Muir Mhòr Offshore Wind Farm

Environmental Impact Assessment Report

Volume 3, Appendix 6.4: Ecosystem Level Effects

Revision No.	Date	Reason for Issue	Author	Reviewer	Approver
01	22/11/2024	Final	GoBe Consultants Ltd.	GoBe Consultants Ltd.	MMOWF Ltd

Document info	
Document ID	**MMH-GBE-A004-ENV-0006-323**
Revision	01
Date	22/11/2024

Contents

1. Introduction 1

1.1. Background 1
1.2. Purpose of the Report 1
1.3. Document Structure 2
1.4. Consultation 2

2. Ecosystem Baseline 6

2.2. Stratification and Primary Producers 6
2.3. Prey Species 9
2.4. Seabirds 14

Baseline Assessment Results 14

2.5. Marine Mammals and Megafauna 17

3. Ecosystem Level Impacts from the Proposed Development 22

3.2. Stratification and Primary Producers 22
3.3. Prey Species 23

Sandeel 23
Herring 24
Other FIsh Prey Species 24
Cumulative and Inter-Related Effects 24

3.4. Seabirds 27

Cumulative and Inter-Related Effects 28

3.5. Marine Mammals and Megafauna 30

Cumulative and Inter-Related Effects 35

4. Changing Baseline and Future Trends 39

4.2. Climate Change 39
4.3. Commercial Fisheries 40
4.4. Offshore Wind Development 41
4.5. INNS 42
4.6. Pollution 42
4.7. Avian Influenza 43

5. Conclusions 44

6. References 45

Annex A 53

Figures

Figure 2-1 Bathymetry: General Bathymetric Chart of the Oceans (GEBCO) (depth in m) of the northern North Sea in relation to the Proposed Development East-west and north-south transects (green dashed) are discussed elsewhere. The magenta box shows the region searched for archived Conductivity, Temperature, and Depth (CTD) profiles. Green squares show comparative locations to the north and south (Annex A of this report). 6

Figure 2-2 Figure from Hill et al. (2008) showing the regions where summer stratification is driven by bottom cool, salty pools (orange) as opposed to cool only (grey). Red shows flows associated with the boundaries of these bottom dense pools (Annex A of this report). 7

Figure 2-3 Maps of Chl-a (mg m $^{-3}$) concentration in winter, summer, spring and autumn, taken from the North Sea Biogeochemical Climatology (NSBC) climatology (Annex A of this Report). 8

Figure 2-4 Maps of the difference between nitrate at 50 m and nitrate at the surface, an indicator of the degree of stratification and nutrient limitation to surface phytoplankton (Annex A of this report). 9

Figure 2-5 Predicted European Nature Information System (EUNIS) Habitats and Faunal Point Data for the Proposed Development and Surrounding Area 11

Figure 2-6 The offshore and intertidal ornithology study area: a 4 km buffer around the Array Area and offshore ECC transects 15

Figure 2-7 The local marine mammal study area 18

Figure 2-8 The wider marine mammal study area including the Marine Mammal MUs 19

Tables

Table 1-1 Consultation Relevant to an Ecosystem Assessment _____ 3

Table 2-1 List of seabird species identified by offshore DAS. _____ 16

Table 3-1 Inter-related effects of Benthic Subtidal and Intertidal Ecology _____ 25

Table 3-2 Inter-related effects of Fish and Shellfish Ecology _____ 26

Table 3-3 Summary of assessment of effects on seabird species of the Proposed Development alone. _____ 27

Table 3-4 Inter-related effects of Offshore and Intertidal Ornithology. _____ 29

Table 3-5 Summary of assessment of effects on marine mammal species and other marine megafauna _____ 31

Table 3-6 Inter-related Effects of Marine Mammals and Megafauna _____ 35

Glossary

Term	Definition
Array Area	The area in which the generation infrastructure (including Wind Turbine Generators and associated foundations and inter-array cables), Offshore Electrical Platform(s), and an interconnector cable will be located.
Baseline	The status of the environment at the time of assessment without the development in place.
Benthic Subtidal and Intertidal Ecology study areas	The benthic subtidal ecology study area is defined by the Array Area and the offshore Export Cable Corridot (ECC). The secondary Zone of influence (Zol) encompasses a buffer of approximately 15 km around both the Array Area and offshore ECC. This buffer represents the area where secondary or indirect impact on the benthic environment might occur and is defined by the distance that suspended sediment plumes may be advected following disturbance and subsequently interact with benthic receptors. The benthic intertidal ecology study area is defined by the intertidal habitats up to the Mean High Water Springs (MHWS) mark within the Proposed Development boundary.
Biotope	A region of habitat associated with a particular ecological community.
Chl-a	Chlorophyll-a is a photosynthetic pigment which serves as a proxy for biological productivity.
Cumulative effects	The combined Impact of the Proposed Development acting cumulatively with the impacts of several different projects, on the same single receptor/ resource.
Cumulative impact	Impacts that result from changes caused by other past, present, or reasonably foreseeable actions together with the Proposed Development.
Demersal	Relating to the seabed and area close to it. Demersal spawning species are those which deposit eggs onto the seabed.
Developer	Muir Mhòr Offshore Wind Farm Limited
E2	The ScotWind Plan Option Area where the Proposed Development is located.
Elasmobranch	Cartilaginous fishes such as sharks, rays, and skates.
Environmental Impact Assessment (EIA)	A statutory process by which certain planned projects must be assessed before a formal decision to proceed can be made. It involves the collection and consideration of environmental information, which fulfils the assessment requirements of the EIA Directive and EIA Regulations, including the publication of an Environmental Impact Assessment Report (EIAR).
EIA Regulations	Collectively the term used to refer to The Electricity Works (Environmental Impact Assessment) (Scotland) Regulations 2017, The Marine Works (Environmental Impact Assessment) Regulations 2007, and The Marine Works (Environmental Impact Assessment) (Scotland) Regulations 2017.
Fish and Shellfish Ecology	Fish and shellfish ecology encompasses the study of the fish and shellfish species in the marine environment, the interactions between them and impacts on the surrounding environment.
Fish larvae	The developmental stage of fish which have hatched from the egg and receive nutrients from the yolk sac until the yolk is completely absorbed.

Term	Definition
Floating Foundations	The floating structures on which the Wind Turbine Generators are installed.
Foundation anchors	The structures which anchor the Floating Foundations to the seabed, connected to the foundation mooring.
Impact	An impact to the receiving environment is defined as any change to its baseline condition, either adverse or beneficial.
Inter-array cables	Cables which link the wind turbines generators to each other and the Offshore Electrical Platform(s).
Interconnector cable	Cable which links the Offshore Electrical Platform(s) to one another, allowing for power to be transferred between the platforms.
Mitigation	Mitigation measures, or commitments, are commitments made by the Proposed Development to reduce and/or eliminate the Likely Significant Effects (LSE) to arise as a result of the Proposed Development. Mitigation measures can be embedded (part of the Proposed Development design) or secondarily added to reduce impacts in the case of LSE.
Offshore Electrical Platform (OEP)	Offshore platform consisting of High Voltage Alternating Current (HVAC) equipment, details depending on the final electrical set up of the Project.
Offshore Export Cable Corridor (ECC)	The area within which the offshore export cables will be installed.
Offshore export cables	The subsea electricity cable circuits running from the Offshore Electrical Platform to the landfall which will transmit the electricity generated by the offshore wind farm to the onshore export cables for transmission onwards to the onshore substation and the national electrical transmission system along with auxiliary cables such as fibre optic cables.
Offshore transmission infrastructure	The proposed transmission infrastructure comprising: Offshore Electrical Platform(s) and associated foundations and substructures; the offshore export cables; and the landfall area up to Mean High Water Springs (MHWS).
Pelagic	Any part of the water column (i.e., the sea from surface to bottom sediments) that is not close to the seabed. Pelagic spawning species release their eggs into the upper layers of the sea.
Project	Muir Mhòr Offshore Wind Farm – comprises the wind farm and all associated offshore and onshore components.
Proposed Development	The offshore Muir Mhòr Offshore Wind Farm project elements to which this Offshore EIA Report relates.
Receptor	A distinct part of the environment on which impacts could occur and can be the subject of specific assessments. Examples of receptors include species (or groups) of animals or plants, people (often categorised further such as ‘residential’ or those using areas for amenity or recreation), watercourses *etc*.
Spawning	The release or deposition of eggs and sperm, usually into water, by aquatic animals
Subtidal	The region of shallow waters which are below the level of low tide (MLWS).
Wind Turbine Generator (WTG)	The wind turbines that generate electricity consisting of tubular towers and blades attached to a nacelle housing mechanical and electrical generating equipment.
Worst case design scenario	A ‘worst case’ design scenario from then design envelope that would lead to the greatest impact for receptors or receptor groups.

Acronyms

Term	Definition
Chl-a	Chlorophyll-a
CTD	Conductivity, Temperature, and Depth
CFP	Common Fisheries Policy
DAS	Digital Aerial Surveys
DDT	Dichlorodiphenyltrichloroethane
DECC	Department of Energy and Climate Change
ECC	Export Cable Corridor
EIAR	Environmental Impact Assessment Report
EU	European Union
GEBCO	General Bathymetric Chart of the Oceans
IBTS	International Bottom Trawl Surveys
ICES	International Council for the Exploration of the Sea
INNS	Invasive Non-Native Species
IAMMWG	Inter-Agency Marine Mammal Working Group
HPAI	Highly Pathogenic Avian Influenza
MD-LOT	Marine Directorate - Licensing Operations Team
MHWS	Mean High Water Springs
MMOb	Marine Mammal Observer
MU	Management Unit
NC MPA	Nature Conservation Marine Protected Area
NMPi	National Marine Plan Interactive
NSBC	North Sea Biogeochemical Climatology
OEP	Offshore Electrical Platform
OWF	Offshore Wind Farm
PCB	Polychlorinated biphenyl
PMF	Priority Marine Feature
PO	Plan Option
POPs	Persistent organic pollutants
PrePARED	Predators and Prey Around Renewable Energy Developments
RIAA	Report to Inform Appropriate Assessment
RSPB	Royal Society for the Protection of Birds
SAMS	Scottish Association of Marine Science
SCANS	Small Cetaceans in European Atlantic waters and the North Sea
SCM	Sub-surface Chlorophyll Maximum
SCOC	Special Committee on Seals
SMU	Seal Management Unit
SNCB	Statutory Nature Conservation Body

Term	Definition
SPA	Special Protection Area
SSC	Suspended Sediment Concentration
TAC	Total Allowable Catch
TKE	Turbulence Kinetic Energy
TTS	Temporary Threshold Shift
UWN	Underwater Noise
WTG	Wind Turbine Generator

1. INTRODUCTION

1.1. BACKGROUND

1.1.1. Muir Mhòr Offshore Wind Farm Limited (hereafter referred to as 'the Developer') is proposing to develop the Muir Mhòr Offshore Wind Farm (hereafter 'the Project'). The Project is made up of both offshore and onshore components. The subject of this offshore Environmental Impact Assessment Report (EIAR) is the offshore infrastructure of the Project seaward of Mean High-Water Springs (MHWS) which is hereafter referred to as 'the Proposed Development'.

1.1.2. The Muir Mhòr Array Area covers an area of approximately 200 km^2 and is located approximately 63 km east of Peterhead on the east coast of Scotland. The offshore infrastructure of the Proposed Development includes Wind Turbine Generators (WTGs) and associated floating foundations, the Offshore Electrical Platforms (OEP(s)) and associated foundations, the inter-array cables, an interconnector cable, offshore export cables and landfall.

1.1.3. Marine ecosystems are home to a wide range of biodiversity, from microscopic plankton to large marine mammals and megafauna. Marine developments (including offshore wind farms (OWFs)) can have complex impacts on marine ecosystems. These ecosystems provide critical services, such as food, carbon sequestration, biodiversity support and coastal protection, which are vital for ecological health and human wellbeing. Understanding the ecosystem-level effects of such developments will help ensure negative impacts on marine ecosystems are minimised which will help to ensure the long-term sustainability of marine environments and the services they provide.

1.1.4. This report has been prepared by GoBe Consultants Limited.

1.2. PURPOSE OF THE REPORT

1.2.1. The impacts of the Proposed Development on key receptors (including inter-related effects) are detailed within the relevant EIAR Chapters (Volume 2, Chapters 7 - 12). This report takes a deeper look and more holistic approach to assessing the impacts of the Proposed Development on the wider marine ecosystem.

1.2.2. The primary purpose of the report is to provide an approach to assessing the impacts arising from the Proposed Development, to demonstrate the Likely Significant Effects (LSE) holistically, across key trophic levels, particularly in relation to the availability of prey species following feedback from consultation with Statutory Nature Conservation Bodies (SNCBs) and other stakeholders (as detailed in Table 1-1).

1.2.3. This report reviews current literature to establish a baseline of the physical environment (stratification), primary producers, prey species and predators (marine mammals and megafauna). The review provides a baseline to inform an ecosystem level assessment of the potential implications, both positive and negative, that the Proposed Development may have.

1.2.4. This report also considers the wider impacts that the ecosystem is facing, highlighting a changing baseline, and considers the future trends across key trophic levels.

1.2.5. This document serves as an appendix to the EIAR and should be read in conjunction with the relevant EIAR Chapters:

- Volume 1, Chapter 3: Project Description;
- Volume 2, Chapter 7: Marine and Coastal Processes;
- Volume 2, Chapter 8: Marine Water and Sediment Quality;
- Volume 2, Chapter 9: Benthic, Subtidal and Intertidal Ecology;
- Volume 2, Chapter 10: Fish and Shellfish Ecology;
- Volume 2, Chapter 11: Offshore and Intertidal Ornithology; and
- Volume 2, Chapter 12: Marine Mammals.

1.3. DOCUMENT STRUCTURE

- **Section 1: Introduction**, including a brief outline of the Proposed Development, the rationale for this document and the relevant consultation to date;
- **Section 2: Ecosystem Baseline**, outlining the baseline data and conclusions of the relevant EIAR Chapters and current status of the relevant physical and ecological receptor groups;
- **Section 3: Ecosystem Level Impacts from the Proposed Development,** detailing the impacts (positive and negative) that may arise from the Proposed Development on the physical and ecological receptor groups: stratification of the water column and primary producers, prey species, seabirds, and marine mammals and megafauna;
- **Section 4: Changing Baseline and Future Trends,** outlining the current and future anthropogenic driven ecosystem level impacts; and
- **Section 5 Conclusions**.

1.4. CONSULTATION

1.4.1. The Offshore Scoping Report (Volume 3, Appendix 5.1 (Offshore Scoping Report)) for the Proposed Development was submitted to the Marine Directorate - Licensing Operations Team (MD-LOT) in June 2023. A detailed response to the Scoping Report's content and questions was provided by MD-LOT, and multiple additional consultees in the September 2023 Scoping Opinion (Volume 3, Appendix 5.2 (Offshore Scoping Opinion)).

1.4.2. A summary of the stakeholder consultation activities specific to this Ecosystem Effects Assessment is provided in Table 1-1. Within this table the issues raised and how these concerns have been addressed within the EIAR are outlined.

1.4.3. Further details on the Proposed Development's overall EIA stakeholder consultation process are presented in Volume 1, Chapter 5 (Consultation) of the EIAR. Topic specific consultation details and feedback can be found in the relevant EIAR Chapters (see paragraph 1.2.5).

Table 1-1 Consultation Relevant to an Ecosystem Assessment

Date	Consultee and Type of Consultation	Description/ Issues Raised	How this has been considered in the EIAR and Ecosystem Effects Assessment
September 2023	Scottish Ministers – Scoping Opinion (via MD-LOT)	Clear links between the marine mammal and offshore ornithology assessments in relation to prey availability should be made to the fish and shellfish assessment within the EIA Report.	A holistic assessment has been undertaken, with links made to key aspects such as ornithology and marine mammals in terms of prey availability. Impacts to key prey species (such as herring and sandeel) have been assessed in Volume 2, Chapter 10 (Fish and Shellfish Ecology). The potential for subsequent impacts to marine mammals and offshore ornithology from impacts to fish prey species has been assessed in Volume 2, Chapter 12 (Marine Mammals) and Volume 2, Chapter 11 (Offshore Ornithology), respectively. Furthermore, this report assesses the ecosystem level impacts from the Proposed Development across the key trophic levels (see Section 3).
September, 2023	Scottish Ministers – Scoping Opinion (via MD-LOT)	Consider including modifications to stratification and frontal features in the scope. A wind farm has the potential to alter water column mixing through the generation of turbulent wakes by its structures and/or by changing near sea surface wind speeds (Christiansen *et al*. 2022; Dorrell *et al*. 2022). Such alterations could significantly impact regions of stratification, like the proposed wind farm area, potentially affecting the extent and timing of seasonal stratification.	Stratification and frontal feature modifications have been included in the scope of the EIAR, as presented within Volume 2, Chapter 7 (Marine and Coastal Processes), as well as Volume 3, Appendix 7.1 (Marine and Coastal Processes Technical Report). A detailed technical assessment of the stratification is also provided in Annex A of this report. Furthermore, this report assesses the ecosystem level impacts from the Proposed Development that may arise as a result of stratification (see Section 3.2).
September 2023	NatureScot - Scoping Opinion (via. MD-LOT	NatureScot advise assessing impact holistically at a wider ecosystem scale in addition to the standard set of discrete individual receptor assessments to enable a better understanding of the consequences (positive or negative) of any potential changes in prey distribution and abundance from the development of the wind farm on seabird and marine mammal (and other top predator) interests and what influence this may have on population level impacts.	A holistic assessment has been undertaken, with links made to key aspects, such as ornithology and marine mammals in terms of prey availability. Impacts to key prey species (such as herring and sandeel) have been assessed in Volume 2, Chapter 10 (Fish and Shellfish Ecology). The potential for subsequent impacts to marine mammals and offshore ornithology from impacts to fish prey species has been assessed in Volume 2, Chapter 12 (Marine Mammals) and Volume 2, Chapter 11 (Offshore Ornithology), respectively. In addition, this report assesses the ecosystem level impacts (both positive and negative) from the Proposed Development across the key trophic levels (see Sections 3.3, 3.4 and 3.5).

Date	Consultee and Type of Consultation	Description/ Issues Raised	How this has been considered in the EIAR and Ecosystem Effects Assessment
September 2023	NatureScot - Scoping Opinion (via. MD-LOT)	NatureScot advise consideration is required in the EIA Report to ensure that impacts to key prey species and their habitats are considered for this development alone and cumulatively with other wind farms. The PrePARED (Predators and Prey Around Renewable Energy Developments) project [1] may be helpful in the understanding of predator-prey relationships in and around offshore wind farms. NatureScot advise that potential impacts on the minke whale protected feature of the Southern Trench Nature Conservation Marine Protected Area (NC MPA) via impacts on prey fish species is scoped into the assessment.	Impacts to key prey species (such as sandeel, herring, sprat and mackerel) and their supporting habitats have been assessed in Volume 2, Chapter 10 (Fish and Shellfish Ecology). Results from the PrePARED project have been used to inform the assessments in Volume 2, Chapter 10 (Fish and Shellfish Ecology) and this Ecosystem Effects Assessment. The potential for subsequent impacts to marine mammals from impacts to prey species has been assessed in Volume 2, Chapter 12 (Marine Mammals) and for ornithological features in Volume 2, Chapter 11 (Offshore and Intertidal Ornithology). Potential impacts on the Southern Trench NC MPA (of which minke whale are a qualifying feature) have been assessed in Volume 3, Appendix 9.2 (Marine Protected Area Assessment Report). This assessment includes consideration of potential impacts on minke whale through potential impacts on prey species. Furthermore, this report assesses the ecosystem level impacts from the Proposed Development across the key trophic levels (see Sections 3.3, 3.4 and 3.5).
September 2023	RSPB Scotland (Ornithology - Prey Species)	The RSPB highlights that sandeel are a Priority Marine Features (PMF) in Scotland due to their ecosystem importance and are vulnerable to impacts from development. The placement of a windfarm or cabling on top of a key sandeel spawning and nursery ground could have wider implications for recruitment into the sandeel population with secondary impacts to seabirds and other sandeel dependent species. The RSPB further notes that the proposed offshore export cable corridor overlaps with the Turbot Bank NC MPA. This is an important sandeel site,	Consideration of impacts to sandeel populations as a PMF from the Proposed Development alone and cumulatively with other projects have been assessed assessment in Volume 2, Chapter 10 (Fish and Shellfish Ecology). Additionally, sandeel have been assessed as a feature of the Turbot Bank NC MPA (see Volume 3, Appendix 9.2 (Marine Protected Area Assessment Report)). Furthermore, the potential effects of impacts to sandeel on local ornithology have also been considered in Volume 2, Chapter 11 (Offshore and Intertidal Ornithology). Lastly, this report assesses the ecosystem level impacts from the Proposed Development across the key trophic levels including seabirds (see Section 3.4).

[1] https://owecprepared.org/

Date	Consultee and Type of Consultation	Description/ Issues Raised	How this has been considered in the EIAR and Ecosystem Effects Assessment
		including for Raitt's sandeel (a UK BAP species) and has been identified as having potential to act as a source of young sandeel for maintaining and restocking surrounding areas.	

2. ECOSYSTEM BASELINE

2.1.1. This section provides an overview of the status of key trophic levels of the marine ecosystem, drawing on the information presented in the relevant EIAR Chapters (as outlined below). The section is structured by trophic level, starting with stratification of the water column and its role in primary production before moving onto prey species and higher trophic levels (seabirds and marine mammals and megafauna).

2.2. STRATIFICATION AND PRIMARY PRODUCERS

2.2.1. This section provides a summary of the baseline provided in Volume 2, Chapter 7 (Marine and Coastal Processes) and the bespoke stratification report produced by the Scottish Association of Marine Science (SAMS) (Annex A of this report).

2.2.2. Stratified seas play a key role in primary photosynthetic production. Primary production is the process that powers ocean ecosystems and contributes significantly to global oxygen and carbon cycles. Phytoplankton are the main producers, responsible for about half of the Earth's oxygen and carbon fixation (Longhurtst, 2007). The placement of anthropogenic structures into seasonally stratified waters can artificially increase the mixing of these waters (Bailey *et al.,* 2014). This may lead to an enhanced nutrient supply which, in turn, could impact the marine ecosystem.

2.2.3. Regional differences in stratification in the North Sea are largely driven by water depth, the strength of tidal currents, the proximity to the shelf edge where exchange with oceanic waters modifies water properties, and the influence of fresher water which is typically found nearshore (Huthnance, 1991). The North Sea is generally deeper in the north, with the deepest areas (exceeding 150 m) north of 57.5°N and between 2°W and 1°E. The Proposed Development has typical bottom depths in the range 60 m to 95 m, with deeper water generally in the north and shallower in the south, although there is local complexity (Figure 2-1).

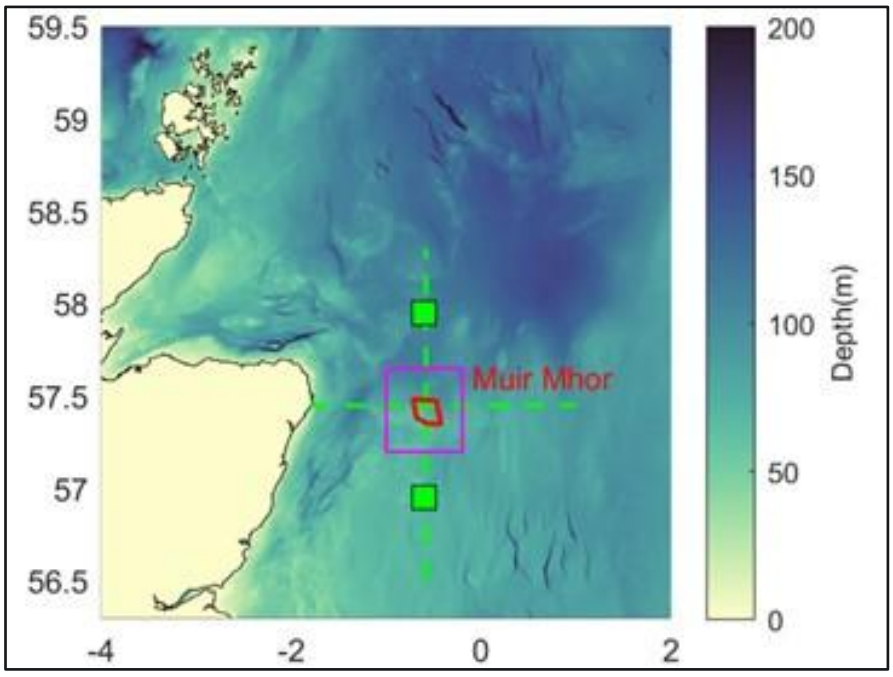

Figure 2-1 Bathymetry: General Bathymetric Chart of the Oceans (GEBCO) (depth in m) of the northern North Sea in relation to the Proposed Development East-west and north-south transects (green dashed) are discussed elsewhere. The magenta box shows the region searched for archived Conductivity, Temperature, and Depth (CTD) profiles. Green squares show comparative locations to the north and south (Annex A of this report).

Figure 2-2 Figure from Hill *et al*. (2008) showing the regions where summer stratification is driven by bottom cool, salty pools (orange) as opposed to cool only (grey). Red shows flows associated with the boundaries of these bottom dense pools (Annex A of this report).

2.2.4. In the winter, the North Sea is only stratified where coastal freshwater influence is significant (Huthnance, 1991), so stratification is driven by salinity. Elsewhere, water properties are uniform from the top to the bottom of the water column. The onset of stratification in spring occurs when the surface can warm through solar heating without being assimilated by stirring into underlying waters. Areas that are shallow or have strong tidal flows remain well-mixed throughout the year because there is enough tidal stirring to overcome the stratifying influence of solar heating. In the deepest areas of the northern North Sea, bottom waters retain their winter temperature and salinity throughout the year (orange in Figure 2-3; Hill *et al.* 2008), whilst the overlying surface waters warm and often freshen. More coastal areas show significant warming of bottom waters in summer, and the resulting gradient in density between these coastal waters and more offshore water leads to a surface current along the boundary between the two. This flows south to the east of Orkney and the outer Moray Firth, and then east into the central North Sea as the Dooley current. An additional influence is the fresher coastal water of the Scottish Coastal Current, which enters the North Sea via the Pentland Firth and to the north of Orkney, then also flows south, augmenting the flow and gradients described above.

2.2.5. During winter the water column in the North Sea is well-mixed, leading to a relatively uniform vertical distribution of chemical tracers such as nutrients and oxygen from the surface to the deep waters. Under these well-mixed conditions, any increase in turbulence kinetic energy (TKE) has little effect on the vertical distribution of nutrients. With the onset of thermal stratification and greater light availability in spring, phytoplankton begin to grow and reproduce, depleting nitrate and other essential nutrients from the surface layer (Annex A of this report). As warming progresses into summer, the surface waters become increasingly stratified from the nutrient-rich deeper waters, preventing the replenishment of nutrients at the

surface. By July, nitrate reaches limiting concentrations at the surface. In autumn, the breakdown of stratification allows nutrients to be resupplied to the surface and the water column becomes well-mixed again by October (Annex A of this report).

2.2.6. Chlorophyll-a (Chl-a), a photosynthetic pigment, serves as a proxy for biological productivity. In the context of this report, it is used to represent primary production, the lowest trophic level. During winter, Chl-a concentrations are low due to limited light and cooler temperatures, which restrict biological activity. In spring, phytoplankton blooms drive high levels of productivity in the North Sea, as nutrient concentrations are still abundant in sunlit surface waters. By summer, productivity declines as nutrient availability becomes limiting, and surface Chl-a concentrations decrease. These patterns of summer stratification and nitrate limitation are typical across the wider North Sea. Under these conditions the establishment of a sub-surface chlorophyll maximum (SCM) is often seen. In more stratified conditions, the SCM is more pronounced and there is a stronger nitricline (difference between surface and deep-water nitrate). An increase in Chl-a is observed in autumn as nutrient replenishment occurs with the breakdown of stratification but further declines with decreasing temperature and light availability in October (Figure *2-3*).

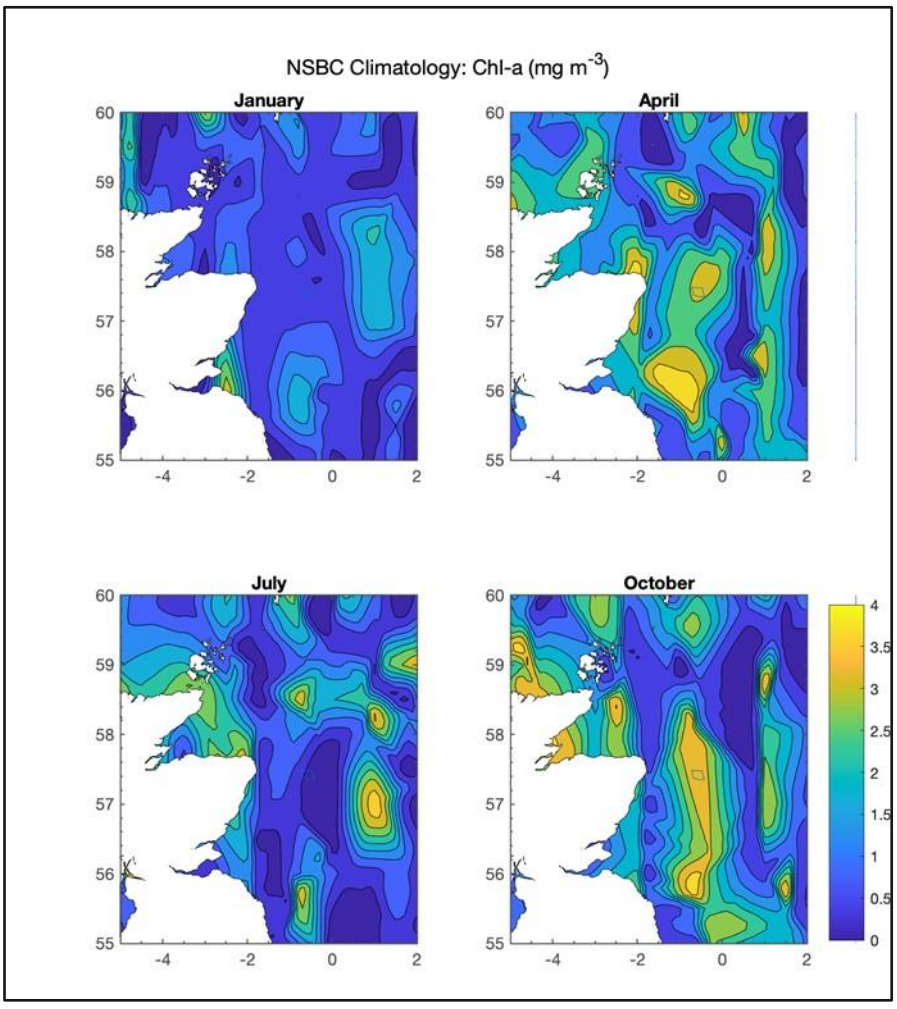

Figure 2-3 Maps of Chl-a (mg m $^{-3}$) concentration in winter, summer, spring and autumn, taken from the North Sea Biogeochemical Climatology (NSBC) climatology (Annex A of this Report).

2.2.7. Nitrate is considered the primary limiting nutrient in the North Sea and shows the sharpest decline, becoming limiting to phytoplankton by May/June Phosphate and silicate concentrations decrease but do not decrease to concentrations considered limiting to phytoplankton (Figure 2-4). Chl-a concentrations are highest from April to September, with

productivity decreasing slightly in summer when surface waters are most stratified from the nutrient replete waters below.

2.2.8. Further details on stratification and primary producers relating to the Proposed Development can be found in Volume 2, Chapter 7 (Marine and Coastal Processes) and the bespoke SAMS Stratification Report (Annex A of this report).

