Investigating the Overlap Between the Mid-Atlantic Bight Cold Pool and Offshore Wind Lease Areas

Rebecca Horwitz
Department of Geology and Environmental Studies
Carleton College
Northfield, USA
hhorwitzb@gmail.com

Travis N. Miles
Center for Ocean Observing Leadership (COOL)
Rugers University
New Brunswick, USA.
tnmiles@marine.rutgers.edu

Daphne Munroe
Department of Marine and Coastal Sciences
Rutgers University
New Brunswick, USA
dmunroe@hsrl.rutgers.edu

Josh Kohut
Center for Ocean Observing Leadership (COOL)
Rugers University
New Brunswick, USA.
kohut@marine.rutgers.edu

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***Abstract*— The Mid-Atlantic Cold Pool is a seasonal mass of cold bottom water that extends throughout the Mid-Atlantic Bight (MAB). The Cold Pool forms from rapid surface warming in the spring and dissipates in the fall due to mixing events such as storms. The Cold Pool supports coastal ecosystems and economically valuable commercial and recreational fisheries along the MAB. Offshore wind energy has been rapidly developing within the MAB in recent years. Studies in Europe demonstrate that existing WEAs can impact seasonal stratification; however, there is limited information on how MAB wind development will affect the Cold Pool. Seasonal overlap between the Cold Pool and wind lease areas in the Southern New York Bight along coastal New Jersey was evaluated using a data assimilative ocean model. Results highlight overlap periods as well as a thermal gradient that persists after bottom temperatures warm above the threshold typically used to identify the Cold Pool. These results also support cross-shelf variability in Cold Pool evolution. This work highlights the need for more focused ocean modeling studies and observations of the Cold Pool and MAB wind lease area overlap.**

Keywords—Stratification, Bottom Temperature, Cold Pool, Offshore Wind, Mid-Atlantic Bight

I. INTRODUCTION

The Mid-Atlantic Cold Pool is a seasonal mass of cold bottom water extending throughout the Mid-Atlantic Bight (MAB) from Nantucket, MA to Cape Hatteras, NC, which results in one of the largest thermal gradients in the world (Fig.1). This stratification and the associated cold bottom temperatures and nutrient-rich environment support a diverse coastal ecosystem including economically important recreational and commercial fisheries [1]. Within the MAB, over 2.3 million acres of the MAB continental shelf has been leased for offshore wind energy projects that are under development, including sites that overlap with the seasonal Cold Pool [1,2]. Limited information exists about the extent of this overlap, as well as the impact of the turbines on the Cold Pool [1].

The Cold Pool develops in the winter as cold water from the Nantucket Shoals, north of the MAB, is transported southward to well-mixed MAB water [3,4]. In the spring, as surface water temperature increases and storm frequency decreases, a strong thermocline develops that isolates the cold, and relatively fresh bottom water, known as the Cold Pool [3, 5]. Stratification within the MAB is controlled and stabilized by salinity and temperature [6]. The strength of the thermocline, driven primarily by temperature, reaches a seasonal peak between July and August, when the Cold Pool also peaks [6]. As surface temperatures begin to decrease in the late summer and early fall, the thermocline weakens and fall storms eventually mix stratified surface waters to the bottom and the Cold Pool dissipates [3-8].

Seasonal Cold Pool evolution is integral to MAB ecosystem processes. Upwelling along the MAB occurs annually transporting Cold Pool waters further inshore and towards the coastal surface, which can drive phytoplankton blooms [9,10]. The presence of Cold Pool water allows species ranges to extend further south than would be anticipated by latitude, supporting many economically and culturally valuable finfish and shellfish fisheries [11–14].

The United States is anticipated to become one of the largest offshore energy markets by 2030 with an estimated 1.7 million acres under lease, and more than 2,100 turbine foundations to be installed [15]. The MAB region leads the nation in proposed offshore wind energy projects with regional offshore wind goals totaling more than 40,083 megawatts (MW) of energy within the next decade [2]. Offshore wind development in the United States is relatively new, while European offshore wind energy has been developed extensively and can provide insight into possible interactions between turbines, physical oceanographic processes, and biological systems despite key differences between the regions [16].

