Technical Summary

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ABSTRACT: Along the East Coast of the U.S., from Massachusetts to North Carolina, there are several planned areas for the development of offshore wind farms (OSW). OSW development has the potential to alter local and regional physical oceanic processes, via their influence on currents, mixing

and waves from wind turbine generator (WTG) foundations and by extracting energy from the wind. These potential oceanic changes could alter the transport of fish and shellfish larvae and change the distribution and settlement of ecologically and commercially important species along the Atlantic Coast of the U.S. This study aims to firstly provide projections of potential changes to ocean hydrodynamics resulting from the development of the planned wind energy areas (WEAs), including current speed and direction, turbulence, waves, and bed shear stress. Secondly, agent-based modeling (ABM) is used to assess the possible resulting impacts on transport, dispersal, settlement patterns, and connectivity of Atlantic Sea Scallop, Surfclam, and Summer Flounder larvae. To achieve this, a regional integrated 3D hydrodynamic model (HDM) and ABM were developed of the Atlantic coast using MIKE Powered by DHI models.

The HDM covers an area from Nova Scotia to Florida, providing baseline oceanographic conditions for the years 2017, 2018, and 2020. Wind energy areas (WEAs) were afforded higher resolution using a flexible mesh and modeled with partial and full build-out scenarios. The scenarios for year 2017 were: baseline (no WTGs), Scenario 2: 12 MW Partial Build-out (2,083 WTGs), Scenario 3: 15 MW Partial Build-out (2,083 WTGs), Scenario 4: 12 MW Full Build-out (4,650 WTGs), Scenario 5: 15 MW Full Build-out (4,650 WTGs), and Scenario 6: 15 MW Full Build-out (4,650 WTGs) for years 2017, 2018, and 2020. The influence of monopile foundations induced drag and turbulence were assessed based on previous Computational Fluid Dynamics (CFD) model results (Johnson et al., 2021), while wind energy extraction and wake effects were estimated using the industry standard PyWake wind wake loss tool. The results of both nearfield sub-analyses were parameterized and integrated into the HDM.

The ABM was developed using MIKE ABM Lab and used to simulate the spawning, movement, and settlement characteristics of the target larval species (Atlantic Sea Scallop (*Placopecten magellanicus*), Atlantic Surfclam (*Spisula solidissima*) and Summer Flounder (*Paralichthys dentatus)*). The baseline ABM results were evaluated by comparing the ABM results for settled larvae density against EFH demarcations (NOAA, 2018), available biomass data, and evaluated statistically using three Pattern Oriented Modeling (POM) analysis techniques.

The HDM results showed that the introduction of the WEAs into the model domain reduced the magnitude of the currents, waves, and bed shear stresses mostly within the WEAs. Of the studied scenarios, Scenario 5: 15 MW Full Build-out produced the maximum impact on the HDM results where, in the entire domain, maximum current changes ranged from between approximately -5.0% and +1.7% in direct vicinity of each WEA.

Changes in sea scallop and surfclam settlement resulting from the introduction of the WEAs were estimated by the ABM. Settlement changes were primarily found in the New Jersey region around the confluence of OSW developments in the region, and to a lesser extent through Delmarva. Localized patches of increased settlement were found centrally and along the coast of the New Jersey region, while decreased settlement was estimated to the north of the New Jersey region for both sea scallop and surfclam and to the south of the New Jersey region for surfclam. The estimated changes in settlement are likely a result of slowed transport of larvae in both north-to-south and south-to-north directions within the New Jersey area. The estimated changes in settlement are four to five orders of magnitude lower than total settlement, and it is unlikely that there will be relevant ecological, or fisheries impacts on a regional level. However, given the persistence of the changes, and the locally substantial changes identified, there could be impacts on the localized sub-population level for these species. Changes in summer flounder settlement were also estimated along the coast, but no clear patterns or consistencies between scenarios emerged. There could be localized impacts in the New Jersey region resulting from the introduction of the OSW developments for summer flounder, as the 15 MW scenario identified change close to the OSW areas. However, it is difficult to conclude whether there will be relevant impacts for summer flounder, given their ability to move to appropriate habitat. More localized studies are likely required to provide further insight into the relevance of the local level changes identified, as well as consideration of survival and recruitment in the areas of settlement change identified in the model results.