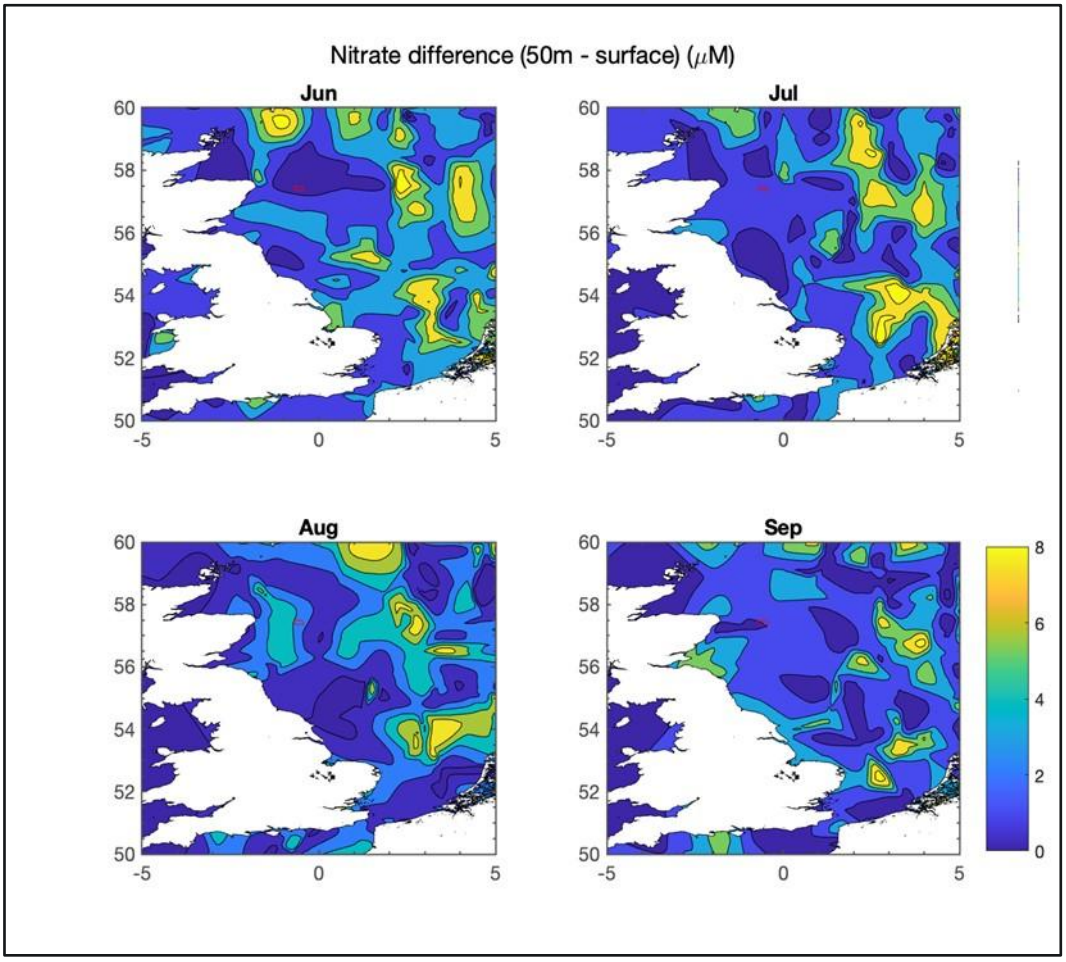

Figure 2-4 Maps of the difference between nitrate at 50 m and nitrate at the surface, an indicator of the degree of stratification and nutrient limitation to surface phytoplankton (Annex A of this report).

2.3. PREY SPECIES

2.3.1. This section provides a summary of the baseline provided in Volume 2, Chapter 9 (Benthic, Subtidal and Intertidal Ecology) and Volume 2, Chapter 10 (Fish and Shellfish Ecology) and wider evidence that is relevant to this ecosystem effects assessment.

2.3.2. Prey species, such as forage fish (such as sandeel, sprat and herring) and invertebrates (such as copepods and krill) are crucial to the marine ecosystem as they form the foundation of the diet for many higher trophic level predators, including larger fish and crustaceans, seabirds and marine mammals. In recent years, the populations of these prey species have shown variability due to a number of anthropogenic factors, including climate change, habitat degradation and fishing pressure.

2.3.3. Copepods and krill (both of which are crustaceans) are key components of the zooplankton community in the North Sea and serve as a critical food source for forage fish such as herring and sandeels. The abundance and distribution of zooplankton has been heavily influenced by warming sea temperatures, which have led to shifts in the composition of zooplankton communities. For example, cold-water species of copepods, such as *Calanus finmarchicus*,

have been declining, while warmer-water species, such as *Calanus helgolandicus*, have been increasing in abundance (Beaugrand *et al.,* 2003). These shifts can affect the availability of nutritious prey for fish larvae, leading to potential bottlenecks in fish population dynamics.

2.3.4. Benthic species are foundational to the structure and function of marine ecosystems, influencing everything from nutrient cycling to habitat formation and food web dynamics (Snelgrove, 1999). During site specific surveys for the Proposed Development, a total of 10,135 individuals, representing 332 taxa were recorded in the grab samples collected at 43 stations across the Array Area. Annelida represented the most diverse and abundant group of animals with 157 taxa identified, representing 39.9% of individuals recorded. Crustacea were represented by 90 taxa and 10.9% of the total individuals, molluscs by 55 taxa and 4.4% of individuals and echinoderms by ten taxa and 10.4% of the total individuals. All other groups (*Chaetognatha, Nematoda, Nemertea and Hemichordata*) were represented by nine taxa (accounting for 24.6% of the total number of individuals). Hydrozoa/bryozoa, hermit crabs (*Pagurus sp.)* and flatfish (*Pleuronectiformes*) were observed frequently across the Array Area. Other fauna such as queen scallop (*Aequipecten opercularis*) were also observed across the three habitats but less frequently overall. The 'Muddy Sand' area in the northern part of the Array Area (Figure *2-5*) featured some fauna unique to this habitat such as phosphorescent sea pen (*Pennatula phosphorea*). Other sessile fauna was found across the Array Area such as anemones (*Actinaria*) and these were found to often associate with hard substrates in the region such as cobbles and boulders. Echinoderms such as the common sea star (*Asterius rubens*) and cushion star (*Porania pulvillus*) were observed frequently throughout the site whereas sea urchins (*Echinoidea*) were rarer.

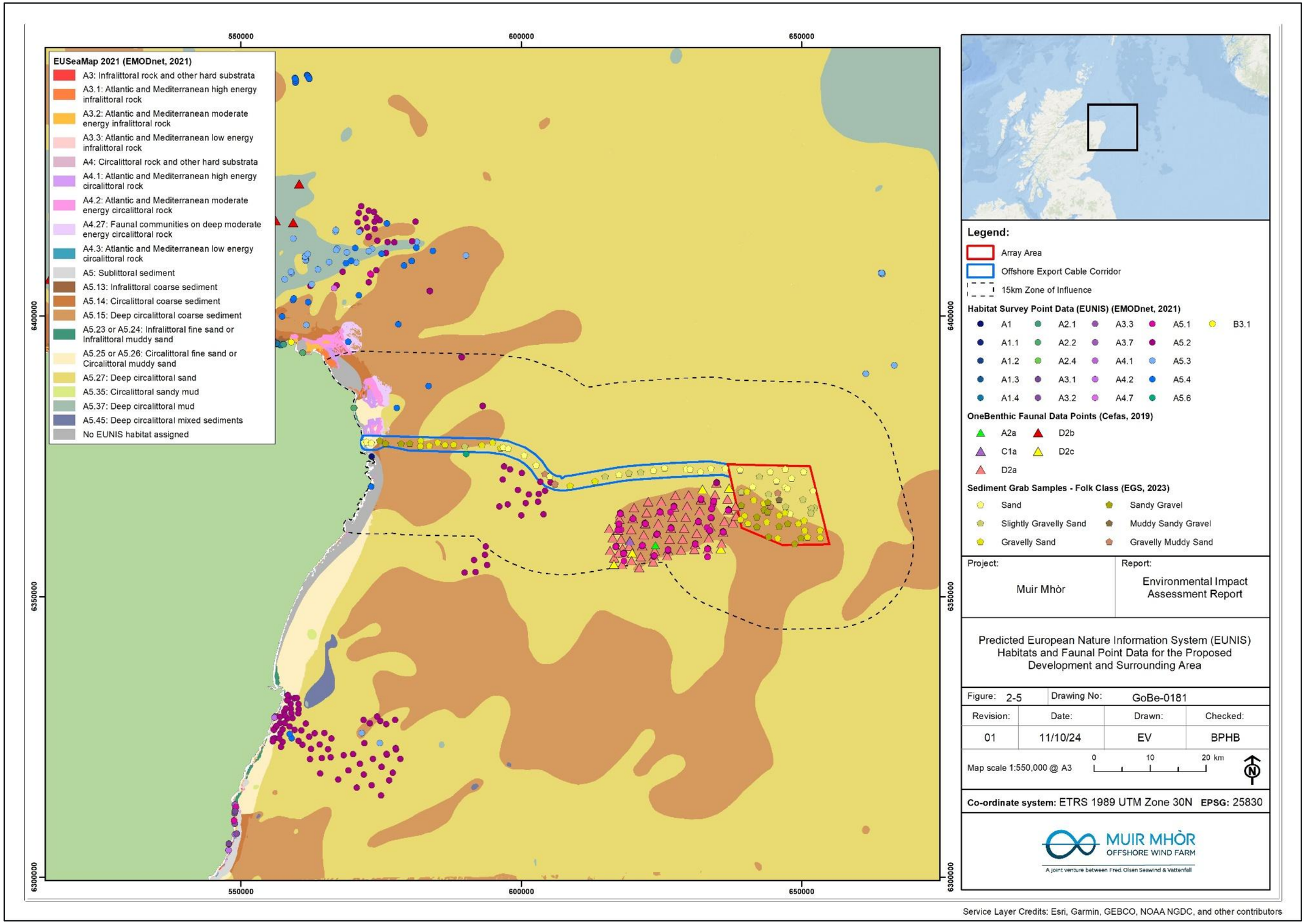

Figure 2-5 Predicted European Nature Information System (EUNIS) Habitats and Faunal Point Data for the Proposed Development and Surrounding Area

2.3.5. The following shellfish species are present within the vicinity of the Proposed Development (as informed by the baseline characterisation (Volume 2, Chapter 10)); veined squid (*Loligo forbesi*), brown crab (Pagurus cancer), velvet crab (*Necora puber*), scallop (*Pecten maximus*), Norway lobster (*Nephrops norvegicus*) (hearafter referred to as 'Nephrops') and European lobster (*Homarus gammarus*) (MMT, 2013). Shellfish stocks in the Northern North Sea, particularly species like brown crab, European lobster, scallops and Nephrops are economically and ecologically important (ICES, 2022). These species are heavily harvested by commercial fisheries, but like many marine stocks, they are affected by a range of pressures, including fishing intensity, environmental changes, and habitat degradation. The status of shellfish stocks in the Northern North Sea varies by species, but overall, stocks are being actively managed to prevent overexploitation. While some stocks, like Nephrops and brown crab, are considered stable, ongoing monitoring and management are necessary to ensure long-term sustainability (ICES 2022).

2.3.6. Bottom trawl and beam trawl surveys were undertaken throughout the northern North Sea, from 2019 and 2023 as part of the North Sea International Bottom Trawl Survey (ITBS) and the North Sea Beam Trawl Surveys (ICES, 2023a). The trawl surveys identified fish assemblages consisting of haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), herring, Norway pout (*Trisopterus esmarkii*), cod (*Gadus morhua*), Atlantic mackerel (*Scomber scombus*), plaice (*Pleuronectes platessa*), anglerfish (*Lophiiformes*) and Raitt's sandeel (*Ammodytes marinus*). An extensive literature review by Ellis *et al.* (2004) found that elasmobranch populations identified within this region include spurdog (*Squalus acanthias*), lesser spotted dogfish (*Scyliorhinus canicular*), starry ray (*Amblyraja radiata*), cuckoo ray (*Leucoraja naevus*), thornback ray (*Raja clavata*) and spotted ray (*Raja montagui*). Otter trawl surveys conducted in March 2021 to identify cod distributions across the Beatrice OWF site, revealed haddock was the most abundant species accounting for the majority of the total by-catch, followed by whiting and squid, whilst cod abundance was relatively low (Beatrice OWF, 2021a).

2.3.7. Site specific surveys have been carried out for the Proposed Development. In the Array Area, eDNA surveys indicated the presence of various fish species, including Atlantic herring, whiting, European hake, Atlantic mackerel, and cuckoo skate/ray, and Norway pout. In the offshore Export Cable Corridor (ECC), surveys recorded the presence of herring, whiting, hake (*Merluccius merluccius*), brown trout (*Salmo trutta*), Atlantic mackerel, and three-spined stickleback (*Gasterosteus aculeatus*).

2.3.8. Several species of fish and shellfish (including key prey species such as herring, plaice, cod and whiting) are known to either spawn or have nursery areas in relatively close proximity to, or potentially overlapping with the Proposed Development (National Marine Plan interactive (NMPi), 2015, as categorised by Coull *et al., 1998* and *Ellis et al.,* 2012). The wider spawning and nursery sites identified within and in proximity to the Proposed Development, as well as spawning timings, are presented in Volume 3, Appendix 10.1 (Fish and Shellfish Technical Report) and summarised below.

2.3.9. The Proposed Development also overlaps with high intensity sandeel spawning grounds as categorised by Coull *et al.,* 1998 and Ellis *et al.,* 2012. Sandeels are considered a key prey species in the North Sea, but their populations have fluctuated significantly over the past few decades (McDonald *et al.,* 2019). Sandeel are highly sensitive to changes in water temperature and habitat conditions, and warming sea temperatures have contributed to declines in their abundance in some areas. Sandeels play a vital role in the Scottish marine ecosystem, acting as a crucial food source for seabirds, marine mammals, and predatory fish. Prior to the recent prohibition on commercial sandeel fishing in Scottish waters, sandeels held a significant position as a target species for Scottish fishing vessels. Sandeel landings by

Scottish vessels experienced notable fluctuations, with quantities often surpassing 100,000 tonnes annually during the early 2000s, reaching a peak of over 150,000 tonnes in 2002 (Marine Scotland, 2023). However, in the late 2000s and 2010s, landings dwindled, averaging around 50,000-70,000 tonnes per year (Marine Scotland, 2023). The recent decline in sandeel populations has had significant repercussions on reliant species, contributing to declines in seabird populations and impacting the overall marine ecosystem's health (Marine Scotland, 2023).

2.3.10. The Array Area and offshore ECC lie within the Buchan herring stock spawning ground that runs along the east coast of Scotland and extends offshore (NMPi, 2015, as categorised by Coull *et al*., 1988). The status of herring in the North Sea is currently stable, with stocks remaining above safe biological limits (ICES, 2023b). The Total Allowable Catch (TAC) for North Sea herring in 2023 is set at 511,171 tonnes, reflecting a cautious approach to ensure the stock remains within safe biological limits (ICES 2023b). This is slightly reduced from previous years due to concerns about recruitment and environmental changes. The Proposed Development sits within ICES Sea Division 4.b. This area remains above the precautionary reference point, indicating that the stock is not at immediate risk of collapse (ICES, 2023b). However, fluctuations in recruitment and environmental changes pose ongoing challenges for future stock sustainability.

2.3.11. Forage fish play a pivotal role in the transfer of energy from some of the lowest to the highest trophic levels within the ecosystem and serve to recycle nutrients from higher levels through the consumption of detritus. Consequently, their populations will be determined by both top-down factors such as predation, and bottom-up factors such as ocean climate and plankton abundance. Forage fish such as sandeel (*Ammodytidae* spp), herring (*Clupea harengus*), and sprat (*Sprattus sprattus*) are important prey items for top marine predators including elasmobranchs, seabirds and cetaceans, and small planktivorous species act as important links between zooplankton and higher trophic levels (Frederiksen *et al.,* 2006). The stocks of these forage fish in the Northern North Sea have fluctuated over the past decade (ICES, 2023c). However, populations are starting to recover after suffering from overfishing during the 20th century, thanks to better fisheries management, including stricter quotas under the European Union's (EU) Common Fisheries Policy (Trenkel *et al*., 2013). However, these species are vulnerable to environmental changes and require close monitoring and resilient management to ensure the health of their stocks and the associated importance they have on the wider ecosystem.

2.3.12. There have been substantial changes in the prey species communities in the northeast Atlantic, specifically the North Sea, over several decades as a result of a number of factors including climate change and fishing activities (Blanchard *et al* 2012; Gordó -Vilesca *et al*., 2024). These communities consist of species that have complex interactions with one another and the natural environment. Fish and shellfish populations are subject to natural variations in population size and distributions, largely as a result of year-to-year variation in recruitment success and these population trends will be influenced by broad-scale climatic and hydrological variations, as well as anthropogenic impacts such as climate change and overfishing (see Section 4).

2.4. SEABIRDS

2.4.1. This section provides a summary of the current status of the baseline provided in Volume 2, Chapter 11 (Offshore and Intertidal Ornithology), and wider evidence that is relevant to this ecosystem effects assessment.

2.4.2. Seabirds play an important role in the marine environment and act as indicators of healthy ecosystems (Wanless *et al*., 1998). They can provide early indications of oceanographic conditions, pollution, and fish stock fluctuations (Barrett *et al*, 2007; Romero *et al*., 2021). For example, seabird tissues can be used to assess bioaccumulation of pollutants, while stress response to changes in the marine environment can be readily seen through monitoring via reduced reproductive effort, breeding success, or survival (Mallory *et al.,* 2010). Changes in prey species are reflected in seabird population abundances (Parsons *et al.,* 2008). For example, sandeel specialists, which include guillemot, razorbill, kittiwake, and puffin (Wanless *et al.,* 1998), constitute one possible indicator of wider ecosystem health, as their decline has been linked to low sandeel availability in their usual foraging areas (Parsons *et al.,* 2008). As such, the productivity of a sandeel specialist seabird provides insights into sandeel availability to other predator groups, such as cetaceans (Parsons *et al.,* 2008). Similarly, chick diet composition in species such as gannet and kittiwake which consume herring can reveal information on the distribution and abundance of juvenile herring (Overholz and Link, 2007; Scopel *et al.,* 2017).

2.4.3. Where preferred prey become scarce, seabirds have been known to switch to other prey species, which can have a negative effect on the growth and survival of chicks due to the differences in prey energy density and amount (Barrett *et al.,* 2007; Kowalcyzk *et al*., 2013; Watanuki *et al.,* 2022). A sudden shift in diet for generalist or opportunistic species can thus serve as an indicator of the wider pelagic ecosystem health (Romero *et al.,* 2021). For example, Romero *et al.* (2021) analysed regurgitations of Corey's shearwater (*Calonecric borealis*) on Selvagens islands in the Northeast Atlantic and found that their shifts in diet (from Atlantic chub mackerel (*Scomber colias*) to Longspine snipefish (*Macroramphosus scolopax*)) were linked to changes in the composition of pelagic fish communities, possibly due to fisheries management and/or the North Atlantic Oscillation.

BASELINE ASSESSMENT RESULTS

2.4.4. The offshore and intertidal ornithological study area is defined as the Proposed Development footprint and a 4 km buffer (Figure 2-6), added to consider the impacts that can occur beyond the extent of the Proposed Development. The study area also includes protected sites within the area, such as Special Protection Areas (SPAs), with designated ornithological features.

2.4.5. Surveys to inform the site-specific Proposed Development area were carried out between April 2021 and March 2023, and to inform the regional survey area between April 2022 and August 2023, both by HiDef Aerial Surveying Limited (HiDef). The surveys encompassed the offshore Array Area as well as part of the ScotWind E2 Plan Option (PO) area, including a 4 km survey buffer. Raw video footage was processed for analysis and reviewed by ornithologists. Birds were identified to species level where possible.

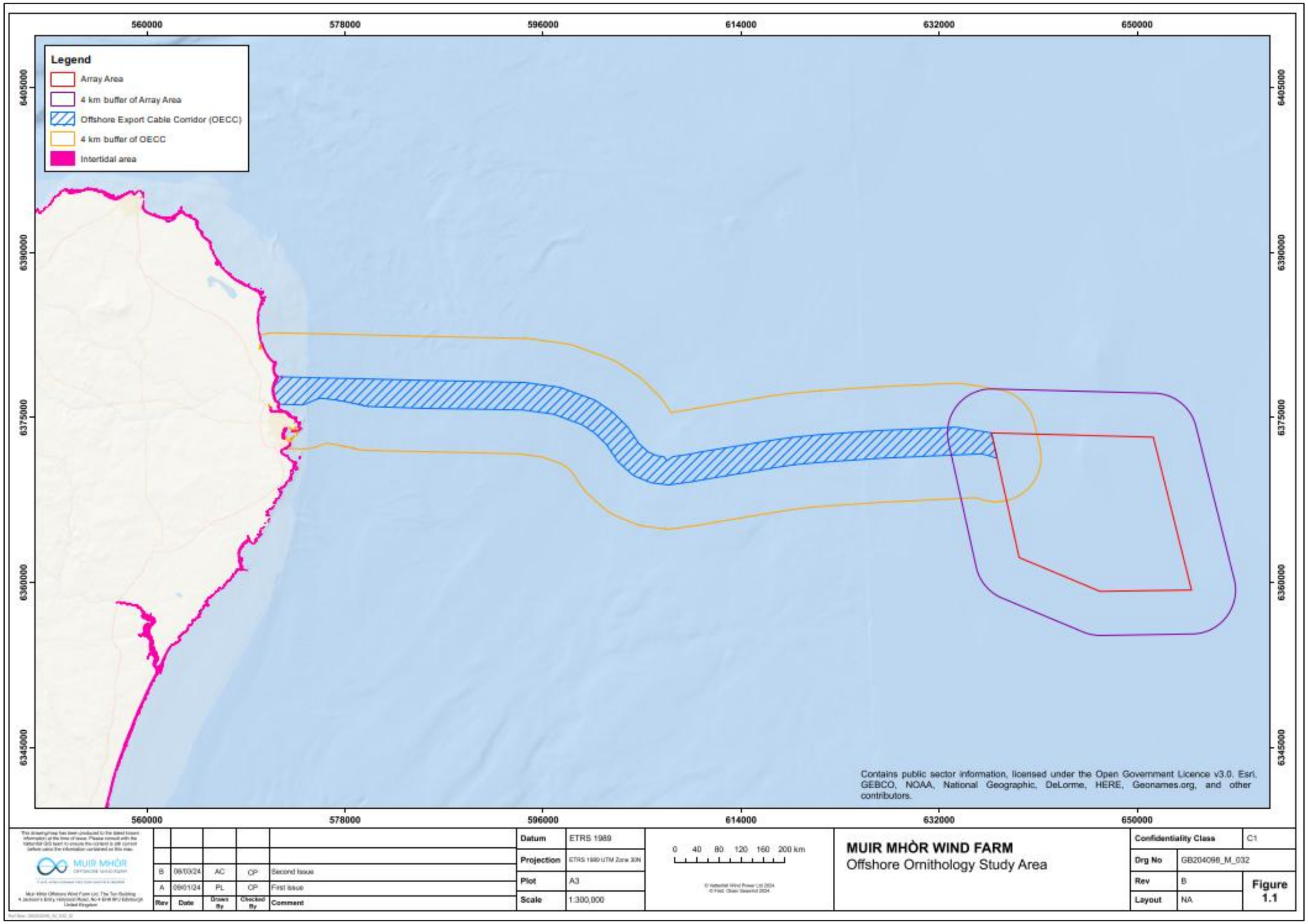

Figure 2-6 The offshore and intertidal ornithology study area: a 4 km buffer around the Array Area and offshore ECC transects

2.4.6. From the surveys, a list of avian species was collected that featured both seabirds and intertidal species such as waders and wildfowl. The list of seabird species identified (offshore area only) can be found in Table 2-1.

Table 2-1 List of seabird species identified by offshore DAS.

Species	Latin name
Arctic tern	*Sterna paradisaea*
Arctic skua	*Stercorarius parasiticus*
Black-headed gull	*Chroicocephalus ridibundus*
Common gull	*Larus canus*
Common tern	*Sterna hirundo*
European storm petrel	*Hydrobates pelagicus*
Fulmar	*Fulmarus glacialis*
Gannet	*Morus bassanus*
Great black-backed gull	*Larus marinus*
Great skua	*Stercorarius skua*
Guillemot	*Uria aalge*
Herring gull	*Larus argentatus*
Kittiwake	*Rissa tridactyla*
Leach's storm petrel	*Hydrobates leucorhous*
Little auk	*Alle alle*
Manx shearwater	*Puffinus puffinus*
Puffin	*Fratercula arctica*
Razorbill	*Alca torda*

2.4.7. Species were scoped in or out for assessment based on the surveys and the number of observations of each species. As such, arctic skua, black-headed gull, common tern, and little auk were scoped out, while the other species listed in Table 2-1 were scoped into the assessments for the offshore areas. The species focused on in this report are guillemot, razorbill, puffin, kittiwake, and gannet, as these species have been identified for compensation following the conclusions of the Report to Inform Appropriate Assessment (RIAA) (Muir Mhòr Offshore Wind Farm Limited, 2024).

2.4.8. Auks (guillemot, razorbill, and puffin) were all recorded in the surveys, and are thought to be present in the offshore study area in both summer and winter (Wakefield *et al.,* 2017; Cleasby *et al.,* 2018; Waggit *et al.,* 2019). They are also a breeding season feature for the following designated sites within the species foraging range from the Proposed Development: Troup, Pennan and Lion's Heads SPA (for guillemot and razorbill), and Buchan Ness to Collieston Coast SPA (all auks). According to Burnell *et al.* (2023), in terms of population trends, between the Seabirds 2000 (1998-2002) counts and the recent Seabirds Counts (2015-2021), puffin populations have declined by 24% in Britain and Ireland, guillemot populations have decreased by 8%, and razorbill populations have increased by 18%.

2.4.9. Kittiwake were recorded in all calendar months and are present in the offshore study area in both summer and winter (Wakefield *et al.,* 2017; Waggit *et al*., 2019). Tracking studies of kittiwakes from Bullers of Buchan, Fair Isle, Isle of May and Whinnyfold show flight tracks that traversed the Proposed Development (BirdLife International, 2023). In terms of population trends, between the Seabirds 2000 (1998-2002) counts and the recent Seabirds Counts (2015-2021), kittiwake populations have declined by 42% in Britain and Ireland (Burnell *et al*., 2023).

2.4.10. Gannet were recorded in almost all calendar months. Gannets are present in the offshore study area in summer and winter (Waggit *et al.,* 2019). Tracking studies have shown that birds from the Bass Rock (the largest gannet colony and part of the Forth Islands SPA) will fly through this area in the summer (Cleasby *et al.,* 2015). Gannets are a breeding season feature for the several designated sites within the species' foraging range from the Proposed Development, including the Outer Firth of Forth and St Andrews Bay Complex SPA. In terms of population trends, between the Seabirds 2000 (1998-2002) counts and the recent Seabirds Counts (2015-2021), gannet populations have increased by 38% in Britain and Ireland (Burnell *et al.,* 2023). However, as discussed in Section 4.7, gannet populations have been particularly affected by Highly Pathogenic Avian Influenza (HPAI) in recent years, with substantial declines recorded (Tremlett *et al.,* 2024).

2.4.11. Threats and pressures currently impacting populations of seabirds on the east coast of Scotland include climate change, fisheries management (i.e., prey availability and by-catch), Invasive Non-Native Species (INNS), recreational activities, human disturbance and interspecific competition (NatureScot, 2024a). In recent years, HPAI has had a devastating impact on seabird populations in Scotland and across Europe more widely (Tremlett *et al*., 2024).

2.5. MARINE MAMMALS AND MEGAFAUNA

2.5.1. This section provides a summary of the marine mammal and megafauna baseline outlined in Volume 2, Chapter 12 (Marine Mammals) and Volume 2, Chapter 10 (Fish and Shellfish Ecology), and wider evidence that is relevant to this ecosystem effects assessment.

2.5.2. Marine mammals are considered generalist feeders and are not dependent on a single prey species (Evans and Hinter, 2013). Most species can likely supplement their diet with other suitable species, if required, making them resilient to changes in prey availability. Minke whales, however, specifically target sandeels within the Southern Trench NC MPA (NatureScot, 2020).

2.5.3. The marine mammal study area is defined at two spatial scales:

- The local study area including site-specific survey area (Scotwind E2 PO site) plus a 4 km buffer (HiDef, 2023a) and the regional survey (Scotwind E1 and E2 PO site) with 12 km buffer (HiDef, 2023b) (Figure 2-7); and
- Wider study area using the Management Units (MUs) defined by the Inter Agency Marine Mammal Working Group (IAMMWG, 2023) and the Seal Management Units (SMUs) defined by the Special Committee on Seals (SCOS, 2023) (Figure 2-8).

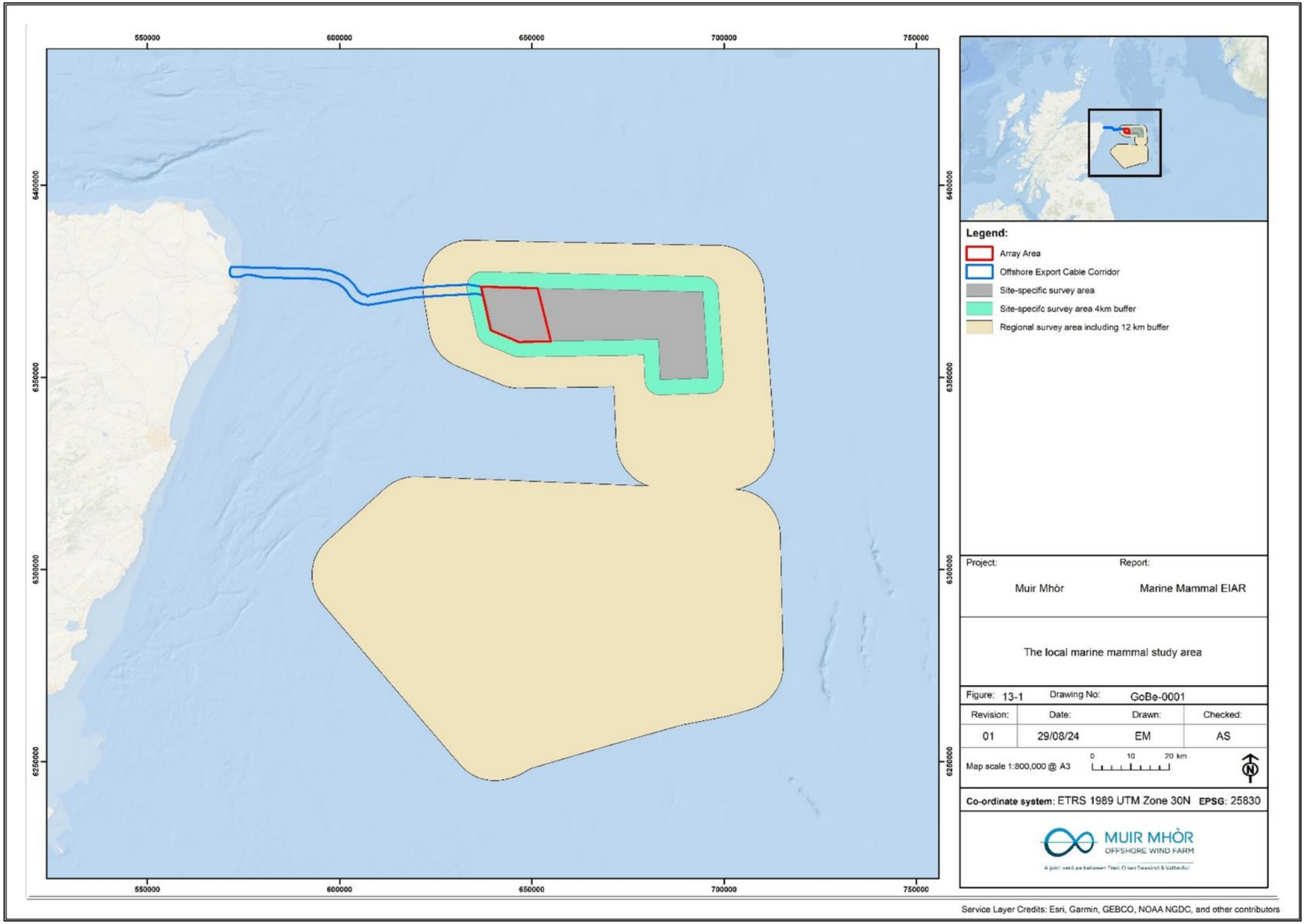

Figure 2-7 The local marine mammal study area

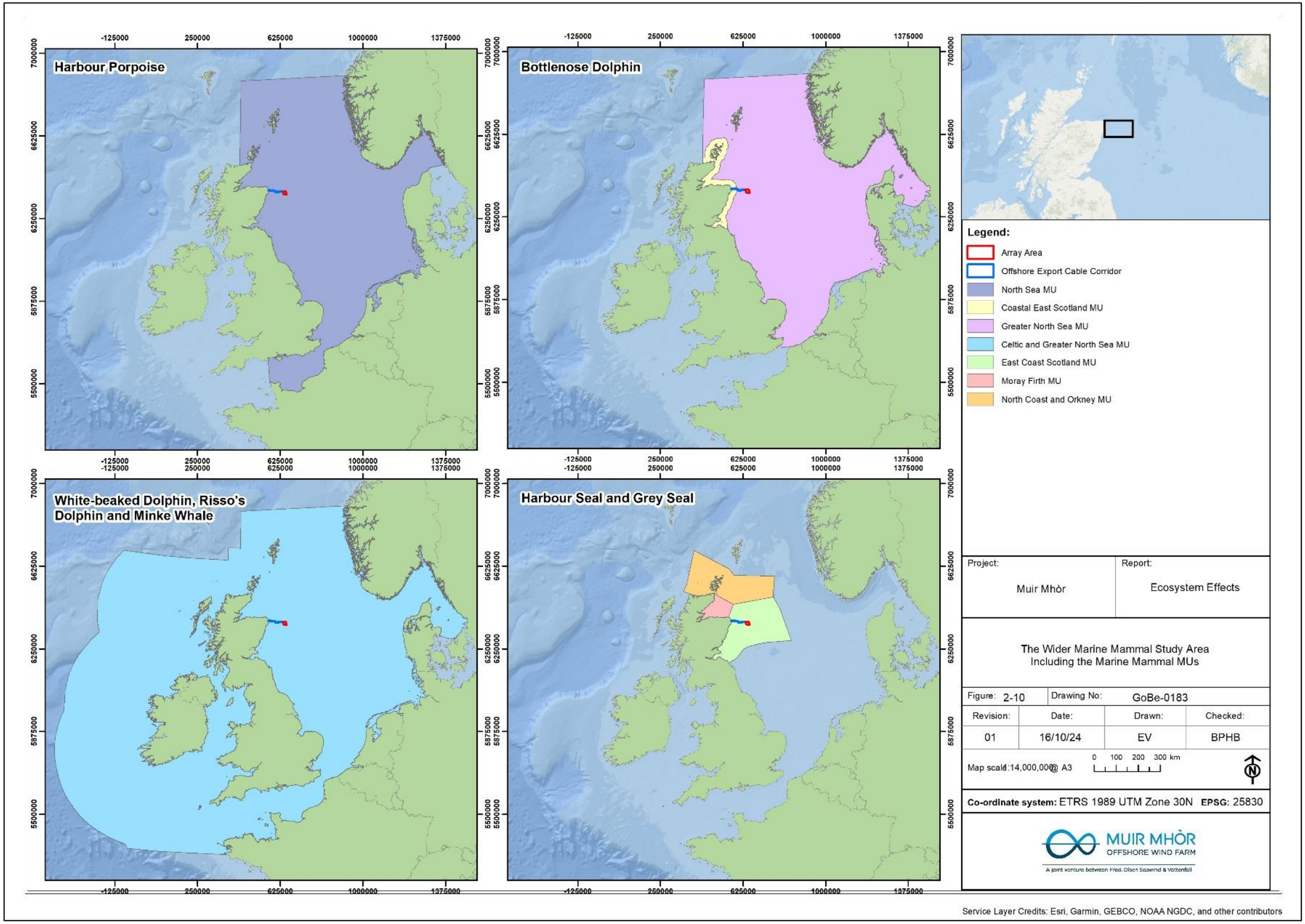

Figure 2-8 The wider marine mammal study area including the Marine Mammal MUs

2.5.4. Site-specific DAS were carried out over the local study area between April 2021 and March 2023 (HiDef Aerial Surveying, 2023a), and regional surveys were carried out between April 2022 and August 2023, both by HiDef (HiDef Aerial Surveying, 2023b). Details of the DAS are outlined in paragraph 2.4.5.

