Bowdun Offshore Wind Farm, Offshore EIA Report

Volume 3, Technical Appendix 7.4: Assessment of Potential Changes to Stratification and Frontal Systems

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Contents

List of Tables

List of Figures

Glossary

Defined Term	Definition
Array Area	The Array Area is the area in which the Offshore Generation Assets will be located.
Chlorophyll-a	Chlorophyll-a is the green substance used by plants to photosynthesise (creating sugars from basic chemical building blocks, using sunlight).
Cumulative Effects	The effects of the Proposed Development assessed together with effects from the Onshore Infrastructure forming the Project as well as one or more different projects on the same receptor/resource.
Effect	Term used to express the consequence of an impact (i.e. the result of change or changes on specific environmental resources or receptors). The significance of an effect is determined by correlating the magnitude of the impact with the importance, or sensitivity of the receptor or resource in accordance with defined significance criteria.
Environmental Impact Assessment (EIA)	Process for the assessment of likely significant environmental effects of a project on the physical, biological and human environment during construction, Operation and Maintenance (O&M) and decommissioning.
Export Cable Corridor	The area seaward of MHWS which connects the Array Area with the Landfall within which the Offshore Export Cables will be installed.
Impact	A change caused by an action that occurs during a project's lifetime.
Inter-Array Cables (IAC)	Cables which link the Wind Turbines to each other and with the Offshore Substation Platforms (OSPs).
Marine Directorate (MD)	The Marine Directorate of the Scottish Government, formerly known as Marine Scotland. The planning and licensing authority for Scotland's seas and custodian of Scotland's National Marine Plan (NMP). The Marine Directorate - Licensing Operations Team (MD-LOT) are specifically responsible for managing Section 36 Consent and Marine Licence Applications seaward of MHWS.
Marine Directorate – Science, Evidence, Data and Digital (MD-SEDD)	The scientific division of the MD, which provides expert scientific, economic and technical advice and services on issues relating to marine fisheries, aquaculture, marine renewable energy, and the aquatic environment and its flora and fauna.
Maximum Design Scenario (MDS)	The scenario within the design envelope likely to result in the greatest impact on a particular topic receptor, and therefore the one that should be assessed for that topic receptor.
Offshore Substation Platform(s) (OSPs)	OSPs comprise the support structure, topside and electrical components used for collecting and/or converting electricity generated by the Wind Turbines for transmission by the Offshore Export Cables.
Piling	The action of installing piles: installation can use various methodologies, the most common of which are impact piling (in which the piles are struck by a "hammer") and drilling (during which a hole is drilled into the seafloor, the drilling tool is removed, and the pile is slotted into that hole).

Defined Term	Definition
Plan Option Area (POA)	A location identified in the Sectoral Marine Plan (SMP) as a preferred area for commercial scale offshore wind development.
Project (the)	An overarching term for the Bowdun Offshore Wind Farm (Bowdun OWF) comprising the offshore and onshore infrastructure required to generate and transmit electricity from the Array Area to the onshore Grid Connection Point (GCP). The Project includes the Offshore Generation Assets, the Offshore Transmission Assets and the Onshore Transmission Assets.
Project Design Envelope (PDE)	A description of the range of possible elements that make up the design options for the Proposed Development under consideration when the exact engineering parameters are not yet known.
Proposed Development	Term used to define the Offshore Infrastructure associated with the Project seaward of MHWS for which consent is being sought. Further details of the parameters are included in Volume 1, Chapter 3: Project Description.
Spring Tidal Excursion	The distance suspended sediment is transported prior to being carried back on the returning tide.
Study Area	For each environmental topic, the baseline environment will be characterised, and the potential environmental impacts will be described within a topic-specific study area. Specific study areas are defined for each topic and are based on the maximum spatial extent across which potential impacts of the Project may be experienced by the relevant receptors (i.e. Zone of Influence).
Wind Turbines	Structures comprising of a tubular tower, rotor blades, and a nacelle which houses the Wind Turbine generator.

Acronyms

Acronym	Definition
ABPmer	ABP Marine Environmental Research
EIA	Environmental Impact Assessment
GOTM	General Ocean Turbulence Model
IAC	Inter-Array Cable
MD-LOT	Marine Directorate – Licensing Operations Team
MD-SEDD	Marine Directorate – Science, Evidence, Data and Digital
MDS	Maximum Design Scenario
MHWS	Mean High Water Spring
OSP	Offshore Substation Platform
OWF	Offshore Wind Farm
O&M	Operation and Maintenance
PDE	Project Design Envelope
PEA	Potential Energy Anomaly
POA	Plan Option Area
PP	Primary Production
SMP	Sectoral Marine Plan
SSM	Scottish Shelf Model
TKE	Turbulent Kinetic Energy
TWP	Thistle Wind Partners Limited

Table of Units

Units	Definition
J	Joule
J/m^2	Joules per square metre
J/m^3	Joules per cubic metre
kg	Kilogram
kg/m^3	Kilogram per cubic metre
km	Kilometre
km^2	Square kilometre
m	Metre
m^2	Square Metre
m/s^2	Metres per second squared
MW	Megawatt
W/m^2	Watts per square metre
°C	Degree Celsius

1 Introduction

1.1.1 This Physical Processes Technical Report presents a detailed baseline characterisation and assessment of stratification and frontal systems for the offshore elements of the Bowdun Offshore Wind Farm (OWF) Project (hereafter referred to as the Proposed Development). The Proposed Development covers the Option Lease Area (OLA) comprises of the Array Area, which is located in the E3 Plan Option Area (POA) detailed in the Scottish Sectoral Marine Plan (SMP) (Scottish Government, 2020), and the Export Cable Corridor. The Array Area is located 38 km from the Aberdeenshire coast at its closest point, covering an area of 187 km^2. The Proposed Development will comprise of Wind Turbines (fixed foundations), Inter-Array Cables (IACs), Offshore Substation Platforms (OSPs), Interconnector Cables, Offshore Export Cables and any necessary scour/cable protection. The Export Cable Corridor will include a maximum of three High Voltage Alternating Current (HVAC) Offshore Export Cables, each with a length of up to 70 km and will make Landfall at Benholm, Aberdeenshire.

1.1.2 The findings from this assessment will be used to inform the significance of effect assessments presented in other chapters of the Offshore Environmental Impact Assessment (EIA) Report, notably Volume 2, Chapter 9: Fish and Shellfish Ecology, Volume 2, Chapter 10: Marine Mammals and Volume 2, Chapter 11: Offshore Ornithology.

1.1.3 There has been increasing interest in the scientific literature on the impact of wind farm developments on stratification, (e.g. Carpenter *et al.* (2016); Cazenave *et al.* (2016); Dorrell (2022)). This interest has been driven at least in part by the proliferation of proposed offshore wind farms further offshore and in deeper water. These settings are typically characterised by seasonal water column stratification, which could therefore potentially be impacted by the installation of Offshore Infrastructure (Figure 1.1 and Figure 1.2).

1.1.4 Turbulence is generated naturally as a result of near-bed and near-surface shear. The installation of Offshore Infrastructure creates an additional source of turbulence through flow-structure induced shear, as illustrated in the schematic in Figure 1.1. Infrastructure wake turbulence mixes cold nutrient rich bottom water with warm nutrient poor surface water, reducing the strength of stratification and potentially enhancing plankton growth in the subsurface chlorophyll layer. Changes in the subsurface chlorophyll layer would have further impacts on nutrient pathways, ecosystem functioning and oceanic carbon sequestration.

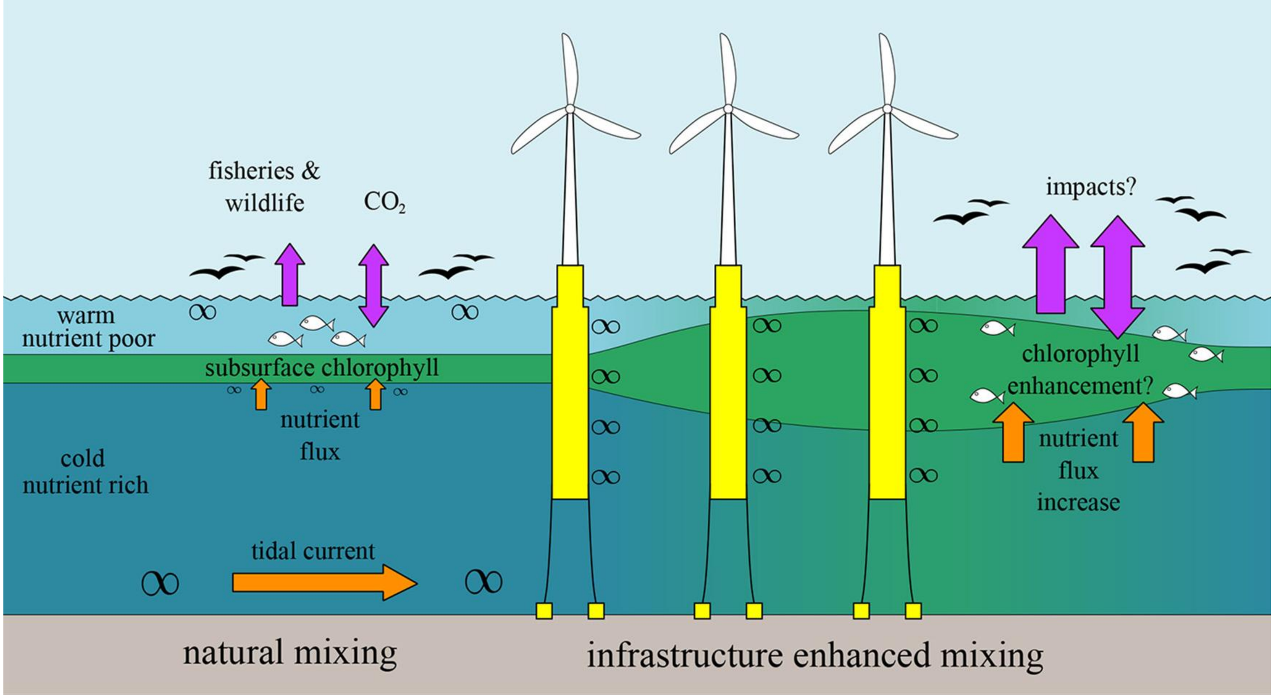

Figure 1.1: Processes Contributing to Natural Stratification, and the Effect of Additional Turbulence Generated by Offshore Infrastructure (from Dorrell *et al.*, 2022)

1.1.5 The fixed foundation type for the Proposed Development will differ from the spar buoy type shown in the schematic. Instead, monopile or jacket foundations, which occupy the whole of the water column, will be used. Turbulence will still be generated throughout the water column as water flows past these structures, acting to weaken stratification, following processes similar to those illustrated in Figure 1.1.

1.1 Consultation to date

1.1.1 A method statement outlining the proposed approach to numerical modelling for the Proposed Development was sent to Marine Directorate - Licensing Operations Team (MD-LOT) and NatureScot for comment (Thistle Wind Partners Limited (TWP), 2024). Responses were received from The Marine Directorate for Science, Evidence, Data and Digital (MD-SEDD) (via MD-LOT) (03 July 2024) and NatureScot (11 July 2024) and are set out in Table 1.1 below. MD-SEDD also commented separately on the Bowdun Scoping Report (BOWF, 2024), with responses captured in the Scoping Opinion (MD-LOT, 2024). These are also summarised in Table 1.1.

1.1.2 The methodological approach adopted has been informed by these consultation responses, with justification for the approach set out in Section 3.

