling studies. However, it is abundantly clear that the particular processes and magnitudes of these impacts vary widely based on study site, wind speed conditions, turbine size, farm size and orientation, and underlying oceanographic and atmospheric conditions. These studies are summarized in Table 1 including study type, focus, wind turbine and farm characteristics, and hydrographic conditions. While a broad set of studies have been carried out, in the following sections, we seek to place these studies in the context of the MAB region, with a particular focus on interactions with the summer Cold Pool.

TABLE 1

Literature review summary.

	Study	Power (MW)	Foundation Diameter (m)	Hub Height (m)	Rotor Diameter (m)	Number of Turbines	Stratification Range (kg/m^3)/m
Offshore wind wakes	*Christiansen & Hasager, 2005; Li et al., 2013;* ***Hasager et al., 2015****;* ***Platis et al., 2018****; Nygaard & Newcombe*, 2018; *Barthelmie et al., 2003*	0.45–6.15	–	38–106	36.5–154	11–140	–
Wind wake–ocean interactions	Broström, 2008; ***Ludwig et al., 2015***; Paskyabi & Fer, 2012; Paskyabi, 2015; Afsharian & Taylor, 2019; Nagel et al., 2018; *Callies et al., 2019*; **Segtnan & Konstantinos, 2015**	2–wind deficit	–	70 -120	42–120	1–farm	~0–2.2
Foundation ocean interactions	*Vanhellemont & Ruddick, 2014*; *Floeter et al., 2017*; Miles et al., 2017a; *Schultze et al., 2020*; *Carpenter et al., 2016*; ***Cazenave et al., 2016***	–	5–7 m	–	–	1–175	~0–3.1

This table presents many of the studies reviewed in this paper categorized by their focus (offshore wind wakes [atmosphere only], wind wake–ocean interactions, and foundation ocean interactions). It also summarizes the type of study, with italicized text denoting an observational study, bold text denoting a realistic modeling study, and underlined text denoting an idealized modeling study. Columns provide approximate estimates of the ranges of wind turbine types, farm sizes, and hydrographic conditions studied in each category. There are very limited common metrics throughout these studies, particularly for stratification ranges, which commonly use only temperature, density, or a derived potential energy anomaly. Where possible, we have approximated stratification ranges in terms of the vertical density gradient ranges; however, these values should be used cautiously, and individual studies should be reviewed on their own merits.

Wind Farm Impacts on the Cold Pool

The majority of studies that explore the processes that link offshore wind turbines to ocean mixing were carried out or simulated to represent coastal waters around Northern Europe. This region is, at the time of writing, home to some of the most extensive offshore wind farms globally. It is important to consider the oceanographic conditions specific to these study sites when applying the results described above in the section on Interactions Among Wind Farms and Ocean Physics to the MAB Cold Pool described in the section on Regional Oceanography and Ecology. Specifically, stratification used in studies of the German Bight (Carpenter et al., 2016; Schultze et al., 2020) and in the eastern Irish Sea (Cazenave et al., 2016) is much less than the peak stratification seen in summer over the MAB. However, it is much more representative of relatively weaker stratification seen during Cold Pool formation and breakdown in spring and fall. Therefore, results from the German Bight studies characterizing potential impacts of offshore wind facilities on stratification are likely more representative of impacts we might expect from offshore wind facilities on the Cold Pool during the relatively weaker stratified time periods in spring and fall (Figure 1). During the highly stratified summer months, it is less likely that the structures will induce mixing sufficient to overcome the strong stratification and impact of Cold Pool integrity or the broad exchange between the surface and bottom water layers.

Local and cumulative impacts must also consider the potential for impacts on Cold Pool processes during time periods of reduced stratification in spring and fall. Flow on many continental shelves in Europe is dominated by strong tidal currents, which can be as high as 1 m/s. In contrast, in the southern and central MAB, tidal currents are significantly weaker (~0.1 m/s; Brunner & Lwiza, 2020), with mean currents driven by winds and large-scale pressure gradients of between 0.1 and 0.2 m/s (Roarty et al., 2020). The northern MAB off of Georges Bank experiences larger tidal currents and amplitudes more similar to those found in Europe, highlighting potential regional differences in ocean responses. Tropical cyclones or winter storms can lead to faster current speeds approaching those found in Europe from tidal forcing; however, these storm events are intermittent and have a limited duration compared to persistent tidal forcing. Turbulence and mixing scales non-linearly with flow speed; for flow around foundations, turbulence and mixing scales with the cube of the water velocity (Carpenter et al., 2016). This suggests that even marginally slower ocean velocities in the southern MAB past foundations and structures could result in significantly less mixing than has been found in Europe, while faster currents in the northern MAB may produce similar mixing. Just as the MAB ambient current velocities and stratification are different from studies in Europe and beyond, it is important to note the atmospheric environment is also different and similarly uncertain. A recent study (Bodini et al., 2019) observed a highly stable and low-turbulence atmospheric boundary layer from a lidar located off Massachusetts in the MAB. However, a prior study (Archer et al., 2016) within Nantucket Sound showed predominantly unstable conditions. An unstable atmosphere would suggest that wind wakes will not extend significant distances from turbines, while a more stable atmosphere would extend the range of turbine influence. As the regional atmospheric research continues to evolve, further studies of the impact on the underlying ocean must also be carried out.