2.5.5. The local study area provides an indication of the local densities of each species whereas the wider study area provides a larger geographic context in terms of species presence. The wider study area for each species is:

- Harbour porpoise (*Phocoena phocoena*): North Sea MU;
- Bottlenose dolphin (*Tursiops truncatus*): Coastal East Scotland and Greater North Sea MUs;
- White-beaked dolphin (*Lagenorhynchus albirostris*): Celtic and Greater North Sea MU;
- Risso's dolphin (*Grampus griseus*): Celtic and Greater North Sea MU;
- Minke whale (*Balaenoptera acutorostrata*): Celtic and Greater North Sea MU;
- Harbour seal (*Phoca vitulina)*: the East Scotland SMU; and
- Grey seal (*Halichoerus grypus)*: the East Scotland, Moray Firth, and North Coast and Orkney SMUs.

2.5.6. In addition, killer whale (*Orcinus orca*) is included within the baseline characterisation based on sightings from Marine Mammal Observers (MMOb) during the geophysical surveys for the Proposed Development. Humpback whales (*Megaptera novaengliae*) have also been included as opportunistic sightings in 2017 and 2018 suggested an increase in the species in the Firth of Forth during winter months (O'Neil *et al.*, 2019). Since then, public sightings of humpback whales in the Firth of Forth have become more numerous (Hague, 2023). For both species there is no defined MU. As both the site-specific data and the wider literature review provided no evidence of Atlantic white-sided dolphin (*Lagenorhynchus acutus*) this species was scoped out.

2.5.7. Throughout the two years of site-specific surveys from April 2021 to March 2023, harbour porpoise was the most abundant non-avian species present. There was clear seasonal variation in harbour porpoise density across the seasons, with the average density highest during the spring (March, April and May) and lowest in winter (December, January and February) (HiDef Aerial Surveying, 2023a). Additionally, white-beaked dolphin, Risso's dolphin, minke whale, harbour seal and grey seals were sighted during the site-specific surveys (HiDef Aerial Surveying, 2023). Bottlenose dolphin were not sighted in any of the project surveys (site-specific, regional or geophysical MMOb surveys) or the Small Cetaceans in European Atlantic waters and the North Sea (SCANS) -IV (Gilles *et al.,* 2023) survey block NS-D that the Proposed Development is in, however, there were sightings in survey block R of SCANS III (Hammond *et al.,* 2021; Lacey *et al.,* 2022).

2.5.8. Marine megafauna are defined as all large organisms (body mass >45 kg) inhabiting the coastal and open oceans including bony fishes and elasmobranchs. Site-specific eDNA surveys were conducted in the Array Area and offshore ECC in September 2023. eDNA surveys are a non-intrusive technique used to detect species presence by analysing the DNA present in water and sediment samples.

2.5.9. In the Array Area, eDNA surveys (Volume 3, Appendix 9.1 (Offshore Baseline Surveys)) indicated the presence of various megafauna species such as long-nosed skate (*Beringraja rhina*) and porbeagle *(Lamna nasus*). Porbeagles are listed as a PMF. In the offshore ECC,

eDNA surveys (Volume 3, Appendix 9.1 (Offshore Baseline Surveys)) also indicated the presence of starry smooth-hound (*Mustelus asterias*).

2.5.10. Basking sharks (*Cetorhinus maximus*) were not detected in any surveys, however, were included within Volume 2, Chapter 10 (Fish and Shellfish Ecology) based on literature reviews and they are listed as PMF. Basking shark have been sighted in and around the Moray Firth region (NMPi, n.a).

3. ECOSYSTEM LEVEL IMPACTS FROM THE PROPOSED DEVELOPMENT

3.1.1. This section provides a summary of the ecosystem level impacts that may arise from the Proposed Development. This section draws on the information provided in the relevant EIAR Chapters and is structured through a 'bottom-up' approach beginning with physical processes and its role in primary production at the base of the marine ecosystem, before moving into the higher trophic levels (prey species, seabirds and marine mammals and megafauna).

3.2. STRATIFICATION AND PRIMARY PRODUCERS

3.2.1. This section provides a summary of some of the conclusions of Volume 2, Chapter 7 (Marine and Coastal Processes), relating to stratification and this ecosystem effects assessment and a summary of the effects outlined in the bespoke Stratification Report produced by SAMS (Annex A of this report).

3.2.2. There is evidence that offshore wind turbine foundations can enhance turbulent mixing in the thermocline, increasing nutrient availability to the SCM, and therefore increase annual primary production (Carpenter *et al.,* 2016; Slavik *et al.* 2018), although these studies have been focused on shallower waters with monopile structures.

3.2.3. The water column at the Proposed Development is deeper and becomes stratified in the summer months, with stratification developing in April/ May, peaking in August and absent by November. The summer nutrient gradient between surface and deep waters appears to be weaker than further east in the Northern North Sea (Annex A of this report). Therefore, the effects of changes to mixing at the Proposed Development are expected to be smaller compared to other regions of the North Sea.

3.2.4. The conversion of energy to TKE due to interactions between ambient flow and turbine structures and moorings have been estimated in two scenarios (Annex A of this report). A 'worst case' scenario consisted of 67 turbines with larger associated structures and fouled catenary mooring lines of up to 1600 m in length. The second 'smaller' scenario consisted of 44 turbines with tension leg moorings. The worst case is very significantly different, in presenting more than six times the surface area to the ambient flow and resulting in a proportional uplift in TKE and associated impacts. In the second smaller scenario, the production of TKE due to the structures was estimated to be around 20% of the production by natural bed stress (Annex A of this report). During stratified periods of the year, this could be inferred to drive a corresponding enhancement of fluxes to surface waters. Simulations suggest that water that experiences enhanced turbulence at the Array Area is transported to the east in the southern flank of the Dooley Current and in a sector between east and south (Annex A of this report). While this does not modify the total excess flux to surface waters, it spreads the impact of this flux and dilutes its local magnitude. Given the large difference between the two turbine scenarios considered, a factor of more than 6 in the energy converted to turbulence, it is important to clarify the exact structure and mooring system to be used. Given the magnitude of energy conversion in the worst case the possibility of modification of the ambient flow should be considered.

3.2.5. As presented by SAMS (Annex A of this report), available datasets and the suite of measurement data (Volume 2 Chapter 7 (Marine and Coastal Processes)) demonstrate that the thermocline depth within the Array Area varies between 10 m and 50 m below the water surface. Additionally, the Proposed Development site does not develop strong nutrient

limitation until August, therefore any effects of changes to mixing will only be over a short duration. The data suggests that the Proposed Development may cause localised alterations to TKE and impact localised stratification, with a greater potential to cause mixing during the summer months. This in turn may increase nutrient availability, during otherwise limiting summer months, which may lead to potential for a positive increase in primary productivity as a result. Stronger mixing would drive more nutrients to the SCM and support enhanced phytoplankton growth, potentially reducing the stratified period. The increases in mixing may shift the onset and breakdown of stratification, having a localised knock-on effect to the marine ecosystem. The length of stratification will likely influence seasonally integrated primary production. From the available nutrient data, it suggests that temporal changes may be limited as the nitrate-limited season is relatively short at the Array Area.

3.3. PREY SPECIES

3.3.1. This section provides a summary of the conclusions of Volume 2, Chapter 9 (Benthic Subtidal Ecology) and Volume 2, Chapter 10 (Fish and Shellfish Ecology) and ecosystem level impacts that may arise from the Proposed Development.

3.3.2. The impacts to prey species are most linked with increased Suspended Sediment Concentrations (SSCs) and associated sediment deposition, Underwater Noise (UWN) and habitat loss and disturbance. All of the impacts from the Proposed Development result in either a minor or negligible impact, in EIA terms, to the key receptors identified in Volume 2, Chapter 9 (Benthic Subtidal Ecology) and Volume 2 Chapter 10 (Fish and Shellfish Ecology).

3.3.3. Although there are a number of prey fish species that are present in the vicinity of the Proposed Development, from an ecosystem perspective it is worth considering the potential impacts to sandeel and herring, and their ability to recover, given their importance in the food web.

SANDEEL

3.3.4. Sandeel are demersal and require specific substrate for spawning which makes them vulnerable to impacts from construction activities (as detailed in Volume 2, Chapter 10 (Fish and Shellfish Ecology)). However, results from a post-construction monitoring study at the Beatrice OWF indicated that sandeel abundance either increased or remained the same when comparing data from 2014 to 2020, with the offshore construction of the wind farm beginning in April 2017 (Beatrice OWF, 2021b). The report found no evidence suggesting that construction had any adverse effects on the local sandeel population. Similarly, both short-term and long-term monitoring studies at the Horns Rev OWF in the Baltic Sea, Denmark, demonstrated that the construction and operation (van Deurs *et al*., 2012) of the wind farm did not result in significant negative impacts on sandeel populations. Additionally, the sandeel populations were observed to recover quickly following construction, suggesting that a similar recovery can be expected for the Proposed Development after construction activities have finished. Specifically, Jensen *et al.,* (2011) found that sandeel populations mix over distances of up to 28 km, implying that some recovery of adult populations will occur with adults recolonising appropriate sandy substrates from nearby unaffected habitats. Recovery may also occur through the larval recolonisation of suitable sandy sediments, as sandeel larvae are likely to be dispersed throughout the sea in the vicinity of the Proposed Development during the spring months following their winter/spring spawning (Ellis *et al*., 2012). This suggests that it is not likely that there will be long-term ecosystem effects arising from a loss or change in population dynamics of sandeel due to the Proposed Development.

HERRING

3.3.5. Herring are demersal spawners and reliant upon the presence of suitable substrates (i.e., gravelly sediments). Herring spawning habitats are widely distributed across the northern North Sea. In addition, the overlap of the Proposed Development with the Buchan spawning grounds (NMPi, 2015, as categorised by Coull *et al*., 1998) is small compared to the overall extent of this spawning ground across the northern North Sea (overlap of the Proposed Development of approximately 5%). Due to the abundant potential herring spawning habitat in the wider North Sea and the minimal overlap between the Proposed Development and Buchan spawning grounds, it is not anticipated that impacts arising from the Proposed Development will significantly impact herring populations in the region. Consequently, it is not likely that there will be an ecosystem level effect through a change in fish population dynamics which would have the potential to disrupt the wider marine ecosystem.

OTHER FISH PREY SPECIES

3.3.6. Many prey species that are found in the vicinity of the Proposed Development as detailed in Section 2.3, including pelagic spawners such as cod and whiting, are less reliant on substrate for their life history and can temporarily flee an area avoiding impacts. Therefore, the impacts from the Proposed Development are not likely to have an impact on their stocks and ultimately their role in the marine ecosystem compared to fish that require specific habitats. However, there are many prey species with spawning/nursery grounds in the vicinity of the Proposed Development including migratory species and elasmobranchs (as detailed in Volume 3, Appendix 10.1 (Fish and Shellfish Technical Report)), yet the impacts associated with the Proposed Development to these receptors are not likely to result in a negative ecosystem level effect due to the minor-negligible significance of impacts, with all impacts expected to be temporary nature and being able to fully recover.

CUMULATIVE AND INTER-RELATED EFFECTS

3.3.7. A cumulative effects assessment for fish and shellfish ecology and benthic subtidal and intertidal ecology are detailed in Volume 2, Chapter 9 (Benthic Subtidal Ecology) and Volume 2, Chapter 10 (Fish and Shellfish Ecology), respectively, which consider the wider potential impacts beyond the Proposed Development. The likely cumulative impact in the absence of further mitigation (beyond the embedded commitments outlined in Chapters) have been assessed as not significant in EIA terms for both fish and shellfish, and benthic subtidal and intertidal receptor groups.

3.3.8. It is recognised that the impacts to receptors alone from the Proposed Development and cumulatively do not provide a holistic approach to assessing the impacts to the marine ecosystem. With consideration to a holistic approach, an inter-related effects assessment has been carried out. This looks at the effects that may occur due to multiple impacts on a receptor or a group of receptors from the Proposed Development. This includes the following:

Project Lifecycle effects - Interactions between impacts across different phases of the Proposed Development i.e., interaction of impacts across construction, operation and maintenance and decommissioning; and

Inter-related Receptor effects - Interactions between impacts on a receptor or group of receptors within an offshore development stage.

3.3.9. Project lifecycle and inter-related receptor effects relating to Benthic Subtidal and Intertidal Ecology are presented in Table 3-1 and the effects relating to Fish and Shellfish Ecology are presented in Table 3-2.

Table 3-1 Inter-related effects of Benthic Subtidal and Intertidal Ecology

Impact	Potential for Likely Significant Inter-Related Effects
Project lifecycle effects	
Temporary habitat loss across all three project phases	When habitat loss or disturbance is considered additively across all phases, although the total area of habitat affected is larger, the habitats affected are typically widespread. Furthermore, all benthic habitats are predicted to recover to the baseline condition within two to ten years, apart from where there is likely to be a permanent loss of habitat, due to the introduction of project infrastructure. Therefore, across the Proposed Development lifetime, the effects on benthic ecology receptors are not anticipated to act in such a way as to result in combined effects of greater significance than the assessments presented for each individual phase. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Indirect impacts to benthic ecology because of the temporary increase in SSC and sediment deposition	The majority of the seabed disturbance (resulting in the highest SSC and sediment deposition) will occur during the construction and decommissioning phases, with any effects being temporary and short-lived. Due to this and the recoverability of the species and habitats affected, the interaction of these impacts across all stages of the development is not predicted to result in an effect of any greater significance than those assessed in the individual project phases. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Inter-Related Receptor Effects	
There is the potential for spatial and temporal interactions between the effects arising from habitat loss/disturbance and increased SSC and sediment deposition during the Proposed Development lifetime. The greatest potential for inter-related effects is predicted to occur through the interaction of both temporary and permanent habitat loss/disturbance from foundation installation/jack-up vessels/anchor placement/scour, indirect habitat disturbance due to sediment deposition and indirect effects of changes in physical processes due the presence of infrastructure in the Array Area. With respect to this interaction, these individual impacts were assigned a significance of negligible to minor adverse significance as standalone impacts and although potential combined impacts may arise (i.e., spatial and temporal overlap of direct habitat disturbance), it is predicted that this will not be any more significant than the individual impacts in isolation. This is because the combined amount of habitat potentially affected would be very limited and where temporary disturbance occurs, full recovery of the benthos is predicted, apart from where there is likely to be a permanent loss of habitat, due to the introduction of project infrastructure (such as the footprint of WTG anchors and any required scour protection that may be required). In addition, any effects due to changes in the physical processes are likely to be limited, both in extent and in magnitude, with receptors having low sensitivity to the scale of changes predicted. As such, these interactions are predicted to be no greater in significance than that for the individual effects assessed in isolation. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.	

Table 3-2 Inter-related effects of Fish and Shellfish Ecology

Impact	Potential for Likely Significant Inter-Related effects
Project lifecycle effects	
Impact from UWN	The impacts of UWN during the construction and decommissioning phases are expected to be short-term and intermittent. Impacts from UWN during the operational phase will be long term but to a very localised extent and to a much lower noise level when compared to the construction (and potential decommissioning) activities. The interaction of these impacts across construction, O&M and decommissioning stages of the development is not predicted to result in an impact of any greater significance than those assessed in the individual project phases. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Increase in SSC and sediment deposition	The impacts of increased SSC and sediment deposition during the construction and decommissioning phases are expected to be short-term and intermittent, and of localised extent with any effects being reversible. The interaction of these impacts across construction and decommissioning stages of the development is not predicted to result in an impact of any greater significance than those assessed in the individual project phases. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Habitat loss and disturbance, and increased SSC and deposition	The impacts of habitat loss and disturbance and increased SSC and deposition during the construction, O&M and decommissioning phases are expected to be short-term and intermittent, and of localised extent. The interaction of these impacts across construction, O&M and decommissioning stages of the development is not predicted to result in an impact of any greater significance than those assessed in the individual project phases. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Inter-Related Receptor effects	
Spatial and temporal interactions between habitat loss/disturbance, increased SSC/deposition, UWN	No spatial or temporal interaction between the effects assessed above is expected during the Proposed Development lifetime.

3.3.10. While there are potential negligible-minor negative impacts on benthic and intertidal habitats and species and fish and shellfish and hence on marine ecosystems in general due to the Proposed Development as detailed in Section 3.3 (and OWF more broadly for that matter), it is worth highlighting that OWF provide several potentially positive effects, particularly by providing opportunity for settlement of prey species that form the second trophic layer of the marine food web. These benefits are primarily from the creation of new habitats through the introduction of hard substrates in the marine environment.

3.3.11. An additional ecosystem benefit of OWF is the potential to reduce or remove anthropogenic pressures such as fishing. There is the potential that OWF areas provide a refuge for fish species and can positively benefit the wider fishing areas by providing stocks for both fish

prey and for human consumption. However, it is worth noting that a reduction or removal of fishing pressure from one area may result in greater impact from fishing at another location.

3.3.12. As stated in Section 3.2, the effects of changes to mixing and stratification at the Proposed Development are not expected to be significant in terms of shelf sea primary production. However, the foundations/anchorage, cable protection and other structures associated with the Proposed Development could serve as an artificial reef through the provision of structure which otherwise would not be there. These structures encourage the growth of biofouling organisms, providing a food source which has the potential to enhance biodiversity in the area (Degraer *et al*., 2020). By providing both open water and reef-like environments, OWF can create localised biodiversity hotspots (Galparsoro *et al*., 2022). This diverse environment has the potential to benefit small pelagic fish species like herring and sprat, as well as various benthic organisms such as crustaceans and mollusks. As a result, predatory species (including cod, whiting and elasmobranchs) could benefit from an increased abundance of prey species around the Proposed Development. Initial findings of PrePARED Project have shown an increased in flatfish and gadoid abundance at Beatrice and Moray East OWFs, when compared with sites outside of the OWF reference sites (PrePARED, 2024).

3.3.13. For all impacts associated with the Proposed Development for benthic ecology and fish and shellfish ecology, please refer to Volume 2, Chapter 9 (Benthic Subtidal and Intertidal Ecology) and Volume 2, Chapter 10 (Fish and Shellfish Ecology), respectively.

3.4. SEABIRDS

3.4.1. This section provides the conclusions of Volume 2, Chapter 11 (Offshore and Intertidal Ornithology), relating to this ecosystem effects assessment.

3.4.2. The magnitude of impact arising from distributional responses and collision for the Proposed Development alone is considered negligible for all species surveyed (Table 3-3).

3.4.3. Indirect distributional responses through impacts on prey species arising from construction activities are discussed in Section 3.3, wherein any effect to sandeel or herring could impact specialist seabird species (Daunt and Mitchell, 2013).

Table 3-3 Summary of assessment of effects on seabird species of the Proposed Development alone.

Effect	Receptor	Magnitude of Impact	Receptor Sensitivity	Effect Significance
Construction				
Direct distributional responses – Array Area and offshore ECC	Kittiwake Puffin Gannet	Negligible	Low	Negligible
	Guillemot Razorbill	Negligible	Medium	Negligible
Indirect distributional responses	All scoped in seabirds	Negligible	Low	Negligible
Operation and Maintenance				
Collision	Kittiwake Common gull Gannet	Negligible	High	Negligible
	Great black-	Negligible	Very high	Negligible

Effect	Receptor	Magnitude of Impact	Receptor Sensitivity	Effect Significance
	backed gull Herring gull			
	Common tern Arctic tern Great skua	Negligible	Medium	Negligible
Entanglement	All scoped in seabirds	Negligible	Medium	Negligible
Artificial lighting	All scoped in seabirds	Negligible	Medium	Negligible
Direct distributional responses – Array Area and offshore ECC	Kittiwake Puffin Gannet	Negligible	Low	Negligible
	Razorbill	Negligible	Medium	Negligible
	Guillemot	Negligible	Medium	Negligible
Indirect distributional responses	All scoped in seabirds	Negligible	Low	Negligible
Decommissioning				
Direct distributional responses – Array Area and offshore ECC	Kittiwake Puffin Gannet	Negligible	Low	Negligible
	Guillemot Razorbill	Negligible	Medium	Negligible
Direct distributional responses - landfall	Guillemot Razorbill	Negligible	Low/medium	Negligible
	Arctic tern	Negligible	Medium	Negligible
Indirect distributional responses	All scoped in seabirds	Negligible	Low	Negligible

CUMULATIVE AND INTER-RELATED EFFECTS

3.4.4. A cumulative effects assessment (considering any impacts of the Proposed Development combined with the impacts of other developments) for seabirds is detailed in Volume 2, Chapter 11 (Offshore and Intertidal Ornithology). Where direct distributional response and/or collision are concerned, conclusions for key species were as follows:

- Kittiwake: high sensitivity, low magnitude of cumulative impact. No significant cumulative effects in EIA terms;
- Gannet: high sensitivity, negligible magnitude of cumulative impact. No significant cumulative effects in EIA terms;
- Herring gull: very high sensitivity, negligible magnitude of cumulative impact. No significant cumulative effects in EIA terms;
- Guillemot: medium sensitivity, negligible magnitude of cumulative impact. No significant cumulative effects in EIA terms;

- Razorbill: medium sensitivity, low magnitude of cumulative impact Not significant in cumulative effects in EIA terms; and
- Puffin: low sensitivity, negligible magnitude of cumulative impact. Not significant cumulative effects in EIA terms.

3.4.5. Project lifecycle and inter-related effects (as defined in paragraph 3.3.8) considers a holistic approach to assessing the impacts to the marine ecosystem. These effects from Offshore and Intertidal Ornithology are presented in Table 3-4.

Table 3-4 Inter-related effects of Offshore and Intertidal Ornithology.

Impact	Potential for Likely Significant Inter-Related Effects
Project lifecycle effects	
All impacts	There is no potential for the effects during one phase of the Proposed Development to interact with the effects of another phase in a way that would result in combined effects of greater significance than the assessments for an individual phase.
Inter-Related Receptor Effects	
Construction phase impacts	The impacts assessed during the construction phase are direct distributional responses and indirect distributional responses. For direct distributional responses, across the relevant receptors the highest significance predicted is minor, which is not significant in EIA terms. For indirect distributional responses, across the relevant receptors the highest significance predicted is negligible, which is not significant in EIA terms. For each of these impacts, the combination of effects would not result in a combined effect of greater significance than the assessments already provided.
Operation and Maintenance phase impacts	The impacts assessed during the operation and maintenance phase are collision, entanglement, artificial lighting, direct distributional responses and indirect distributional responses. For collision, across the relevant receptors the highest significance predicted is negligible, which is not significant in EIA terms. For entanglement, across the relevant receptors the highest significance predicted is negligible, which is not significant in EIA terms. For artificial lighting, across the relevant receptors the highest significance predicted is minor, which is not significant in EIA terms. For direct distributional responses, across the relevant receptors the highest significance predicted is minor, which is not significant in EIA terms. For indirect distributional responses, across the relevant receptors the highest significance predicted is negligible, which is not significant in EIA terms. For kittiwake and gannet, combined effects of direct distributional impacts and collision are assessed under direct distributional responses. For other species, the combination of effects would not result in a combined effect of greater significance than the assessments already provided.
Decommissioning phase impacts	The impacts assessed during the decommissioning phase are direct distributional responses and indirect distributional responses. For direct distributional responses, across the relevant receptors the highest significance predicted is minor, which is not significant in EIA terms. For indirect distributional responses, across the relevant receptors the highest significance predicted is negligible, which is not significant in EIA terms. For each of these impacts, the combination of effects would not result in a combined effect of greater significance than the assessments already provided.

3.4.6. While there are potential negative impacts on marine ecosystems arising from the Proposed Development and other OWFs, it is worth noting that OWFs provide the opportunity for the settlement of prey species that form the base of the marine food web. For instance, the WTGs can serve as artificial reefs, which act as nursery areas for juvenile fish species and can provide feeding grounds sheltered from predation (Wilson and Elliott, 2009). OWFs can thus increase prey availability for seabirds by creating refuge areas for fish away from fishing pressures, or where turbine bases and scour protection support a large diversity of substratum and associated fish assemblages (Wilson *et al*., 2010).

3.4.7. Furthermore, the use of renewable energy reduces the reliance on oil and gas as a source of energy, and as such attempts to tackle the climate crisis (Snyder and Kaiser, 2009). Indeed, the impacts of climate change threaten all species, including seabirds, and the negative ecological impacts of OWFs should be assessed in comparison with those of fossil fuel use on birds on a per MW basis (Snyder and Kaiser, 2009).

3.4.8. For all offshore and intertidal ornithological impacts associated with the Proposed Development please refer to Volume 2, Chapter 11 (Offshore and Intertidal Ornithology).

3.5. MARINE MAMMALS AND MEGAFAUNA

3.5.1. This section provides the conclusions of Volume 2, Chapter 12 (Marine Mammals) and Volume 2, Chapter 10 (Fish and Shellfish) (for megafauna), relating to this ecosystem effects assessment.

3.5.2. The magnitude of impacts of the Proposed Development alone is considered negligible to low for all species (Table 3-5). The impacts studied look at the effects of UWN (auditory injury, disturbance) from multiple sources across development phases, and the physical effects of WTGs and vessels on marine mammals (i.e., collisions, and entanglements). Indirect effects through impacts to prey species and effects to the supporting habitats of marine mammals are also considered.

3.5.3. Indirect effects through prey species arising from construction activities are discussed in Section 3.3, wherein any effect to sandeel or herring will cause a level of change in the prey community that marine mammal species depend on.

3.5.4. No significant impacts to megafauna have been identified within Volume 2, Chapter 10 (Fish and Shellfish). The magnitude of impacts of the Proposed Development alone is considered medium to negligible for elasmobranch species (Table 3-5). The impacts studied look at the effects of increases in SSC, habitat disturbance and underwater noise (mortality, recoverable injury, Temporary Threshold Shift (TTS), behavioral impacts) from multiple sources across development phases, and the physical effects of WTGs on elasmobranchs (i.e., entanglements). Indirect effects through impacts to the supporting habitats of elasmobranchs, are also considered.

Table 3-5 Summary of assessment of effects on marine mammal species and other marine megafauna

Effect	Receptor	Magnitude of Impact	Receptor Sensitivity	Effect Significance
Construction				
Auditory injury Permanent Threshold Shift (PTS) from pre-construction and construction geophysical surveys	All marine mammals	Negligible – low (varies based on equipment)	Negligible – low (varies based on equipment)	Negligible
Disturbance from pre-construction and construction geophysical surveys	All marine mammals	Negligible – low (varies based on equipment)	Negligible – low (varies based on equipment)	Negligible
Auditory injury (PTS) from Unexploded Ordnance (UXO) clearance	Harbour porpoise, bottlenose dolphin, white-beaked dolphin, Risso's dolphin, killer whale	Negligible	Low	Negligible
	Minke whale, humpback whale, harbour seal, grey seal	Negligible	Medium	Negligible
Disturbance from UXO clearance	All marine mammals (except minke whale)	Negligible – low (varies based on assessment method)	Low	Negligible
	Minke whale	Low – medium (varies based on assessment method)	Low	Negligible - minor
Auditory injury (PTS) from piling	All marine mammals	Negligible - low	Low	Negligible
Disturbance from piling	Harbour porpoise, bottlenose dolphin, Risso's dolphin, killer whale, harbour seal, grey seal	Negligible – low	Negligible - low	Negligible
	White-beaked dolphin	Medium	Low	Minor
	Minke whale, humpback whale	Low	Medium	Minor
Auditory injury (PTS) from other construction activities	All marine mammals	Negligible	Low - medium	Negligible
Disturbance from other construction	All marine mammals	Low	Negligible - low	Negligible

Effect	Receptor	Magnitude of Impact	Receptor Sensitivity	Effect Significance
activities	(except minke whale)			
	Minke whale	Low	Medium	Minor
Disturbance associated with vessel activity	All marine mammals	Low	Medium	Minor
Indirect impacts on prey availability and distribution	All marine mammals	Negligible	Low - medium	Negligible
Increases in SSC and deposition of disturbed sediments to the seabed	Elasmobranchs	Low	Low	Negligible
Temporary habitat disturbance	Elasmobranchs	Low	Negligible	Negligible
Direct and indirect seabed disturbance leading to release of sediment contaminants	Elasmobranchs	Negligible	Low	Negligible
Direct damage (e.g. crushing) and disturbance	Elasmobranchs	Low	Negligible	Low
Mortality, and mortal injury arising from underwater noise	Group 1 (fleeing) (elasmobranchs)	Low	Low	Negligible
Recoverable injury arising from underwater noise	Group 1 (fleeing) (elasmobranchs)	Low	Low	Negligible
TTS arising from underwater noise	Group 1 (fleeing) (elasmobranchs)	Medium	Low	Minor
Behavioural impacts arising from UWN	Group 1 (fleeing) (elasmobranchs)	Medium	Low	Minor
Noise and vibration arising from UXO clearance	Group 1 (fleeing) (elasmobranchs)	Medium	Low	Minor
Noise and vibration arising from other noise sources during construction	Group 1 (fleeing) (elasmobranchs)	Low	Low	Negligible
Operation and Maintenance				
Operational noise impacts from floating WTGs	All marine mammals (except minke whale)	Medium	Negligible	Negligible
	Minke whale	Medium	Low	Minor
Risk of collision with WTG structures	All marine mammals	Negligible – low	Negligible – low	Negligible
Risk of injury from entanglement – primary	All marine mammals	Negligible	High	Minor

Effect	Receptor	Magnitude of Impact	Receptor Sensitivity	Effect Significance
entanglement				
Risk of injury from entanglement – secondary and tertiary entanglement	All marine mammals	Low	High	Minor
Indirect impacts on prey availability and distribution	All marine mammals	Negligible	Low - medium	Negligible
Long-term habitat changes, displacement and/or barrier effects due to the presence of WTGs	Harbour porpoise, bottlenose dolphin, white-beaked dolphin, Risso's dolphin, killer whale, grey seal, harbour seal	Low	Negligible	Negligible
	Minke whale, humpback whale	Medium	Low	Minor
Permanent and/or long-term habitat loss/alteration due to addition of infrastructure to the area	Elasmobranchs	Low	Negligible	Negligible
Electromagnetic Fields (EMF) impacts arising from cables during operational phase	Elasmobranchs	Low	Medium	Minor
Ghost fishing due to lost fishing gear becoming entanglement in installed infrastructure	Elasmobranchs	Low	Medium	Minor
Introduction of new hard substrates and potential for fish aggregation	Elasmobranchs	Low	Low	Negligible
Underwater noise and vibration from operational WTGs and vessels	Elasmobranchs	Negligible	Low	Negligible
Decommissioning				
Auditory injury (PTS) from decommissioning activities	Harbour porpoise, bottlenose dolphin, white-beaked dolphin, Risso's dolphin, killer whale, grey seal, harbour seal	Low	Low	Negligible
	Minke whale, humpback whale	Low	Medium	Minor

Effect	Receptor	Magnitude of Impact	Receptor Sensitivity	Effect Significance
Disturbance form decommissioning vessels and activities	All marine mammals	Low	Low	Negligible
Indirect impacts on prey availability and distribution	All marine mammals	Negligible	Low - medium	Negligible
Long-term habitat changes, displacement and/or barrier effects due to the presence of WTGs	Harbour porpoise, bottlenose dolphin, white-beaked dolphin, Risso's dolphin, killer whale, grey seal, harbour seal	Low	Negligible	Negligible
	Minke whale, humpback whale	Medium	Low	Minor
Increases in SSC and deposition of disturbed sediments to the seabed	All valued ecological receptors (including elasmobranchs)	Low	Medium (maximum)	Minor (maximum)
Temporary habitat loss	All valued ecological receptors (including elasmobranchs)	Low	Medium (maximum)	Minor (maximum)
Direct and indirect seabed disturbances leading to release of sediment contaminants	All valued ecological receptors (including elasmobranchs)	Low	Medium (maximum)	Minor (maximum)
Direct damage (e.g., crushing) and disturbance	All valued ecological receptors (including elasmobranchs)	Low	Medium (maximum)	Minor (maximum)
Mortality, injury and behavioural changes resulting from UWN arising from decommissioning activity	All valued ecological receptors (including elasmobranchs)	Low	Medium (maximum)	Minor (maximum)

CUMULATIVE AND INTER-RELATED EFFECTS

3.5.5. A cumulative effects assessment is detailed in Volume 2, Chapter 12 (Marine Mammals) and Volume 2, Chapter 10 (Fish and Shellfish) which considers the wider potential impacts beyond the Proposed Development.