BACKGROUND: The goal of this study was to assess the potential cumulative regional impacts on oceanographic transport patterns along the East Coast of the U.S. resulting from the development of offshore wind (OSW) energy leases in the region. This modeling study assessed the potential changes in hydrodynamic conditions resulting from OSW development, and the associated impacts on the transport of fisheries pertinent larvae, namely, Atlantic sea scallop (Placopecten magellanicus), Atlantic surfclam (Spisula solidissima) and summer flounder (Paralichthys dentatus) larvae, from North Carolina to Massachusetts. This study built upon previous work completed on the potential impacts on larval transport, dispersal, and settlement patterns (Chen et al., 2016; Johnson et al., 2021), by extending the model domain from Johnson et al., (2021) from Nova Scotia to Florida so as to include North Carolina and northern South Carolina WEAs; as well as important oceanographic processes in the area such as the formation of the "Cold Pool".

OBJECTIVES: The key objective of this study was to determine the regional effects of OSW developments on coastal and oceanic environmental conditions and the resulting impacts on larval dispersal and settlement, including changes in settlement patterns and connectivity. To achieve this key objective, this study aimed to develop and use fine resolution regional hydrodynamic models, with monopile drag and turbulence and wind turbine wake models to determine the changes in oceanic conditions such as current speed and direction, turbulent mixing, and bed sheer stress resulting from OSW development. The second aim was to develop and integrate an agent-based model (ABM) that simulates larval dispersal, movement, and settlement for the three target species, with the hydro-dynamic model (HDM). The final aim was to analyze the potential effects of hydrodynamic changes on larval settlement and connectivity of the three target species.

METHODS: The project was divided into six major tasks: 1. Data Management, 2. Desktop Review and Statistical Analysis, 3. Model Development, 4. Model Calibration, 5. Modeling Scenarios and Analysis, and 6. Report and Technical Summary. The initial stages (i.e., 1 and 2) of the project involved collecting the background studies, peer reviewed literature, oceanographic data, and ecological survey data necessary to refine the hydrodynamic, wind turbine wake, and agent-based modeling approaches. Five OSW build-out scenarios were chosen, as well as three target species.

The target species selected for analysis included:

- Atlantic sea scallops (*Placopecten magellanicus*)
- Atlantic Surfclams (*Spisula solidissima*)
- Summer flounder (*Paralichthys dentatus*)

The WEAs selected for the study were characterized as those that had a Construction and Operations Plan (COP) publicly available on BOEM's website at the time of study initiation (i.e., labelled as "with COP"); and those where a COP was not yet submitted but where potential leases had been identified (i.e., labelled as "Generic"). The scenarios modeled were:

- Scenario 1: Baseline years 2017, 2018, and 2020 – modeled without any WTGs, all three species modeled for 2017. Only sea scallops modeled for 2018 and 2020.
- Scenario 2: Partial Build-out 12 MW year 2017 - currently proposed developments with publicly available COPs, with 2,083 12 MW turbines for year 2017, all three species modeled in ABM,
- Scenario 3: Partial Build-out 15 MW year 2017 – currently proposed developments with publicly available COPs, with 2,083 15 MW turbines for year 2017, all three species

modeled in ABM

- Scenario 4: Full build-out, 12 MW year 2017 – currently proposed developments with publicly available COPs and generic layouts for remaining lease areas, with 4,650 12 MW turbines for year 2017, all three species modeled in ABM
- Scenario 5: Full build-out, 15 MW year 2017 – currently proposed developments with publicly available COPs and generic layouts for remaining lease areas, with 4,650 15 MW turbines for year 2017, all three species modeled in ABM
- Scenario 6: Full build-out, 15 MW years 2017, 2018 and 2020 – currently proposed developments with publicly available COPs and generic layouts for remaining lease areas, with 4,650 15 MW turbines. Only sea scallops modeled for 2017, 2018 and 2020 in ABM.

While it was originally planned to include sequential years of analysis for Scenario 6, the year 2019 was omitted due to a late Project stage discovery of some misaligned model setup features. This led to an unacceptable level of validation for 2019 and that had consequences on ABM test results. HDM results for 2019 were therefore omitted. As the Sea scallop spawning and settlement cycle aligns with a calendar year, this decision did not affect the ability to complete an inter-annual variability analysis for this species.