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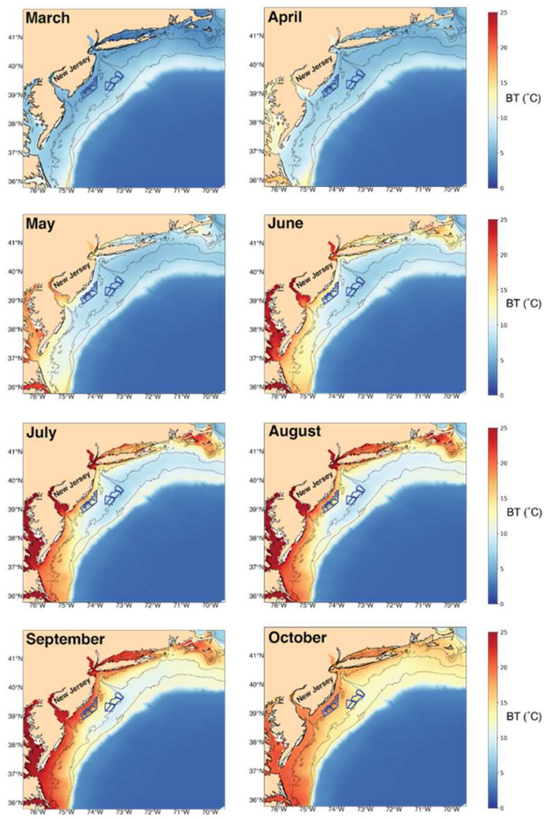

Fig.1. Monthly averaged bottom temperatures based on Doppio simulations spanning 2007 to 2020 within the MAB. Only peak Cold Pool months are included. The Cold Pool is highlighted with white and blue colors when the bottom temperature reaches below 10˚C. Wind lease areas included in this study are outlined in blue. The 25, 50 and 75m isobaths are shown in black.

While still applicable, results from European studies are more representative of conditions in the MAB during relatively weakly stratified periods, and do not represent Cold Pool conditions [1]. Likewise, many European lease areas use smaller turbines with different density and spacing, further adding to uncertainty about how relevant European research is to MAB conditions [16].

Wind turbines can directly impact the hydrodynamics within and around the site through their underwater infrastructure, and indirectly through changes in both the surface and atmospheric wind fields [17]. Structure-induced friction and blocking from flow past cylindrical structures often forms Von Kármán vortex streets, increasing the turbulence directly downstream of the turbine. In the context of the Cold Pool, this could lead to less stratified conditions [1]. It is unclear what the effects will be on the highly stratified system like the MAB Cold Pool if the area of increased turbulence is expanded [17-18]. Likewise, the extraction of atmospheric kinetic energy by turbines may be amplified by larger clusters of wind turbines in turn reducing shear-driven forcing at the sea surface and decreasing horizontal velocities, and turbulent mixing within several kilometers of the wind site [19]. This could potentially mean that within the MAB, offshore wind projects within the Cold Pool could strengthen stratification. The implications of offshore wind on the hydrodynamic features of the MAB require further study, however, because of the broader spatial extent of wind lease areas, the weaker tidal strength and increased storm frequency within the MAB versus Europe, as well as the technological differences in turbine design.

In this paper, we evaluate the extent and cross-shelf variability of spatial overlap between wind lease areas and the Cold Pool. We will focus on projects proposed in waters off the state of New Jersey to highlight trends in these differences. Specifically, we will evaluate the duration, strength, and variability of stratification where the Cold Pool overlaps with wind lease areas within the southern New York Bight, off of New Jersey (NJ) using output from a data assimilative regional ocean model known as Doppio [20].

II. Methods

Data used in this study was simulated by the Doppio model, a Regional Ocean Modeling System (ROMS) application of the MAB and the Gulf of Maine [20]. Doppio is computed using 4-Dimensional variational assimilation of satellites, HF-radar ocean surface currents and all available *in situ* observations from MARACOOS and NERACOOS regional associations of the U.S Integrated Ocean Observing System (IOOS). The model resolution is a uniform 7 km horizontal grid with 40 vertical layers. The output of Doppio used in this study is from a free-running regional model run with simulations spanning from 2007 to 2021. Data was accessed in March 2022 using the thredds link: (https://tds.marine.rutgers.edu/thredds/roms/doppio/catalog.html?dataset=DopAnV3R3-ini2007_da_monthly_averages).