3.5.6. The conclusion of the cumulative effects assessment for disturbance from piling on marine mammals was:

- Harbour porpoise, bottlenose dolphin, white-beaked dolphin and Risso's dolphin: low sensitivity, medium magnitude of cumulative impact. No significant cumulative effects in EIA terms;
- Minke whale: medium sensitivity, low magnitude of cumulative impact. No significant cumulative effects in EIA terms; and
- Harbour seal and grey seal: low sensitivity, negligible to low magnitude of cumulative impact. No significant cumulative effects in EIA terms.

3.5.7. The conclusion of the cumulative effects assessment on temporary increases in SSC was:

- Elasmobranch: medium sensitivity, low magnitude of cumulative impact. No significant cumulative effects in EIA terms.

3.5.8. The conclusion of the cumulative effects assessment on mortality, injury and behavioural changes from underwater noise was:

- Elasmobranchs: low sensitivity, medium magnitude of cumulative impact. No significant cumulative effects in EIA terms.

3.5.9. Project Lifecycle and inter-related effects (as defined in paragraph 3.3.8) considers a holistic approach to assessing the impacts to the marine ecosystem. These effects from marine mammals and megafauna are presented in Table 3-6.

Table 3-6 Inter-related Effects of Marine Mammals and Megafauna

Species group	Impact	Potential for Likely Significant Inter-Related Effects
Project lifecycle effects		
Marine mammals	Disturbance from underwater noise (including vessels)	Disturbance to marine mammals from underwater noise shall be present throughout each of the construction, operations & maintenance, and decommissioning phases of the Proposed Development. This results in a potential project lifetime, inter-related effect. It should be noted that project mitigation is proposed for several disturbance from underwater noise pathways. These contribute to the overall conclusion of disturbance from underwater noise being not significant in EIA terms, for both marine mammals and megafauna. When disturbance is considered additively across all phases, the duration of the disturbance effect is greater than when considering each phase in isolation. However, marine mammals and megafauna are expected to recover from disturbance effects in the short-term (up to several days or less), reducing the risk of prolonged disturbance. It is not expected that the spatial extent of disturbance would increase; indeed, the spatial extent will be greatest during the construction phase, and much smaller during the operation and maintenance phase. Therefore, across the Proposed

Species group	Impact	Potential for Likely Significant Inter-Related Effects
		Development lifetime, the effects on marine mammal and megafauna are not anticipated to act in such a way as to result in combined effects of greater significance than the assessments presented for each individual phase. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Marine mammals	Changes to marine mammal and megafauna prey species	Impacts and changes to marine mammal prey species have been assessed as part of each of the construction, O&M, and decommissioning phases of the Proposed Development. The effect of changes to marine mammal and megafauna prey species is not significant across all phases. Furthermore, inter-related effects to prey species have been considered in Table *3-1*. The conclusion of that assessment was that inter-related effects would not result in an effect on prey species of any greater significance than those assessed in the individual project phase. Therefore, it can be determined that the conclusions for each project phase regarding changes to marine mammal and megafauna prey species is applicable to the conclusion for inter-related effects i.e. that it is not significant. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Elasmobranchs	Disturbance from underwater noise	The impacts of UWN during the construction and decommissioning phases are expected to be short-term and intermittent. Impacts from UWN during the operational phase will be long term but to a very localised extent and to a much lower noise level when compared to the construction (and potential decommissioning) activities. The interaction of these impacts across construction, O&M and decommissioning stages of the development is not predicted to result in an impact of any greater significance than those assessed in the individual project phases. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Elasmobranchs	Increase in SSC and sediment deposition	The impacts of increased SSC and sediment deposition during the construction and decommissioning phases are expected to be short-term and intermittent, and of localised extent with any effects being reversible. The interaction of these impacts across construction and decommissioning stages of the development is not predicted to result in an impact of any greater significance than those assessed in the individual project phases. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.

Species group	Impact	Potential for Likely Significant Inter-Related Effects
Elasmobranchs	Habitat loss and disturbance, and increased SSC and deposition	The impacts of habitat loss and disturbance and increased SSC and deposition during the construction, O&M and decommissioning phases are expected to be short-term and intermittent, and of localised extent. The interaction of these impacts across construction, O&M and decommissioning stages of the development is not predicted to result in an impact of any greater significance than those assessed in the individual development phases There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Inter-Related Receptor Effects		
Marine mammals	Combination of disturbance from underwater noise (including vessels) and indirect impacts on marine mammal prey items per phase	When acting in combination with one another during a single phase, the greatest potential for spatial and temporal interactions arising from the Proposed Development are associated with underwater noise impacts and the presence of vessels. Piling activities and vessel presence within the Array Area could occur at the same time. There is evidence that the presence of vessels prior to piling can disturb marine mammal species (Benhemma-Le Gall *et al*., 2023), and thus limit the amount of disturbance and/or displacement individuals may experience as a result of piling activities. In addition, the spatial footprint of disturbance from piling noise is significantly greater than that from vessels and so is likely to encompass any vessel disturbance footprints, without acting additively. Similarly, effects on prey as a result of project activities (including noisy activities) is likely to be within the footprint of disturbance or displacement by marine mammals, as marine mammals have a higher sensitivity and so disturbance or displacement effect. As such, for each of these impacts, the combination of effects would not result in a combined effect of greater significant that the assessments already provided. There will therefore be no inter-related effects of greater significance compared to the impacts considered alone.
Elasmobranchs	Spatial and temporal interactions between habitat loss/disturbance, increased SSC/deposition, UWN	No spatial or temporal interaction between the effects assessed above is expected during the Proposed Development lifetime.

3.5.10. As detailed in paragraph 3.4.6, while there are potential impacts on marine ecosystems arising from the Proposed Development, OWFs provide the opportunity for the settlement and colonisation of prey species that form the base of the marine food web.

3.5.11. The presence of anthropogenic structures in the marine environment can act as fish aggregating devices and artificial reef systems (Guerin *et al*., 2007; Zawawi *et al*., 2012). Initial findings of the PrePARED project have shown an increase in flatfish and gadoid abundance at Beatrice and Moray East OWFs, when compared with sites outside of the offshore

windfarms reference site (PrePARED, 2024). This supports several studies which have reported the increased presence of foraging marine mammals within operational OWFs. To illustrate, data from tagged harbour and grey seals demonstrates grid-like movement patterns as individuals move between the WTGs, suggesting these structures are being used for foraging (Russell *et al*., 2014). Additionally, in the Moray Firth in Scotland, Fernandez-Betelu *et al*. (2022) found that the probability of harbour porpoise occurrence and foraging activity decreased with distance from offshore structures and that there was a significant increase in porpoise occurrence and foraging during night-time compared to daytime around all the offshore structures. Therefore, it is considered there are positive impacts on marine mammals from the operational phase of the Proposed Development.

4. CHANGING BASELINE AND FUTURE TRENDS

4.1.1. This section outlines the major current and future anthropogenic driven ecosystem level impacts to the key trophic levels of the marine ecosystem. This section investigates the role of known future pressures (climate change, commercial fisheries, OWF development, INNS, pollution and avian influenza) and how they may influence the marine ecosystem in future years.

4.2. CLIMATE CHANGE

4.2.1. Climate change can alter the stratification of the water column, which in turn affects nutrient cycling and the availability of nutrients for primary producers which are the base of the marine food web and are responsible for producing the bulk of organic matter through photosynthesis that supports marine life. In the Northern North Sea, stronger stratification due to warmer surface waters can reduce the mixing of nutrient-rich deeper waters with the upper photic zone, where phytoplankton require nutrients for growth (Lowe *et al*., 2009). Reduced nutrient availability in the surface waters may lead to lower primary productivity. This phenomenon could particularly affect larger phytoplankton species, such as diatoms, which require more nutrients than smaller species. As a result, overall phytoplankton biomass may decline, and the species composition could shift toward smaller, less productive taxa, further impacting food availability for higher trophic levels.

4.2.2. Climate change can affect environmental conditions in various ways including increasing sea surface temperature. As sea temperatures rise due to global climate change, the composition of phytoplankton species in the North Sea is expected to shift. Warmer waters tend to favour smaller, fast-growing phytoplankton species such as flagellates, which are less energy-dense compared to larger diatoms, traditionally dominant in the colder waters of the North Sea (McQuatters-Gollop *et al.,* 2007). This shift in species composition could have significant implications for higher trophic levels. Diatoms, which are larger and more nutritious, form the preferred food source for many zooplankton species. A reduction in diatom populations could result in lower-quality food for secondary producers, affecting the entire food web.

4.2.3. A potential impact of increased sea surface temperatures is that some fish species will extend their distribution into deeper, colder waters (Poloczanska *et al.,* 2013). In these cases, however, habitat requirements are likely to become important, with some shallow water species having specific habitat requirements in shallow water areas which are not available in these deeper areas. For example, sandeel is less likely to be able to adapt to increasing temperatures as a result of its specific habitat requirements for coarse sandy sediment and declining recruitment in sandeel in parts of the UK has been correlated with increasing temperature (Heath *et al*., 2012). Climate change may also affect key life history stages of fish and shellfish species, including the timing of spawning and migrations (Poloczanska *et al*., 2013). However, climate change impacts on marine fish populations are difficult to predict and the evidence is not easy to interpret and therefore it is difficult to make accurate estimations of the future baseline scenario for the entire lifetime of the Proposed Development (approximately 35 years).

4.2.4. Climate change will also influence fish (including prey species) distribution and abundance, affecting growth rates, recruitment, behaviour, survival and response to changes of other trophic levels (Prakash and Srivastava, 2019). As mentioned above, climate change is contributing to the declining levels of primary production in the North Sea which in turn impacts the dynamics of higher trophic levels and fish recruitment (Capuzzo *et al*., 2018). Projected warming scenarios indicated regime shifts between sandeels and their copepod prey,

resulting in sandeel recruitment declines (Regnier *et al*., 2019). Increased sea surface temperatures in the North Sea may lead to an increase in the relative abundance of species associated with more southerly areas. For example, data on spawning herring and sardine (*Sardina* spp.) landings at ports in the English Channel showed that higher spawning herring landings were correlated with colder winters, while warm winters were associated with large catches of sardine (Alheit and Hagen, 1997). A reduction in the abundance or quality of seabird prey species such as those mentioned above, coupled with a shift in breeding timings due to warming sea temperatures causing seabirds to become de-synchronised from their prey, is already having a direct impact on seabird populations in the UK (Daunt and Mitchell, 2013).

4.2.5. It is considered that current trends with regard to the northward shift of specific species (e.g. sandeels) and an increase in the abundance of typically warmer water species (e.g. sardines) will continue in a warming climate, which may result in alterations to the existing baseline. However, considering the timescales of warming oceans and changes in distribution of species, it is likely that in the near to medium term, this would be changes in the relative abundances of species rather than wholesale changes in the community structure.

4.3. COMMERCIAL FISHERIES

4.3.1. The North Sea is one of the world's most heavily fished marine regions and is experiencing significant ecosystem stress from commercial fishing activities (O'Leary *et al*., 2017). Overfishing, climate change, habitat destruction, and unsustainable practices have already led to changes in biodiversity, fish stocks, and ecosystem dynamics (O'Leary *et al*., 2017). The future impacts of fisheries on the North Sea marine ecosystem will largely depend on how fisheries adapt to environmental changes, implement sustainable practices, and respond to shifting species distributions.

4.3.2. Despite improvements in fisheries management through the EU's Common Fisheries Policy (CFP), stock recovery of many commercially important species such as cod, haddock and herring has been slow, and some species remain at critically low levels. As fishing continues in the future, there is the risk of further depletion of already vulnerable stocks, which could have cascading effects on marine ecosystems. Overfishing reduces the reproductive capacity of fish populations, limiting their ability to recover and maintain sustainable levels (Engelhard *et al*., 2014). Species declines due to overfishing not only reduce biodiversity but also destabilise the food web. When predators (such as cod) are removed, the balance between predator and prey populations is disrupted. For example, overfishing of cod has been linked to increases in their prey species, such as small fish and invertebrates (Heath *et al*., 2014). This trophic cascade can lead to unpredictable changes in the ecosystem, reducing its overall resilience to other stressors like climate change or pollution. In addition, changes in fish populations can influence other marine life, such as seabirds and marine mammals, which rely on fish stocks for food. A decline in available prey can lead to reduced reproductive success and survival rates for these higher trophic levels, exacerbating the effects of fisheries on the broader ecosystem (Huse *et al*., 2002). Bycatch can also impact the wider ecosystem through the removal of non-target prey species or the accidental capture of marine mammals, seabirds and other predatory species which are vital to maintaining ecological balance (Kelleher, 2005).

4.3.3. Sandeel are an important prey species in the region and designated under the Turbot Bank NC MPA, which sits adjacent to the Proposed Development. Recent legislation prohibits commercial sandeel (lesser & Raitt's sandeel) fishing in Scottish waters (announced by the Scottish Government in January 2024, which came into force in March 2024). The ban aims to benefit seabirds and other wildlife reliant on sandeels as a vital component of their diet.

This regulatory measure is a response to the decline in sandeel populations, critical for various species, including marine mammals, seabirds, and predatory fish. The ban is intended to bolster the broader marine ecosystem and enhance resilience among vulnerable species, particularly considering the challenges posed by climate change and warming seas (Coull *et al*., 1998). This closure sits alongside previous management measures, such as the closure in sandeel management area 4 implemented since 2000 to mitigate cod and haddock bycatch and the negative subsequent impacts on seabird food supply. These regulatory changes are likely to have implications for the future baseline of the researched area, potentially reshaping fishing practices, ecosystem dynamics, and species interactions.

4.3.4. The future of the North Sea marine ecosystem is dependent on how fisheries adapt to environmental changes and if existing and innovative sustainable practices are implemented. Effective management, ecosystem-based approaches, and enforcement of regulations can help to mitigate the negative impacts of fisheries on the marine ecosystem. A coordinated, long-term approach that considers both ecological and socio-economic factors is essential to ensure the sustainability of this vital marine ecosystem.

4.4. OFFSHORE WIND DEVELOPMENT

4.4.1. Offshore wind development will be critical in the delivery of net zero commitments. As these demands continue to grow, so does the need for a long-term, holistic approach to managing this critical resource. The UK's offshore wind market is one of the largest and most successful in the world, with more than 50 wind farms around the UK coastline at various stages of development, producing enough renewable energy to power half of all UK homes. The UK's offshore wind pipeline currently stands at approximately 95GW, with a government ambition to decarbonise the power system by 2030, including increasing offshore wind capacity in the same timeframe (The Crown Estate, 2024). With Offshore Wind Leasing Round 5 due to proceed to an auction (Invitation to Tender Stage 2) in Spring 2025 and the emergence of Offshore Wind Leasing Round 6, there is certainty that OWFs will increase in UK waters (The Crown Estate, 2024).

4.4.2. With this expansion of renewable wind energy generation, marine environments may face both negative and positive population, community and ecosystem-level direct and indirect impacts. This can be through introducing new habitat (hard substrata from development infrastructure), effects from construction activities and alterations to physical processes (van der Molen *et al*., 2014; Cazenave *et al*., 2016; Zijl *et al.,* 2021). Whilst negative cumulative impacts could arise from this growing industry, it is worth noting that there is an emergence in Nature Inclusive Designs which may help to alleviate some of the pressures on marine ecosystems. It is also worth noting the emerging research into ecosystem level effects, such as through projects like the PrePARED project which will be crucial in effectively assessing these wider impacts to all trophic levels.

4.4.3. An increase in OWFs could have further indirect benefits to the marine ecosystem. For example, OWFs often result in fisheries exclusion zones, where methods such as trawling and dredging are restricted or prohibited. As a result, the presence of wind farms can facilitate the restoration of overexploited species (Püts *et al*., 2023). For example, prey species such as forage fish may increase in areas where fishing activities are restricted. This recovery could lead to more abundant prey species, supporting higher trophic levels such as seabirds and marine mammals, and contribute to the overall stability of the marine ecosystem. However, there is also the potential that fishing pressure is just displaced to other areas. As such the overall impact, positive or negative, on fish populations as a result of a larger number of offshore windfarms is unclear.

4.5. INNS

4.5.1. Invasive Non-Native Species (INNS) can have a detrimental effect on marine ecosystems, either by outcompeting existing taxa for habitat and food or due to predation on existing species. With the increase in marine developments, there is a risk that with the increased introduction of hard substrate (including those associated with OWFs) into sedimentary habitats will enable the colonisation by INNS that might otherwise not have had a suitable habitat, thereby enabling their spread. This, along with the increased movements of vessels, which can potentially increase the risk of introductions of INNS through ballast water, or act as a vector to transfer INNS from one area to another, has the potential to impact biodiversity locally and in the broader region. It should be noted that there is a widespread presence of marine INNS across the North Sea. Marine INNS that are widespread and well established in Scottish seas include, but are not restricted to, wireweed (*Sargassum muticum*), green sea-fingers (*Codium fragile*) subsp. *tomentosoides*, red algae *Dasysiphonia japonica*, acorn barnacle (*Austrominius modestus*), Japanese skeleton shrimp (*Caprella mutica*), leathery sea squirt (*Styela clava)*, orange tipped sea squirt (*Corella eumyota*) and orange ripple bryozoan (*Schizoporella japonica*) (NatureScot, 2023). In site-specific surveys for the Proposed Development, the *Styelidae* family (which is a family of ascidian tunicates) was recorded in sediment eDNA analysis in the offshore ECC, however not identified to species level.

4.5.2. Predation by invasive mammal species also poses a serious threat to seabird colonies, particularly those on islands (Ellis *et al*., 2007; Brooke *et al*., 2018). Species such as brown and black rats (*Rattus norvegicus, R. rattus*), feral cats (*Felis catus*), and mustelids such as American mink (*Neovison vison*are known to predate seabird eggs, chicks, and adults (Latorre *et al*., 2013; Craik, 1997; Ratcliffe *et al*., 2010). Feral cats, which are capable of preying on larger birds, are particularly harmful to seabird populations and have contributed to the rapid decline of seabirds on Ascension Island (Ratcliffe *et al*., 2010), for example. Rats, however, are considered the most significant threat, impacting 75 seabird species across 61 islands studied globally (Jones *et al*., 2008). On Lundy Island, rat predation was confirmed as the cause of seabird population declines through comparisons with seabird numbers on the rat-free islands of Skomer and Skokholm (RSPB England, 2021). Rats and mustelids are excellent swimmers and can easily reach nearshore islands, while some mammalian predators are brought to vulnerable island habitats by humans, most often unintentionally via boats (Biosecurity for Life, 2024).

4.5.3. Tree mallow (*Malva arborea*) is a species of mallow native to western Europe and the Mediterranean. This biannual plant is native to the southwest of the UK but has been introduced by humans to a wide range of coastal sites in Scotland, including in the Firth of Forth (van der Wal, 2006). The entrances of puffin burrows on Craigleith island provide the moist and fertile soil needed for tree mallow to germinate and grow, as it is difficult for seedlings to establish themselves in dense grass swards (van der Wal, 2006). As tree mallow grows, it prevents puffins from accessing their burrows to nest and as such, puffin populations have declined following the introduction of tree mallow on Craigleith (van der Wal, 2006). The SOS Puffin Project led by the Scottish Seabird Centre works to manage tree mallow on Craigleith and the nearby islands of Frida and the Lamb, where puffin populations are also threatened (Scottish Seabird Centre, 2024).

4.6. POLLUTION

4.6.1. Pollution in the marine environment which can affect all levels of the marine ecosystem. Heavy metals, such as mercury, lead, and cadmium have been introduced into the North Sea through industrial discharges and runoff and they can bioaccumulate in marine organisms, causing

toxicity and disrupting food chains. For instance, concentrations of mercury, cadmium and lead in mussels and fish in the North Sea are above background levels (OSPAR, 2016). Persistent organic pollutants (POPs), such as Polychlorinated biphenyl (PCB) and Dichlorodiphenyltrichloroethane (DDT), are a class of pollutants that can persist in the environment for many years, contaminating marine organisms and posing risks to their health and reproduction. For example, POPs can accumulate in the fatty tissues of marine mammals leading to reproductive problems and impaired immune systems (Reckendorf *et al.,* 2023).

4.6.2. Plastic pollution and marine debris are also a concern in the North Sea. Marine litter is persistent, manufactured and/or processed anthropogenic material found in the marine environment, the most common of which is plastics and fishing gear (UN Environment Programme, 2021). Between 2016 and 2020, plastic production in Europe increased by almost 10% (Plastics Europe, 2021), a proportion of which is likely to end up in the marine environment as plastic waste. After encountering marine litter, many marine species such as marine mammals and seabirds may end up ingesting it or becoming entangled, which can be fatal (Good *et al*., 2010; Roman *et al*., 2019; Zantis *et al*., 2021). The impacts to the marine ecosystem from plastic pollution are likely to be further exacerbated by the effects of climate change due to increased degradation and fragmentation of plastics through heat degradation and increases storm activity (Deng *et al.,* 2021).

4.7. AVIAN INFLUENZA

4.7.1. The most recent outbreak of HPAI emerged in 2020 in the form of HPAI H5N1 clade 2.3.4.4b virus and was first reported in gulls and gannets, although the initial impact on populations was minimal (Falchieri *et al*. 2022). The epidemic became widely known in spring 2022, when it spread to marine and coastal birds. Gannet colonies experienced a decline of 25% in the UK between 2022 and 2023 (Tremlett *et al*., 2024). At least 760 kittiwake deaths were recorded in Scotland in 2022, while a minimum loss of 1,908 guillemot was recorded in Scotland and 3,775 guillemots in England in 2022 including adults, juveniles and un-aged birds (Tremlett *et al*., 2024).

4.7.2. HPAI spreads between birds via bodily fluids such as saliva, secretion, and faeces (Charostad *et al*., 2023). The virus can also be transmitted through organic materials like soil and nesting materials and can remain inactive in freshwater at low temperatures for several months, as such increasing the risk of waterborne transmission to aquatic birds (NatureScot, 2024b). Migratory birds carry the virus along their migration routes, which is believed to be the cause of the virus's arrival into the UK (NatureScot, 2024b).

4.7.3. Whilst the virus does not appear to be well adapted to mammals, there have been several reports of seals, foxes, and otters testing positive for HPAI in the UK (NatureScot, 2023). Elsewhere, more than 300 seals have died from HPAI in eastern North America, while over 20,000 sea lions and thousands of elephant seals have been lost in South America (Whittle, 2024). Additionally, evidence of the virus has been found in common dolphin, harbour porpoise, bottlenose dolphin and white-sided dolphin (Leguia *et al.,* 2023; Thorsson *et al*., 2023; Murawski *et al*., 2024). HPAI has also been associated with unusual mortality events of harbour and grey seals (Puryear *et al.,* 2024). The mammal-to-mammal transmission recorded in Spain, Peru, and the Caspian Sea raise concerns of greater potential to spread between species (NatureScot, 2023).

5. CONCLUSIONS

5.1.1. In conclusion, this assessment highlights that the Proposed Development is not likely to result in significant negative ecosystem-level effects, however there are potential positive ecological benefits that could arise. As detailed within this report, there is potential for OWF to enhance local biodiversity, support prey species populations (including commercially important species), and contribute to the overall productivity of marine ecosystems. The North Sea is a region that is facing increasing anthropogenic driven pressure in the future which will require well informed and strategic management, to mitigate against ecosystem level impacts. The development of OWF is part of this increased pressure on the marine environment. However, OWFs can provide positive ecosystem benefits and will help tackle the broader impacts of climate change which will indirectly benefit marine ecosystems.

6. REFERENCES

Alheit, J. and Hagen, E. (1997), 'Long-term climate forcing of European herring and sardine populations'. Fisheries Oceanography, 6: 130-139.

Bailey, H., Brookes, K. L., and Thompson, P. M. (2014). 'Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future'. Aquatic Biosystems, 10/1: 8.

Barrett, R.T. *et al*. (2007) 'Diet studies of seabirds: a review and recommendations', ICES Journal of Marine Science, 64/9: 1675-1691.

Beatrice OWF (2021a) Pre-Construction Cod (Gadus morhua) Spawning Survey – Technical Report

Beatrice OWF (2021b) Post-Construction Baseline Sandeel Survey – Technical Report

Beggs, S.E., Cardinale, M., Gowen, R.J. and Bartolino, V. (2013), 'Linking cod (Gadus morhua) and climate: investigating variability in Irish Sea cod recruitment'. Fisheries Oceanography 23: 54-64.

Beaugrand, G., Reid, P. C., Ibañez, F., Lindley, J. A. and Edwards, M. (2003). 'Reorganization of North Atlantic marine copepod biodiversity and climate'. Science, 296/5573: 1692-1694.

Benhemma-Le Gall, A., Thompson, P., Merchant, N. and Graham, I. (2023). 'Vessel noise prior to pile driving at offshore windfarm sites deters harbour porpoises from potential injury zones'. Environmental Impact Assessment Review 103: 107271.

Biosecurity for Life (2024) Biosecurity for Life. https://biosecurityforlife.org.uk [Accessed: September 2024].

BirdLife International (2023) Seabird Tracking Database. https://www.seabirdtracking.org/. [Accessed: October 2024].

Blanchard, J.L., Jennings, S., Holmes, R., Harle, J., and Merino, G. (2012) 'Potential consequences of climate change for primary production and fish production in large marine ecosystems', Philosophical Transactions of the Royal Society B: Biological Sciences, 367/1605: 2979–2989.

Brooke, M. de L. *et al*. (2018) 'Seabird population changes following mammal eradications on islands', Animal Conservation, 21/1: 3-12.

Burnell, D., Perkins, A.J., Newton, S.F., Bolton, M., Tierney, T.D. and Dunn, T.E. (2023) Seabirds Count: A census of breeding seabirds in Britain and Ireland (2015-2021) (Barcelona: Lynx Nature Books).

Capuzzo, E., Lynam, C.P., Barry, J., Stephens, D., Forster, R.M., Greenwood, N., McQuatters-Gollop, A., Silva, T., van Leeuwen, S.M. and Engelhard, H.G. (2018), 'A Decline in Primary Production in the North Sea over 25 Years, Associated with Reductions in Zooplankton Abundance and Fish Stock Recruitment'. Global Change Biology 24/1: 352-364.

Carpenter, J. R., Merckelbach, L., Callies, U., Clark, S., Gaslikova, L., and Baschek, B. (2016). 'Potential impacts of offshore wind farms on North Sea stratification'. PloS one, 11/8

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

Charostad, J., Rukerd, .M.R.Z., Mahmoudvand, S., Bashash, D., Hashemi S.M.A., Nakhalie, M., and Zandi, K. (2023) 'A comprehensive review of highly pathogenic avian influenza (HPAI) H5N1: An imminent threat at doorstep,' Travel Medicine and Infectious Disease, 55: 102638.

Chen, W., Staneva, J., Grayek, S., Schulz-Stellenfleth, J., and Greinert, J., (2022). 'The role of heat wave events in the occurrence and persistence of thermal stratification in the southern North Sea'. Nat. Hazards Earth Syst. Sci., 22: 1683-1698.

Christiansen, N., Daewel, U. and Schrum, C. (2022), 'Tidal mitigation of Offshore Wind Wake Effects in Coastal Seas', Frontiers in Marine Science, 9: doi:10.3389/fmars.2022.1006647.

Cleasby, I.R., Wakefield, E. D., Bearhop, S., Bodey, T.W., Votier, S.C., Hamer, K.C. (2015) 'Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms', Journal of Applied Ecology, 52/6: 1474-1482.

Cleasby, I. R., Owen, E., Wilson, L., & Bolton, M. (2018) Combining habitat modelling and hotspot analysis to reveal the location of high density seabird areas across the UK: Technical report (No. 63). RSPB Research Report.

Coull, K.A., Johnstone, R. and Rogers, S.I. (1998), 'Fisheries Sensitivity Maps in British Waters'. Published and distributed by UKOOA Ltd. Aberdeen, 63.

Craik, C. (1997) 'Long-term effects of North American Mink Mustela vison on seabirds in western Scotland', Bird Study, 44/3: 303-309.

Dale, A. and Tuerena, R (2024). 'Understanding the impacts of floating turbine structures at the Proposed Development Array Area on shelf sea stratification, nutrient fluxes and primary production'. A report by SAMS Enterprise for GoBe and Muir Mhòr Offshore Wind Farm

Daunt, F. and Mitchell, I. (2013) 'Impacts of climate change on seabirds', MCCIP Science Review, 2013: 125-133.

Deng, H., He, J., Feng, D., Zhao, Y., Sun, W., Yu, H., and Ge, C. (2021). 'Microplastics pollution in mangrove ecosystems: a critical review of current knowledge and future directions. Science of the Total Environment', 753: 142041.

Dorrell, R, Lloyd, C, Lincoln, B, Rippeth, T, Taylor, J, Caulfield, C., C, Sharples, J, Polton, J, Scannell, B, Greaves, D, Hall, R and Simpson, J. (2022), 'Anthropogenic Mixing of Seasonally Stratified Shelf Seas by Offshore Wind Farm Infrastructure', Frontiers in Marine Science, 9: 830927.

Ellis, J.R., Cruz-Martinez, A., Rackham, B.D., and Rogers, S.I. (2004). 'The distribution of chondrichthyan fishes around the British Isles and implications for conservation'. Journal of Northwest Atlantic Fishery Science, 35: 195-213.

Ellis, J.C., Shulman, M.J., Jessop, H., Suomala, R., Morris, S.R., Seng, V., Wagner, M. and Mach, K. (2007) 'Impact of raccoons on breeding success in large colonies of great black-backed gulls and herring gulls', Waterbirds, 30/3: 375-383.

Ellis, J.R., Milligan, S.P., Readdy, L., Taylor, N. and Brown, M.J. (2012), 'Spawning and nursery grounds of selected fish species in UK waters'. Cefas Scientific Series Technical Report 147.

Engelhard, G. H., Peck, M. A., Rindorf, A., Smout, S. C., van Deurs, M., Raab, K. and Pinnegar, J. K. (2014). 'Forage fish, their fisheries, and their predators: who drives whom?' ICES Journal of Marine Science, 71/1: 90-104.

Evans, P. and Hintner, K. (2013). Review of the direct and indirect impacts of fishing activities on Marine Mammals in Welsh Waters.

Falchieri, M., Reid, S.M., Ross, C.S., James, J., Byrne, A.M.P., Zamfir, M., Brown, I.H., Banyard, A.C., Tyler, G., Philip, E. and Miles, W. (2022) 'Shift in HPAI infection dynamics causes significant losses in seabird populations across Great Britain', Veterinary Record, 191: 294-296.

Fernandez-Betelu, O., Graham, I. M. and Thompson, P. M. (2022). 'Reef effect of offshore structures on the occurrence and foraging activity of harbour porpoises'. Frontiers in Marine Science, 9.

Frederiksen, M., Edwards, M., and Halliday, N. C. (2006). 'The role of forage fish in marine ecosystems: implications for management and conservation'. ICES Journal of Marine Science, 63/3: 470-482.

Galparsoro, I., Menchaca, I., and Garmendia, J.M. (2022). 'Reviewing the ecological impacts of offshore wind farms'. npj Ocean Sustainability 1/1.

Gilles, A., Authier, M., Ramirez-Martinez, N., Araújo, H., Blanchard, A., Carlström, J., Eira, C., Dorémus, G., Fernández-Maldonado, C., Geelhoed, S., Kyhn, L, Laran, S., Nachtsheim, D., Panigada, S., Pigeault, R., Sequeira, M., Sveegaard, S., Taylor, N., Owen, K., Saavedra, C., Vázquez-Bonales, J., Unger, B. and Hammond, P. (2023). 'Estimates of cetacean abundance in European Atlantic waters in summer 2022 from the SCANS-IV aerial and shipboard surveys'. Final report published 29 September 2023.

Good, T.P., June, J.A., Etnier, M.A. and Broadhurst, G. (2010). 'Derelict fishing nets in Puget Sound and the Northwest Straits: patterns and threats to marine fauna'. Marine Pollution Bulletin, 60: 39-50.

Gordó-Vilaseca, C., Costello, M.J., Coll, M., Jüterbock, A., Reiss, H., and Stephenson, F. (2024). 'Future trends of marine fish biomass distributions from the North Sea to the Barents Sea,' Nature Communications, 15/1: 2491.

Guerin, A. J., Jensen, A. and Jones, D. (2007). 'Artificial reef properties of North Sea oil and gas production platforms'. OCEANS 2007-Europe. IEEE. 1-6

Hague, E. (2023). Forth Marine Mammals: Firth of Forth, Scotland, Collaborative Community Science Sightings aps 2021-2023.

Hammond, P., Lacey, C., Gilles, A., Viquerat, S., Börjesson, P., Herr, H., Macleod, K., Ridoux, V., Santos, M., Scheidat, M., Teilmann, J., Vingada, J. and Øie, N. (2021). Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys - revised June 2021.