Tasks 3 to 5 involved developing, calibrating, validating and then running the HDM, wind wake loss model, and ABM, which entailed the integration of selected MIKE Powered by DHI models. The HDM, developed with MIKE 3 FM HD, MIKE 21 SW and other nearfield models, was established as a 3D regional model ranging from offshore Nova Scotia to Cape Canaveral. A finer model mesh was embedded in the wind energy areas (WEAs). Localized turbulence effects of individual monopile foundations were addressed first, using a single monopile and applying a Computational Fluid Dynamics (CFD) model of water flow around turbine foundations. Based on the CFD model, a general parameterization was established for the energy conversions and thereby the impacts on current velocity, turbulence levels and mixing (thermal and salinity). Each turbine was implemented as sub-grid feature using extra source terms for: a.) the drag force from the tower as a mean momentum sink b.) a source term for turbulent kinetic energy from the extra production in the wake, and c.) increase the eddy viscosity adding mixing of momentum, temperature and salinity. The sub-grid model ensures that energy was converted accurately. This approach follows normal practice in ocean models (Rennau, 2012; Jakobsen, 2010) or wind resource modeling (Fitch, 2012). An industry standard wind wake loss model, PyWake (Pedersen et al., 2023), was implemented for this study. For each WEA region a localized wind wake model acting on the Climate Forecast System Reanalysis (CFSR) wind fields was produced by the PyWake model. These results were then transferred into the regional HDM mesh. In summary, the overall HDM implemented near and far field oceanic processes including surface wind wake losses due to the wind turbine generators (WTGs), ocean currents (both lateral and vertical) losses due to the monopile foundations, air pressure, precipitation/ evaporation, surface heat flux, water temperature and salinity.

The ABM was developed using MIKE ABM Lab templates which, via coupling with the HDM, allowed for larval dispersal modeling. ABM Lab offers an open and flexible coding environment for defining and customizing simple to advanced biological traits and processes using a series of user-defined arithmetic expressions and state variables, which allows simulated agents (e.g., larvae) to react and interact with a dynamically changing virtual environment. ABM templates were customized for each species with their key spawning and development characteristics, movement traits, settlement requirements and habitat preferences. The ABM was subsequently tested, calibrated and evaluated. The ABM was carried out using an ensemble technique, with execution of multiple "clones" of the same model set-up. A connectivity analysis was also carried out, which tracked where larvae spawn and where they settle, in order to capture any potential changes in larval transport resulting from the introduction of the OSW developments. The ABM was evaluated by plotting the simulated settled larvae density against EFH demarcations (NOAA, 2018) and available biomass data, and statistically through the application of three Pattern Oriented Modeling (POM) analysis techniques.

RESULTS: *Hydrodynamic Results:* Changes caused by the various OSW developments to current speeds, waves, bed shear stresses and thermal stratification were captured by the HDM; but were relatively modest. For example, maximum changes to 95th percentile non-exceedance probability depth averaged current speeds in all WEAs for Scenario 5 (15 MW Full Build-out), the scenario with the most pertinent change, ranged from approximately -5.0% to +1.7%. Whereas maximum changes to the 95th percentile non-exceedance probability depth averaged currents for sensitivity modeling analyses i.e., a 15 MW Full Build-out with an artificially doubled wind wake effect, resulted in changes ranging from approximately -6.1% to +2.3%. In terms of detailed wave results, the biggest reduction in 95th percentile non-exceedance probability significant wave heights (Hm0) were observed in the New York Bight (NY Bight) / Maryland-Delaware (MD-DE) region. Here, wave height reduction was on the order of 10 cm for waves that were on the order of 2.5 m Hm0 or ~-4% lower. Modeled changes in bed shear stress were also small, leading to the conclusion that WTGs should have no increased effect on deposition and marginal reductions in the potential of seabed sediment mobilization in the WEAs.

The effect of the WTGs on the sea surface wind stress is evident in model results of the vertical thermal stratification influenced by the slowing of the currents inside the OSW farms. The greatest effect was observed from the 15 MW full build-out scenario in the NY Bight / MD-DE WEAs. In winter, the OSW farms shifted the isotherms down slightly and expanded the bottom isotherm up ~3 m, which elongated the bottom 10 °C cold water isotherm toward the southwest by ~20 km. In spring, the isotherms shifted down by ~0.5 m in the upper 20 m of the water column, and shifted up ~0.5 m to 1.5 m at depths below 30 m. In the summer, the isotherms shifted down ~3 m in the upper 10 m of the water column, with little change between 10 m and 30 m water depths. However, in the deeper waters the isotherms moved up and expanded the size of the cooler water mass. In fall, the isotherms shifted down in the upper 20 m of the water column in the OSW farm area on the southwest side, while there was not much change noted deeper than 20 m water depths and deeper.