The presence and location of the Cold Pool is defined as locations where the vertical temperature gradient is 0.2˚C/m or greater and the bottom temperature is 10˚C or less [1, 3, 7, 21–24]. The density stratification over the MAB region is primarily thermally controlled during the peak Cold Pool months, thus stratification is determined by calculating the temperature gradient:

$$0.2^\circ C/m \leq \delta T/\delta z \ \& \ T \leq 10^\circ C \tag{1}$$

Seven wind lease areas (WLAs) were identified as the closest geographically to the New Jersey shoreline and were selected for this study (Fig. 2). Six study locations were selected approximately central within or at a boundary between the seven WLAs. Monthly averaged temperature values were obtained from Doppio simulations for each study location (Fig. 2). Using all 40 vertical layers of the monthly averaged temperature data, a monthly vertical temperature gradient was calculated for each location (n=180). The monthly average bottom temperature was also calculated for each location. Temporal trends and variability in Cold Pool evolution were determined using ensemble monthly averages (i.e the mean of all January temperature values from 2007-2021) and standard deviation calculated for both bottom temperature and temperature gradients for all 15 years at each study location.

III. Results

Based on the temperature gradient and bottom temperature criteria, the Cold Pool was present at all six selected study locations within the seven wind lease areas (Fig. 3,Table I,Table II). Despite the fifteen-year temporal span of the ensemble monthly averages of bottom temperature and the temperature gradient, variability across the time series at each study point was limited. Bottom temperature during peak Cold Pool months varied by 0.13˚C (standard deviation) while temperature gradient varied by 0.02˚C/m (standard deviation) across all sites and years.

There were limited latitudinal differences in the duration or strength of the Cold Pool across the six study locations (Fig. 3,Table I,Table II). Four study points are offshore in 50m water depth, while two are relatively inshore at approximately 25m of depth. All four offshore study locations had bottom water temperature below 10˚C and a thermal gradient greater than 0.2˚C/m in the month of April signifying the presence of the Cold Pool (Fig. 3). The bottom temperature at these four offshore study points exceeded 10˚C in July meaning the Cold Pool duration there was approximately three months (Fig. 3,Table I). Despite the warming bottom temperatures in all four offshore sites, the thermal gradient value above 0.2˚C/m was maintained for two additional months dissipating in September (table I). In the four offshore sites, the minimum bottom water temperature occurred at approximately the same time as the temperature gradient exceeded 0.2˚C/m in either March or April (Fig. 3, Table I, Table II). The peak temperature gradient occurred simultaneously with bottom water warming above 10˚C (Fig. 3). The highest bottom temperatures occurred as stratification broke down around October or November (Fig. 3).

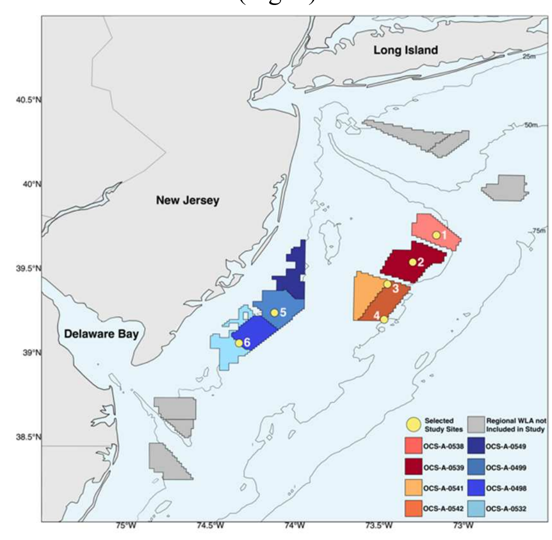

Fig. 2**.** Study locations are depicted with yellow circles and associated wind lease areas (WLA) are shown as colored blocks, with different colors for different lease blocks. Blue WLA correspond to nearshore study points while red WLA are offshore study points. Other WLA not included in this study are shown in gray. The 25, 50 and 75m isobaths are shown in black.