Heath, M.R., F. M. G. and Reilly, J. (2012) 'Sandeel growth and abundance off the East Coast of Scotland', Frontiers in Marine Science, 9: 1-15

Heath, M. R., Speirs, D. C. and Steele, J. H. (2014). 'Understanding patterns and processes in models of trophic cascades in exploited ecosystems'. Proceedings of the Royal Society B: Biological Sciences, 281(1782), 20132350.

HiDef Aerial Surveying Limited. (2023a). Digital video aerial surveys of seabirds and marine megafauna at Muir Mhòr: Two-Year Report April 2021 to March 2023.

HiDef Aerial Surveying Limited. (2023b). Digital video aerial surveys of seabirds and marine megafauna at SSE Regional Survey: 18-month Report April 2022 to August 2023.

Hill, A. E., Bronw, J., Fernand, L., Holt, J., Horsburgh K. J., Proctor, R., Raine, R. and W. R. Turrell. (2008) 'Thermohaline circulation of shallow tidal seas'. Geophysical Research Letters, 35: L11605

Huse, G., Railsback, S., and Ferno, A. (2002). 'Modelling changes in migration pattern of herring: collective behaviour'.

Huthnance, J. M. (1991). 'Physical oceanography of the North Sea. Ocean and shoreline management', 16/3-4: 199-231.

IAMMWG. (2023). Review of Management Unit boundaries for cetaceans in UK waters (2023). JNCC Report 734, JNCC, Peterborough, ISSN 0963-8091.

International Council for the Exploration of the Sea (ICES). (2022). ICES Advice on Shellfish Fisheries in the North Sea. ICES. https://doi.org/10.17895/ices.pub.c.5796935 [Accessed September 2024]

International Council for the Exploration of the (ICES). (2023a). Offshore Beam Trawl Surveys (2019-2023). ICES. https://www.ices.dk/community/groups/Pages/WGBEAM.aspx [Accessed September 2024]

International Council for the Exploration of the Sea (ICES). (2023b). Herring (Clupea harengus) in Division 4.b (Central North Sea). ICES Advice on fishing opportunities, catch, and effort. https://doi.org/10.17895/ices.advice.21641360.v1 [Accessed September 2024]

International Council for the Exploration of the Sea (ICES). (2023c) Fish Stocks in the North Sea. ICES. https://doi.org/10.17895/ices.pub.c.6976944 [Accessed September 2024]

Jensen, H., Rindorf, A., Wright, P.J. and Mosegaard, H. (2011), 'Inferring the location and scale of mixing between habitat areas of lesser sandeel through information from the fishery'. ICES Journal of Marine Science 68: 43–51.

Jones, H.P., Tershy, B.R., Zavaleta, E.S., Croll, D.A., Keitt, B.S., Finkelstein, M.E., Howald, G.R. (2008) 'Severity of the effects of invasive rats on seabirds: a global review', Conservation Biology, 22/1: 16-26.

Kelleher, K. (2005). 'Fisheries bycatch: a review of the national and international approaches to reducing bycatch'. Marine Policy, 29/3: 335-346.

Kowalcyzk, N.D., Chiaradia, A., Preston, T.J., and Reina, R.D. (2013) 'Linking dietary shifts and reproductive failure in seabirds: a stable isotope approach', Functional Ecology, 28/3: 755-765.

Lacey, C., Gilles, A., Börjesson, P., Herr, H., Macleod, K., Ridoux, V., Santos, M., Scheidat, M., Teilmann, J., Sveegaard, S., Vingada, J., Viquerat, S., Øien, N. and Hammond, P. (2022). Modelled density surfaces of cetaceans in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys.

Latorre, L., Larrinaga, A. R. and Santamaría, L. (2013) 'Rats and seabirds: effects of egg size on predation risk and the potential of conditioned taste aversion as a mitigation method', PLoS ONE, 8/9: e76138.

Leguia, M., Garcia-Glaessner, A., Muñoz-Saavedra, B., Juarez, D., Barrera, P., Calvo-Mac, C., Jara, J., Silva, W., Ploog, K., Amaro, L., Colchao-Claux, P., Johnson, C.K., Uhart, M.M., Nelson, M.I. and Lescano, J. (2023). Highly pathogenic avian influenza A (H5N1) in marine mammals and seabirds in Peru. Nature Communications, 14/1.

Longhurst, A. (2007). Ecological Geography of the Sea (2nd ed.). Academic Press.

Lowe, J. A., Gregory, J. M. and Flather, R. A. (2009). 'Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by climate model output'. Climate Dynamics, 24/3-4: 383-407.

Lu, Z., Li, G., Liu, Z. and L Wang (2022). 'Offshore wind farms changed the spatial distribution of chlorophyll-a on the sea surface'. Front. Mar. Sci. 9 https://doi.org/10.3389/fmars.2022.1008005 [Accessed September 2024]

MacDonald, A., Speirs, D. C., Greenstreet, S. P. R., and Boulcott, P. (2019). 'Trends in Sandeel Growth and Abundance off the East Coast of Scotland'. Frontiers in Marine Science, 6, 201.

Mallory, M.L., Robinson, S.A., Hebert, C.E., and Forbes, M.E. (2010) 'Seabirds as indicators of aquatic ecosystem conditions: A case for gathering multiple proxies of seabird health', Marine Pollution Bulletin, 60/1: 7-12.

Marine Scotland (2023) Monitoring the consequences of the Northwestern North Sea sandeel fishery closure, Marine Scotland. https://marine.gov.scot/sma/data/monitoring-consequences-northwestern-north-sea-sandeel-fishery-closure [Accessed September 2023]

McQuatters-Gollop, A., Reid, P. C., Edwards, M., Burkill, P. H., Castellani, C. and Batten, S. D. (2007). 'The continuous plankton recorder survey: Monitoring the health of the North Sea ecosystem for 75 years'. Oceanography, 20/2: 32-45.

MMT (2013) Hywind Scotland OWF Benthic and Geophysical Survey Report.

Murawski, A., Fabrizio, T., Ossiboff, R., Kackos, C., Trushar Jeevan, Jones, J.C., Kandeil, A., Walker, D., Jasmine, Patton, C., Govorkova, E.A., Hauck, H., Mickey, S., Barbeau, B., Y. Reddy Bommineni, Torchetti, M., Lantz, K., Kercher, L., Allison, A.B. and Vogel, P. (2024). 'Highly pathogenic avian influenza A(H5N1) virus in a common bottlenose dolphin (Tursiops truncatus) in Florida'. Communications biology, 7/1.

Natural Power (2023) Muir Mhòr Offshore Wind Farm Baseline Ornithology Report: April 2021 – March 2022. Natural Power document reference number 1304815.

NatureScot (2023) NatureScot Scientific Advisory Committee Sub-Group on Avian Influenza Report on the H5N1 outbreak in wild birds 2020-2023. https://www.nature.scot/doc/naturescot-scientific-advisory-committee-sub-group-avian-influenza-report-h5n1-outbreak-wild-birds [Accessed: September 2024].

NatureScot (2024a) Protected Nature Sites. https://informatics.sepa.org.uk/ProtectedNatureSites/ [Accessed: April 2024].

NatureScot (2024b) Highly pathogenic avian influenza (bird flu) – Guidance for site managers. https://www.nature.scot/doc/highly-pathogenic-avian-influenza-bird-flu-guidance-site-managers [Accessed: September 2024].

NatureScot. (2020). Conservation and Management Advice - Southern Trench MPA. NatureScot.

NMPi (2015) Fisheries datasets. Marine Scotland. https://marinescotland.atkinsgeospatial.com/nmpi/ [Accessed September 2024]

NMPi. (n.a.). Basking shark incidental sightings and distribution in Scotland's seas. Basking shark incidental sightings and distribution in Scotland's seas | marine.gov.scot [Accessed October 2024]

O'Leary, B.C., Robins, P.E., and Jones, K. (2017). 'Environmental change and the future of fish populations in the North Sea'. Marine Biology, 164/2: 1-12.

O'Neil, K. E., Cunningham, E. G. and Moore, D, M. (2019). 'Sudden seasonal occurrence of humpback whales Megaptera novaeangliae in the Firth of Forth, Scotland and first confirmed movement between high-latitude feeding ground and United Kingdom waters. Marine Biodiversity Records' 12/12.

OSPAR (2016) 'Status and Trend for Heavy Metals (Mercury, Cadmium, and Lead) in Fish and Shellfish' Available at: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/contaminants/metals-fish-shellfish/ [Accessed September 2024]

Overholtz, W.J. and Link, J.S. (2007) 'Consumption impacts by marine mammals, fish, and seabirds on the Gulf of Maine–Georges Bank Atlantic herring (Clupea harengus) complex during the years 1977–2002', ICES Journal of Marine Science, 64: 83-96.

Parsons, M., Mitchell, I., Butler, A., Ratcliffe, N., Frederiksen, M., Foster, S., and Reid, J.B (2008) 'Seabirds as indicators of the marine environment,' ICES Journal of Marine Science, 65: 1520-1526.

Plastics Europe. (2021). Plastics–the facts 2021. Plastics Europe, pp.1-64.

Poloczanska, E.S., Brown, C.J., and Sydeman, W.J. (2013) 'Global imprint of climate change on marine life', Nature Climate Change, 3/10: 919-925

Popper, A. N. Hawkins, A. D. Fay, R. R. Mann, D. Bartol, S. Carlson, Th. Coombs, S. Ellison, W. T. Gentry, R. Hal vorsen, M. B. Lokkeborg, S. Rogers, P. Southall, B. L. Zeddies, D. G. and Tavolga, W. N. (2014) 'Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI'. Springer and ASA Press, Cham, Switzerland.

Prakash, S. and Srivastava, S. (2019) 'Climate Change: Impact on Biodiversity and Ecosystem Functioning', International Journal of Biodiversity and Conservation, 11/3: 62-66.

PrePARED. (2024). PrePARED – The First Two Years. Report from the PrePARED Annual Knowledge Exchange Meeting 2024 (AKEM24). PrePARED.

Püts, M., Kempf, A., Möllmann, C., and Taylor, M. (2023). 'Trade-offs between fisheries, offshore wind farms and marine protected areas in the southern North Sea – Winners, losers and effective spatial management'. Marine Policy. 152: 105574

Puryear, W., Sawatzki, K., Hill, N., Foss, A., Stone, J.J., Doughty, L., Walk, D., Gilbert, K., Murray, M., Cox, E., Patel, P., Mertz, Z., Ellis, S., Taylor, J., Fauquier, D., Smith, A., DiGiovanni, R.A., Guchte, A. van de, Gonzalez-Reiche, A.S. and Khalil, Z. (2023). Early Release - Highly Pathogenic Avian Influenza A(H5N1) Virus Outbreak in New England Seals, United States - Volume 29, Number 4—April 2023 - Emerging Infectious Diseases journal - CDC. wwwnc.cdc.gov, [online] 29/4.

Ratcliffe, N., Bell, M., Pelembe, T., Boyle, D., Benjamin, R., White, R., Sanders, S. (2010) 'The eradication of feral cats from Ascension Island and its subsequent recolonization by seabirds', Oryx, 44/1: 20-29.

Reckendorf, A., Siebert, U., Parmentier, E., Das, K. (2023). Chemical Pollution and Diseases of Marine Mammals. In: Brennecke, D., Knickmeier, K., Pawliczka, I., Siebert, U., Wahlberg, M. (eds) Marine Mammals. Springer, Cham. https://doi.org/10.1007/978-3-031-06836-2_5 [Accessed September 2024].

Regnier, T., Gibb, F. and Wright, P. (2019). 'Understanding Temperature Effects on Recruitment in the Context of Trophic Mismatch'. Scientific Reports, 9.

Romero, J., Catry, P., Alonso, H., Granadeiro, J.P. (2021) 'Seabird diet analysis suggests sudden shift in the pelagic communities of the subtropical Northeast Atlantic', Marine Environmental Research, 165: 105232.

Roman, L., Lowenstine, L., Parsley, L.M., Wilcox, C., Hardesty, B.D., Gilardi, K., and Hindell, M. (2019). 'Is plastic ingestion in birds as toxic as we think? Insights from a plastic feeding experiment'. Science of the Total Environment. 665: 660-667.

RSPB England (2021) Celebrating Seabird Success on the Island of Lundy and the Isles of Scilly. https://community.rspb.org.uk/ourwork/b/rspb-england/posts/celebrating-seabird-success-on-the-island-of-lundy-and-the-isles-of-scilly/ [Accessed: September 2024].

Scopel, L.C., Diamond, A.W., Kress, S.W., Hards, A.R., and Shannon, P. (2017) 'Seabird diets as bioindicators of Atlantic herring recruitment and stock size: a new tool for ecosystem-based fisheries management', Canadian Journal of Fisheries and Aquatic Sciences, 75/8: 1215-1229.

SCOS (2023) Scientific Advice on Matters Related to the Management of Seal Populations: 2022.

Scottish Seabird Centre (2024) The SOS Puffin Project. https://www.seabird.org/projects/SOSPuffin [Accessed: October 2024].

Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., & Wirtz, K. W. (2018). The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. Hydrobiologia, 845/1: 35-53.

Snelgrove, P. V. R. (1999). Getting to the Bottom of Marine Biodiversity: Sediment Habitats. Oceanography, 12/3: 60-70.

Snyder, B. and Kaiser, M.J. (2009) 'Ecological and economic cost-benefit analysis of offshore wind energy', Renewable Energy, 34/6: 1567-1578.

The Crown Estate (TCE). 2024. 'Marine Delivery Roadmap'. Available at: https://www.datocms-assets.com/136653/1725984848-tce_future-offshore-wind.pdf [Accessed October 2024]

Thorsson, E., Siamak Zohari, Anna Marie Roos, Fereshteh Banihashem, Bröjer, C. and Aleksija Neimanis (2023). 'Highly Pathogenic Avian Influenza A(H5N1) Virus in a Harbor Porpoise, Sweden'. Emerging Infectious Diseases, 29/4: 852–855.

Tremlett, C.J., Morley, N., and Wilson, L.J. (2024). UK seabird colony counts in 2023 following the 2021-22 outbreak of Highly Pathogenic Avian Influenza. RSPB Research Report 76. RSPB Centre for Conservation Science, RSPB, The Lodge, Sandy, Bedfordshire, SG19 2DL.

Trenkel, V. M., Hintzen, N. T., Röckmann, C. and Schade, F. M. (2013). 'Herring management under uncertainty: Harvest control rules and the carrying capacity of the environment'. ICES Journal of Marine Science, 70/1: 44-55

UN Environment Programme. (2021). From Pollution to Solution: a global assessment of marine litter and plastic pollution. United Nations Environment Programme, Nairobi. Available at: https://www.unep.org/ resources/pollution-solution-global-assessmentmarine-litter-and-plastic-pollution [Accessed on: September 2024].

Van der Molen, J., Smith, H.C., Lepper, P., Limpenny, S. and Rees, J. (2014) 'Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem', Continental shelf research, 85: 60-72.

Van der Wal, R. (2006) The management of tree mallow and puffin habitat on Craigleith: a first proposal. Centre for Ecology and Hydrology, 11pp. (CEH: Project Report Number C02823).

Van Deurs, M., Grome, T., Kaspersen, M., Jensen, H., Stenberg, C., Sørensen, J., Støttrup, J., Warnar, T. and Mosegaard, H. (2012). 'Short- and Long-Term Effects of an Offshore Wind Farm on Three Species of Sandeel and Their Sand Habitat'. Marine Ecology Progress Series, 458: 169-180.

Waggitt, J.J., Evans, P.G.H., Andrade, J., Banks, A.N., Boisseau, O., Bolton, M., and Leopold, M. (2019) Data from: Distribution maps of cetacean and seabird populations in the North-East Atlantic.

Wakefield, E.D., Owen, E., Baer, J., Carroll, M.J., Daunt, F., Dodd, S.G., and Bolton, M. (2017) 'Breeding density, fine-scale tracking, and large-scale modeling reveal the regional distribution of four seabird species. Ecological Applications', 27/7: 2074-2091.

Wanless, S., Harris, M.P., Greenstreet, S.P.R. (1998) 'Summer sandeel consumption by seabirds breeding in the Firth of Forth, south-east Scotland', ICES Journal of Marine Science, 55: 1141-1151.

Watanuki, Y. *et al*. (2022) 'Seabird reproductive responses to changing climate and prey communities are mediated by prey packaging', Marine Ecology Progress Series, 683: 179-194.

Whittle, P. (2024) Bird flu is decimating seal colonies. Scientists don't know how to stop it, AP [online], 22 March. https://www.rspb.org.uk/birds-and-wildlife/avian-influenza-updates [Accessed: September 2024].

Wilson, J.C. and Elliott, M. (2009) 'The Habitat-creation Potential of Offshore Wind Farms', Wind Energy, 12: 203-212.

Wilson, J. *et al*. (2010) 'Coastal and Offshore Wind Energy Generation: Is It Environmentally Benign?', Energies, 3/7: 1383-1422.

Zantis, L.J., Caroll, E.L., Nelms, S.E., and Bosker, T. (2021. 'Marine mammals and microplastics: A systematic review and call for standardisation'. Environmental Pollution. 116142.

Zawawi, N. W. A., Liew, M. and Na, K. (2012). Decommissioning of offshore platform: A sustainable framework. Pages 26-31 in Humanities, Science and Engineering (CHUSER), 2012 IEEE Colloquium on. IEEE.

Zijl, F., Laan, S.C., Emmanouil, A., van Kessel, T., van Zelst, V.T.M., Vilmin, L.M. and van Duren, L.A. (2021). ‘Potential ecosystem effects of large upscaling of offshore wind in the North Sea – Bottom-up approach’. Deltares Report.

ANNEX A

Investigating the impacts of floating turbine structures at the Proposed Development Array Area on shelf sea stratification, nutrient fluxes and primary production

Investigating the impacts of floating turbine structures at the Proposed Development Array Area on shelf sea stratification, nutrient fluxes and primary production

Issue 02

October 2024

MUIR MHÒR
OFFSHORE WIND FARM

SAMS Applied Marine Science Enterprise Ltd. (trading as SAMS Enterprise)
Registered Office: ECMB, Dunbeg, Oban, Argyll, PA37 1QA
T: +44 (0) 1631 559470 F: +44 (0) 1631 559001
E: info@sams-enterprise.com W: http://www.sams-enterprise.com
Vat Registration No GB 828 9579 61 Company Registered in Scotland No. SC224404

HIE Highlands and Islands Enterprise
Europe and Scotland Making it work together
PART OF THE SAMSgroup

Report Title	Investigating the impacts of floating turbine structures at the Proposed Development Array Area on shelf sea stratification, nutrient fluxes and primary production
Project Name	GoBe Stratification
Client/Customer	GoBe and Muir Mhòr Offshore Wind Farm
SAMS Enterprise Project Reference	05146
Document Number	05146_001

Revision History

Revision	Originator	Checked	Approved	Date
Draft A	AD	RT	-	18/09/2024
Draft Issue 01	AD	AW	AW	19/09/2024
Issue 01	AD/RT	LV	LV	27/09/2024
Issue 01A	AD/RT	AW	-	28/10/2024
Issue 02	AD	RT	AW	31/10/2024

Revision	Changes
Draft A	Internal issue
Draft Issue 01	Draft report submission to customer
Issue 01	First issue of report to customer
Issue 01A	Internal issue to address customer comments
Issue 02	Second issue of report to customer

This report was produced by SAMS Enterprise for its Customer GoBe and Muir Mhòr Offshore Wind Farm for the specific purpose understanding the impacts of floating turbine structures on shelf seas stratification, nutrient fluxes and primary production. This report may not be used by any person other than SAMS Enterprise's Customer without its express permission. In any event, SAMS Enterprise accepts no liability for any costs, liabilities or losses arising because of the use of or reliance upon the contents of this report by any person other than its Customer.

SAMS Applied Marine Science Enterprise Ltd. (trading as SAMS Enterprise), ECMB, Dunbeg, Oban, Argyll, PAR37 1QA Tel +44 (0)1631 559 470; www.sams-enterprise.com

Table of Contents

1 Introduction 6
1.1 Project Background 6
1.2 Stratification and mixing by floating offshore wind turbine foundations 6
1.3 Impact of mixing on biological productivity 7
2 Stratification and currents 9
2.1 Overview of the northern North Sea 9
2.2 Climatological stratification in the region 10
2.3 Historical water column profiles 13
2.4 The AMM15 hydrodynamic model 17
2.5 Estimation of turbulent kinetic energy due a turbine structure 19
2.6 Turbine scenarios considered 19
2.7 Comparison between turbine-induced turbulence and natural turbulence from wind and bed stress 21
2.8 Transport and dispersion of induced turbulence and mixing 24
3 Nutrient biogeochemistry and Primary Production 27
3.1 Methods 27
3.2 Seasonal variability in nutrients and chlorophyll over the wider North Sea 28
3.3 Depth variability in nutrients and chlorophyll-a at the Proposed Development Array Area 31
3.4 Implications of changing stratification to primary production 33
3.5 Wider North Sea perspective 35
4 Discussion and Conclusions 37
4.1 Characteristics of site 37
4.2 Energetics of turbine interactions 37
4.3 Some points of uncertainty and potential further work 37
5 References 39

List of Figures

Figure 1. Schematic of proposed turbine structures alongside the typical physical and biogeochemical structure of a seasonally stratified shelf sea in summer. This study considers a site where the water depth is typically between 60 and 95 m. The floating structures under consideration extend to a depth of up to 20 m in the water column, with associated mooring lines to the seabed, so may impinge into the depth range of the thermocline and SCM. Nitrogen (mostly in the oxidised form of nitrate) is the primary limiting nutrient in this region. 8
Figure 2. Bathymetry (GEBCO) (depth in m) of the northern North Sea in relation to the Proposed Development Array Area. East-west and north-south transects (green dashed) are discussed in 2.2.6 and the associated Figures 6 and 7. The magenta box shows the region searched for archived CTD profiles. Green squares show comparative locations to the north and south (2.2.5). 9
Figure 3. Figure from Hill et al. (2008) showing the regions where summer stratification is driven by bottom cool, salty pools (orange) as opposed to cool only (grey). Red shows flows associated with the boundaries of these bottom dense pools. 10
Figure 4. Surface practical salinity from the ICES/WODC climatology in January, April, July and November. The location of the Proposed Development Array Area is indicated in red. 11

Figure 5. (a) Monthly ICES climatological values for surface (red) and bottom (blue) temperature and salinity in the Proposed Development Array Area. (b) Annual cycle of top to bottom difference in ICES climatological temperature and salinity at the Proposed Development Array Area (black) compared with sites 0.5 degrees to the north (green) and south (magenta) (locations shown in Figure 2). 12
Figure 6. East-west transect (green in Figure 2) of climatological surface and bed temperature and salinity at the latitude of the Proposed Development Array Area, which lies within the longitude range indicated by grey shading. 12
Figure 7. North-South transect (green in Figure 2) of climatological surface and bed temperature and salinity at the longitude of the Proposed Development Array Area, which lies within the latitude range indicated by grey shading. 13
Figure 8. The distribution of vertical CTD profiles accessed from WOD and BODC archives. The underlying image is of bathymetry (depth in metres) from GEBCO. The Proposed Development Array Area is shown red and the search region for profiles, which extends beyond the site boundaries, is shown in magenta. 14
Figure 9. The annual cycle of stratification expressed as the difference in the potential density between the surface and bed in a box containing the Proposed Development Array Area. Each dot shows a single measured profile obtained from BODC or WOD. ICES climatological values are shown as red discs. 15
Figure 10. The annual cycle of the potential energy required to fully mix the water column ($\emptyset \boldsymbol{H}$) in the box containing the Proposed Development Array Area. Each blue dot represents $\emptyset \boldsymbol{H}$ for a single measured profile obtained from BODC or WOD. Red dots show the contribution of salinity stratification to $\emptyset \boldsymbol{H}$. 16
Figure 11. Depth of the thermocline at varying times of year from historical vertical profiles in the vicinity of the Proposed Development Array Area. The thermocline depth has been estimated as the depth of the mid-point of the profile temperature range, with a threshold gradient used to eliminate well-mixed or weakly stratified cases. 16
Figure 12. Observed (WOD and BODC) temperature profiles from July in the box containing the Proposed Development Array Area illustrating the variability in the depth of the summer thermocline. 17
Figure 13. Annual, vector-averaged surface velocities from AMM15 for 2019, with the Fair Isle and Dooley currents indicated. Background shading shows the current speed in ms^{-1}. 18
Figure 14. The 'realistic' case (left) and 'worst' case (right) turbine array scenarios considered for the proposed development (44 turbines and 67 turbines respectively). 20
Figure 15. The total power delivered to turbulent kinetic energy in the water column in (top) the realistic scenario with 44 turbines, and (bottom) the worst-case scenario with 67 turbines. Hourly values have been detided, but spring-neap cycling remains, so the two-weekly peaks occur at spring tides and the troughs at neap tides. Periods during which the water column is not significantly stratified are shown red. At these energy will be dissipated to heat rather than reducing stratification through mixing. 22
Figure 16. Annual average TKE production due to turbine structures and bed stress, in a west-east transect at the latitude of the Proposed Development Array Area (green in Figure 2). This is for the high-drag case $\boldsymbol{cD = 1}$ and the 'realistic' scenario with 44 turbines and tension leg moorings. The longitude range of the proposed array is shown grey. At other longitudes, the turbine-induced TKE is based on a turbine density that matches the 'realistic' scenario. 23
Figure 17. Maps of TKE enhancement due to the 'realistic' 44-turbine array at the Proposed Development Array Area after 4, 8 and 12 weeks from an assumed onset of stratification on 1st May 2019. The TKE enhancement is followed in a particle tracking approach using surface velocities from AMM15. TKE decays over much shorter timescales, so these values should be interpreted as the amount of

excess TKE that the water column at a given location has been exposed to since 1st May. A component of this energy will have been used to mix that water column. 26
Figure 18. Gridded biogeochemical data used from the Proposed Development Array Area and across the wider North Sea. The SCO is highlighted with a red cross. 27
Figure 19. Maps of surface nitrate concentration in winter, summer, spring and autumn, taken from the NSBC climatology..... 28
Figure 20. Maps of surface nitrate concentration in winter, summer, spring and autumn, taken from the NSBC climatology..... 29
Figure 21. Seasonal variability in nitrate (upper), phosphate (middle) and silicate (lower) in surface waters at the Proposed Development Array Area. 30
Figure 22. Seasonal variability in Chl-a (upper) and nitrate (lower) in surface waters at the Scottish Coastal Observatory site at Stonehaven. 31
Figure 23. Monthly profiles of nitrate taken from the grid points in the box inset in Figure around the Proposed Development Array Area. 32
Figure 24. (a) Chlorophyll-a and (b) nitrate profiles from the Proposed Development Array Area during July. (c) Nitrate gradients are used to calculate the diapycnal nitrate flux in (d), assuming a background $\boldsymbol{Kz}$ of 10^{-4} m^2 s^{-1} and a 20% increase in Kz shown in red. The nitrate convergence is shown in (e). 33
Figure 25. (a) Chlorophyll-a and (b) nitrate profiles from the Proposed Development Array Area during July. (c) Nitrate gradients are used to calculate the diapycnal nitrate flux in (d), assuming a background $\boldsymbol{Kz}$ of 10^{-4} m^2 s^{-1} and a 20% increase in $\boldsymbol{Kz}$ is shown in red. The nitrate convergence is shown in (e)..... 34
Figure 26. (a) Chlorophyll-a and (b) nitrate profiles from the Proposed Development Array Area during August. (c) Nitrate gradients are used to calculate the diapycnal nitrate flux in (d), assuming a background $\boldsymbol{Kz}$ of 10^{-4} m^2 s^{-1} and a 20% increase in $\boldsymbol{Kz}$ shown in red. The nitrate convergence is shown in (e). 34
Figure 27. Maps of the difference between nitrate at 50 m and nitrate at the surface, an indicator of the degree of stratification and nutrient limitation to surface phytoplankton. 36

Equations

Equation 1: $\emptyset = \mathbf{1}\boldsymbol{Hbedsurf}\boldsymbol{\rho 0} - \boldsymbol{\rho 0}\boldsymbol{gz}\,\boldsymbol{dz}$ (1) 15
Equation 2: $\boldsymbol{Pturbine} = \mathbf{12}\boldsymbol{\rho 0}\boldsymbol{cDAu3}$ (2) 19
Equation 3: $Pbot = \rho 0 cDbotu3$ (3) 22
Equation 4: $\boldsymbol{NO3flux} = \boldsymbol{Kz} \cdot (\boldsymbol{dNO3dz})\ (\boldsymbol{mol\,m-2\,s-1})$ (4) 33

Please cite report as:
Dale, A., & Tuerena, R (2024). Investigating the impacts of floating turbine structures at the Proposed Development Array Area on shelf sea stratification, nutrient fluxes and primary production. A report by SAMS Enterprise for GoBe and Muir Mhòr Offshore Wind Farm, pp. 40

Acronyms & Abbreviations

AMM15	Atlantic Margin Model, 1.5 km
BODC	British Oceanographic Data Centre
CTD	Conductivity, temperature and depth
GEBCO	General Bathymetric Chart of the Oceans
ICES	International Council for the Exploration of the Sea
JV	Joint Venture
MD-LOT	Marine Directorate-Licensing Operations Team
NSBC	North Sea Biogeochemical Climatology
PAR	Photosynthetically Active Radiation
SAMS	Scottish Association for Marine Science
SCM	Sub-surface Chlorophyll Maximum
SCO	Scottish Coastal Observatory
TKE	Turbulent Kinetic Energy
WOD	World Ocean Database
WODC	World Ocean Data Centre
NSBC	North Sea Biogeochemical Climatology

Glossary

Term	Meaning
Hydrodynamic model	A computational simulation of the motion and density structure of a fluid (here, the ocean) in response to applied forces.
Nutricline	A depth range in which nutrient concentrations change rapidly with depth (usually increasing).
Primary Production	The synthesis of organic compounds by primary producers, in the ocean, carried out primarily by photoautotrophs in the sunlit surface layer.
Stratification	Vertical variation in ocean properties, and in particular water density due to differences in salinity and temperature.
Sub-surface Chlorophyll Maximum	A region below the surface of water at which the maximum concentration of chlorophyll occurs. In stratified summer months a chlorophyll maximum forms below the surface in the area of the water column where there are enough nutrients and light to sustain photosynthesis and growth.
Turbulent Kinetic Energy	The kinetic energy associated with the fluctuating, turbulent component of flow, as opposed to the underlying mean or slowly-varying component.
Thermocline	Temperature gradient in water column with higher temperatures at the surface and lower temperatures below.

1 INTRODUCTION

1.1 Project Background

1.1.1 Muir Mhòr Offshore Wind Farm Limited (hereafter referred to as 'the Developer') is proposing to develop the Muir Mhòr Offshore Wind Farm (hereafter 'the Proposed Development Array Area'). The Project is made up of both offshore and onshore components. The subject of this offshore Environmental Impact Assessment Report (EIAR) is the offshore infrastructure of the Project seaward of Mean High-Water Springs (MHWS) which is hereafter referred to as 'the Proposed Development'.

1.1.2 The Proposed Development Array Area covers an area of approximately 200 km^2 and is located approximately 63 km east of Peterhead on the east coast of Scotland. The offshore infrastructure of the Proposed Development includes Wind Turbine Generators, and associated floating foundations, the Offshore Electrical Platforms and associated foundations, the inter-array cables, interconnector cable, offshore export cables and landfall.

1.1.3 This report has been developed in response to the Proposed Development Offshore Scoping Opinion (Volume 3, Appendix 5.2, Offshore Scoping Opinion), which highlighted the need to assess "the link between stratification and fronts to primary productivity and higher trophic levels".

1.1.4 Most offshore wind farms to date have been built in shallow (nearshore) and often unstratified (well-mixed) seas using fixed foundations. With the development of floating offshore wind technologies, the sector is moving into deeper waters requiring larger turbine support structures, often within seasonally stratified shelf seas (see Dorrell et al. 2022). Stratified seas play a key role in primary production (and are linked to biogeochemical cycles). The placement of anthropogenic structures into seasonally stratified waters can artificially increase the mixing of these waters. This may lead to an enhanced nutrient supply which, in turn, could impact the marine ecosystem.

1.2 Stratification and mixing by floating offshore wind turbine foundations

1.2.1 A stratified water column is a water column that is layered, with denser (cooler or saltier) water found at depth compared to close to the surface. An unstratified water column has no differences in density between the surface and bottom of the column. When a particularly strong vertical density gradient occurs at some level in the water column, this is termed a pycnocline and may occur at the base of a well-mixed surface layer. Similarly, a strong temperature gradient is termed a thermocline; a strong gradient of nutrients is termed a nutricline, etc.

1.2.2 Mixing reduces the density differences in a stratified water column by stirring it vertically, with the end point being an unstratified ('well-mixed') water column, which has a density that is uniform with depth. A well-mixed water column has a greater potential energy than a stratified water column. Mixing therefore requires energy to be supplied to provide this

increase in potential energy. Energy sources for mixing include wind and waves, which stir from the surface, or energy may be taken from tidal and other currents by bed friction, which stirs upwards from the seabed.

1.2.3 In winter, the North Sea is largely unstratified. Areas that are shallow or have strong tidal flows remain well-mixed throughout the year because there is enough tidal stirring to overcome the stratifying influence of solar heating. Elsewhere, the onset of stratification in spring occurs when the surface can warm through solar heating without being stirred into underlying waters. The top to bottom density difference typically increases during summer, peaks in August, then is eroded by November with a return to unstratified winter conditions.