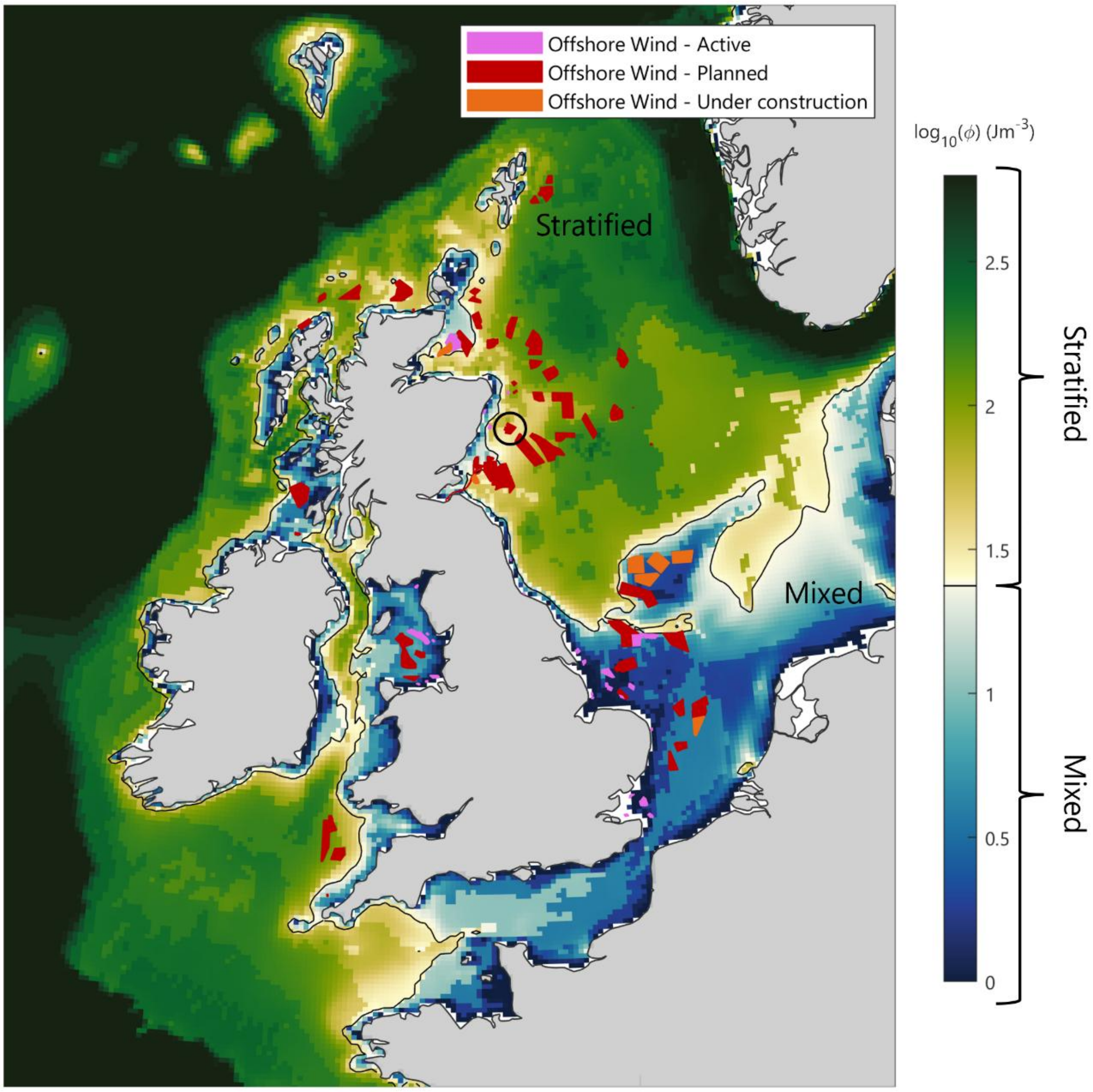

Figure 1.2: Northwest Europe Summer Potential Energy Anomaly (PEA), ϕ, a Measure of the Amount of Stratification, Calculated from Copernicus Model Output. Black Circle Denotes Location of the Array Area

Table 1.1: Summary of consultation responses from MD-SEDD and NatureScot relating to stratification and frontal systems

Consultee	Consultation Response
MD-SEDD, 03/07/2024 (in response to method statement (TWP, 2024))	MD-SEDD advise the baseline description for most processes requires additional data sources. This is especially the case for stratification and frontal systems as the proposed methodology does not include the modelling of the vertical water column, temperature or salinity.
	MD-SEDD note that at the scoping workshop they proposed the use of vertical temperature and salinity profiles from Copernicus Marine Service and confirm that this would be essential for the baseline description of stratification.
	MD-SEDD advise that the proposed modelling methodologies are not suitable for the assessment of potential change to stratification and frontal systems.
	Table 3.1 outlines that “outputs from the hydrodynamic modelling will be used to undertake a semi-quantitative assessment of the potential for change in water column stratification and the strength/persistence and position of

Consultee	Consultation Response
	frontal systems". No further details of this semiquantitative assessment were provided and MD-SEDD request that a method statement for this assessment approach be provided. The outputs from the 2D hydrodynamic tidal modelling will not be sufficient for an assessment on 3D water column structure, as the model is incapable of modelling the vertical water column and does not model temperature and salinity which heavily influence the vertical structure.
	The fundamental mechanism for stratification to be impacted is through the addition of turbulence within the water column (e.g. Dorrell, 2022). MD-SEDD recommend the use of existing 3D ocean model output, e.g. data available from the Copernicus Marine Service or the SSW-RS, and observational data, to characterise the water column structure within the region throughout the year, paying particular attention to the onset/decay of seasonal stratification and fronts.
	MD-SEDD recognise there is no clear methodology or guidance available on how to assess the impact of wind farm structures on stratification. The use of a 1D vertical model, such as the General Ocean Turbulence Model (GOTM), could be a pragmatic way to model the potential impact of the wind farm structures on mixing. A 1D vertical model would require boundary conditions, and these could be supplied from the proposed 2D model (velocities) and existing 3D hydrodynamic model data (temperature and salinity).
	MD-SEDD advise the potential impact on stratification should be assessed as this would influence the timing of plankton blooms and the wider ecosystem. The timing, extent and magnitude of stratification is naturally variable, and the potential changes due to the wind farm should be assessed against this backdrop.
	Another potential influence on mixing is the change in near sea surface wind speeds due to the wind farm. MD-SEDD recognise there is no pragmatic method, or modelling guidance, available for modelling this potential impact, and therefore advise that a qualitative assessment be performed using the published research findings, e.g. Christiansen *et al*. (2022).
NatureScot, 11/07/2024 (in response to method statement (TWP, 2024))	No comments made specifically relating to stratification and frontal systems
MD-SEDD, 09/10/2024 (in response to scoping report (BOWF, 2024))	The proposed wind farm is in a region of shelf sea that is likely to experience intermittent seasonal stratification, and the potential changes to water column structure including magnitude, timing and extent of seasonal stratification should be considered in the EIA. MD-SEDD note this impact is scoped into the operational development phase and that the scoping report proposes the use of hydrodynamic modelling to conduct an assessment on stratification. MD-SEDD advise that the hydrodynamic model used needs to resolve the vertical water column, e.g. using a 3D or 1D-vertical model.
	Water column structure is controlled by competing processes including atmospheric heating, freshwater input and mixing. An OWF could affect water column mixing by the structures generating turbulent wakes (e.g. Dorrell *et al*. 2022) and/or by altering the near sea surface wind speeds (e.g. Christiansen *et al*. 2022). MD-SEDD consider the structure induced mixing is more likely to have near-field effects, whereas the wind speed deficit is likely to have more subtle far-field effects.
	MD-SEDD advise the baseline description should include a description of prevailing baseline water column conditions, including the timing of stratification and frontal positions. This should include the evolution of water

Consultee	Consultation Response
	column structure through the year (e.g. weekly to monthly temperature, salinity, density profiles) and when typically, the region stratifies, and how key parameters change through the year (e.g. surface mixed layer depth and potential energy anomaly).
	For baseline characterisation MD-SEDD advise the use of existing 3D ocean model output, e.g. data available from the Copernicus Marine Service or the Scottish Shelf Waters Reanalysis Service (SSW-RS, https://tinyurl.com/SSW-Reanalysis), and observational data, to characterise the water column structure within the region throughout the year, paying particular attention to the onset/decay of seasonal stratification and fronts. The timing, extent and magnitude of stratification is naturally variable, and this variability should be described to enable the potential changes due to the wind farm to be assessed against this backdrop.
	MD-SEDD advise the EIA investigates whether the potential change in mixing could delay the onset of stratification and what pathways to impact this could have on biological receptors, including primary production and the wider ecosystem. The potential impact of the structures (e.g. Dorrell *et al*. 2022) and the potential wind-wake impact (e.g. Christiansen *et al*. 2023) should be assessed and compared with one-another.
	MD-SEDD recognise there is no clear methodology or guidance available on how to assess the impact of wind farm structures or wind deficit on stratification. The use of a 1D vertical model, such as the GOTM, could be a pragmatic way to model the potential impact of the wind farm structures on mixing. A 1D vertical model would require boundary conditions, and these could be supplied from existing 3D hydrodynamic model data (temperature, salinity, velocities), or potentially from any other hydrodynamic model being used as part of the EIA. An alternative approach is to investigate how turbine structures could change Turbulent Kinetic Energy (TKE) (e.g. Carpenter *et al*. 2016) and comparing this with background/baseline TKE values. The potential impact of these changes in TKE on the timing of stratification should be included, and whether fronts are likely to be affected.
	MD-SEDD recognise there is no pragmatic method, or modelling guidance, available for modelling the potential impact of the wind wake, and therefore suggest that a qualitative assessment be performed using published research findings, e.g. Christiansen *et al*. (2022). MD-SEDD advise that changes to mixing have the potential to impact other receptors, such as productivity as well as higher trophic levels, and following the assessment of modelling. outlined above, this should also be qualitatively assessed in the EIA.
	MD-SEDD advise the potential impact on Nature Conservation Marine Protect Areas (MPA) where fronts are a designated feature should be included.

1.2 Report aims

1.2.1 The aims of this report are to:

- characterise the baseline stratification timing and strength within, and surrounding, the Array Area;
- characterise the baseline tidal mixing front dynamics within, and surrounding, the Array Area; and
- conduct a project specific EIA for the Maximum Design Scenario (MDS) for Offshore Infrastructure in the Array Area.

2 Physical Processes Study Area

2.1.1 The Physical Processes Study Area is located off the Aberdeenshire coast (Figure 2.1). It has been defined on the basis of:

- the distance away from the Proposed Development which suspended sediment plumes may be advected (and interact with potentially sensitive receptors). This has been defined by a spring tidal excursion buffer around the Array Area and Export Cable Corridor;
- the distance up/down drift from the Landfall, that littoral processes could theoretically be impacted by Offshore Infrastructure associated with the Proposed Development, has been defined through consideration of coastal sub-cell information set out in Ramsay and Brampton (2000); and
- the distance from the Array Area that wave blockage impacts could theoretically be detected has been informed by expert judgment, drawing upon (amongst other things), the evidence base from other projects (e.g. ABPmer, 2021) and consideration of the prevailing wave directions.