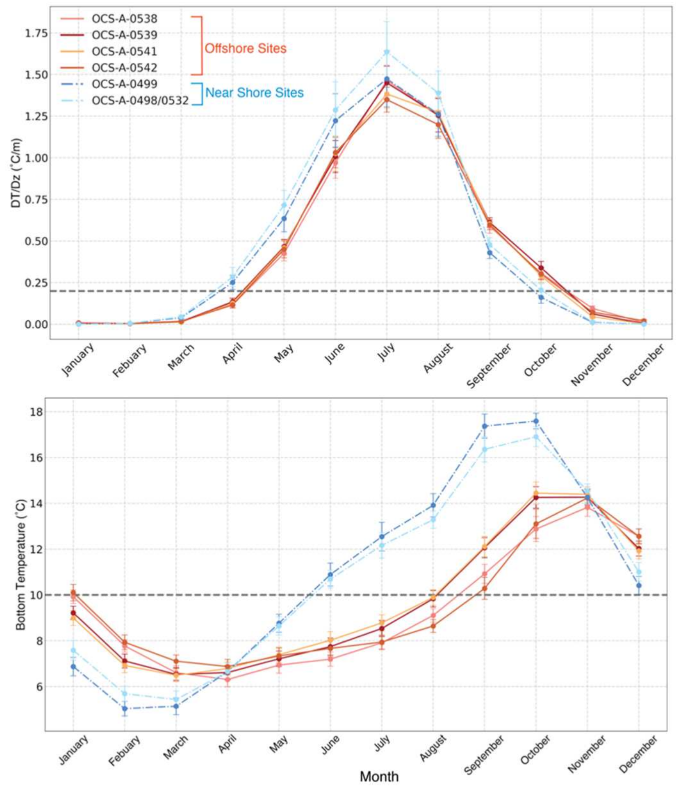

Fig.3. Monthly average bottom temperature (lower panel) and dt/dz values (upper panel) from 2007-2021 for study locations. Colors correspond to the specified wind lease area (Fig. 2). Blue colors represent nearshore sites while red colors symbolize offshore sites. The Cold Pool exists when bottom temperature values remain below the dashed grey line and when dt/dz values are above the above grey dashed line.

TABLE I. The duration of the Cold Pool based on ensemble averages from 2007-2021 according to the traditional definition as well as the duration of the thermal gradient above 0.2˚C/m for each study location. The Cold Pool start signifies the thermal gradient passing 0.2˚C/m and the Cold Pool end occurs when bottom temperatures surpass 10˚C. Wind lease area (WLA) names correspond to official lease call numbers.

Study Location	**WLA Name (OCS-A-)**	**Cold Pool**			**dT/dz>0.2˚C/m**	
		Start	***End***	***Length***	***End***	***Length***
1	0538	Apr.	Jul.	3	Sep.	5
2	0539	Apr.	Jul.	3	Sep.	5
3	0541	Apr.	Jul.	3	Sep.	5
4	0542	Apr.	Jul.	3	Sep.	5
5	0499	Mar.	Apr.	1	Sep.	7
6	0498/0532	Mar.	Apr.	1	Sep.	7

TABLE II. Minimum bottom temperature (BT) and maximum thermal gradient (dT/dz) values based on ensemble averages from 2007-2021 for each study location. Timing of each value is also shown. Wind lease area (WLA) names correspond to official lease call numbers.

Study Location	WLA Name (OCS-A-)	Min. BT (˚C)	Month	Max. dT/dz (˚C/m)	Month
1	0538	6.30	Apr.	1.46	Jul.
2	0539	6.53	Mar.	1.45	Jul.
3	0541	6.49	Mar.	1.38	Jul.
4	0542	6.87	Apr.	1.35	Jul.
5	0499	5.03	Feb.	1.47	Jul.
6	0498/0532	5.43	Mar.	1.64	Jul.

There are notable differences in the Cold Pool evolution between the nearshore and offshore points (Fig. 3, Table I,Table II). In the two nearshore study sites, the Cold Pool duration was shorter, spanning approximately one month, starting in March with increasing thermal gradient values and ending in April when the bottom temperature surpassed 10˚C (Fig. 3). Despite the short duration of the Cold Pool, the heightened thermal gradient values in these two nearshore sites lasted longer than at the four offshore sites (Fig. 3,Table I). In study sites five and six, the thermal gradient above the Cold Pool threshold extended for seven months (Fig. 3,Table I). Despite an earlier development in sites five and six, the thermal gradient dissipated at approximately the same time as the offshore sites (Fig. 3,Table I). In both nearshore sites, the minimum bottom temperature occurred at a similar time to the offshore sites but was more than 1˚C cooler than the offshore sites. Peak thermal gradients in both nearshore sites occurred in July, despite the bottom temperature warming above 10˚C in April. Bottom temperature and thermal gradients reached a greater maximum value at the nearshore sites.