1.2.4 A floating offshore wind turbine foundation could provide energy to mixing at intermediate levels within the water column as the flow interacts with the structure, generating a turbulent wake. Turbulence consists of multi-scale stirring motions with their own inherent kinetic energy (turbulent kinetic energy, TKE). The conversion of energy during mixing is from the kinetic energy of the background flow to TKE and then to a combination of potential energy, through mixing, and heat, through friction within the water column.

1.2.5 Quantifying the impact of an offshore wind structure on stratification is dependent upon several variables, including the initial stratification, the background flow speed, and the design and depth extent of the structure. In general, even if all these factors are known, it is difficult to estimate the impact because it depends upon complex, turbulent processes. Model studies can simulate the mixing behaviour in specific cases, but the extrapolation of outcomes to differing flow speeds, structures or stratification conditions involves considerable uncertainty.

1.2.6 The mixing efficiency, the proportion of TKE that is used for mixing (as opposed to dissipated by friction), depends on the variables (as listed above) and the fluid dynamical processes involved. However, a rule of thumb is that the proportion of TKE used for mixing is rarely greater than 20% as the majority of TKE is dissipated by friction (Gregg et al., 2018), and usually significantly less.

1.3 Impact of mixing on biological productivity

1.3.1 When the surface waters of the North Sea develop thermal stratification, the spring bloom of phytoplankton depletes surface nutrients and growth becomes limited by the lack of nutrients in the surface layer. Surface waters are then isolated from the higher nutrient waters below during the summer. The sub-surface chlorophyll maximum (SCM) typically develops between 20 and 40 m below the surface and is sustained by a balance between sufficient sunlight from the surface and sufficient nutrient supply by turbulent mixing which drives an upward flux across the thermocline. The SCM may account for up to 50% of annual primary production (this is all the production by photoautotrophs in the euphotic zone) in seasonally stratified seas (Hickman et al., 2012).

1.3.2 Floating offshore wind turbine support structures may enhance turbulent mixing in the thermocline, increase nutrient availability to the SCM, and therefore increase annual primary production (**Error! Reference source not found.**). Existing studies of the influence of floating offshore wind structures on primary production in stratified conditions (Carpenter et al., 2016; Slavik et al. 2018) have focussed on shallower waters than those considered here, and turbine piles associated with fixed wind turbines that extend through the full water column.

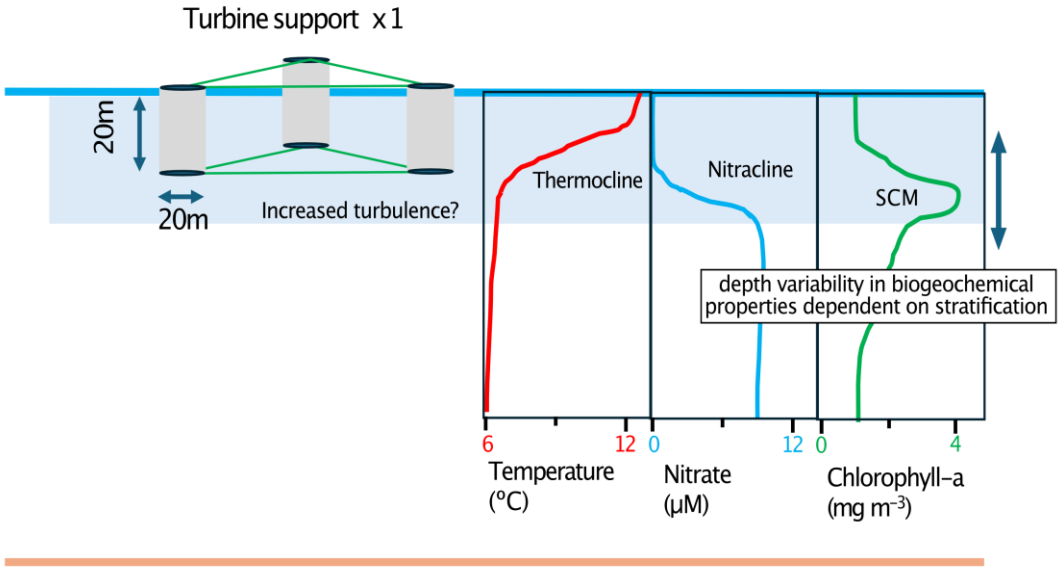

Figure 1. *Schematic of proposed turbine structures alongside the typical physical and biogeochemical structure of a seasonally stratified shelf sea in summer. This study considers a site where the water depth is typically between 60 and 95 m. The floating structures under consideration extend to a depth of up to 20 m in the water column, with associated mooring lines to the seabed, so may impinge into the depth range of the thermocline and SCM. Nitrogen (mostly in the oxidised form of nitrate) is the primary limiting nutrient in this region.*

1.3.3 This study considers the impacts on shelf sea stratification of structures at the Proposed Development site. It includes an estimation of the resulting mixing and its implications for nutrient fluxes and primary production.

2 STRATIFICATION AND CURRENTS

2.1 Overview of the northern North Sea

2.1.1 Regional differences in stratification in the North Sea are largely driven by water depth (Figure 2), the strength of tidal currents, the proximity to the shelf edge where exchange with oceanic waters modifies water properties, and the influence of fresher water which is typically found nearshore (Huthnance, 1991). The North Sea is generally deeper in the north, with the deepest areas (exceeding 150 m) north of 57.5°N and between 2°W and 1°E.

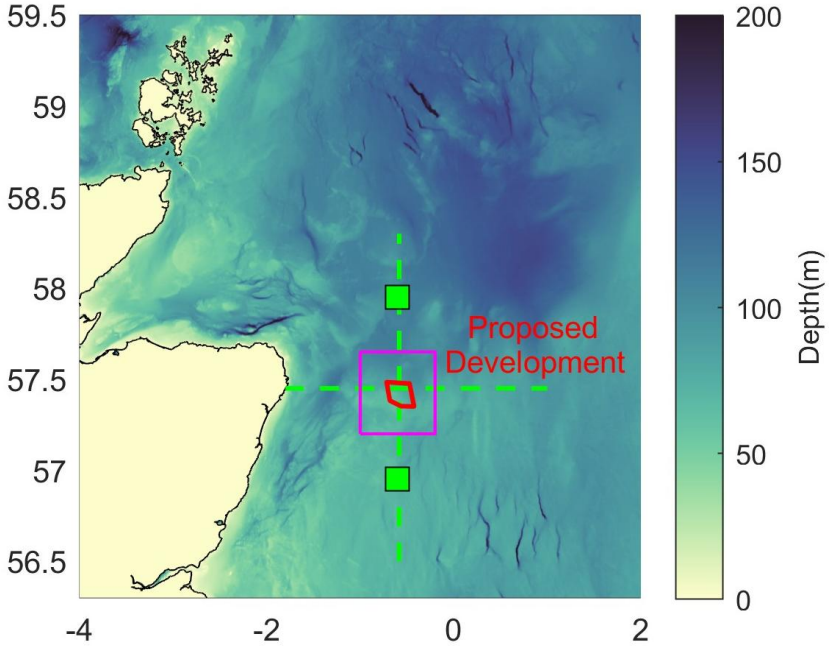

Figure 2. *Bathymetry (GEBCO) (depth in m) of the northern North Sea in relation to the Proposed Development Array Area. East-west and north-south transects (green dashed) are discussed in 2.2.6 and the associated Figure 6 and Figure **7**. The magenta box shows the region searched for archived CTD profiles. Green squares show comparative locations to the north and south (2.2.5).*

2.1.2 The Proposed Development Array Area has typical water depths in the range 60 m to 95 m, with deeper water generally in the north and shallower in the south, although there is local complexity.

2.1.3 In the winter, the North Sea is only stratified where coastal freshwater influence is significant (Huthnance, 1991), so stratification is driven by salinity. Elsewhere, water properties are uniform from the top to the bottom of the water column. The onset of stratification in spring occurs when the surface can warm through solar heating without being assimilated by stirring into underlying waters.

2.1.4 In the deepest areas of the northern North Sea, bottom waters retain their winter temperature and salinity throughout the year (orange in Figure 3; Hill et al. 2008), whilst

the overlying surface waters warm and often become less saline. More coastal areas show significant warming of bottom waters in summer, and the resulting gradient in density between these coastal waters and more offshore water leads to a surface current along the boundary between the two. This flows south to the east of Orkney and the outer Moray Firth, and then east into the central North Sea as the Dooley current.

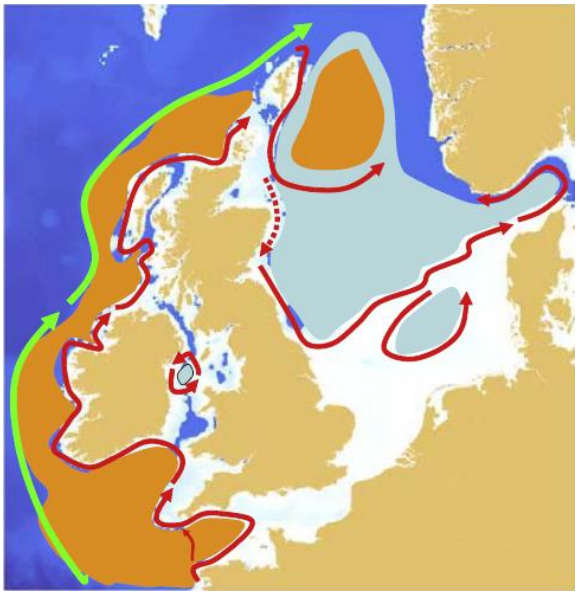

Figure 3. *Figure from Hill et al. (2008) showing the regions where summer stratification is driven by bottom cool, salty pools (orange) as opposed to cool only (grey). Red shows flows associated with the boundaries of these bottom dense pools.*

2.1.5 An additional influence is the fresher coastal water of the Scottish Coastal Current, which enters the North Sea via the Pentland Firth and to the north of Orkney, then also flows south, augmenting the flow and gradients described above.

2.2 Climatological stratification in the region

2.2.1 Climatological values of temperature and salinity represent average conditions calculated from available historical measurements. Descriptions here are based on the ICES/WODC climatology of surface and near-bed temperature and salinity (Berx and Hughes, 2009; https://data.marine.gov.scot/dataset/climatology-surface-and-near-bed-temperature-and-salinity-north-west-european-continental). This represents average values for the period 1971-2000 and is provided on a 1/6° (longitude) by 1/10° (latitude) spatial grid, roughly 10 km by 11 km at this latitude.

2.2.2 Climatological values inherently blur sharp features, such as fronts, or variable conditions. The ICES/WODC climatology is also restricted to the surface and near-bottom, so does not provide information on the sharpness of vertical gradients, for instance within the pycnocline. For these reasons, the use of climatology has been supplemented with an investigation of individual archived vertical profiles of temperature and salinity (section 2.3).

2.2.3 The climatological surface salinity (Figure 4) shows the highest salinity in the central part of the northern North Sea, corresponding to the greatest water depths. Fresher surface occurs closer to shore and in shallower areas to the south. The east-flowing Dooley Current is in part driven by the resulting north to south decrease in salinity.

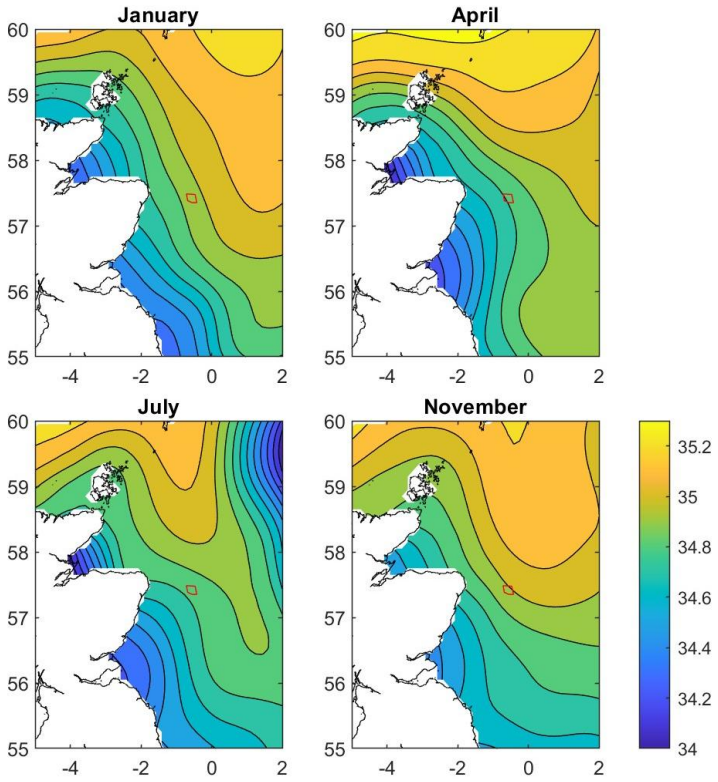

Figure 4. *Surface practical salinity from the ICES/WODC climatology in January, April, July and November. The location of the Proposed Development Array Area is indicated in red.*

2.2.4 Within the Proposed Development Array Area (Figure 5a), surface and bottom temperatures are lowest in March. Temperature stratification (surface to bed difference) is first significant in May, peaks in August, before falling rapidly until there is no longer significant stratification in November. Salinity stratification is small in winter (November to February), largest in March, and otherwise fairly constant during the temperature stratified months, with fresher water at the surface, although temperature, rather than salinity, is the prime driver of density stratification.

2.2.5 Conditions at the Proposed Development Array Area have been compared with those at sites 0.5° (56 km) to the north and south (Figure 5b). Shown is that the surface to bottom temperature difference is similar in magnitude and seasonality, whilst the salinity difference is significantly greater in the north, largely due to the greater water depth.

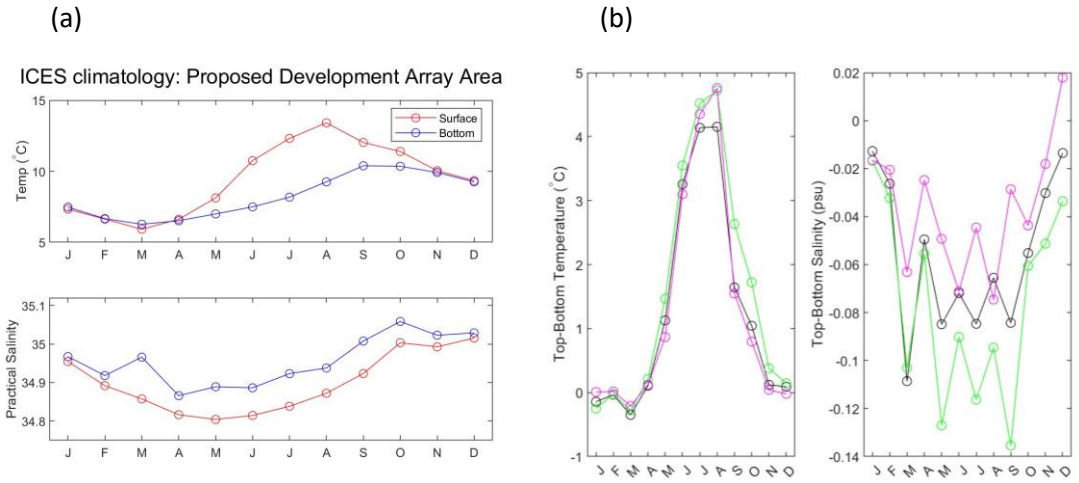

Figure 5. *(a) Monthly ICES climatological values for surface (red) and bottom (blue) temperature and salinity in the Proposed Development Array Area. (b) Annual cycle of top to bottom difference in ICES climatological temperature and salinity at the Proposed Development Array Area (black) compared with sites 0.5 degrees to the north (green) and south (magenta) (locations shown in Figure 2).*

2.2.6 East-west and north-south transects through the Proposed Development Array Area (green lines in Figure 2) at varying times of year (Figure 6Figure 7) show a horizontal gradient of surface water properties, with salinity increasing to the east and north. It is this gradient that is associated with the east-flowing Dooley Current.

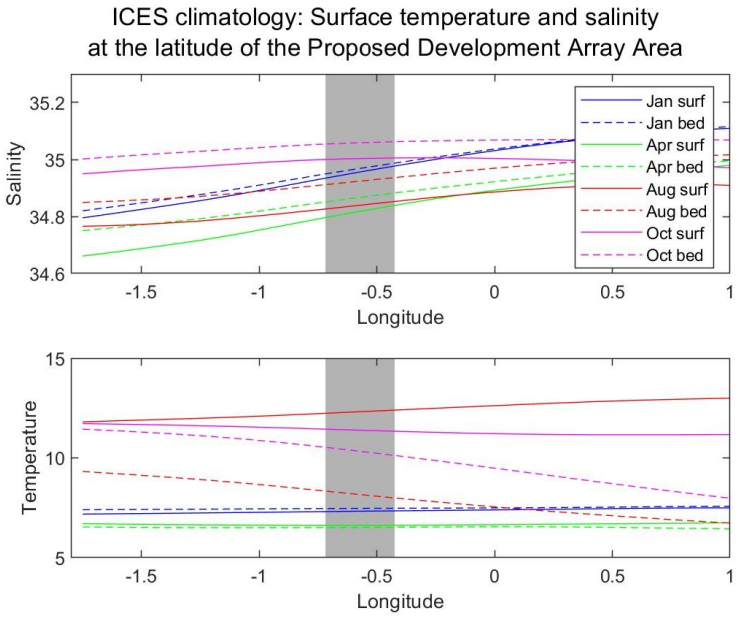

Figure 6. *East-west transect (green in Figure 2) of climatological surface and bed temperature and salinity at the latitude of the Proposed Development Array Area, which lies within the longitude range indicated by grey shading.*

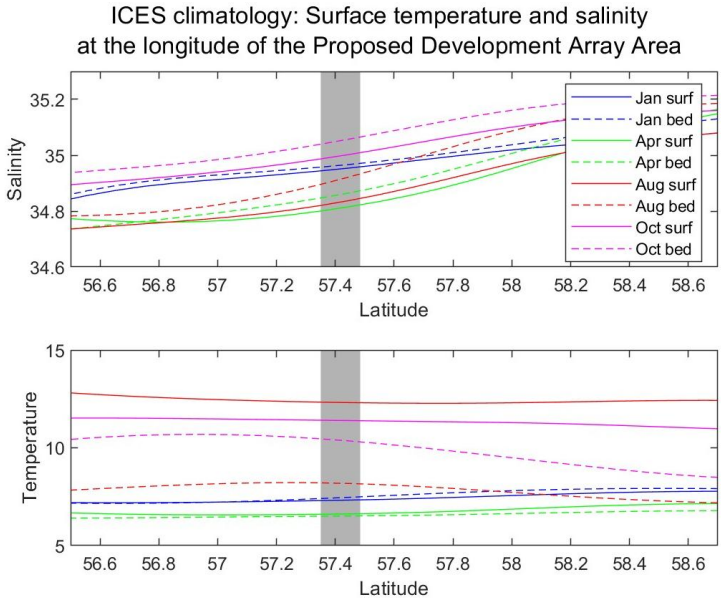

Figure 7. *North-South transect (green in Figure 2) of climatological surface and bed temperature and salinity at the longitude of the Proposed Development Array Area, which lies within the latitude range indicated by grey shading.*

2.3 Historical water column profiles

2.3.1 Directly measured vertical profiles of temperature and salinity have been accessed in data repositories held by the British Oceanographic Data Centre (BODC; https://www.bodc.ac.uk/data/bodc_database/) and the World Ocean Database (WOD; https://www.ncei.noaa.gov/access/world-ocean-database-select/dbsearch.html). These provide good coverage of the region and complement the climatology described above by providing an indication of the variability expected because of differing conditions at the time of measurement. They are not independent of those climatological datasets, however, since the climatologies are based on the same archived datasets.

2.3.2 Profiles were sought within a box-shaped region containing the Proposed Development Array Area and surrounding waters (Figure 8). The extension of the search area beyond the Array Area itself was to draw in a larger number of available profiles, however there are gradients in properties, so the more distant profiles may not fully represent conditions in the Array Area.

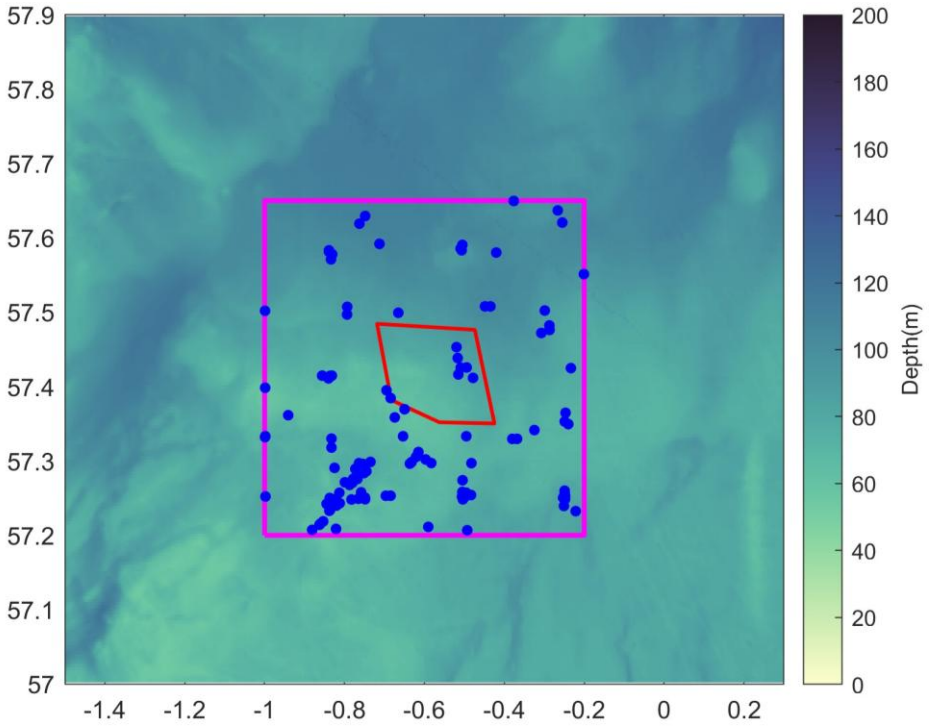

Figure 8. *The distribution of vertical CTD profiles accessed from WOD and BODC archives. The underlying image is of bathymetry (depth in metres) from GEBCO. The Proposed Development Array Area is shown red and the search region for profiles, which extends beyond the site boundaries, is shown in magenta.*

2.3.3 In total 122 distinct profiles were identified, spanning the period 1989-2020 and all months except May. Although only six of these profiles lay directly within the boundaries of the Proposed Development Array Area, the remaining 116 lay within approximately 20 km of those boundaries. Some of the profiles were duplicated between the two sources, however 19 appeared only in the BODC archive and 64 only in WOD.

2.3.4 Stratification was first assessed by taking the difference between the surface and bottom density in each profile (Figure 9). This measure was directly compared with the ICES climatological values.

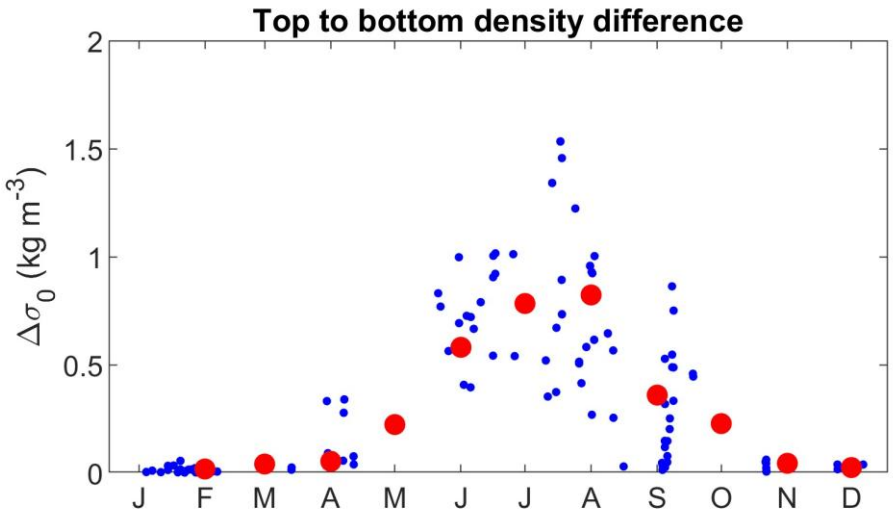

Figure 9. *The annual cycle of stratification expressed as the difference in the potential density between the surface and bed in a box containing the Proposed Development Array Area. Each dot shows a single measured profile obtained from BODC or WOD. ICES climatological values are shown as red discs.*

2.3.5 A more sophisticated measure of stratification is the potential energy anomaly Ø

$$\emptyset = \frac{1}{H}\int_{bed}^{surf}(\rho_0 - \overline{\rho_0})gz\,dz \qquad (1)$$

where ρ_0 is the potential density, $\overline{\rho_0}$ is the depth mean of potential density, g is the gravitational acceleration, z is vertical distance (increases upwards) and H is the water depth (Simpson, 1981). Multiplying Ø by H yields the energy required (per unit area) to fully mix the water column (Figure 10). This can be related to the mixing energy being supplied by natural or artificial sources, at the seabed, at the surface, or within the water column.

2.3.6 The potential energy anomaly has also been calculated using the observed salinity profile but as a depth-averaged value for temperature (red dots in Figure 10). This separates the salinity influence on stratification from the temperature influence. The salinity contribution to Ø is generally small compared to the temperature contribution.

2.3.7 The depth of the thermocline has been estimated from each profile (Figure 11) by identifying the maximum and minimum temperatures in a profile, averaging them, then looking for the depth at which that average temperature occurred. Only profiles where the maximum vertical temperature gradient exceeded 0.1°Cm^{-1} were considered to have a thermocline, eliminating winter profiles. Inspection of individual profiles suggests that, despite its simplicity, this method performs well.

2.3.8 At the Proposed Development Array Area, following the development of a thermocline in spring, there is no clear trend in its depth during the summer months. There is, however, considerable variation between individual profiles, broadly in the 10 m to 50 m range

(Figure 11). In September, there is some evidence of deepening, after which winter mixed conditions develop.

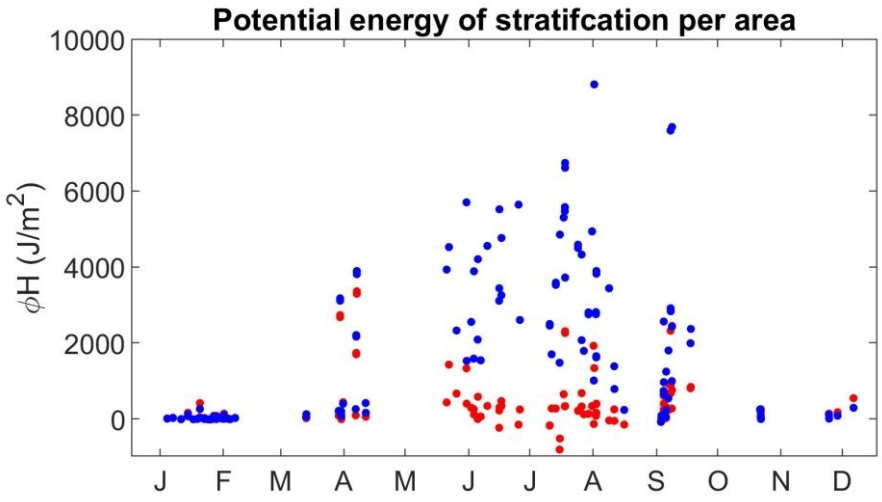

Figure 10. *The annual cycle of the potential energy required to fully mix the water column ($\emptyset\boldsymbol{H}$) in the box containing the Proposed Development Array Area. Each blue dot represents $\emptyset\boldsymbol{H}$ for a single measured profile obtained from BODC or WOD. Red dots show the contribution of salinity stratification to $\emptyset\boldsymbol{H}$.*

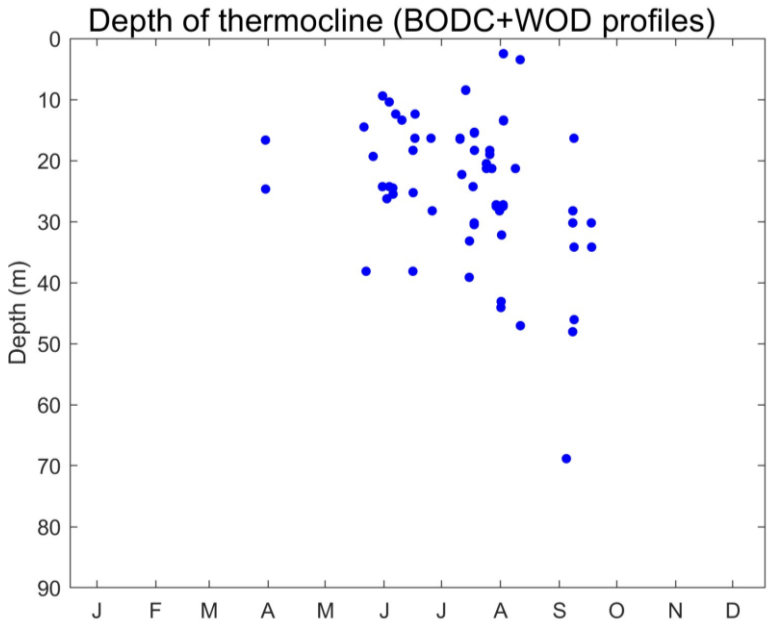

Figure 11. *Depth of the thermocline at varying times of year from historical vertical profiles in the vicinity of the Proposed Development Array Area. The thermocline depth has been estimated as the depth of the mid-point of the profile temperature range, with a threshold gradient used to eliminate well-mixed or weakly stratified cases.*

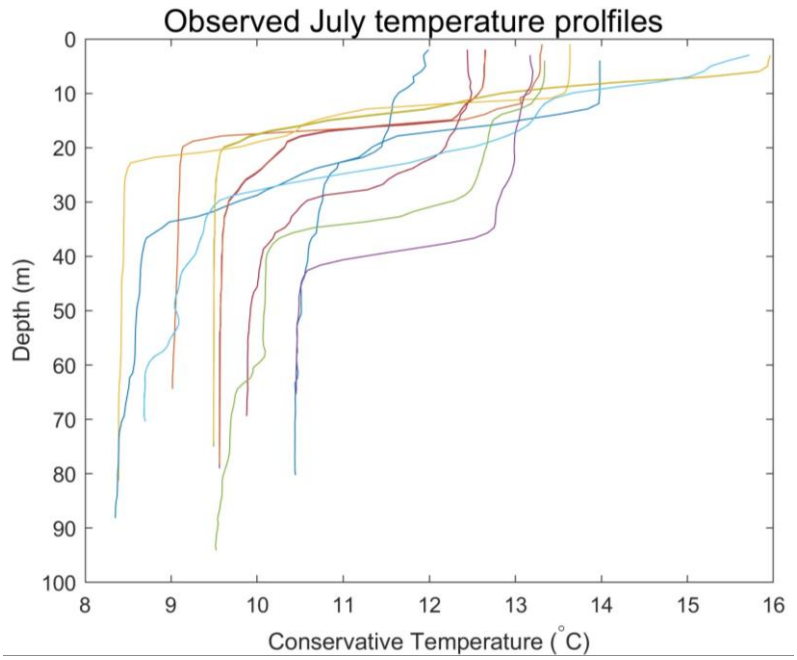

Figure 12. *Observed (WOD and BODC) temperature profiles from July in the box containing the Proposed Development Array Area illustrating the variability in the depth of the summer thermocline.*

2.4 The AMM15 hydrodynamic model

2.4.1 Hydrodynamic model data (temperature, salinity, and currents) has been taken from the UK Met Office AMM15 model (Atlantic Margin Model, 1.5 km), accessed via the Copernicus Marine Service (marine.copernicus.eu) as data product NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013. Note that this product is currently (September 2024) provided to Copernicus via a different and slightly lower resolution model, run by Nologin. The calculations described here are, however, based on AMM15 simulations from 2019 to 2020, which were previously archived from Copernicus.

2.4.2 AMM15 is the present state-of-the-art hydrodynamic model for the NW European shelf seas and consists of simulations carried out on a regularly spaced (1.5 km) horizontal grid (Graham et al., 2018). It represents a comprehensive range of physical processes including tides, meteorologically-driven and density-driven dynamics so can be considered the best-available simulation of the evolving physical environment of the North Sea.

2.4.3 The advantage of a hydrodynamic model is that it provides fully three-dimensional simulations of the evolving oceanic stratification and currents, so it helps to clarify spatial patterns and evolution that may not be apparent from isolated real-world observations. The patterns of stratification and currents appear to represent well the patterns described above, and extensive use is made of AMM15 in the following sections to estimate turbine-induced turbulence.

2.4.4 The Proposed Development Array Area is in a region of significant mean flow to the east, of order 0.1 ms^{-1} (Figure 13). This represents the southern flank of the Dooley Current. A symmetric tidal flow would average to zero, so this mean represents a combination of more steady density or wind-driven flows plus any residual flow resulting from tidal asymmetry.