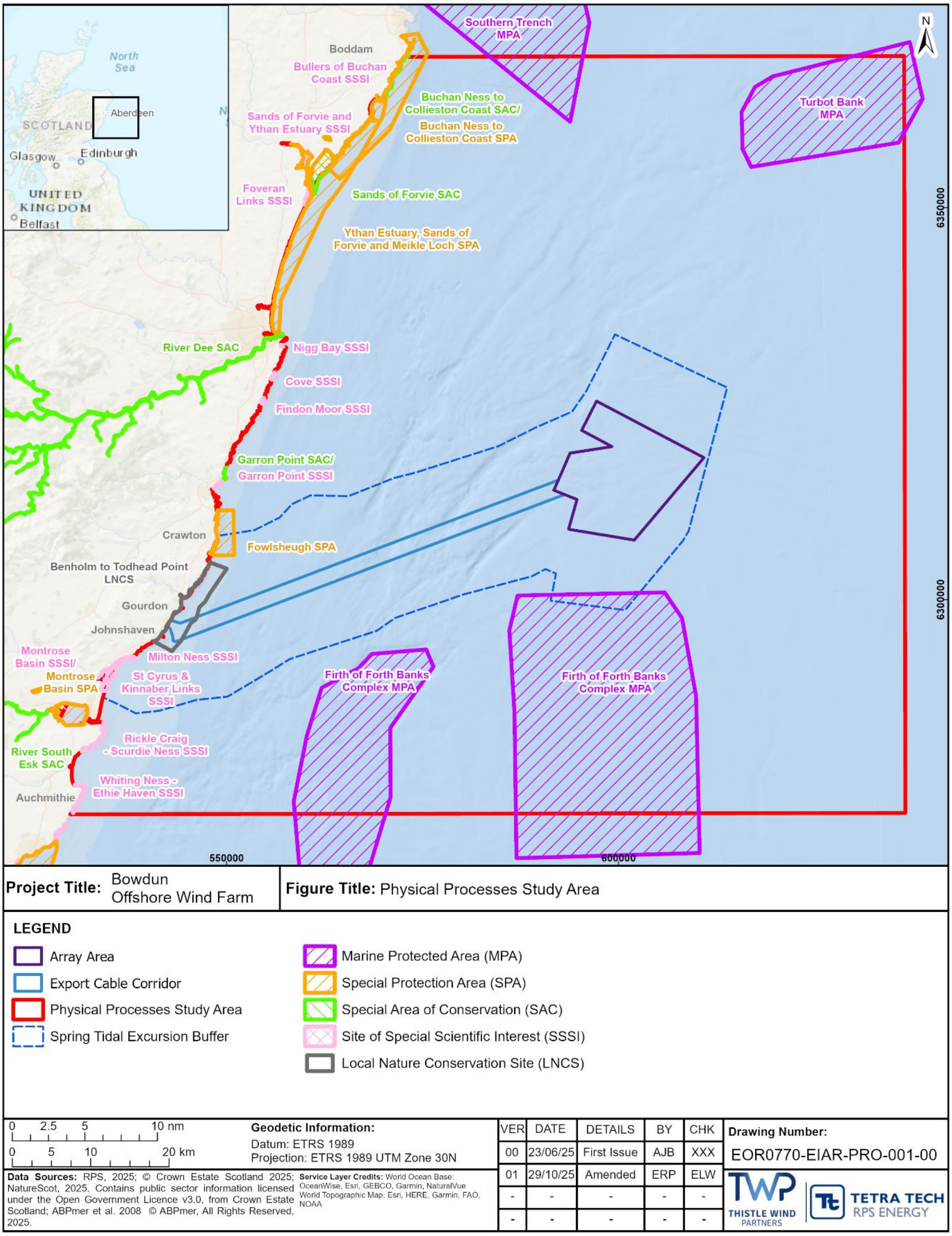

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Figure 2.1: Physical Processes Study Area

3 Methodology

3.1 Overview

3.1.1 In order to provide a robust assessment of the potential impact of the MDS of the Offshore Infrastructure in the Array Area this study provides:

- A detailed baseline characterisation of stratification (approach summarised in Section 3.2), including:
    - An overview of terminology and the natural processes causing or affecting stratification in shelf seas and in the general vicinity of the Array Area.
    - A quantitative characterisation of stratification strength over the Northwest European Shelf and within the Physical Processes Study Area, including general patterns of spatial and temporal (seasonal) variation, and inter-annual variability.
    - The characteristics and natural processes causing or affecting tidal mixing fronts (between areas of relatively more mixed and more stratified water).
    - Projected changes to the future baseline characterisation of stratification, due to the effects of climate change.
- A project specific EIA (approach summarised in Section 3.3) for the MDS for the Offshore Infrastructure in the Array Area, addressing the following questions:
    - How might the wind farm structures change mixing?
    - How might this change in mixing influence the timing of seasonal stratification and frontal positions?
    - What impacts could this have on primary production (PP) and the wider ecosystem?
    - What impacts could the change in near-surface wind speeds have on water column mixing and stratification?

3.2 Baseline Characterisation

3.2.1 The baseline understanding of the existing temporal/spatial pattern of stratification and positioning of tidal mixing fronts has been developed using readily available three-dimensional numerical model outputs from Copernicus Marine Service (Copernicus, 2024a; 2024b).

3.2.2 Temperature, salinity and chlorophyll-a reanalysis datasets across the Northwest European Shelf were generated by integrating past observations from satellites and *in situ* measurements with coupled physical-biogeochemistry model systems. This dataset provides timeseries from 2010 to 2024, at a 7 km horizontal resolution and over 24 standard Intergovernmental Oceanographic Commission geopotential levels, concentrated in the upper 200 m of the water column. A detailed description of the model production, calibration and validation is available in Tonani *et al.* (2022) and Ciavatta *et al.* (2018) for the physical and biogeochemical models, respectively.

3.2.3 The use of Copernicus reanalysis data allowed for a detailed examination of spatial and temporal variability over a range of scales, from broader seasonal and inter-annual changes to shorter term fluctuations occurring over a tidal cycle. Vertical temperature and salinity profiles facilitated the calculation of density profiles, which were used to assess stratification strength through the PEA, as discussed in Section 4.2. Chlorophyll-a profiles served as a proxy for PP, with elevated concentrations often indicating increased productivity linked to the onset of stratification or the positioning of tidal mixing fronts, discussed in greater detail in Section 4.3.

3.2.4 The Scottish Shelf Model (SSM) 3.02 Reanalysis hindcast is another potential data source for establishing the stratification baseline and conducting impact assessments for the Physical Processes Study Area. The SSM provides hourly data on horizontal currents and water elevations, as well as daily averages of three-dimensional currents, temperature, and salinity. Since the SSM is forced by the same Copernicus data used here, the two model outputs are expected to be similar. Additionally, the Copernicus model offers higher temporal resolution, providing hourly three-dimensional data (as opposed to daily in the SSM), which allows for a more detailed assessment of stratification variability over shorter timescales, such as diurnal tidal cycles.

3.3 Impact Assessment

3.3.1 To assess the impact of Offshore Infrastructure on water column mixing and stratification, the method outlined by Carpenter *et al.* (2016) was used. This approach uses empirical equations to estimate two key timescales: the mixing timescale, which predicts the time required for complete mixing of stratified layers due to increased Turbulent Kinetic Energy (TKE) generated by the Wind Turbine structures, and the advective timescale, which quantifies how long a water parcel remains within the Array Area, experiencing enhanced TKE. These estimates provide insight into the influence of Wind Turbines on local stratification and are discussed in more detail in Section 5.2.

3.3.2 One-dimensional depth-profile models, such as the GOTM, could offer a more detailed analysis of mixing processes within a limited distance of individual foundations within the Array Area. However, the absence of sufficient measured data for model validation poses a significant challenge, limiting the usefulness of the results. A one-dimensional modelling approach would not provide a suitably realistic description of the two or three-dimensional result of localised turbulent interaction between the flow and individual foundations in an array of widely spaced foundations, and where water passing through the Array Area may or may not be repeatedly affected. Whilst a bespoke model might be theoretically possible, the extensive effort required to develop, calibrate/validate, and implement such a model would be disproportionate to the findings.

4 Baseline Characterisation

4.1 Overview

4.1.1 Stratification is a naturally occurring seasonal hydrodynamic process related to the vertical and horizontal distribution of seawater temperature and salinity. Where present, stratification plays a key role in nutrient availability and the distribution of marine flora and fauna.

4.1.2 During summer, solar heating and higher air temperatures warm the surface waters, creating a marked temperature difference between the warmer, buoyant upper layer and the colder, denser bottom waters. In the North Sea, this temperature difference can reach up to 10°C, forming a sharp vertical density gradient, or pycnocline, which acts as a physical barrier to vertical mixing. This separation limits the upward transport of nutrients from deeper waters, which can limit PP in surface waters as nutrients become depleted over time.

4.1.3 The development of stratification is counterbalanced by turbulent mixing, which is generated at the seabed by tidal currents and at the surface by wind and wave action. Consequently, stratification is more likely to form in deeper waters but can also occur in shallower areas with low current speeds and limited wind exposure. The interplay between these forces determines whether stratification will persist or break down, affecting the overall productivity of the ecosystem.

4.1.4 Tidal mixing fronts form at the boundaries between well-mixed and stratified waters, creating regions of enhanced biological activity. These fronts, common in shelf seas like the North Sea (Hill *et al.*, 2005; 2008), facilitate nutrient exchange between surface and deeper layers, promoting PP through the stimulation of phytoplankton growth. Fronts act as biological hotspots, concentrating nutrients and attracting higher trophic levels, making them important features for fisheries and marine biodiversity. The strength and position of these fronts are influenced by factors such as tidal current speeds, freshwater inputs, and wind patterns, which can vary on timescales ranging from hours to years.

4.1.5 The North Sea is characterised by significant spatial and temporal variation in the vertical distribution of temperature and salinity. An assessment of intra-annual patterns of stratification in the North Sea has been undertaken by van Leeuwen *et al.* (2015), using a long term (51 year) regional scale hydro-biogeochemical model simulation. The Array Area is located in an area described by van Leeuwen *et al.* (2015) as being “intermittently stratified”, defined as <40 days in the year where the water column is stratified and between 120 and 250 days in the year where the water column is fully mixed.

4.2 Stratification

4.2.1 The PEA provides a measure of the amount of energy per unit volume (J/m^3) required to completely mix a stratified water column, making density vertically homogenous. The significance of PEA lies in its ability to provide a single, scalar value that captures the complexity of stratification in terms of both temperature and salinity gradients. It is widely used in oceanography to assess the strength of stratification in a water body, for example Simpson (1981); Gowan *et al*. (1995); Yamaguchi *et al.* (2019) and Dorell *et al*. (2022).

4.2.2 PEA (ϕ) is calculated as:

$$\phi = \frac{g}{h}\int_{-h}^{0}(\rho - \bar{\rho})\, z \cdot dz$$

4.2.3 Where h is the water depth, g is acceleration due to gravity (9.81 m/s^2), ρ is the water density and $\bar{\rho}$ is the density calculated using the depth-mean water temperature and salinity. To calculate water density, the Gibbs SeaWater (GSW) Matlab toolbox is used alongside three-dimensional temperature and salinity data available from the Copernicus reanalysis dataset.

4.2.4 The threshold values of PEA can vary depending on the specific water body. Based on the density profiles and calculated PEA values for the Physical Processes Study Area and its surrounding regions, along with thresholds used in the literature (Gowan *et al.,* 1995; Dorrell *et al*., 2022), the following PEA classifications are applied in this study:

- mixed water column: $\phi < 25$ J/m^3;
- weakly stratified water column: $25 \leq \phi < 50$ J/m^3;
- moderately stratified water column: $50 \leq \phi < 100$ J/m^3; and
- strongly stratified water column: $\phi > 100$ J/m^3.

4.2.5 PEA values were calculated for the Physical Processes Study Area and its surrounding region at monthly intervals, from January 2010 to December 2023. This approach enabled the assessment of both seasonal and inter-annual variability in stratification strength. Figure 4.1, Figure 4.2 and Figure 4.3 illustrate the results for three specific years, 2023, 2012 and 2015, representing years with stronger stratification, intermediate stratification and weaker stratification, respectively. In the figures, seas are partitioned into those defined as mixed (ϕ<25 J/m^3) and stratified (ϕ≥25 J/m^3).

4.2.6 During the winter months (October to April), reduced solar heating and increased turbulent mixing from wind and waves result in well-mixed waters in the Array Area, characterised by homogeneous temperature and density profiles, with PEA values around 10 J/m^3 to 15 J/m^3. With the onset of spring and summer, calmer weather and longer, warmer days enhance stratification, overcoming the mixing effects of tide and winds. From May to September, this leads to a vertical temperature gradient and an increase in PEA values. Over the 14-year analysis period (2010 to 2023), PEA typically reaches around 40 J/m^3 in mid-summer, indicating a weakly stratified water column, consistent with the findings of van Leeuwen *et al.* (2015). However, there is variability in the strength of summer stratification from year to year, with mid-summer PEA values ranging from approximately 30 J/m³ (indicating weak stratification) in 2015 to around 60 J/m³ (indicating moderate stratification) in 2023 (Figure 4.4).