Wind Farm Overlap With the Cold Pool

The dynamic nature of the MAB leads to high variability that significantly impacts the strength and location of the Cold Pool. Given the dynamic nature of this ocean feature in time and location, overlap with offshore wind areas and their potential impacts on the Cold Pool will also vary. Figure 1 demonstrates the seasonal progression of the Cold Pool and, in conjunction with Table 2, demonstrates the duration of overlap with many planned wind energy areas. In late spring to early summer, the Cold Pool reaches its largest spatial area extending from the nearshore out toward the shelf break. During this period, the likelihood of overlap with coastal lease areas is more likely. During the summer as the stratification above the Cold Pool reaches its maximum (Figure 1), it can slosh back and forth across the shelf, subject to the overlying winds. Therefore, during this time of year, the overlap with offshore wind facilities, as currently planned, will be more variable and dependent on the wind forcing, with southwesterly winds driving the Cold Pool offshore and northeasterly winds driving the Cold Pool onshore. In fall, stratification begins to weaken as the Cold Pool breaks down beginning in the southern MAB. Typically, during this time of year, the Cold Pool is located further from the coast, limiting the potential interaction with the offshore wind facilities. It should be noted that the maps illustrating this typical seasonal movement of the Cold Pool are based on a modeled climatology. Interannual and within-season variability can significantly alter the average conditions discussed here.

Potential Influence of Offshore Wind on the Cold Pool

During summer, the strong thermocline isolates the Cold Pool from the surface and provides important thermal refuge for many species of the MAB. Wind farm structures may have an impact on the stratification during these summer months by mixing nutrient-rich Cold Pool water to the surface, promoting primary productivity. It should be noted that this mixing occurs in the absence of offshore structures, not only leading to summer phytoplankton blooms but also slowly warming the Cold Pool over the summer months as it

TABLE 2

Percentage of cold pixels (temp ≤ 10°C and dT/dz ≥ 0.2°C/m) out of the total number of ocean pixels in each lease area shown in Figure 1.

Percentage of Lease Area Occupied by the Cold Pool							
Lease Areas	**May**	**June**	**July**	**August**	**Sept**	**October**	**Total pixels**
Mass./RI	6.3	91.7	100	72.9	0	0	48
New York	100	100	80	80	20	0	5
New Jersey	89.5	73.7	63.2	68.4	0	0	17
Delaware	60	40	0	0	0	0	5
Maryland	100	66.67	50	16.7	0	0	6
Virginia	11.1	0	0	0	0	0	9
North Carolina	0	0	0	0	0	0	6

Mass., Massachusetts; Sept, September; temp, temperature; RI, Rhode Island.

gradually moves south (Houghton et al., 1982; Lentz, 2017).

During spring when the Cold Pool forms and again in fall when it breaks down, stratification is reduced and is perhaps more susceptible to changes in hydrodynamics due to the presence of wind farm structures. Studies of hydrodynamic effects of offshore wind turbines on seasonal stratification have been done in the German Bight (Carpenter et al., 2016; Schultze et al., 2020). Carpenter et al. (2016) conducted an analysis of the impact of increased mixing in the water column due to the presence of offshore structures on the seasonal stratification of the German Bight. They offer a conclusion that, at the current build, out-of-offshore facilities planned in the German Bight are unlikely to alter seasonal stratification dynamics in that region but could impact the seasonal stratification if the area is developed to a point that wind structures significantly cover the stratified shelf. Additionally, a remaining important research topic is the influence of extraction of wind energy by the offshore turbines on ocean mixing. There is a critical need to understand the influence of large offshore turbines 10s of meters above the sea surface on the wind stress at the ocean surface. This must be quantified to understand the net impact of the turbines on ocean mixing, balancing the loss of wind energy at the ocean surface by the turbines above with the increase in ocean mixing linked to the foundations in the water column below (Carpenter et al., 2016). The balance between potential reduction in ocean mixing due to wind extraction and increase in mixing due to the presence of offshore wind foundations must be assessed specific to what is known about our regional oceanography and relevant turbine specifications, including foundation size and type, hub height, and blade length. If these studies were to be performed, the net influence of the offshore wind facilities on ocean mixing could be assessed through the seasonal changes of the Cold Pool and considering both individual wind farm impacts and cumulative impacts across multiple offshore facilities.