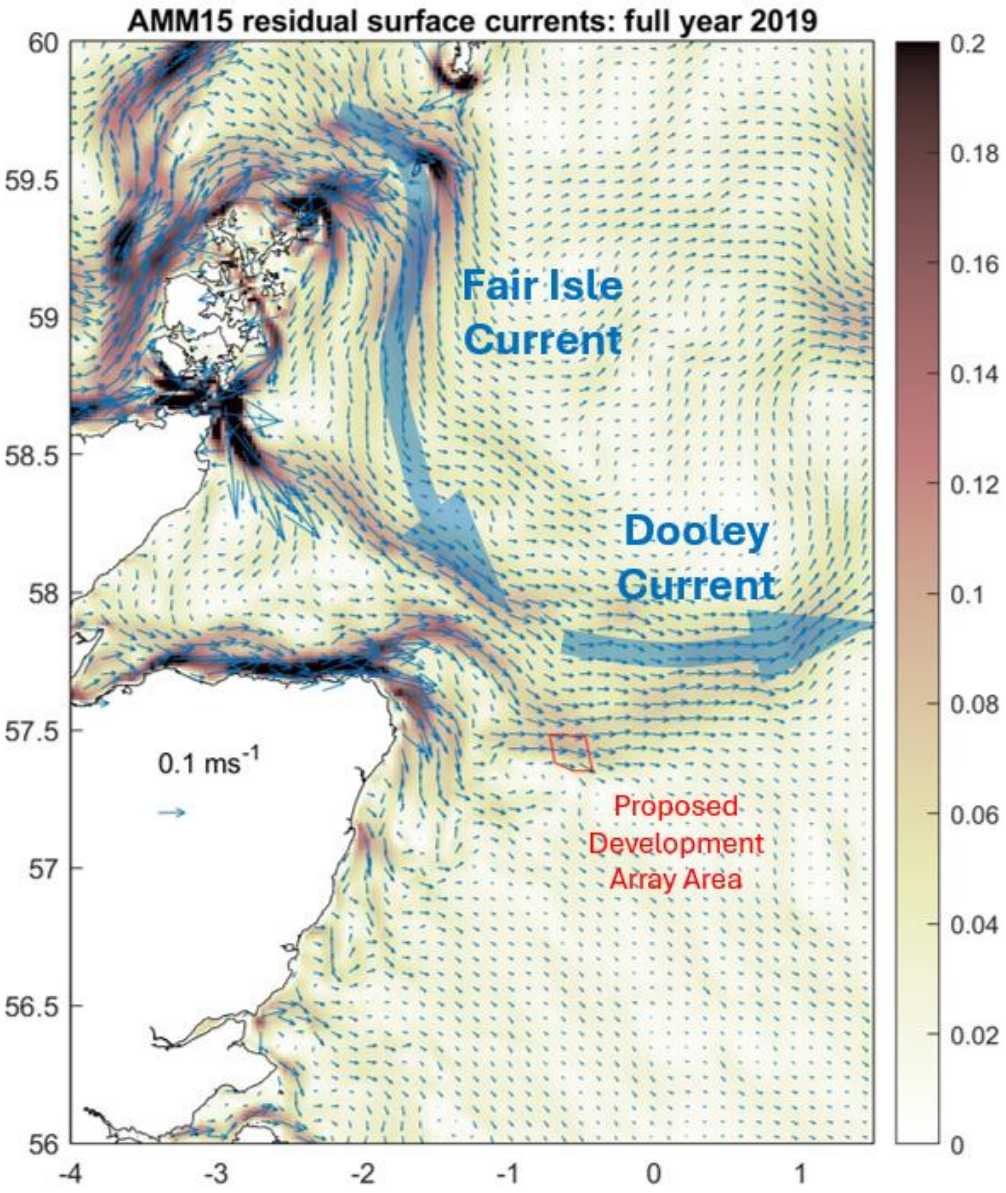

Figure 13. *Annual, vector-averaged surface velocities from AMM15 for 2019, with the Fair Isle and Dooley currents indicated. Background shading shows the current speed in* ms^{-1}.

2.4.5 The location of the Proposed Development Array Area within a region of significant mean flow means that water that has encountered the array will be transported downstream as a wake rather than remaining local to the site and continuing to experience its influence.

2.5 Estimation of turbulent kinetic energy due a turbine structure

2.5.1 The TKE provided to the water column by flow past a turbine structure is estimated using a drag coefficient-based approach in which the power removed from the ambient flow is:

$$\boldsymbol{P_{turbine} = \frac{1}{2}\rho_0 c_D A|u|^3} \quad (2)$$

where A is the area presented by the structure to the flow, $|u|$ is the background current speed at a moment in time, ρ_0 is a typical water density, and c_D is a drag coefficient.

2.5.2 Values for the drag coefficient c_D have been chosen following Carpenter (2016) who used a range of 0.35 to 1 to represent low and high drag limits. All calculations presented here use $c_D = 1$, so they represent a high-drag limit.

2.5.3 More accurate estimates of $P_{turbine}$ would require detailed modelling of circumstances of stratification, current and configuration of the structure. Such modelling would have large computational requirements, so more accurate parameterisations of TKE supply would not be straightforward to obtain. In the approach used here, the TKE supply scales linearly with the drag coefficient c_D, so uncertainty in the value of c_D is easily interpreted in terms of its impact on TKE.

2.5.4 The efficiency with which TKE is used for mixing, the flux Richardson number R_F, also has considerable uncertainty. In well-mixed (winter) conditions, there is no stratification to erode, so all TKE must ultimately be dissipated to heat ($R_F = 0$). In stratified conditions, the relation between the depth of the thermocline and the base depth of the turbine support structure has implications for the physical processes responsible for mixing. This may lead to significant variation in R_F, though values greater than 0.2 (20% of TKE used for mixing) are rarely observed.

2.5.5 The most significant nutrient fluxes occur when mixing can draw nutrients towards the surface and resupply nutrient-depleted surface waters. In summer, a gradient of nutrient concentration tends to coincide with the thermocline, so there is particular interest in fluxes within the summer thermocline.

2.6 Turbine scenarios considered

2.6.1 Two scenarios for turbine arrays have been considered, a ‘realistic’ and a ‘worst’ case consisting of 44 and 67 turbines respectively within the boundary of the Proposed Development Array Area (Figure 14). Turbines were separated by at least 1.67 km or 1.46 km, respectively, from their nearest neighbour at a mean density across the site of 0.22 or 0.34 turbines per square kilometre.

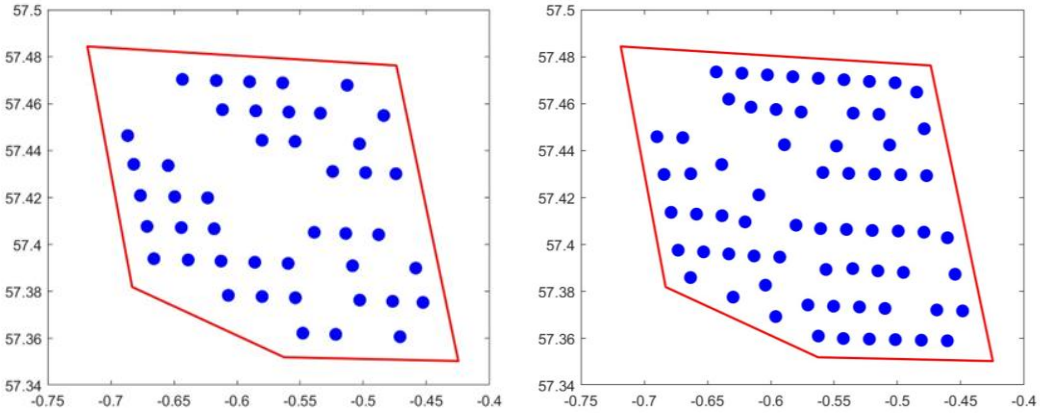

Figure 14. *The 'realistic' case (left) and 'worst' case (right) turbine array scenarios considered for the proposed development (44 turbines and 67 turbines respectively).*

2.6.2 The design of the turbine support structure and moorings also represented a 'realistic' case and a 'worst' case, supplied by the Developer. The 'realistic' structure consisted of three legs in a triangular arrangement, each with a diameter of 20 m and a draught below the water surface of 20 m. Turbines were assumed to be moored by 12 tension legs, with a total cross-sectional area of 1500 m^2 (see Volume 2, Chapter 3 (Project Description)), which has been scaled by $2/\pi$ to reflect averaging over all possible orientations to the ambient flow.

2.6.3 The 'worst' case support structure, which presented a greater area to the flow and therefore generated more energetic turbulence, also consisted of three legs in a triangular arrangement, each with a diameter of 20 m and a draught below the water surface of 40 m. An additional central column also had a diameter of 20 m and a draught of 40 m. It is assumed that nine catenary mooring lines were used, and that these lines were fouled by marine growth, presenting a total cross-sectional area of 10,800 m^2 to the flow, which was, again, scaled by $2/\pi$ to reflect averaging over all possible orientations to the ambient flow.

2.6.4 Based on these designs, the area presented to the flow by each turbine structure and mooring system was taken to be 2,155 m^2 (realistic case) and 8,876 m^2 (worst case). It is these areas that have been used in estimating the production of turbulent kinetic energy.

2.6.5 Idealised, unstratified flow past a cylindrical obstacle leads to a wake which may consist of a street of vortices or a more random, turbulent structure. Behaviour depends on the Reynolds number of the flow $\mathrm{Re} = \mathrm{uD}/\nu$ where u is the flow speed, D is the diameter of the cylinder, and ν is the kinematic viscosity (ν = 1.36×10^{-6} m^2s^{-1} at 10 °C and salinity 35 g kg^{-1}; Nayar et al., 2016). The drag coefficient c_D is also sensitive to the Reynolds number, so it is important to consider whether the differing scale of the structure designs described above would yield significantly differing drag coefficients.

2.6.6 The AMM15 modelled surface flow speed largely falls within the range of zero to 0.6 ms^{-1} and with a mean of 0.38 ms^{-1}. The Reynolds numbers for flow past the key structural

elements of the turbine foundations suggest that at most times this flow is in a supercritical, high Reynolds number ($\mathrm{Re} > 10^6$), regime where a turbulent wake is expected. The drag coefficient would be anticipated to increase somewhat with the Reynolds number (i.e. increasing with flow speed and the dimension of the structural element) (Roshko, 1961), although TKE supply mostly results from stronger flows where there is less sensitivity.

2.7 Comparison between turbine-induced turbulence and natural turbulence from wind and bed stress

2.7.1 The principal sources of turbulent mixing in natural conditions are wind and wave effects at the surface and the frictional stress resulting from flow near the seabed. Wind and wave stirring are variable in response to weather conditions, but bottom stress is more predictable and often largely tidal. Whilst this tidal bottom stress is considered the key source influencing the distribution of shelf sea stratification, wind is significant at lower tidal current speeds. Simpson and Bowers (1981) found that, in the Irish and Celtic Seas, wind mixing was of a similar magnitude to tidal mixing when the spring tidal current speed was 0.75 ms^{-1}, which is similar to that at the Proposed Development Array Area (ABPMer, 2007).

2.7.2 The predicted power supplied to TKE by offshore wind structures in the array (Figure 15) has been calculated using equation $\boldsymbol{P_{turbine} = \frac{1}{2}\rho_0 c_D A|u|^3}$ (***2***) with hourly surface current velocities from AMM15 interpolated to each turbine location. High drag $c_D = 1$ has been assumed, and the result expressed per unit area of the array. The dependence on the cube of the velocity leads to a strong spring-neap signal in the (detided) power, with spring tide TKE around an order of magnitude greater than neap tide TKE.

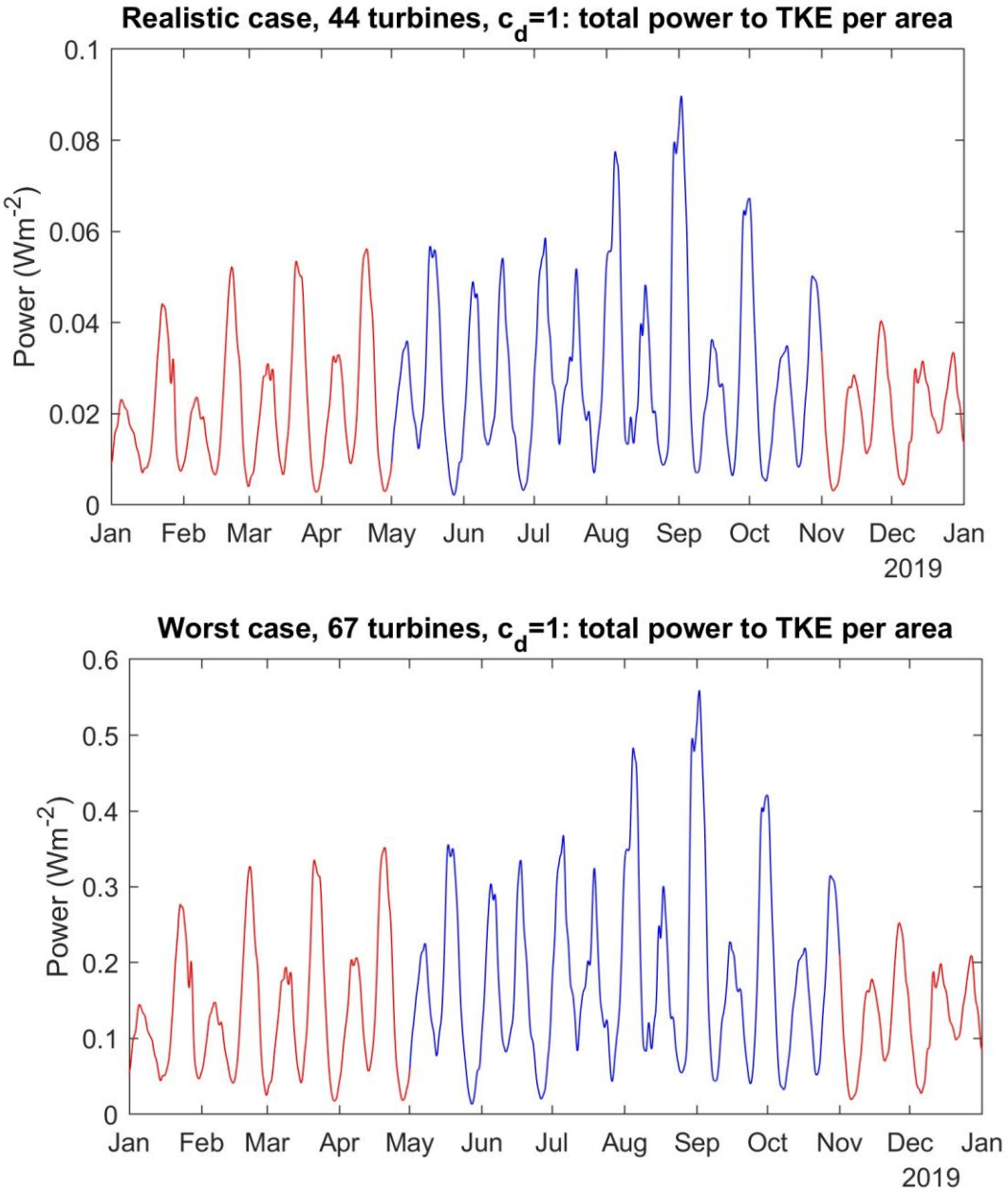

Figure 15. *The total power delivered to turbulent kinetic energy in the water column in (top) the realistic scenario with 44 turbines, and (bottom) the worst-case scenario with 67 turbines. Hourly values have been detided, but spring-neap cycling remains, so the two-weekly peaks occur at spring tides and the troughs at neap tides. Periods during which the water column is not significantly stratified are shown red. At these energy will be dissipated to heat rather than reducing stratification through mixing.*

2.7.3 A comparison can be made with the equivalent power supply, per area, from bed stress:

$$P_{bot} = \rho_0 c_{Dbot} |u|^3 \qquad (3)$$

using a value of $c_{Dbot} = 2.5 \times 10^{-3}$. This directly follows the methodology of Carpenter et al. (2016).

2.7.4 Comparative west-east transects of the production of TKE by bottom stress and by offshore wind structures (Figure 16) have, again, been based on a high drag coefficient for the turbine structure of $c_D = 1$. In this calculation, the turbine induced drag assumes that turbines are present everywhere in this transect, at the same density as in the proposed array scenario. The longitude range of the Proposed Development Array Area is highlighted by grey shading in the figure. The power due to structures and bottom stress have been averaged over a full year.

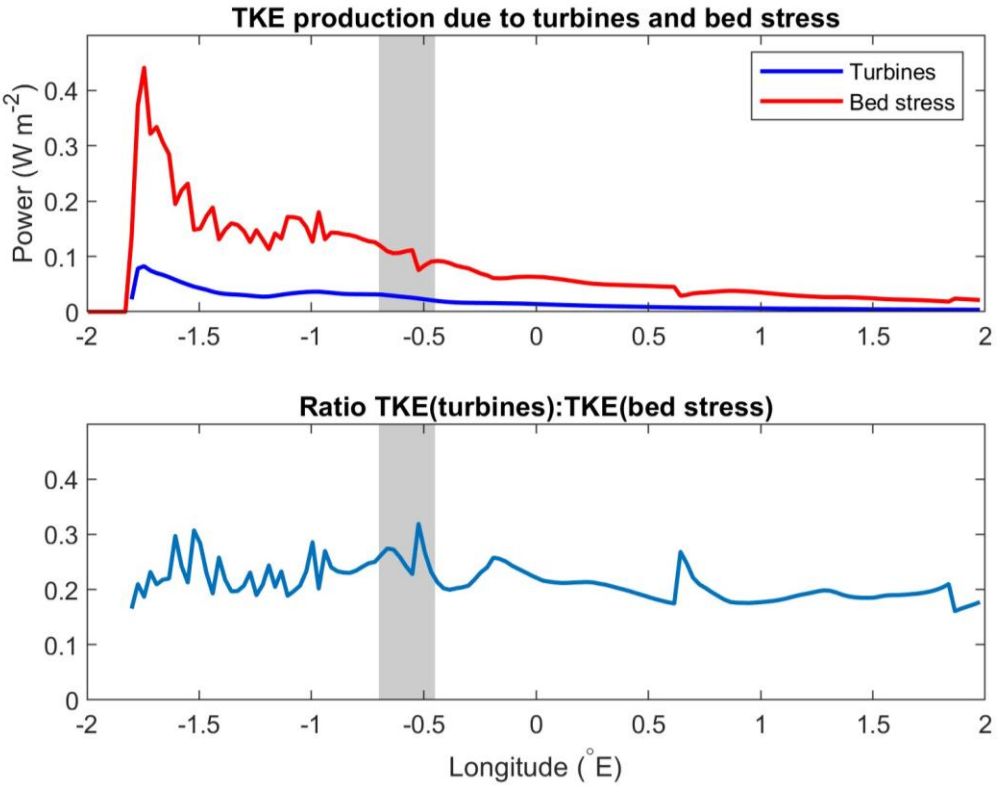

Figure 16. *Annual average TKE production due to turbine structures and bed stress, in a west-east transect at the latitude of the Proposed Development Array Area (green in Figure 2). This is for the high-drag case* $\boldsymbol{c_D = 1}$ *and the 'realistic' scenario with 44 turbines and tension leg moorings. The longitude range of the proposed array is shown grey. At other longitudes, the turbine-induced TKE is based on a turbine density that matches the 'realistic' scenario.*

2.7.5 Calculated TKE production at the latitude of the Proposed Development Array Area shows higher values nearshore, at the western end of the transect, reflecting stronger tidal currents. The predicted TKE production by bed stress at the site is around 0.1 Wm^{-2} and production by interaction with turbine structures is roughly 20% of that value in the realistic 44-turbine scenario. That percentage would scale linearly with the drag coefficient for the turbine structure, so would be a factor of three lower in a low drag scenario.

2.7.6 The worst-case scenario with 67 turbines and catenary mooring lines presents a total of around six times the surface area to the ambient flow, meaning that TKE production by flow-turbine interaction is proportionally larger, and in fact would exceed the TKE production by bed stress.

2.7.7 The exact efficiency with which the TKE generated by turbine structures leads to mixing and nutrient fluxes in the summer thermocline is unknown. Simpson and Bower (1981) estimated that the efficiency with which wind-generated TKE is used for mixing is approximately six times that of TKE due to bed stress, and a similar ratio might be assumed here since the turbine-related TKE is largely delivered into the surface waters. A ratio of six would elevate the mixing expected due to turbine structures in the realistic case to the same order of magnitude as that due to natural bed stress, with the caveat that this is in a high-drag case and would reduce in proportion to the drag coefficient in lower drag cases.

2.8 Transport and dispersion of induced turbulence and mixing

2.8.1 Turbulence and mixing resulting from interaction between a turbine structure and ambient flow will decay rapidly (minutes to hours). In a purely tidal (oscillating) flow, the same water column would be repeatedly mixed, however an underlying mean flow would tend to transport water that had encountered the array downstream, so it would experience turbine-induced mixing for a limited time only. It is important to estimate the transport and dispersion (or dilution) of this impacted water to assess the net implications of enhanced mixing relative to an unaffected water column.

2.8.2 Estimates of the transport and dispersion of water encountering a turbine field have been carried out, incorporating both tidal and background flow. In particular this includes the mean flow of the Dooley Current which transports water to the east into the central North Sea.

2.8.3 A particle tracking approach has been used, based on hourly surface AMM15 velocities and a 4th order Runge-Kutta numerical scheme. In a simulation, particles are released into the flow at each turbine in the 'realistic' scenario every 10 minutes then tracked as they are transported and dispersed. Each particle is tagged with the energy converted to TKE during those 10 minutes. The energy 'content' of the particles at subsequent times is then mapped spatially as an energy density per surface area of the water, in Jm^{-2}.

2.8.4 For ease of interpretation, the TKE densities due to turbine interaction, in Jm^{-2}, have also been expressed as timescales over which the same TKE would be supplied by bottom stress at a rate of 0.1 Wm^{-2} (Figure 17).

2.8.5 In a simulation starting at the beginning of May, around the onset of spring stratification (Figure 17), the influence of TKE enhancement is seen to be transported from the Proposed Development Array Area in a complex manner in a sector from east to south, in part reflecting the eastward flow of the Dooley Current.

2.8.6 The highest TKE enhancement due to the Proposed Development, approaching 15000 Jm^{-2} after 8-weeks of simulation, is equivalent to that expected to result from 1.7 days of bottom stress at 0.1 Wm^{-2}. So, over a summer, this water column experiences a TKE supply due to turbine interaction that is two orders of magnitude smaller than the TKE supply due to bottom stress. As noted in 2.7.7, the efficiency of conversion of this turbine-related TKE to mixing may be significantly greater than that due to bed stress, but the net impact on the stratification of water columns would still be small.

2.8.7 The enhancement of TKE by turbine structures would also be expected to delay the onset of stratification in spring and hasten its erosion after its August peak. Since a particular water column would only experience the array for a short period, however, before being transported outside the array bounds, this shift in the timing of the onset and breakdown of stratification is also expected to be small. Mixing would be cumulative if water experiences more than one array, so a regional assessment of the net impact of multiple arrays on stratification would be valuable.

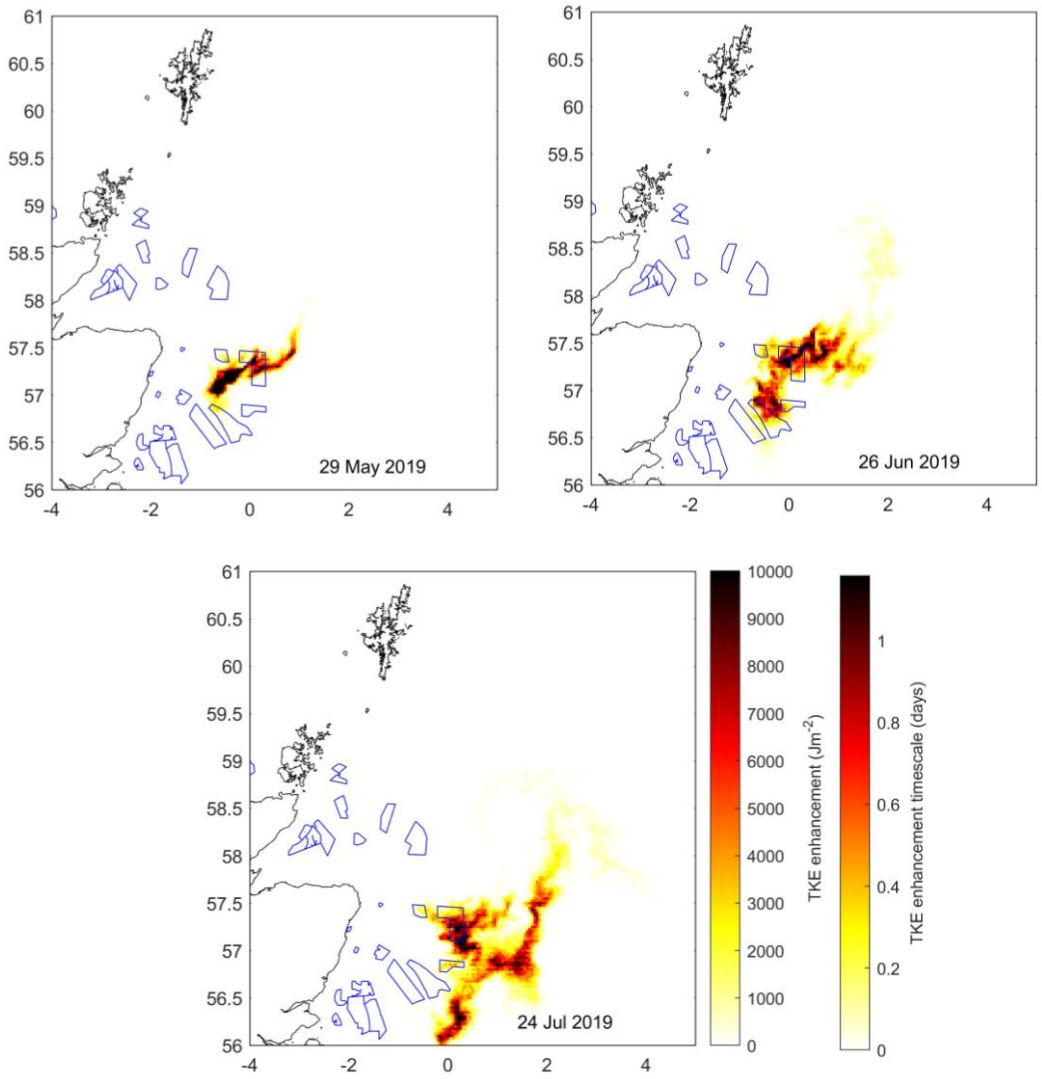

Figure 17. *Maps of TKE enhancement due to the 'realistic' 44-turbine array at the Proposed Development Array Area after 4, 8 and 12 weeks from an assumed onset of stratification on 1st May 2019. The TKE enhancement is followed in a particle tracking approach using surface velocities from AMM15. TKE decays over much shorter timescales, so these values should be interpreted as the amount of excess TKE that the water column at a given location has been exposed to since 1st May. A component of this energy will have been used to mix that water column.*

3 NUTRIENT BIOGEOCHEMISTRY AND PRIMARY PRODUCTION

3.1 Methods

3.1.1 Biogeochemical data has been taken from the North Sea Biogeochemical Climatology (NSBC, https://www.cen.uni-hamburg.de/en/icdc/data/ocean/nsbc.html). The climatology contains 3D fields of monthly and annually averaged biogeochemical parameters on a 0.25° x 0.25° grid (Figure 18). Nutrient (nitrate, ammonium, phosphate, silicate) and chlorophyll-a data were extracted to look at spatial and seasonal variability in biogeochemical tracers. A smaller subset of this dataset was used to determine seasonal changes at the Proposed Development Array Area.

3.1.2 The NSBC dataset was cross validated with measurements from the Scottish Coastal Observatory (SCO) at Stonehaven (Figure 18).

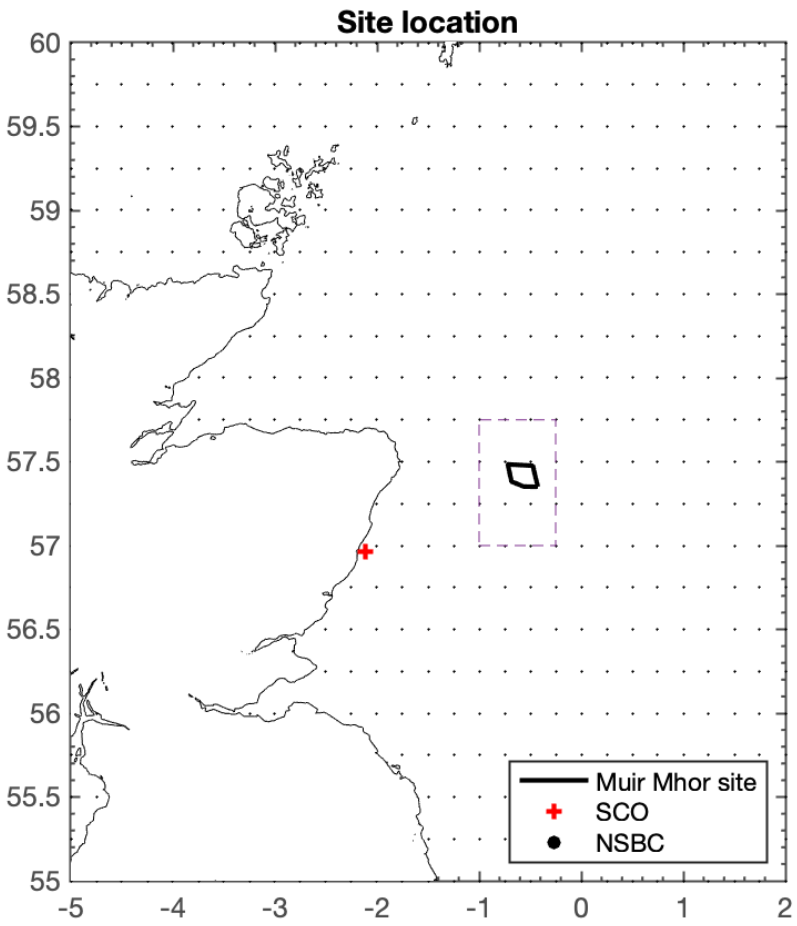

Figure 18. *Gridded biogeochemical data used from the Proposed Development Array Area and across the wider North Sea. The SCO is highlighted with a red cross.*

3.2 Seasonal variability in nutrients and chlorophyll over the wider North Sea

3.2.1 During winter, the water column is well-mixed, leading to a relatively uniform vertical distribution of chemical tracers such as nutrients and oxygen from the surface to the deep waters. Under these well-mixed conditions, any increase in turbulence or kinetic energy (TKE) has little effect on the vertical distribution of nutrients.

3.2.2 With the onset of thermal stratification and greater light availability in spring, phytoplankton begin to grow and reproduce, depleting nitrate and other essential nutrients from the surface layer. As warming progresses into summer, the surface waters become increasingly stratified from the nutrient-rich deeper waters, preventing the replenishment of nutrients at the surface. By July, nitrate reaches limiting concentrations at the surface (Figure 19).

3.2.3 In autumn, the breakdown of stratification allows nutrients to be resupplied to the surface and the water column becomes well-mixed again by October.

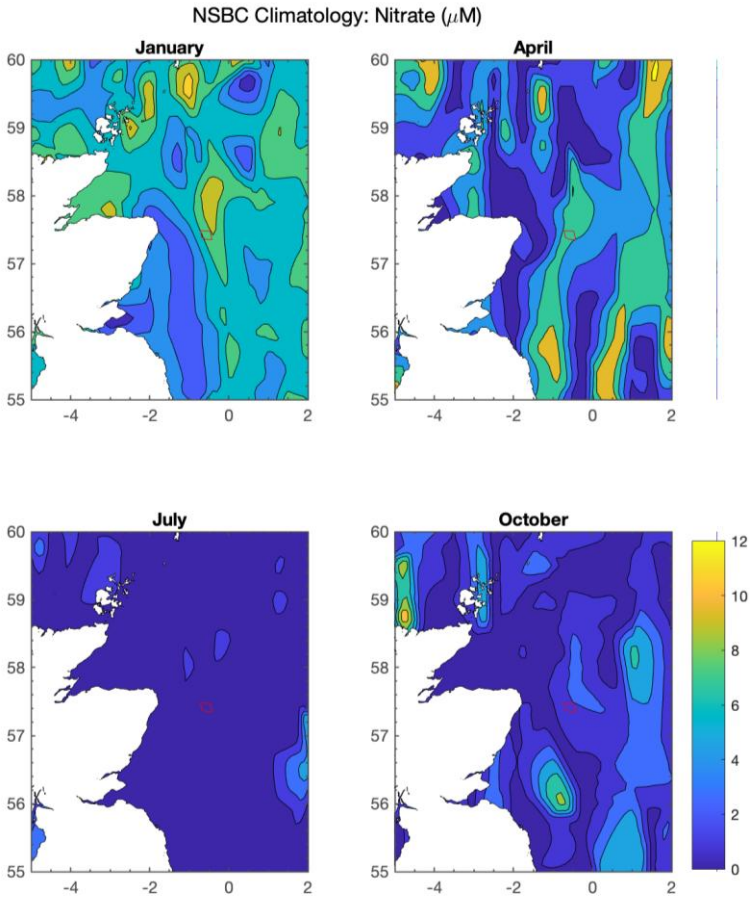

Figure 19. *Maps of surface nitrate concentration in winter, summer, spring and autumn, taken from the NSBC climatology.*

3.2.4 Chlorophyll-a (Chl-a), a photosynthetic pigment, serves as a proxy for biological productivity. During winter, Chl-a concentrations are low due to limited light and cooler temperatures, which restrict biological activity. In spring, phytoplankton blooms drive high levels of productivity in the North Sea, as nutrient concentrations are still abundant in sunlit surface waters.