Sea Scallop Results: Changes in sea scallop settlement (areas of both decreased and increased settlement) were concentrated in the New Jersey and Delmarva regions and extend beyond the WEA areas (please see Figure 7.1 for WEA locations). A decrease in settlement was estimated in and around WEAs 5 and 6 to the North of the New Jersey region, and along the coast of Delaware near WEA 8 and 9. An increase in settlement was estimated along the coast of New Jersey and around WEA7, and to a lesser extent through the Delmarva region. Average changes in sea scallop settlement per destination area were four orders of magnitude lower than total settlement, and in some cases, show little to no overall change in the New Jersey region, once the smaller scale hotspots of increase and decrease were averaged over a larger area. Transport of larvae appears to be slowed within the New Jersey region, which may explain the localized hotspots of settlement change observed. The connectivity analysis showed changes in settlement were mostly from larvae originating in the Mid-Atlantic Bight (MAB). It is possible that the slowed transport of larvae from the more southern portion of the MAB spawning area results in greater settlement further south and west, with the introduction of the OSW developments, and a decrease in settlement to the north and east, suggesting overall slowing of transport south to north. There was inter-annual variability in sea scallop settlement between 2017, 2018, and 2020 years with slightly different hotspots of increase or decrease within New Jersey, but the overall patterns were the same (i.e., changes are found mainly in New Jersey, on the same order of magnitude and in the same areas).

Surfclam Results: Changes in surfclam settlement were also concentrated in the New Jersey and Delmarva regions and extend beyond the WEA areas. Areas of decreased settlement were found in and around WEAs 5 and 6 to the North of the New Jersey region, as well as further south - to the east of

WEAs 8 and 9. An increase in settlement was found concentrated in the middle of the New Jersey region and around WEA7, and through Delmarva. Average changes in surfclam settlement per destination area were five orders of magnitude lower than total settlement. The connectivity analysis indicated that slowed north to south transport of surfclam larvae appears to contribute to the areas of decreased settlement in the New Jersey region; while areas of increased settlement appear to a result in greater settlement of larvae originating from the south (Delmarva) as well as the New Jersey region itself.

Summer Flounder Results: Changes in summer flounder settlement are concentrated along the coast. However, the results are noisy meaning that there are no clear patterns of change in settlement between Scenarios. Additionally, with respect to the cluster analysis there were no clear consistent patterns of change between Scenarios, which were seen in the other two species. Nevertheless, there do appear to be changes in settlement occurring along the coasts of New Jersey, Long Island and around Nantucket shoals, as well as the North Carolina and South Virginia (SVA destination area) but different areas are highlighted in the different scenarios. It should be noted that the changes appear to be much smaller than the defined destination areas, which may indicate the possibility of very localized larval settlement changes resulting from the OSW developments.

Relevance of ABM Results: The relevance of scallop and surfclam ABM results are similar, whereas summer flounder results differ significantly. Hotspots of settlement change in sea scallop and surfclam larvae were identified in areas where there are harvest efforts. Over the entire modeling domain these differences are small but persistent (i.e., over the life of the projects, about 30 years). It is noted that settlement does not necessarily equal recruitment into the fishery, as individuals that settle may not reach maturity. The unknowns regarding post-settlement survival contribute to uncertainty in estimating recruitment in most marine fisheries. The relevance of the changes in settlement to recruitment of market-sized individuals into the sea scallop and surfclam fishery will depend on growth and survival beyond settlement. It is not likely that the modeled changes in settlement will lead to measurable declines in total biomass of sea scallop and surfclam at larger regional scales (i.e., over the MAB and New Jersey region). However, spatial persistence of the change may be relevant on a local scale, where hotspots have been identified. At this local scale, changes in settlement may impact patches (subpopulations) or beds of sea scallop and surfclam and any local fisheries they may support.

The two bivalve species exhibited similar patterns in transport and settlement over the modeling domain, but summer flounder differed. No clear patterns of settlement change from baseline were observed in modeled scenarios for summer flounder, with the exception of some localized shifts in larval transport to the north or south near the WEAs. Pre-settlement summer flounder are competent swimmers which may facilitate shoreward movement towards shallow water and entrances to rivers, bays, or estuaries. Nearshore settlement is a well-established aspect of summer flounder life history, and although not specifically studied, settlement and grow-out may also occur in nearshore coastal waters. Any local scale shifts in settlement therefore may be mitigated by the ability of juvenile summer flounder to swim to appropriate habitats.

CONCLUSIONS: The main conclusion from the HDM results, is that there are likely to be perceivable changes in current speeds resulting from the development of the WEAs assessed in this study. Changes in the depth averaged current speed are both positive and negative, with decreased speeds primarily within the WEAs and increased speeds outside the WEAs. Current speed change is small in percentage, as well as in magnitude, where the maximum increase or decrease in current speed is ~0.025 ms-1. These estimated changes in current speeds result in discernable changes in settlement of sea scallop and surfclam, but less so for summer flounder.