4.2.7 To the east of the Array Area, increasing depths lead to stronger stratification with greater distance from the Array Area. Conversely, closer to the coastline, shallower depths and stronger tidal currents result in reduced stratification. Approximately 25 km west of the Array Area, the water column remains well-mixed throughout the year. Immediately west of the Array Area, a deeper region (>100 m) results in a more strongly stratified patch between the weakly stratified waters of the Array Area and well-mixed waters adjacent to the coastline.

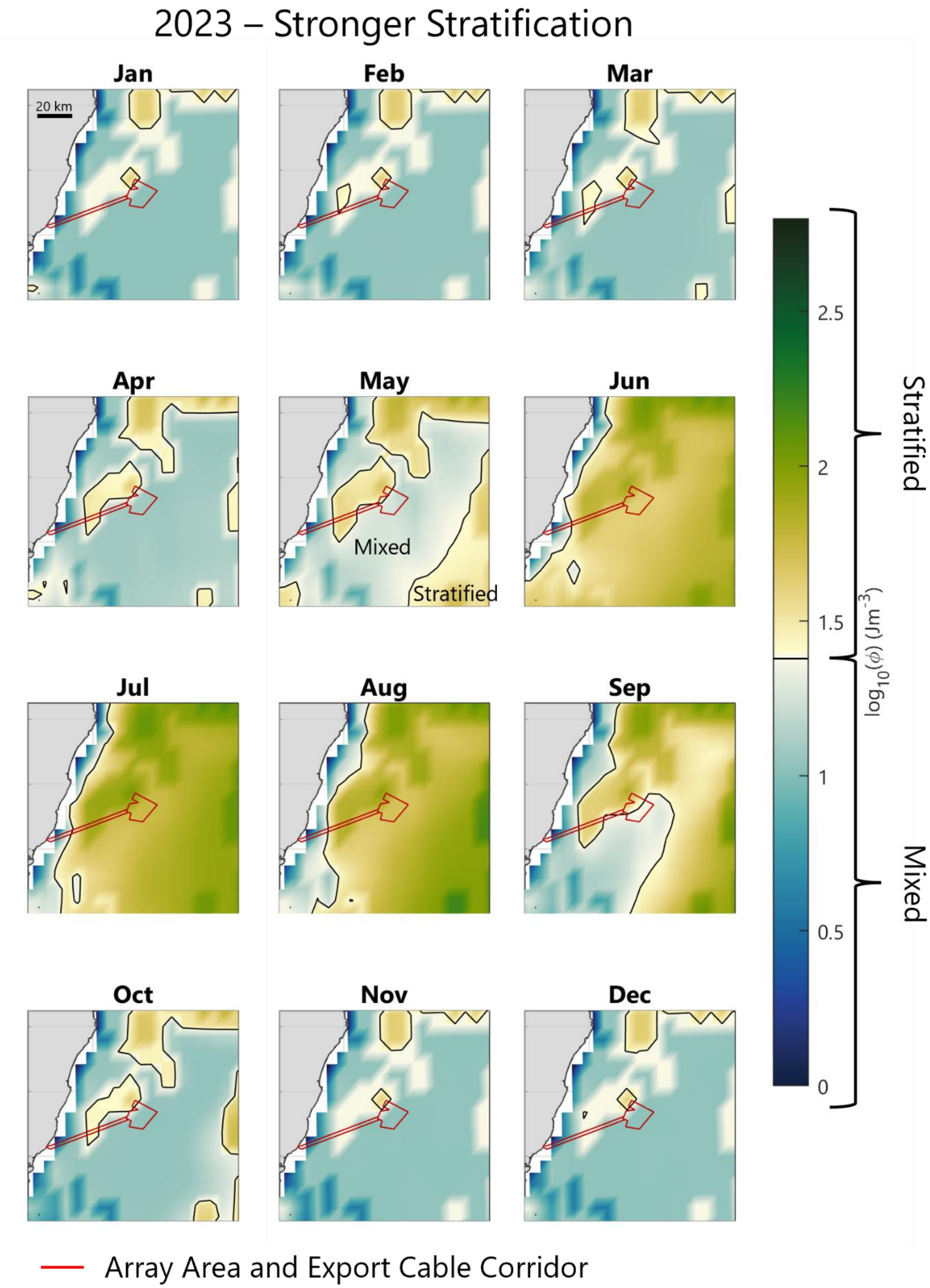

Figure 4.1: Calculated PEA (ϕ), Based on the Copernicus Reanalysis Monthly Temperature and Salinity Data for 2023, a Stronger Stratification Year

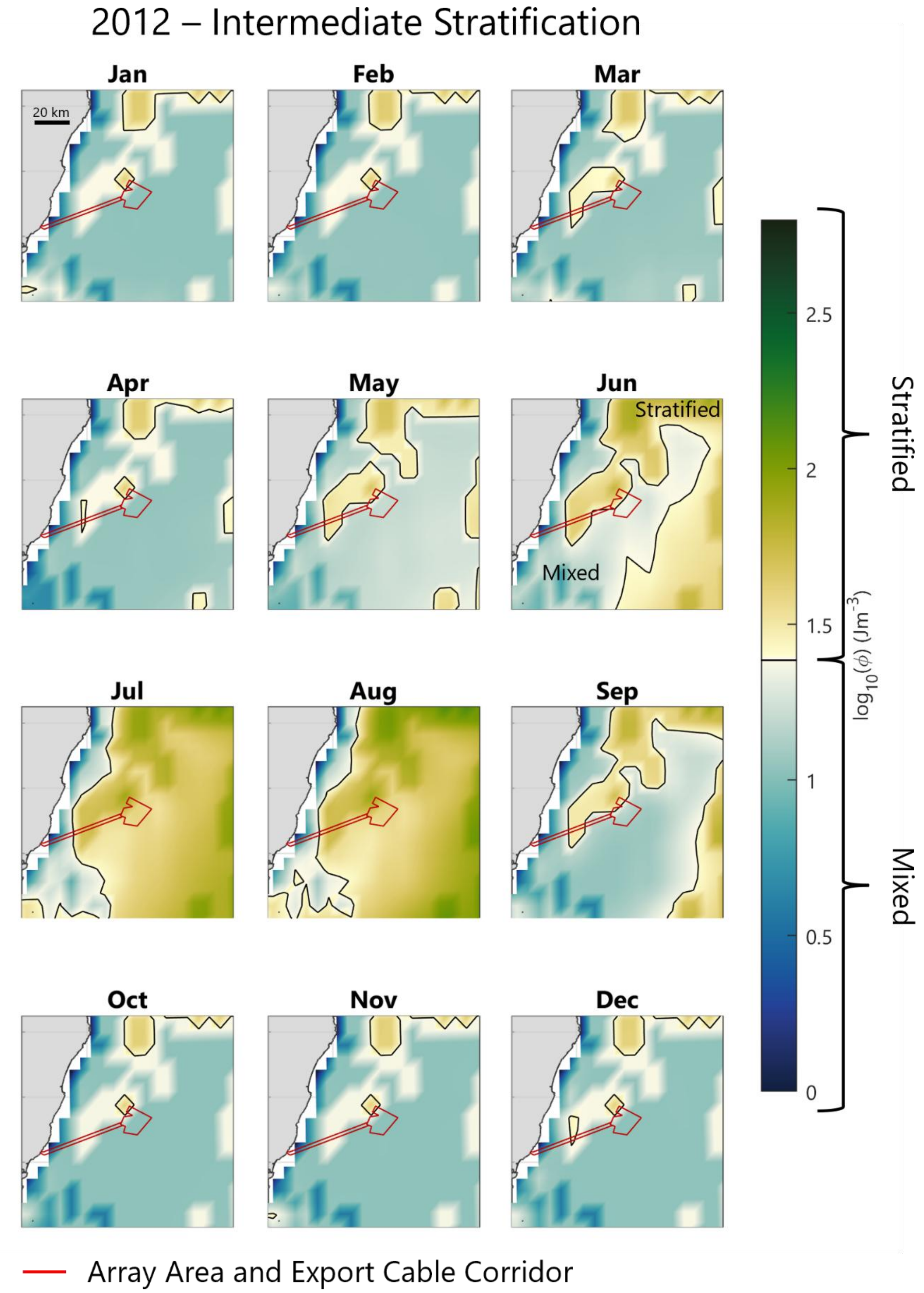

Figure 4.2: Calculated PEA (ϕ), Based on the Copernicus Reanalysis Monthly Temperature and Salinity Data for 2012, an Intermediate Stratification Year

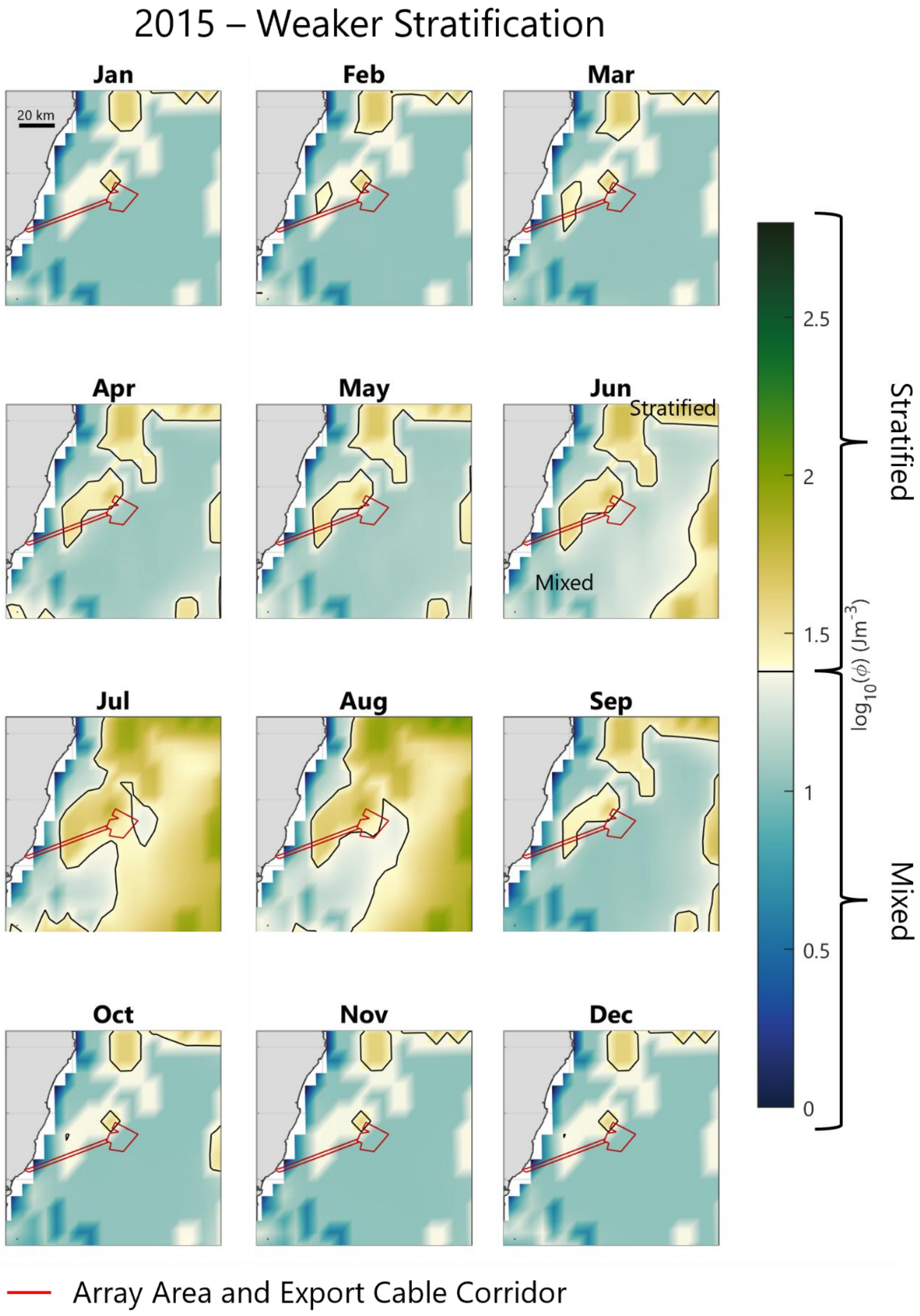

Figure 4.3: Calculated PEA (ϕ), Based on the Copernicus Reanalysis Monthly Temperature and Salinity Data for 2015, a Weaker Stratification Year