3.2.5 By summer, productivity declines as nutrient availability becomes limiting, and surface Chl-a concentrations decrease. These patterns of summer stratification and nitrate limitation are typical across the wider North Sea. Under these conditions we often see the establishment of a sub-surface chlorophyll maximum (SCM, **Error! Reference source not found.**). In more stratified conditions, the SCM will be more pronounced and there will be a stronger nitricline (difference between surface and deep water nitrate).

3.2.6 An increase in Chl-a is observed in autumn as nutrient replenishment occurs with the breakdown of stratification (Figure 20) but further declines with decreasing temperature and light availability in October.

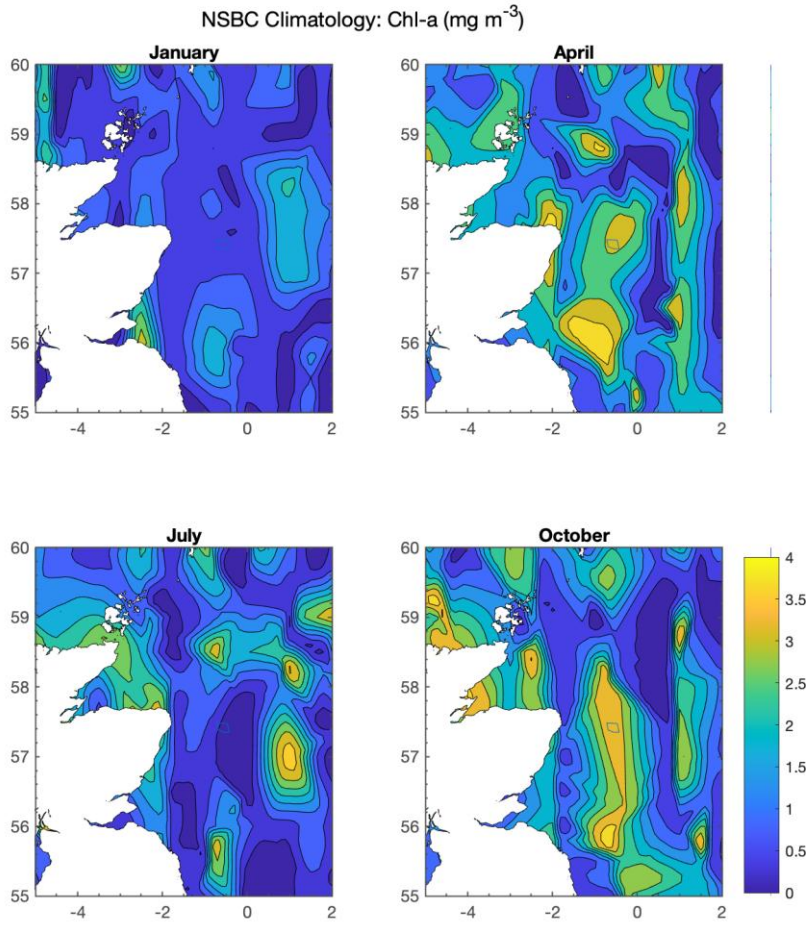

Figure 20. *Maps of surface nitrate concentration in winter, summer, spring and autumn, taken from the NSBC climatology.*

3.2.7 At the Proposed Development Array Area, there is a marked decrease in inorganic nutrients in surface waters during spring (April/May, Figure 21). Nitrate is considered the primary limiting nutrient in the North Sea and shows the sharpest decline, becoming limiting to phytoplankton by May/June. Phosphate and silicate concentrations decrease but do not decrease to concentrations considered limiting to phytoplankton.

3.2.8 Chl-a concentrations are highest from April to September, with productivity decreasing slightly in summer when surface waters are most isolated, by stratification, from the nutrient replete waters below.

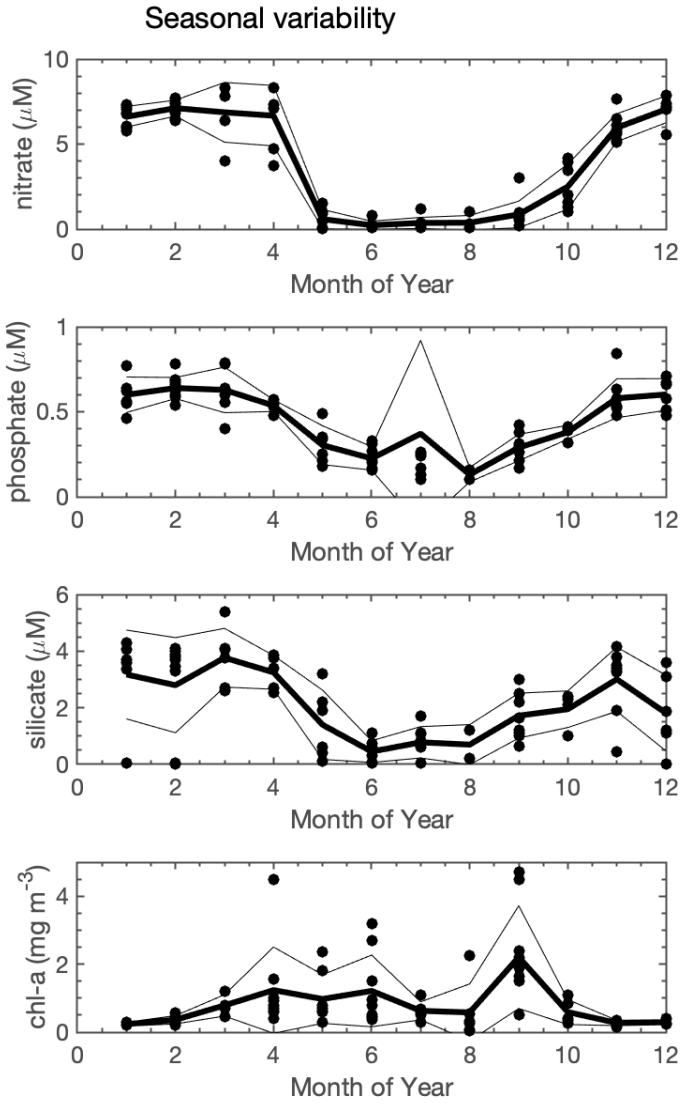

Figure 21. *Seasonal variability in nitrate (upper), phosphate (middle) and silicate (lower) in surface waters at the Proposed Development Array Area.*

3.2.9 A comparison with the SCO Stonehaven dataset reveals similar trends. Nitrate decreases to limiting concentrations by May and remains low until September (Figure 22). Nitrate decreases to lower stoichiometric concentrations than phosphate or silicate.

3.2.10 Chl-a is highest in spring and decreases into summer as nitrate concentrations decline with the onset of stratification.

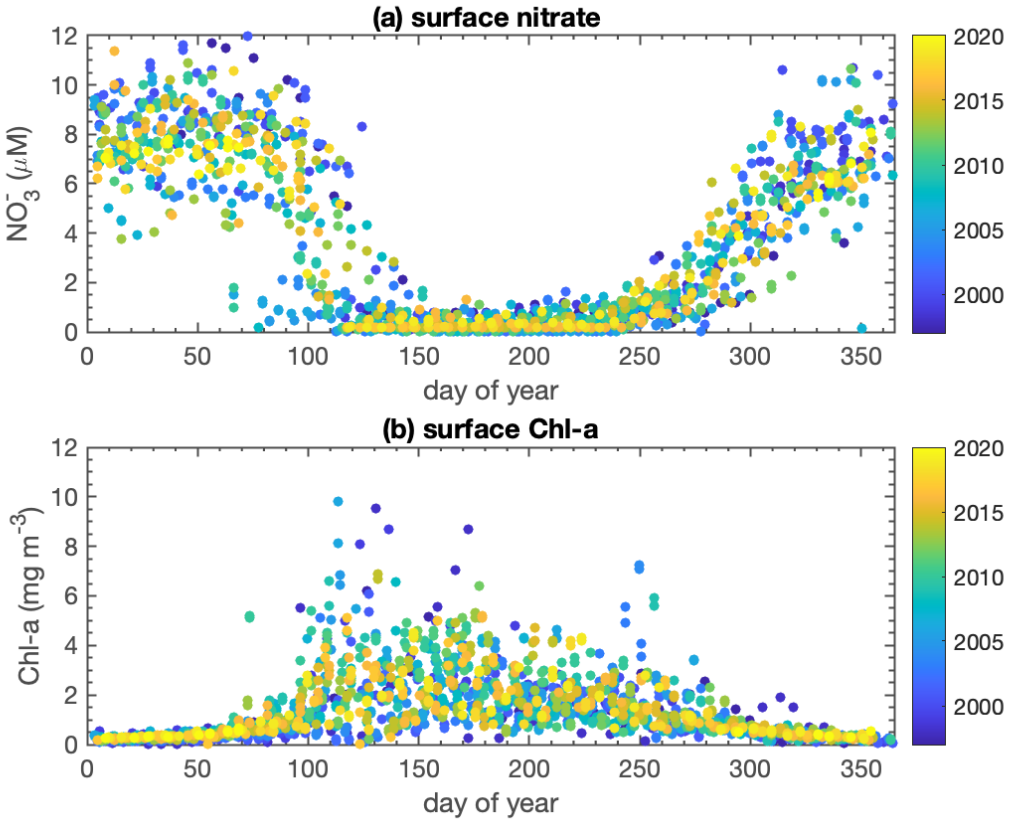

Figure 22. *Seasonal variability in Chl-a (upper) and nitrate (lower) in surface waters at the Scottish Coastal Observatory site at Stonehaven.*

3.3 Depth variability in nutrients and chlorophyll-a at the Proposed Development Array Area

3.3.1 To determine whether changes to the TKE at the Proposed Development Array Area will affect nutrient availability and primary production, the changes in nutrients with depth need to be understood. Nitrate decreases into summer months but stays relatively constant with depth in the upper 60 m until June (Figure 23). In June-August, with the onset of stratification, nitrate at the surface become more depleted than the waters below. In these months, increased turbulence could enhance nutrient supply to the surface.

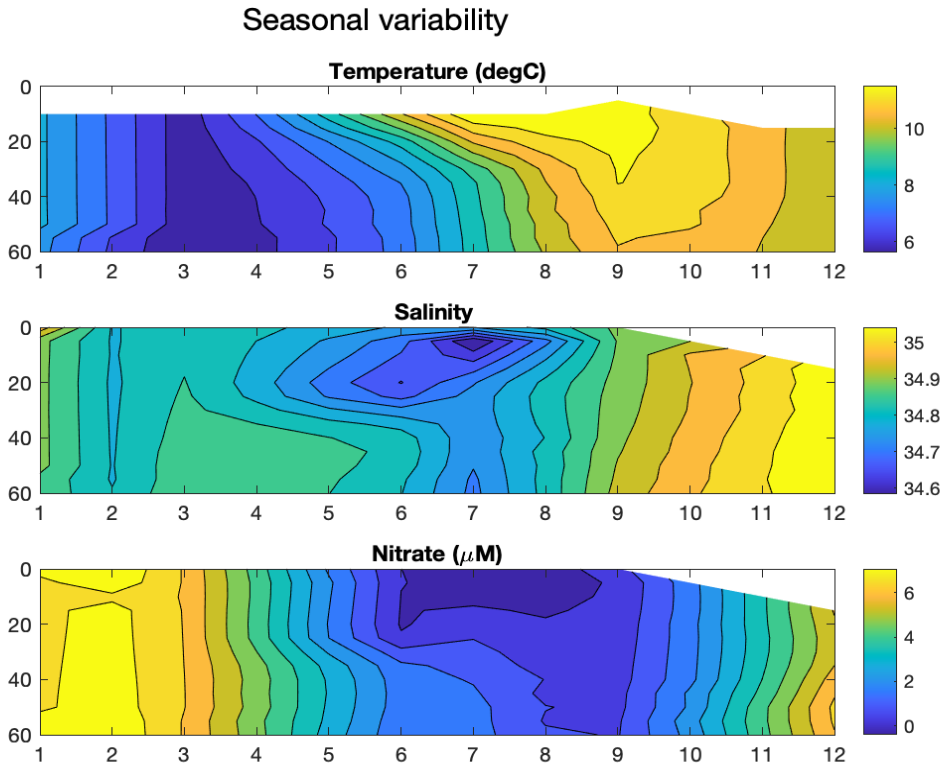

Figure 23. *Monthly profiles of nitrate taken from the grid points in the box inset in Figure around the Proposed Development Array Area.*

3.3.2 In June and July, Chl-a concentrations remain relatively high (1-2 mg m^{-3}) and the nitracline is not fully developed (where a steep gradient in nitrate is visible from surface to deep). This suggests that although surface nutrients are low, stratification is relatively weak in these months and there are regular injections of nutrients to the surface (Figure 23).

3.3.3 In August, a typical stratified shelf sea nitracline develops (Figure 24, bottom right panel), where nitrate is fully depleted in the mixed layer, there is a sharp increase in nitrate from 20-40m, and deeper bottom waters have higher, homogenous concentrations. Under these conditions, increases in TKE may enhance nutrient supply to the nutrient-limited surface waters and increase biological productivity.

3.3.4 These profiles from the NSBC suggest that increased tidal mixing may only enhance nutrient supply in August, or a relatively short length of time (<2 months).

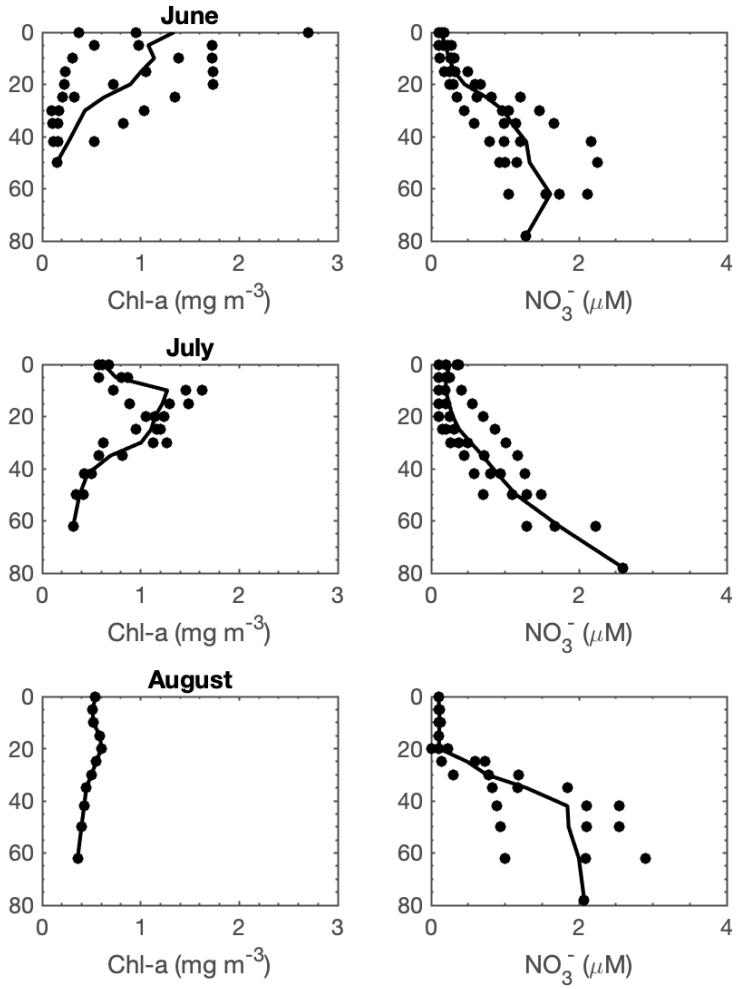

Figure 24. *(a) Chlorophyll-a and (b) nitrate profiles from the Proposed Development Array Area during July. (c) Nitrate gradients are used to calculate the diapycnal nitrate flux in (d), assuming a background* $\boldsymbol{K_z}$ *of* 10^{-4} m^2 s^{-1} *and a 20% increase in Kz shown in red. The nitrate convergence is shown in (e).*

3.4 Implications of changing stratification to primary production

3.4.1 Diapycnal nitrate fluxes (fluxes across density levels) to the SCM can be estimated by combining the local diapycnal diffusivity (K_z) with vertical nitrate gradients at the base of the SCM:

$$\boldsymbol{NO3_{flux} = K_z \cdot \left(\frac{dNO3}{dz}\right)\ (mol\ m^{-2}\ s^{-1})} \qquad (4)$$

There is an upward nitrate supply to the SCM whenever there is a convergence in this diapycnal nitrate flux. As nitrate becomes depleted above the SCM and the vertical nitrate gradient becomes small, then a diapycnal nitrate flux at the base of the SCM corresponds to a diapycnal supply of nitrate. Higher K_z increases the diapycnal nitrate flux at the base

of the SCM and so increases the nitrate supply to the SCM, which can either increase nitrate in the SCM or sustain more phytoplankton growth.

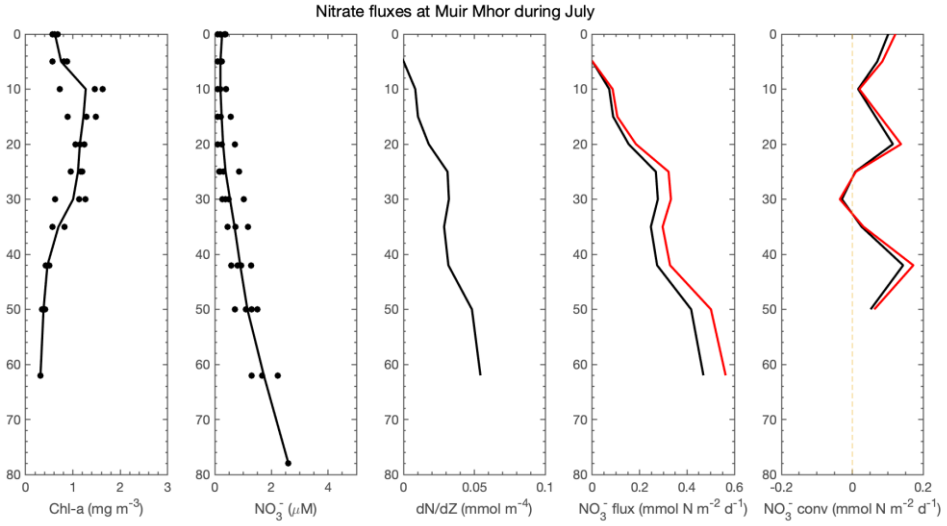

Figure 25. *(a) Chlorophyll-a and (b) nitrate profiles from the Proposed Development Array Area during July. (c) Nitrate gradients are used to calculate the diapycnal nitrate flux in (d), assuming a background* $\boldsymbol{K_z}$ *of* 10^{-4} m^2 s^{-1} *and a 20% increase in* $\boldsymbol{K_z}$ *is shown in red. The nitrate convergence is shown in (e).*

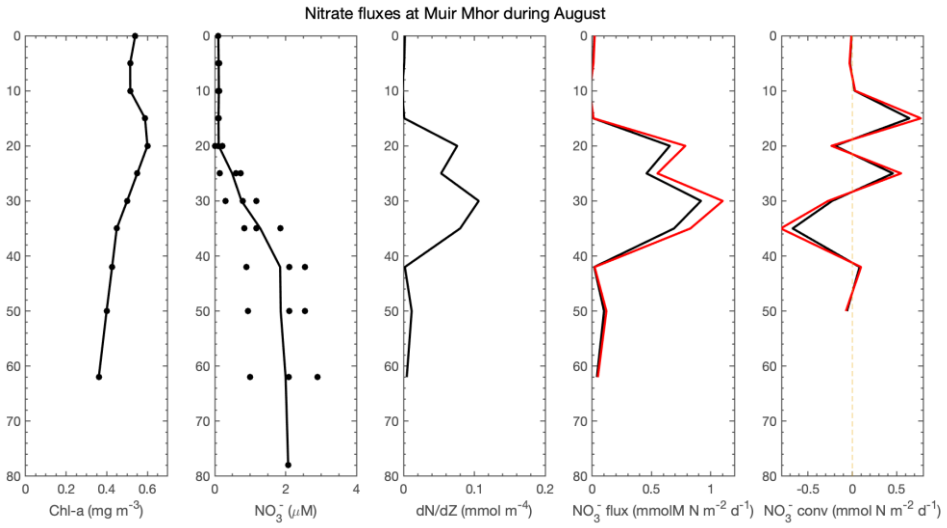

Figure 26. *(a) Chlorophyll-a and (b) nitrate profiles from the Proposed Development Array Area during August. (c) Nitrate gradients are used to calculate the diapycnal nitrate flux in (d), assuming a background* $\boldsymbol{K_z}$ *of* 10^{-4} m^2 s^{-1} *and a 20% increase in* $\boldsymbol{K_z}$ *shown in red. The nitrate convergence is shown in (e).*

3.4.2 At the Proposed Development Array Area, at the onset of thermal stratification in summer, the nitrate gradient at the base of the SCM increases as nitrate in the surface layer approaches zero. In the southern North Sea, this typically develops in June/July, however our best available dataset for this region suggests weaker stratification and the development of the SCM and a nitrate depleted surface only in August (Figure 25Figure 26).

3.4.3 The maximum nitrate gradient in August, reaches ~0.1 mmol m^{-4}, and coincides with the base of the SCM (30 m), a depth which is likely to experience enhanced turbulence from floating wind turbines.

3.4.4 Using the nitrate gradients from the Array Area, if we assume that the K_z at the base of the SCM is typically 10^{-4} m^2 s^{-1}, then the diapycnal nitrate supply to the SCM would be ~1 mmol N m^{-2} d^{-1} (Figure 26). Assuming Redfield stoichiometry and complete nitrate utilisation, this would lead to carbon production of 0.08 g C m^{-2} d^{-1} and 2.39 g C m^2 over a stratified period of 30 days. This is an estimate of the primary production occurring at the SCM in August where nitrate in surface waters is low and limiting production. As a comparison, spring bloom new production in UK shelf seas is in the order of 18.5 g C m^{-2}.

3.4.5 If local K_z increased by 20% at the base of the SCM through interaction of turbine structures with the flow, this could lead to approximately 0.016 g C m^{-2} d^{-1} more carbon being fixed. Spring bloom production in the shelf sea is typically on the order of 6 g C m^{-2} d^{-1} (Pingree et al 1976). Although our estimate of enhanced production at the SCM is small, these production rates may be maintained for weeks during the stratified period.

3.4.6 Our estimate of enhanced SCM production due to enhanced diffusivity from turbines is very small compared to the spring bloom (approximately 0.2%). At the SCM, light is about 1-10% of surface photosynthetically active radiation (PAR), and so production rates are much lower than the spring bloom where nutrients are utilised at the surface. However, the longevity of summer stratification makes the N flux to the SCM significant and up to 50% of annual primary production in certain regions of the North and Celtic Seas (Hickman et al., 2012). At the Proposed Development Array Area, the proportion of annual primary production occurring at the SCM is likely to be much lower than this, as there is a shorter period of stratification and sustained nutrient limitation.

3.5 Wider North Sea perspective

3.5.1 Nutrient stratification increases south and east of the Proposed Development Array Area, reducing the resupply of nutrients to surface waters (Figure 27). The more stratified and nutrient limited a given area of the North Sea, the greater the impact of changes to tidal-induced mixing.

3.5.2 The addition of offshore wind infrastructure in the North Sea will likely have a greater impact on nutrient supply further south and east of the Proposed Development Array Area.

3.5.3 Although the effects of reduced wind-driven mixing (because of the atmospheric turbine wake) have not been investigated in this study, we predict changes to wind induced mixing would have greatest impacts to nutrient supply in spring and autumn at the onset and breakdown of stratification. Reduced wind-driven mixing may increase the stratified period, which at the Proposed Development Array Area may have a greater impact on nutrient availability and primary production.

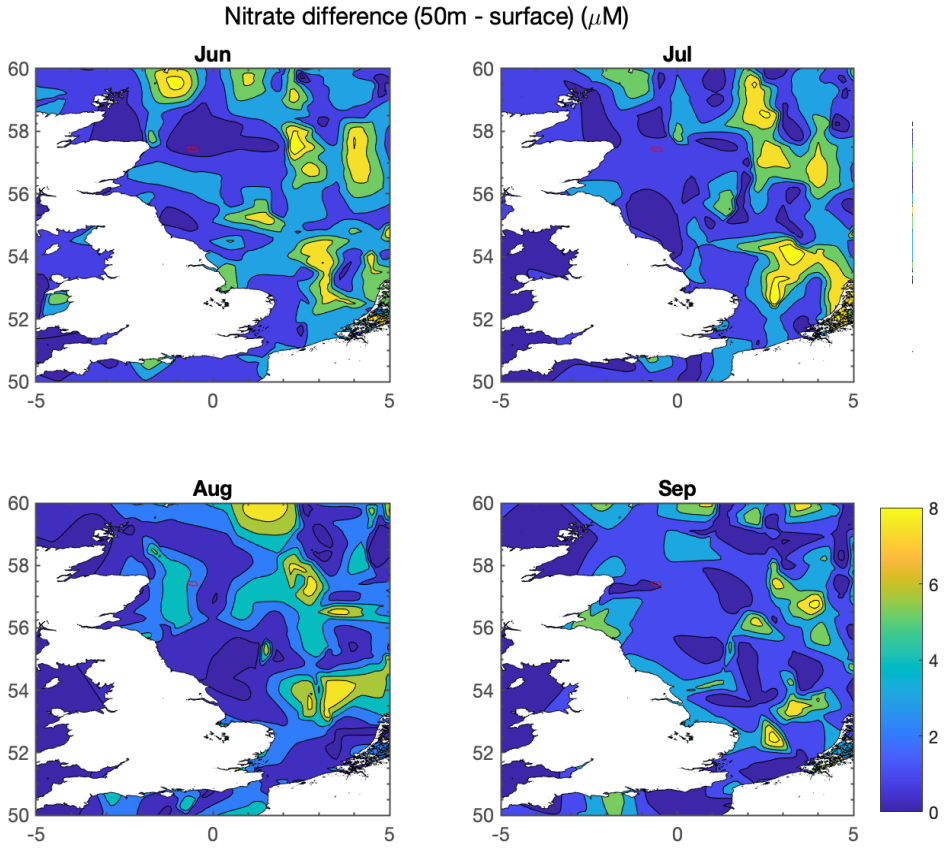

Figure 27. *Maps of the difference between nitrate at 50 m and nitrate at the surface, an indicator of the degree of stratification and nutrient limitation to surface phytoplankton.*

4 DISCUSSION AND CONCLUSIONS

4.1 Characteristics of site

4.1.1 The Array Area is in a seasonally stratified area of the western North Sea in water depths between 60 m and 97 m. The site sits on the southern flank of the Dooley Current, an eastward flow from coastal waters into the central North Sea associated with gradients in salinity and water depth, which both increase to the north and east.

4.1.2 The water column becomes stratified in the summer months, with stratification developing in April/May, peaking in August and being erased by November.

4.1.3 The summer nutrient gradients between surface and deep waters appear to be weaker in the northern North Sea than in other regions of the North Sea (Figure 27). Therefore, the effects of changes to mixing at this particular site are expected to be smaller than elsewhere.

4.2 Energetics of turbine interactions

4.2.1 The conversion of energy to TKE due to interactions between ambient flow and turbine structures and moorings was estimated in two scenarios. The first 'realistic' scenario consisted of 44 turbines with tension leg moorings. A 'worst case' scenario consisted of 67 turbines with larger associated structures and fouled catenary mooring lines of up to 1600 m in length. This second case is very significantly different, in presenting more than six times the surface area to the ambient flow and resulting in a proportional increase in turbulent kinetic energy production and associated impacts.

4.2.2 In the realistic scenario, with a high drag coefficient, the production of turbulent kinetic energy due to the turbine structures was estimated to be around 20% of the production by natural bed stress. The efficiency with which this enhanced turbulent kinetic energy yields mixing and enhances nutrient fluxes is uncertain, but it is expected to be significantly higher than for the conversion of bed stress. The mixing due to turbine structures is potentially comparable, therefore, to that due to bed stress and wind effects, although uncertainty is large.

4.2.3 Simulations suggest that water that experiences enhanced turbulence due to the Proposed Development is transported, to the east in the southern flank of the Dooley Current and in a sector between east and south. While this does not modify the total excess nutrients supplied to surface waters, it spreads the impact of this enhanced flux and dilutes its local magnitude, so the local impacts are expected to be small.

4.3 Some points of uncertainty and potential further work

4.3.1 Given the large difference between the two turbine scenarios considered, a factor of more than 6 in the energy converted to turbulence, it is important to clarify the exact structure and mooring system to be used.

4.3.2 In light of the magnitude of energy conversion in the 'worst' case, the possibility of modification of the ambient flow should be considered. Here it was assumed that flow was as simulated in the AMM15 hydrodynamic model, which does not include the influence of turbine structures.

4.3.3 The parameterisation of turbulent kinetic energy production by ambient flow interaction was treated in a simple manner based on the area presented by the structure to the flow and a drag coefficient. While this provides an initial estimate, the dynamics of particular cases of stratification and turbine structure may be complex. The efficiency of the conversion of turbulent kinetic energy to mixing was an additional uncertainty. Detailed, turbulence-resolving modelling or observations would be required to improve these estimates.

4.3.4 From our best available dataset, The Array Area does not develop strong nutrient limitation until August, therefore the effects of changes to mixing are not that significant in terms of shelf sea primary production. These estimates are from a sparse and sometimes inconsistent dataset. The variable patterns in Figure 27 suggest that the NSBC climatology may not be adequate to determine patterns in small areas of the North Sea, such as the Proposed Development Array Area. With direct measurements of nitrate and chl-a from the site across a seasonal cycle, we could better determine the effects of offshore wind infrastructure on the local biogeochemical functioning. High resolution sensor data could be used to determine changes in nutrients and Chl-a as a result of variable mixing over tidal cycles.

4.3.5 Stronger mixing would drive more nutrients to the SCM and support enhanced phytoplankton growth, potentially reducing the stratified period. The increases in mixing may shift the onset and breakdown of stratification, having knock on effects to the marine ecosystem. The length of stratification will have a significant effect on seasonally integrated primary production and could be investigated in further work by analysing Chl-a products from satellites (Lu et al., 2022). From the available nutrient data, we suggest that temporal changes may be limited as the nitrate-limited season is relatively short at the Array Area.

5 REFERENCES

ABPMer (2008). Atlas of UK Marine Renewable Energy Resources. Date of access: 29/10/2024. https://www.renewables-atlas.info/.

Berx, B., & Hughes, S. L. (2009). Climatology of surface and near-bed temperature and salinity on the north-west European continental shelf for 1971–2000. Continental Shelf Research, 29(19), 2286-2292. https://doi.org/10.1016/j.csr.2009.09.006

Carpenter, J. R., Merckelbach, L., Callies, U., Clark, S., Gaslikova, L., & Baschek, B. (2016). Potential impacts of offshore wind farms on North Sea stratification. PloS one, 11(8), e0160830. https://doi.org/10.1371/journal.pone.0160830

Dorrell, R. M., Lloyd, C. J., Lincoln, B. J., Rippeth, T. P., Taylor, J. R., Caulfield, C. C. P., ... & Simpson, J. H. (2022). Anthropogenic mixing in seasonally stratified shelf seas by offshore wind farm infrastructure. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.830927

Graham, J. A., O'Dea, E., Holt, J., Polton, J., Hewitt, H. T., Furner, R., ... & Mayorga Adame, C. G. (2018). AMM15: a new high-resolution NEMO configuration for operational simulation of the European north-west shelf. Geoscientific Model Development, 11(2), 681-696. https://doi.org/10.5194/gmd-11-681-2018

Gregg, M. C., D'Asaro, E. A., Riley, J. J., & Kunze, E. (2018). Mixing efficiency in the ocean. Annual Review of Marine Science, 10(1). 10.1146/annurev-marine-121916-063643

Hickman A. E., Moore C. M., Sharples J., Lucas MI., Tilstone GH., Krivtsov V., & Holligan PM. (2012). Primary production and nitrate uptake within the seasonal thermocline of a stratified shelf sea. Mar Ecol Prog Ser 463:39-57. https://doi.org/10.3354/meps09836

Hill, A. E., Bronw, J., Fernand, L., Holt, J., Horsburgh K. J., Proctor, R., Raine, R. & W. R. Turrell. Thermohaline circulation of shallow tidal seas. Geophysical Research Letters 35, L11605 https://doi.org/10.1029/2008GL033459

Huthnance, J. M. (1991). Physical oceanography of the North Sea. Ocean and shoreline management, 16(3-4), 199-231. https://doi.org/10.1016/0951-8312(91)90005-M

Lu, Z., Li, G., Liu, Z. & L Wang (2022). Offshore wind farms changed the spatial distribution of chlorophyll-a on the sea surface. Front. Mar. Sci. 9 https://doi.org/10.3389/fmars.2022.1008005

Nayar, K. G., Sharqawy, M. H., & Lienhard, J. H. (2016). Seawater thermophysical properties library. http://web.mit.edu/seawater

Roshko, A. (1961). Experiments on the flow past a circular cylinder at very high Reynolds number. *Journal of Fluid Mechanics*, 10(3), 345-356.

Simpson, J. H. (1981). The shelf-sea fronts: implications of their existence and behaviour. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 302(1472), 531-546. https://doi.org/10.1098/rsta.1981.0181

Simpson, J. H., & Bowers, D. (1981). Models of stratification and frontal movement in shelf seas. Deep Sea Research Part A. Oceanographic Research Papers, 28(7), 727-738. https://doi.org/10.1016/0198-0149(81)90132-1

Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., & Wirtz, K. W. (2018). The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. Hydrobiologia, 845(1), 35-53. https://doi.org/10.1007/s10750-018-3653-5