Estimated settlement changes were primarily found in the New Jersey region for sea scallop and surfclam, with some lesser change through the Delmarva region. Average changes in settlement per destination area for sea scallop and surfclam are four and five orders of magnitude (104 and 105) lower than total baseline settlement. It is difficult to discern the population and fisheries relevance of these changes in settlement, as settlement does not necessarily equal recruitment into the fishery or to reproductive maturity. However, it appears that regional scale changes in settlement will have minimal impact on recruitment of these two species, but the persistent nature of the change in isolated hotspots, could cause localized changes (e.g., in landings) at the subpopulation scale. Summer flounder results are noisy and inconsistent, but show some change possibly related to the OSW developments. However, it is difficult to draw conclusions as to the relevance of these changes in summer flounder settlement, especially as juvenile summer flounder can move into appropriate habitat.

There are larger changes in settlement found for all species for the 15 MW scenario than the 12 MW, but changes in settlement from both scenarios are still on the same order of magnitude. For the sensitivity analysis (Scenario 5) simulation where the effects of the 15 MW wind wake model were doubled, the changes in larval settlement were approximately 1.5 to 2 times greater than Scenario 5: 15 MW full build-out, but the overall patterns remained the same. Change in sea scallop settlement was modeled for years 2017, 2018, and 2020. The results show inter-annual variability, with slightly different hotspots of increase or decrease within New Jersey, but the overall patterns of settlement change are similar for each year.

The main recommendations for potential improvement for the HDM involve improved parameterization of the monopile wake and the WTG wind wakes. There is potential for future improvement of the HDM due to some uncertainties in the hydrodynamic response resulting from ocean wakes caused by the monopiles. This uncertainty may be reduced by further study (observations and modeling) of the wake mixing around large monopiles that may inform the parameterization within the sub-grid modeling approach. Additionally, there are uncertainties in the hydrodynamic response to the wind wakes caused by the WTG effect on air-sea interactions, that may be reduced by further study (observational and modeling) of the wake deficits, turbulence, and heat exchange around individual WTGs and large-scale OSW farms. This work on the WTG wind wakes may further inform and improve the parameterization employed in this study.

The main recommendations for potential improvement for the ABM of larval settlement and connectivity include the following collection of either dedicated separate research or relatively small modeling or analysis steps:

- Develop area and species-specific impact threshold limits for acceptability of changes in larvae settlement,
- Extend the ABM analyses for juvenile stages of target species development, especially where patterns of larval settlement change are more prominent and deemed to entail a level of impact risk. This will aid in understanding potential changes in recruitment and longer-term effects,
- Carry out localized levels of analysis through the application of dedicated local observational data / knowledge; and localized and more temporally refined ABM result post-processing for:
  - New Jersey / Delmarva areas to better understand the sea scallop /surfclam spawning variables and altered oceanic conditions causing the observed hotspots of settlement change,
  - Summer flounder – to obtain clarity around the modeling noise associated with observed settlement changes in inshore areas of Long Island/Nantucket, New Jersey / Delmarva, and North Carolina. This will allow for any localized changes in settlement and recruitment to be better understood, and
- Include the artificial reef effect (Mineur et al. 2012, Degraer et al. 2020, Glarou et al. 2020) in

ABM analyses, with specific focus on the 'Spillover Effect' (van Berkel et al. 2020). This would allow experts to better understand the extent at which proposed OSW developments have the potential to be become new habitat for fisheries relevant species and gain more insight into the relevance of oceanic response induced larval settlement changes in light of these other known OSW influences.

In summary, this study met the overall the overall objective to determine whether there are regional effects due to the OSW developments on coastal and oceanic environmental conditions that then influence the larval settlement, including changes in settlement patterns and connectivity.

STUDY PRODUCT(S):

1. BOEM study report: Johnson TL, Simpson, E, Bell MA, van Berkel JJ, Svenstrup Petersen, O, Hansen, FT, Hernandez, B, Saw, YK, Mortensen LO, Snyder, DB, Thomsen, F: 2024. Offshore Wind Impact on Oceanographic Processes: North Carolina to New York. Lakewood (CO): US Department of the Interior, BOEM. 336 p. OCS Study BOEM 2025-015. Contract No.: 0140M0120C0010.

MAP OF STUDY AREA: Full regional hydrodynamic model mesh from Nova Scotia to Florida (Cover image of report OCS Study BOEM 2025-015).