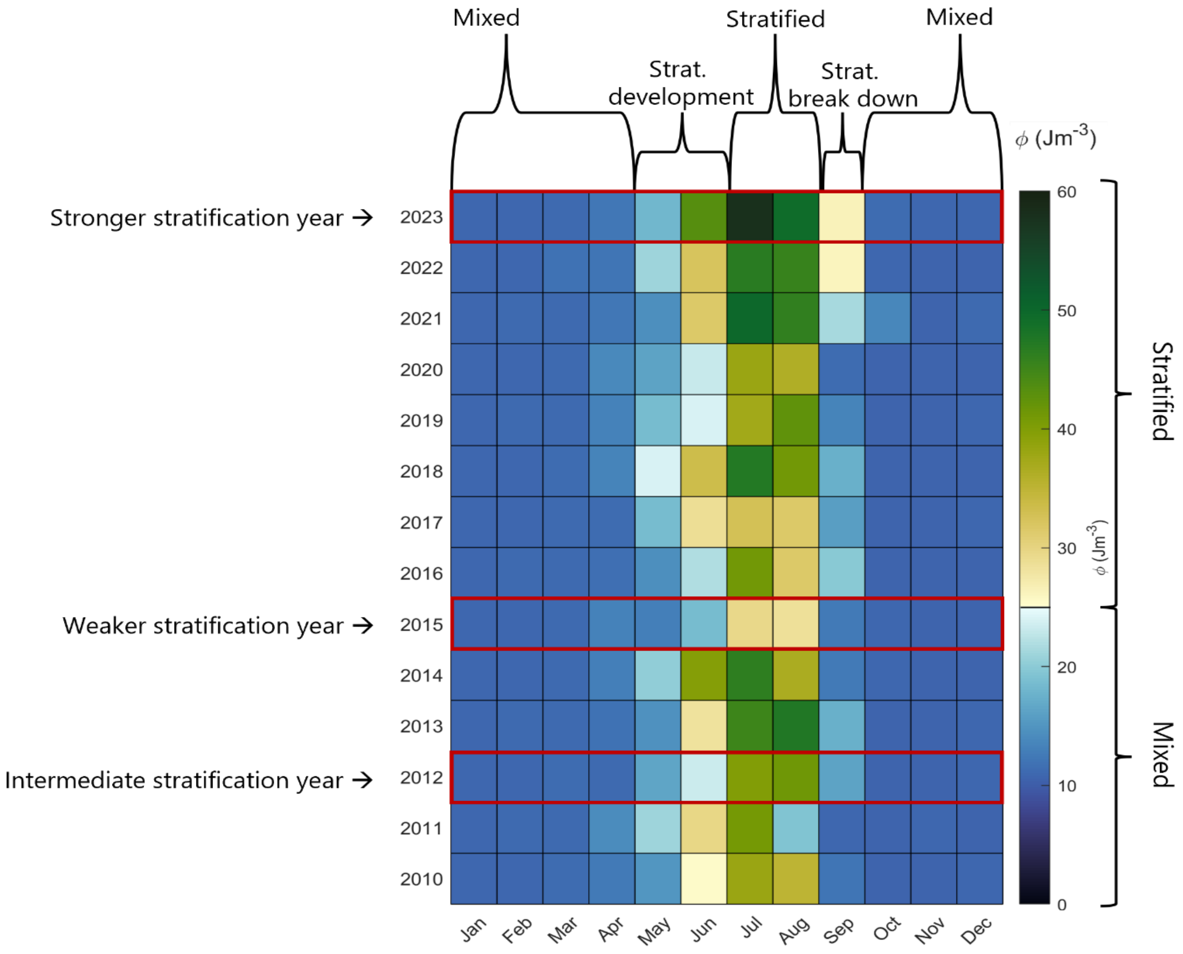

Figure 4.4: Monthly PEA (ϕ) Values, Based on the Copernicus Reanalysis Monthly Temperature and Salinity Data, in the Array Area from 2010 to 2023

4.3 Tidal Mixing Fronts

4.3.1 The relative abundance of chlorophyll-a is proportional to phytoplankton biomass, and local patterns or gradients in concentration can serve as an effective proxy indicator for locating tidal mixing fronts (Garcia-Nieto *et al.*, 2024). Phytoplankton rely on sunlight and nutrients for photosynthesis and thrive in areas where both are readily available. In stratified waters, nutrients tend to be trapped below the thermocline, making them inaccessible to phytoplankton in the sunlit surface layer. The physical mixing at fronts locally supplies a relatively higher concentration of nutrients into the sunlit surface layer, therefore creating more favourable conditions for phytoplankton growth by preventing nutrient depletion in the surface layers. As a result, these areas often support higher levels of PP (and chlorophyll-a) compared to both the mixed and stratified waters on either side of the front.

4.3.2 Figure 4.5, Figure 4.6 and Figure 4.7 illustrate the maximum chlorophyll-a concentrations throughout the water column for the years 2023 (strong stratification year), 2012 (intermediate stratification year) and 2015 (weaker stratification year), capturing both deep chlorophyll maxima and surface peaks. During the summer months, elevated chlorophyll-a concentrations (likely linked to a tidal mixing front) are observed east of the Array Area. This is consistent across all years analysed (2010 to 2023) and suggests that higher PP is occurring at the boundary between the more strongly stratified waters located further offshore, as opposed to the weakly stratified waters in the Array Area. In the Array Area, stratification appears to be a more transient feature, leading to lower and less sustained phytoplankton growth compared to the more stable stratification further offshore.

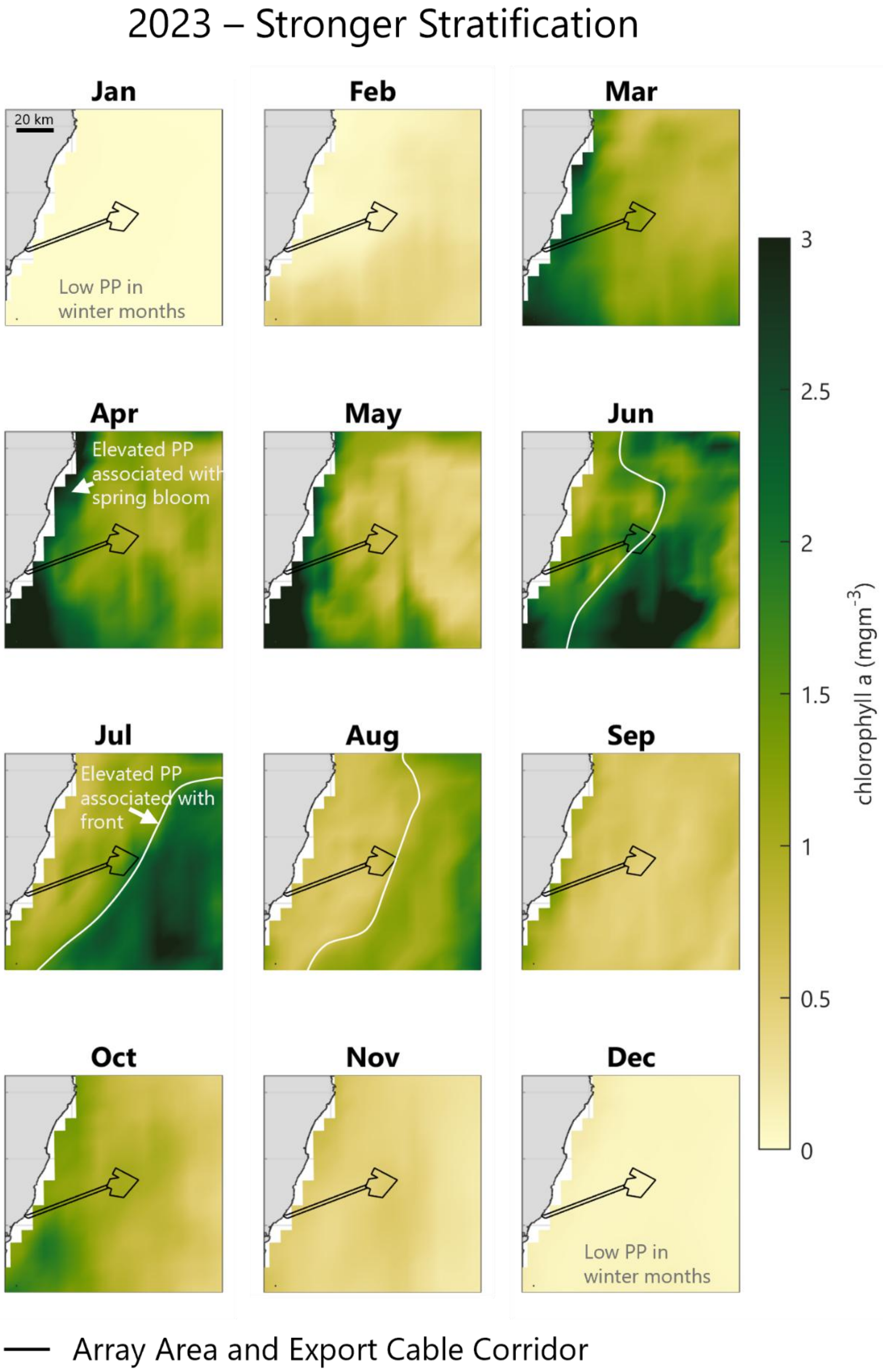

Figure 4.5: Copernicus Reanalysis Monthly Maximum Chlorophyll-a Concentration Throughout the Water Column for 2023 a Stronger Stratification Year