IV. Discussion

Findings of regional Cold Pool trends offshore of New Jersey in this study are consistent with those of previous papers that discuss the spatial and temporal variability of the Cold Pool [3, 4, 6–8, 21, 23]. Nearshore bottom temperatures warmed more quickly (0.02˚C/day) than offshore bottom temperatures (0.06˚C/day) which is consistent with results from previous papers [7, 8]. Generally, the Cold Pool is shorter in duration at areas of relatively shallow depths [7,8]. Previous studies have defined the Cold Pool dissipation as the decrease in stratification strength in early fall [7,8]. While findings in this study support the strengthened thermal gradient extending into the early fall, bottom temperatures were consistently above the Cold Pool threshold after July. The thermal gradient in the southern New York Bight, where all six study sites are located, has been observed to be greater than in other areas of the MAB because of lower thermal diffusivity in the area [7,8]. Previous studies indicate the maximum temperature gradients to be around between 0.5 and 0.8 ˚C/m, while in both offshore and nearshore sites the values in this study exceeded 1˚C/m [7,8].

Cold Pool dissipation has previously been associated with bottom temperatures warming above 10˚C [3,7, 8]; however, we found that the thermal gradient remains above 0.2˚C/m well beyond when the bottom temperature warms. Even in the nearshore sites, stratification extends months after the bottom temperature warms and reaches higher maximum thermal gradient values than within the offshore sites. This finding is important as stratification is the buoyancy force that inhibits mixing by flow past structures such as wind turbines, and it maintains ecologically important habitat [1]Atlantic Surf clams, Ocean Quahogs and Sea Scallops are some of the most dominant and economically valuable fisheries within the larger MAB as well as within the state of New Jersey [1, 13, 25, 26]. These species are thermally sensitive and their distribution is often an indicator of changing bottom temperatures [13, 25].Thermal gradients and changes in bottom temperature could have direct impacts on these and other commercially and ecologically important species. Results indicate a larger spatial and temporal overlap between offshore NJ wind lease areas and the MAB Cold Pool versus near shore wind lease areas following traditional Cold Pool definition. It is still uncertain the extent to which impacts from WEA development will affect the Cold Pool. European studies have shown that wind lease areas do influence the hydrodynamic features of coastal environments [17–19]. These impacts, however, depend heavily on the spatial extent of the WEAs as well as the temporal and spatial variability of stratification and mixing [18-19]. The current wind lease areas within the German Bight occupy a significantly smaller area than those proposed along the MAB. The stratification within the German Bight is quantified as a 5-10˚C difference between surface and bottom water temperature and tidal currents in this region can reach near 1.0 m/s [18-19]. At the peak of thermal stratification in the German Bight during the year 2014, the bottom water temperature along the 25m isobath only reached 14˚C resulting in a maximum thermal gradient of 0.2˚C/m [18]. Local tidal forcing within the MAB is much weaker than the German Bight (>0.1 m/s) despite more frequent storms within the MAB [27]. The German Bight, therefore, has significantly weaker stratification than the MAB and stronger currents. Because of the spatial, technological, and environmental differences between the German Bight and the MAB, it is uncertain what the hydrodynamic impacts of offshore wind on the Cold Pool will be, however, the above characteristics of the MAB and findings of this study suggest that the impacts from turbines will be less than those found in the German Bight.

V. Conclusion

The MAB Cold Pool is an invaluable coastal ocean feature that supports some of the most economically and culturally valuable fisheries in the United States. The Cold Pool influences a variety of oceanographic processes, such as atmospheric and oceanic circulation, coastal primary productivity, and carbon sequestration. The development of offshore wind has been rapidly expanding off of coastal NJ. This study found that there is notable overlap between proposed offshore wind lease areas in NJ and the Cold Pool. In addition, it was found that thermal gradient values above the Cold Pool threshold extended past when bottom temperatures warmed above the Cold Pool criteria. Results also supported results from previous studies that nearshore bottom temperatures warm more rapidly than offshore, despite stronger thermal gradient values in nearshore sites. It is unclear from the technological, environmental, and spatial differences between the German Bight and the MAB what the impacts of the development of offshore wind on the Cold Pool will be. Future studies to determine the interdecadal trends of Cold Pool evolution is necessary to further evaluate the extent of overlap between the Cold Pool and the MAB wind lease areas are needed. Additional study is also necessary to determine the effects of newer turbine technology on the MAB seasonally stratified environment.

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