To consider the cumulative impacts, it is important to adapt analyses of offshore wind facilities in other coastal regions to the conditions specific to the Mid-Atlantic Cold Pool. Additionally, as stated earlier, it is important to consider the impact on the evolution of the Cold Pool throughout its annual cycle, including its shifting location and evolving stratification. How will the cumulative impact of multiple offshore facilities impact seasonal dynamics of the Cold Pool? During the less stratified time periods in spring and fall, when the Cold Pool forms and breaks down, it is perhaps more susceptible to alterations in water column mixing associated with the structures. Cumulative impacts given multiple wind facilities throughout the region should consider the impact of these structures on the seasonal stratification associated with the Cold Pool throughout its annual lifespan from formation in spring through peak stratification in summer to breakdown in fall. How local are these impacts expected to be? What amount of development would lead to larger scale impacts on stratification as stated in Carpenter et al. (2016)? Will the presence of structures alter mixing enough to change the Cold Pool duration either through earlier or later formation in the spring or breakdown in the fall (Pacheco, 1988)? What impact will this altered timing (if any) have on migration or dynamic habitat of commercially and ecologically important species? It will be critical to consider these unique aspects of the Mid-Atlantic Cold Pool when applying the results of studies based on ocean conditions within the wind energy facilities already deployed throughout Europe (Carpenter et al., 2016; Schultze et al., 2020).

Future Research Priorities

To better understand turbine impacts on seasonal Cold Pool dynamics, the highest priority need is to quantify the impacts of turbine-induced mixing on ocean stratification specific to this region. This priority essentially customizes the prior work detailed above to the specific conditions associated with the MAB Cold Pool throughout its seasonal evolution from formation in spring to its ultimate breakdown each year in fall, the output of which will provide a guide for future impact analysis.

Recognizing that the Cold Pool is highly dynamic in both space and time, temporal and spatial shifts in ocean stratification must also be considered. In the spatial domain, one fundamental question remains: what is the overlap between the Cold Pool and the present (Figure 1) and future offshore wind lease areas? A summary of the Cold Pool overlap with individual lease areas is presented in Table 2. The Cold Pool is an incredibly dynamic feature that undergoes significant variability from its formation in spring to its ultimate breakdown in fall. Throughout this annual lifespan, the Cold Pool changes size and location as it continually interacts with adjacent water masses. Taking advantage of the significant existing knowledge of the Cold Pool and available observations and data assimilative models of the feature, the time-dependent overlap should be determined. In the time domain, the Cold Pool undergoes significant variability in the strength of stratification. Linking the dynamic movement of the Cold Pool throughout the year and from year to year with the changing magnitude of stratification will be a critical step toward a more informed assessment of offshore wind farm influences in the seasonal stratification in this region. At first order, this variability is seasonally dependent with the size, location, and strength of the Cold Pool constantly changing from its formation in the spring to its strengthening in the summer and its ultimate breakdown each fall.

Integrating the output of these research priorities, from the likelihood of impact to the spatial and temporal considerations, will permit site-specific impact assessments. Accounting for the seasonal shift in stratification and the thresholds identified in our first priority above, the seasonally dependent impact can be quantified. Given the seasonally dependent ecology tied to the Cold Pool variability, assessment of the impacts of offshore wind on the Cold Pool can be extended to broader scale ecological impacts.

Conclusion

Physical oceanographic conditions are being considered in impact analyses of offshore wind development off the U.S. East Coast (Bureau of Ocean Energy Management [BOEM], 2020). It is critical to understand that the physical oceanographic processes and their significant variability drive an equally variable ecosystem from the primary producers to the highly migratory fisheries throughout the region. Tight coupling between ocean conditions and habitat preferences of commercially and recreationally targeted species lead to a distribution of essential habitat that can significantly vary from season to season and year to year. In this study, we have summarized relevant physical ocean processes within and around the planned offshore wind energy areas along the Mid-Atlantic coast of the United States. Specifically, we focus particular attention on a unique ocean feature in the MAB, the Cold Pool, that undergoes significant variability throughout its seasonal lifespan and from 1 year to the next. As there are currently no existing utility scale offshore wind facilities deployed in this region, we rely on prior work that examined impacts of ocean processes within facilities throughout Europe. These studies have primarily used models to estimate impacts given ocean conditions common to European wind facilities. In this study, we have translated these studies to the ocean processes specific to the Cold Pool off the Mid-Atlantic coast. In doing so, we have prioritized research needs to advance our understanding of potential impacts to ocean processes specific to the Cold Pool. These priorities are not inclusive of all research topics needed to inform our understanding of potential environmental impacts, but we feel they address the immediate research needs to inform ongoing review and planning activities associated with the emerging offshore wind industry.

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