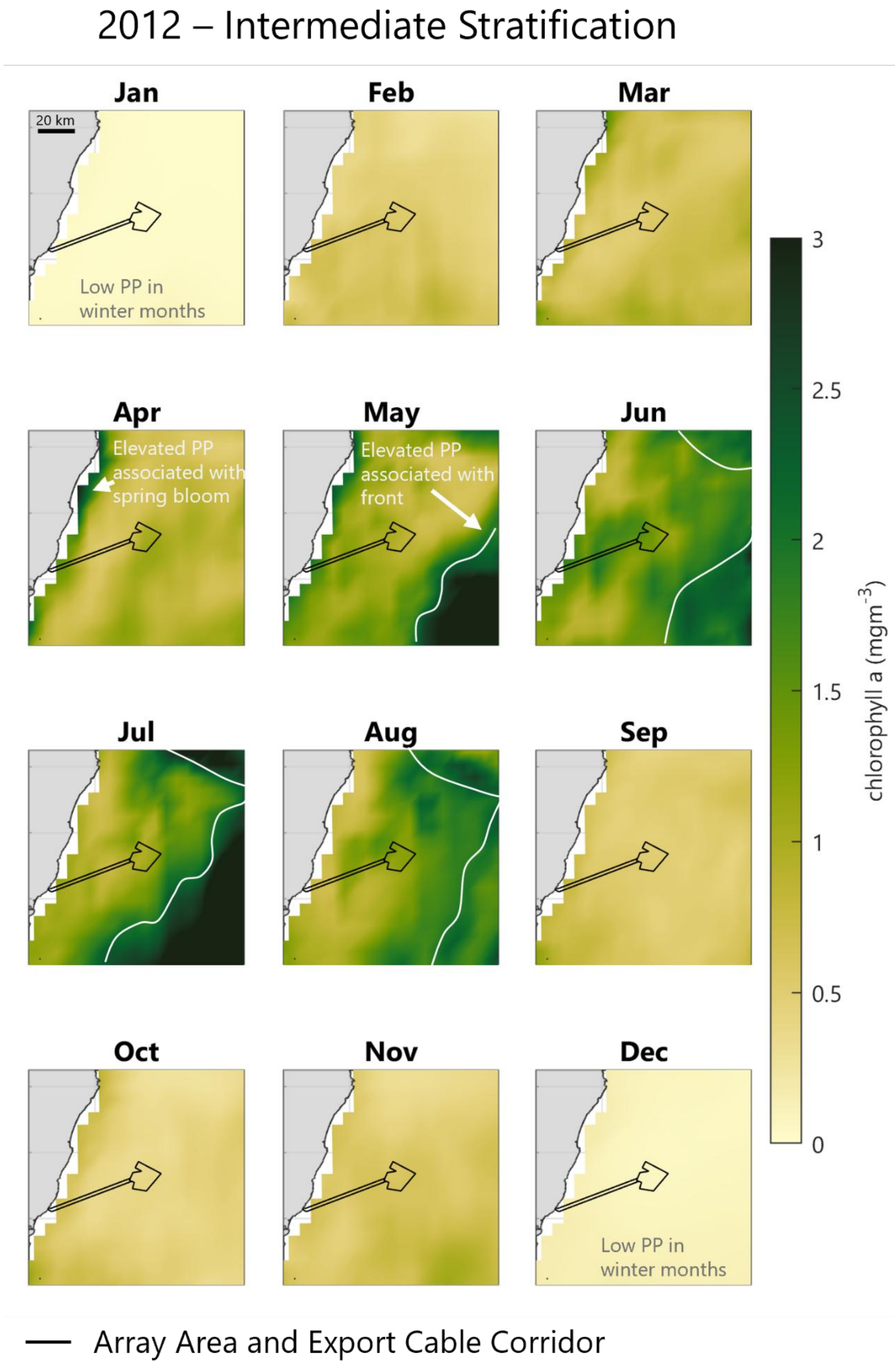

Figure 4.6: Copernicus Reanalysis Monthly Maximum Chlorophyll-a Concentration Throughout the Water Column for 2012 an Intermediate Stratification Year

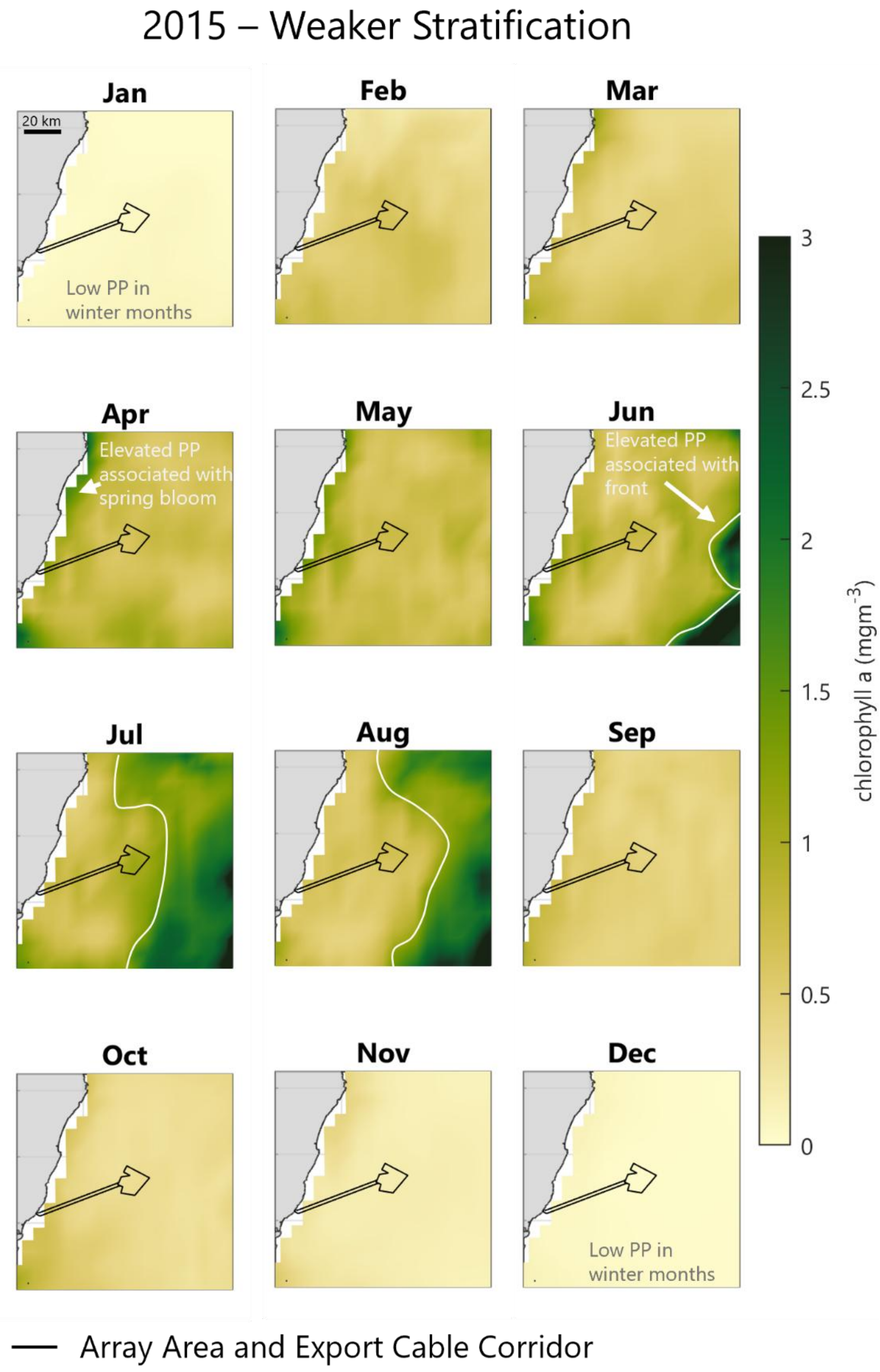

Figure 4.7: Copernicus Reanalysis Monthly Maximum Chlorophyll-a Concentration Throughout the Water Column for 2015 a Weaker Stratification Year

4.4 Future Change

4.4.1 The stratification dynamics in the North Sea are expected to undergo significant changes due to the changing climate. With the Proposed Development potentially beginning commercial operation in 2035, and a project lifetime of ~30 years, it is important to consider how the timing and strength of stratification will evolve during this time.

4.4.2 The timing of stratification is influenced by the interplay between solar heating and tidal mixing, with a smaller but notable contribution from wind-driven mixing. Global warming and changes to meteorological conditions is likely to alter the timing of spring stratification, and subsequently the timing of the spring phytoplankton bloom.

4.4.3 Model projections suggest that by 2100, the thermal stratification period in UK shelf seas will extend by approximately two weeks (Sharples *et al.*, 2025), with stratification occurring about one week earlier and breaking down 5 to 10 days later than present (Sharples *et al.*, 2022). The dominant driver behind this shift is the increase in air temperature, which accelerates solar heating of the surface waters and thus strengthens thermal gradients. Historically, stratification timing in the north-western North Sea has advanced by about 0.5 days per year since the late 1980s, based on analyses from 1974 to 2003 (Sharples *et al.*, 2006; Holt *et al.*, 2012). While these observed trends in stratification timing are relatively weak and difficult to separate from inter-annual variability (Jardine *et al.,* 2022), they offer some indication of potential future patterns based on a 'business as usual' climate projection (Figure 4.8).

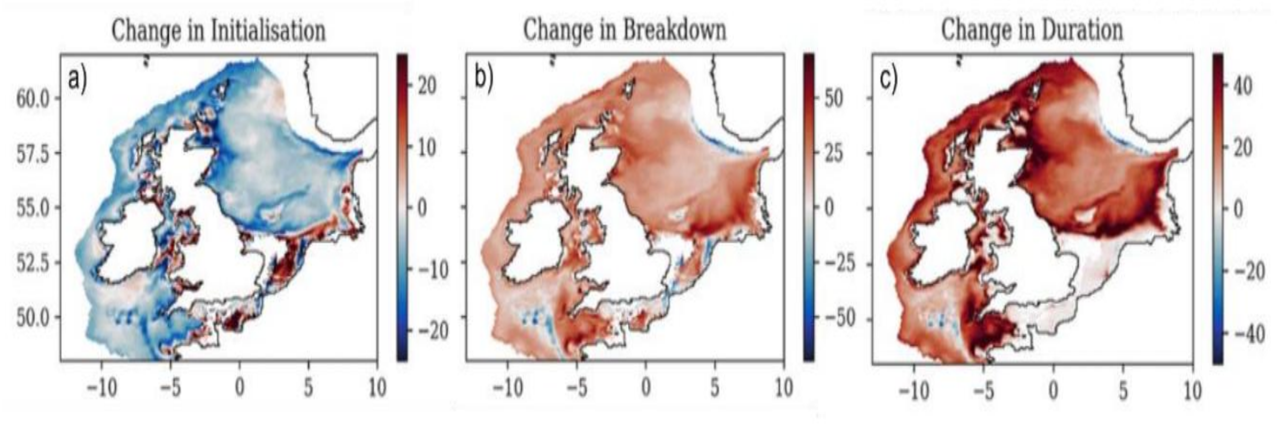

Figure 4.8: Comparison Between Present Day (1961 to 1990) and Future (2070-2098) Timing of the Onset (a), Breakdown (b) and Duration (c) of Seasonal Stratification (from Sharples *et al.*, 2025)

4.4.4 Model projections also suggest that seas across the north-west European shelf, including the northern North Sea, will experience greater surface-to-bottom temperature differences as the seasonal heating cycle intensifies (Tinker *et al.*, 2016), resulting in stronger stratification (Figure 4.9). Alongside the strengthening stratification there will be small shifts in the position of tidal mixing fronts as thermal stratification pushes into shower waters and/or stronger tidal regions.

4.4.5 Climate warming is also expected to lead to more frequent Marine Heat Waves. Marine Heat Waves will act to strengthen seasonal stratification through more intense heating of the surface ocean (Sharples *et al.*, 2025)

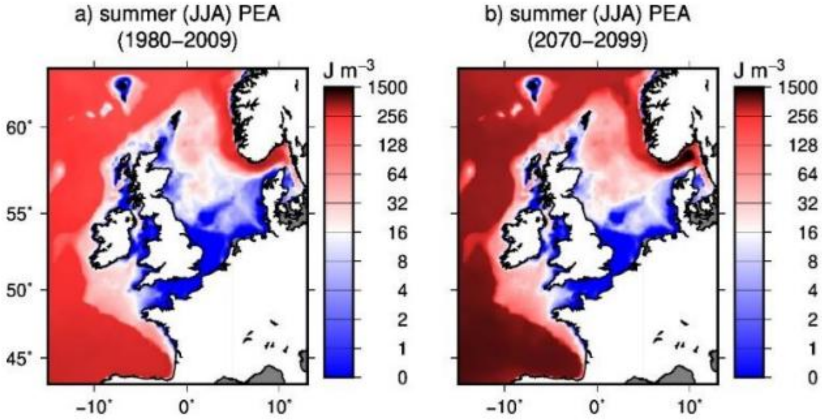

Figure 4.9: Present Day (a) and Predicted Strength of Stratification at the End of the Century (b) (from Sharples *et al.*, 2022)

4.4.6 Strengthening stratification reduces vertical mixing, limiting the upward transport of nutrients from the deep layers to the surface, where they fuel PP. This could lead to a decline in overall PP, as suggested by Chust *et al.* (2014).

5 Impact Assessment

5.1 Maximum Design Scenario

5.1.1 Several foundation types detailed in the Project Design Envelope (PDE) were considered (monopile, jacket on pin piles and jacket on suction buckets). The realistic worst case for impacts to stratification and frontal systems occurs during the Operation and Maintenance (O&M) phase of the Proposed Development and is associated with the PDE design option providing the largest hydrodynamic blockage within the water column. This is calculated by considering the foundation type, foundation dimensions and foundation number. The MDS for subsurface blockage contributing to potential impacts on stratification is summarised as follows:

- 67 x 15 MW Wind Turbines;
- minimum horizontal spacing of 1,038 m;
- 4-legged jacket on pin piles foundation type;
- diameter of jacket main members is 3.1 m;
- diameter of jacket secondary members is 1.5 m;
- pile diameter is 3.8 m;
- pile height above seabed is 5 m;
- scour protection diameter (including pile) is 28.8 m; and
- scour protection height above seabed is 1 m.

5.1.2 To the best of the author's knowledge, all of the academic analyses to date which considers the potential impacts from wind farms on mixing processes has focused on flow around monopile (i.e. simple fixed bottom) foundations (e.g. Carpenter *et al.* 2016; Cazenave *et al.* 2016; and Dorrell *et al.* 2022). The assessment presented in this section draws upon this research pertaining to fixed bottom monopile foundations, while applying an MDS blockage cross-section calculated for a jacket foundation. This method is intended to capture the worst-case impacts on stratification and frontal systems from the range of design options considered for the project.

5.2 How Might the Wind Farm Structures Change Mixing?

5.2.1 Turbulent mixing acts to breakdown stratification, it is a naturally occurring, omnipresent process driven at the seabed by tidal currents and at the surface by wind and wave action. Flow past individual Wind Turbine foundations within the Array Area will provide another source of turbulence generation, driving additional water column mixing compared to the baseline scenario.

5.2.2 To assess the impact of the Wind Turbine structures on the strength of localised water column mixing, the method outlined by Carpenter *et al.* (2016) was employed. This approach uses empirical equations to estimate two key timescales: the mixing timescale, which predicts the time required for complete mixing of stratified layers due to increased TKE generated by the Wind Turbine structures, and the advective timescale, which quantifies how long a water parcel remains within the Array Area, experiencing enhanced TKE.

5.2.3 Power is removed from the flow as it is forced around a Wind Turbine foundation. This can be expressed as power consumption per unit area (P_{str}) in W/m^2 by the following equation:

$$P_{str} = \frac{\rho_0 C_D A \langle |\bar{u}|^3 \rangle}{2L^2}$$

5.2.4 Where: ρ_0 is the water density (1,026 kg/m^3); C_D is the drag coefficient; A is the cross-sectional area of the Wind Turbine foundation in the water column; L is the distance between equally spaced Wind Turbines; and, $|\bar{u}|^3$ is the time mean, depth-mean current velocity, cubed (i.e. a measure of the power of the current throughout the year).

5.2.5 The drag coefficient of a structure is highly variable, dependent on a range of factors such as roughness, length, scale and turbulence in the approaching flow. A range of values for C_D have been applied in previous studies. The highly conservative value of $C_D = 1$, as used by Carpenter *et al.* (2016) and similar to values suggested by Faltinsen (1990) for floating structures and ships, is applied here.

5.2.6 The cross-sectional area of each foundation type provided in the PDE was calculated, and the maximum total blockage area used – this was for a 4-legged jacket foundation type which gave a representative individual foundation cross-sectional area of 1,647 m^2, equivalent to a monopile of 25.2 m diameter in 65 m of water (the mean water depth within the Array Area). The smallest Wind Turbine spacing distance provided in the PDE, 1,038 m, was used as L. P_{str} was calculated over a year period from hourly instantaneous tidal velocity magnitudes (extracted for a central point within the Array Area from ABPmer’s NW European Shelf Hydrodynamic model (ABPmer, 2017)), and the mean average power removed from the flow then calculated (Figure 5.1).

5.2.7 These values and assumptions provide an estimate of power removal per unit area across the Array Area of 0.043 W/m^2, representing a mean value calculated over a year-long period. This approach accounts for the diurnal and spring-neap variability in tidal currents, and thus P_{str}. However, the actual instantaneous P_{str} will fluctuate over time (Figure 5.1). For instance, during peak spring tides, higher current velocities (u) will lead to increased P_{str} values—scaling with velocity cubed—effectively shortening the timescale required to break down stratification in the Array Area. Conversely, during neap tides, when velocities are lower, P_{str} values will decrease, resulting in a longer stratification breakdown period.

5.2.8 Since hydrodynamic conditions constantly shift between these extremes, and stratification response to mixing is not instantaneous, the effects evolve as the hydrodynamics change. Therefore, using a mean value provides a representative measure of the longer-term, persistent impact of power removal—capturing the cumulative effect over time, rather than just transient fluctuations.

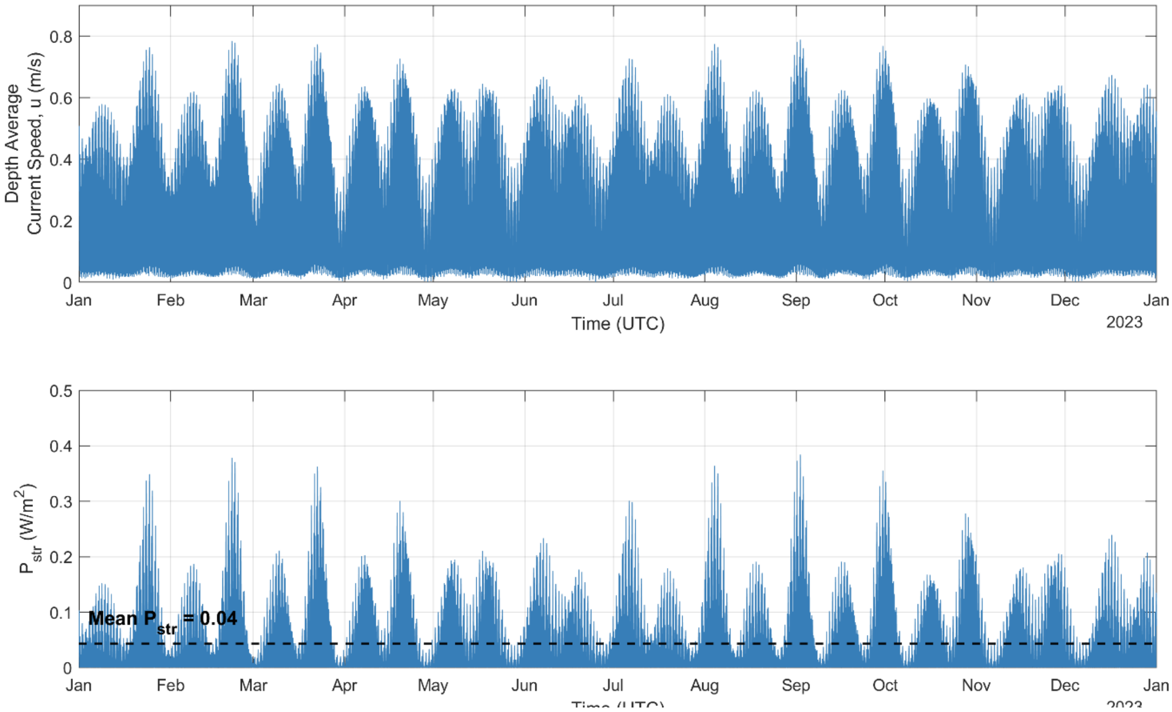

Figure 5.1: Year Timeseries of Tidal Current Speed (top) and Power Removed From the Tidal Flow (P_{str}) by the MDS Description of All Wind Turbine Structures (bottom)

5.2.9 The estimate of the power removed by a Wind Turbine foundation structure is assumed to be equal to the power put into TKE production (Carpenter *et al.*, 2016), which mixes the water column stratification. Therefore, given the strength of the stratification, represented by the PEA, a timescale to mix a water column completely by only the TKE generated by Wind Turbine structures (T_{mix}) can be estimated by:

$$T_{mix} = \frac{\phi_{max} h}{R_f P_{str} b}$$

5.2.10 Where: R_f is the Richardson number, a value of 0.17 is commonly used in oceanographic studies; h is the representative water depth in the Array Area (65 m); ϕ_{max} is the PEA value (J/m^2) for the maximum stratification case, ϕ_{max} values for a stronger (2023), intermediate (2012) and weaker (2015) stratification year were considered (Table 5.1); and, b is the thickness of the pycnocline region during maximum stratification, calculated from density profiles for the most strongly stratified month in the years of interest (Figure 5.2), these values are given in Table 5.1.

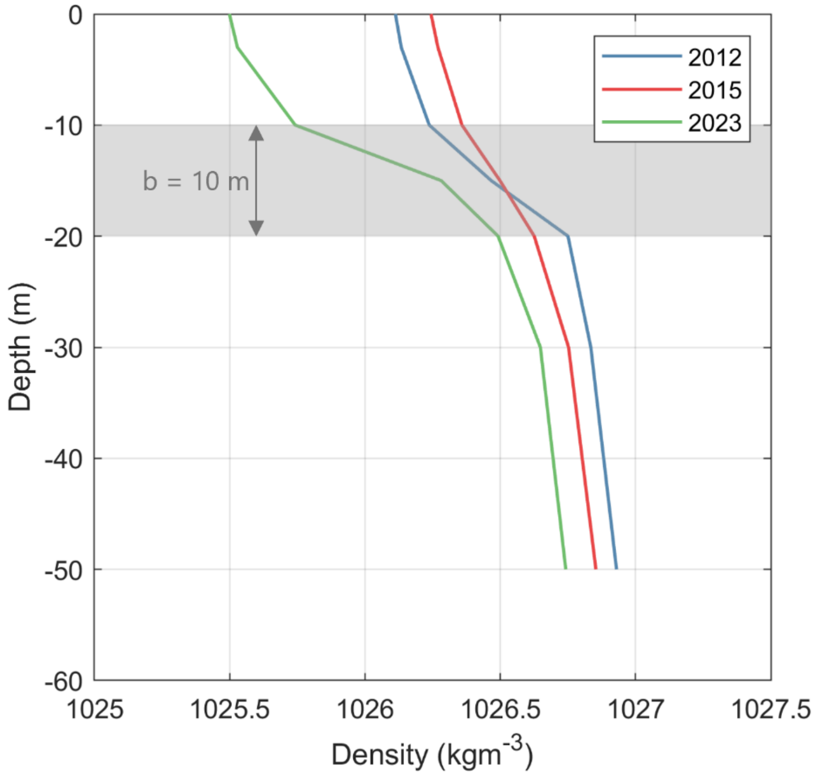

Figure 5.2: Array Area Density Profiles for Stronger (2023), Intermediate (2012) and Weaker (2015) Stratification Years

Table 5.1: Mixing Timescales for Stronger (2023), Intermediate (2012) and Weaker (2015) Stratification Years

	Stronger stratification year	**Intermediate stratification year**	**Weaker stratification year**
Year	2023	2012	2015
MDS blockage (m^2)	1,647	1,647	1,647
h (m)	65	65	65
ϕ_{max} **(J/m^3)**	60	40	30
ϕ_{max} **(J/m^2)**	3,918	2,612	1,959
P_{str} **(W/m^2)**	0.043	0.043	0.043
b (m)	10	10	10
T_{mix} **(days)**	40.2	26.8	20.1
T_{adv} **(days)**	13.9	13.9	13.9
T_{adv}/T_{mix}	0.35	0.52	0.69

5.2.11 The calculated mixing timescales for a range of stratification strengths observed in the Array Area are given in Table 5.1. To provide context for these values, it is necessary to determine a timescale of advection (T_{adv}), (i.e. how long a parcel of water is likely to experience enhanced turbulent mixing induced by the OWF structures). This was estimated using bespoke hydrodynamic models - built to inform the Physical Processes EIA Chapter and described in Volume 3, Technical Appendix 7.2: Physical Processes Model Design and Validation - to derive the mean residual current speed across the Array Area (Figure 5.3) and the Array Area's length scale, resulting in a T_{adv} value of 13.9 days. This indicates that a parcel of water is not exposed to the elevated TKE from OWF structures for a sufficiently long time to completely break down the stratification present in the water column, even for more weakly stratified years such as 2015. Stratification will be weakened by the elevated TKE but will not be fully broken down. The water column within the Array Area during the summer months is defined as weakly stratified ($25 \leq \phi < 50$ J/m³) for most years analysed. Therefore, weakly stratified waters will remain weakly stratified after the effect of OWF mixing.

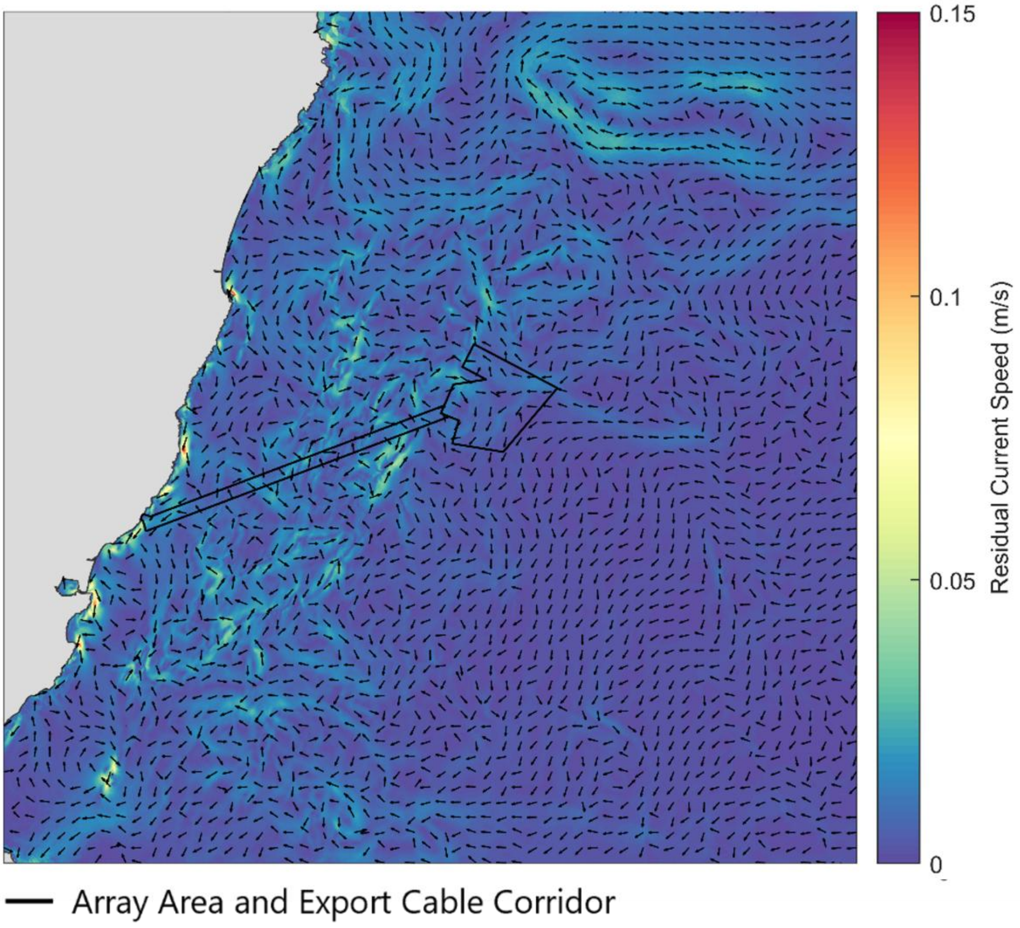

Figure 5.3: Residual Current Speed and Direction Across the Array Area

5.2.12 To better understand the predicted impact in the context of natural variability, hourly PEA values were calculated for the Array Area during a stratified summer month, July 2023, using Copernicus reanalysis data (Figure 5.4). The results show that PEA fluctuates significantly over short timescales, with variations of ±15 J/m³ within a tidal cycle (12 hours). This indicates that the stratification weakening caused by elevated turbulent mixing in the wake of Wind Turbine foundation structures falls within the natural variability of the system. Hourly data are only available from Copernicus for 2023, so similar plots cannot be provided for the weaker and intermediate stratification years of 2015 and 2012, respectively.

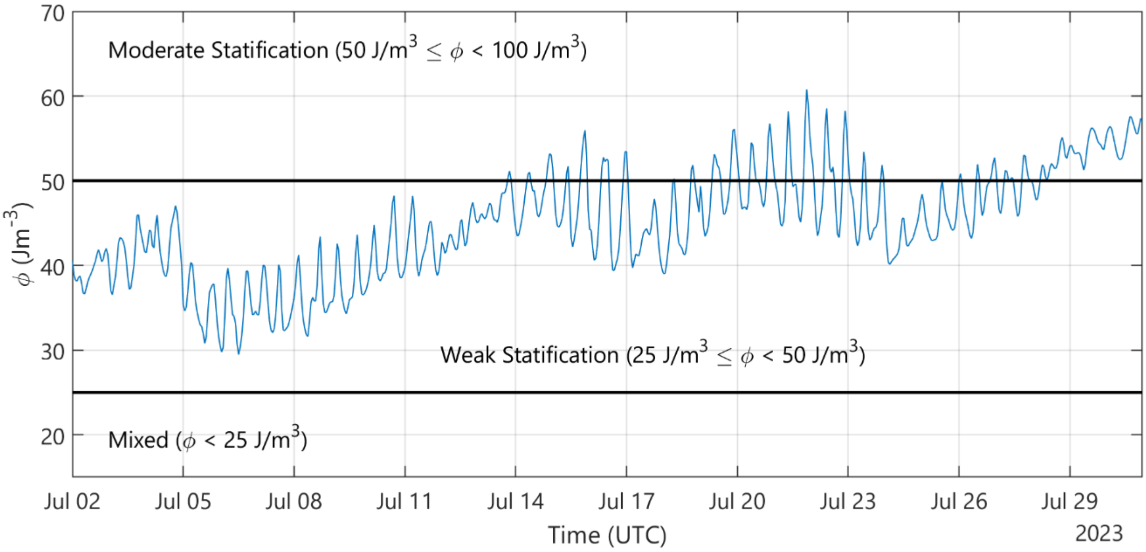

Figure 5.4: Array Area Hourly PEA Values for a Strong Stratification Month July 2023

5.2.13 The foundation induced mixing described in this section will primarily occur directly behind individual Wind Turbine foundations, extending only a short distance downstream. Research by Miles *et al*. (2017) using scaled flume tank models found that while monopile foundations initially reduced flow velocity and increased turbulence in their wake, these effects largely dissipated within 8.3 pile diameters downstream. This limited spatial influence on flow and turbulence suggests that the impact of Wind Turbine foundations on stratification will also be spatially constrained, affecting only small portions of the shelf sea and minimising the likelihood of cumulative impacts with other planned OWFs.

5.3 How Might This Change in Mixing Influence the Timing of Seasonal Stratification and Frontal Positions?

5.3.1 The impact of the Proposed Development on seasonal stratification and frontal positions is expected to be small, especially when taking into account the high degree of natural variability of the system. Stratification in the Array Area is subject to considerable inter-annual variability (Figure 4.4), with some years experiencing moderate stratification to weak stratification, while in other years the water column remains relatively well-mixed for most of the summer. Given this variability, the additional mixing induced by the wind farm structures is unlikely to produce major changes to the overall stratification dynamics.

5.3.2 The onset of stratification in spring depends on surface heating overcoming vertical mixing. The Proposed Development induced mixing could theoretically delay the onset of stratification, but during years when the water column remains mostly mixed or weakly stratified, this additional mixing would have little noticeable impact. In such years, stratification forms late into the summer, meaning the Wind Turbine foundations’ influence on delaying stratification would be negligible.

5.3.3 Similarly, the breakdown of stratification in autumn may be slightly accelerated by the Proposed Development’s enhanced TKE. However, in years where stratification is naturally weak, the water column is already close to being mixed, so the additional mixing would have little effect. Overall, in both strong and weak stratification years, the Proposed Development’s influence on seasonal timing is expected to be small, falling within the natural variability of the system.

5.3.4 Frontal systems form at boundaries between mixed and stratified waters, and their position and intensity can be influenced by vertical mixing. The added turbulence from the Wind Turbine foundations might shift these fronts, but this effect is expected to be localised. The additional mixing could slightly reduce the strength of stratification near the Array Area, leading to small displacements in the position of fronts. However, given the variability in stratification from year to year, the overall impact of the Proposed Development on frontal positioning is expected to be minimal. In years where the water column remains largely mixed, the Wind Turbine foundations will have little to no effect on front formation.

5.3.5 This limited spatial influence on flow and turbulence suggests that the impact, if any, of Wind Turbine foundations on frontal positions will also be spatially constrained, minimising the likelihood of cumulative impacts with other planned OWFs.

5.4 What Impacts Could This Have on Primary Production and the Wider Ecosystem?

5.4.1 Potential impacts on PP and the wider marine ecosystem will be reported on separately, within other chapters of this Offshore EIA Report, notably Volume 2, Chapter 9: Fish and Shellfish Ecology, Volume 2, Chapter 10: Marine Mammals and Volume 2, Chapter 11: Offshore Ornithology. However, the potential impact of the Proposed Development on PP and the wider ecosystem is expected to be minimal, especially when considering the natural variability and existing patterns of productivity in the region. Elevated PP consistently occurs to the east of the Array Area, near the boundary between areas of relatively weaker and more strongly stratified waters (Figure 4.5 to Figure 4.7) and is indicative of the tidal mixing front location.

5.4.2 The Array Area is located outside this key area of productivity, which limits the potential for any direct impacts (i.e. direct local mixing at the location of the front, or nearby on the more stratified side). Any indirect advected effect of additional mixing reducing stratification extending from the Array Area is unlikely to overlap or significantly alter the nutrient dynamics at the existing front, because there is no clear hydrodynamic pathway connecting the two locations: the front is not aligned to the Array Area along the tidal current axis or within one tidal excursion distance; and, the residual current direction from the Array Area is away from the front, towards the west (Figure 5.3).

5.4.3 In terms of the wider ecosystem, the localised mixing effects near the Wind Turbine structures are unlikely to affect ecosystem processes beyond the immediate vicinity of the array. This limited spatial influence means the likelihood of cumulative impacts with other planned OWFs is minimal.

5.4.4 The present day and recent historical PP hotspots and associated biological activities, such as zooplankton blooms and fish aggregations, are concentrated at the tidal front, which is and will continue to be created and controlled by natural processes and will be subject to natural variation in strength and timing, unaffected by the Proposed Development's influence.

5.5 What Impacts Could Change in Near-surface Wind Speeds Have on Water Column Mixing and Stratification?

5.5.1 Another potential influence on mixing is the change in near sea surface wind speeds due to the Proposed Development. This has been investigated by Christiansen *et al.* (2022). A detailed hydrodynamic model was set up to simulate the seasonal cycle of summer stratification in the southern North Sea, with multiple OWFs in operation. The simulations show the emergence of large-scale attenuation in the wind forcing and associated alterations in the local hydro- and thermodynamics. Induced changes in the vertical and lateral flow were found to be sufficiently strong to influence the residual currents and entail alterations of the temperature and salinity distribution in areas of wind farm operation. Ultimately, these were found to affect the stratification development in the southern North Sea. In the German Bight in particular, the reduction of mixing at OWFs was found to enhance or maintain stratification strength during the autumn breakdown phase of summer stratification.

5.5.2 However, whilst the modelling analyses of Christiansen *et al.* (2022) provide theoretical evidence for atmospheric OWF wakes to impact water column stratification, the findings are based on the presence of a very large number of OWFs (>50) in relatively close proximity with a large total number of Wind Turbines (>2,500) present within the theoretical scenario study area. In contrast, the Array Area is further offshore and is not part of such a large group of closely spaced OWFs and is itself much smaller (up to 67 Wind Turbines). Even when considering cumulative effects of the Proposed Development and neighbouring planned OWFs, together the number of Wind Turbines is considerably lower than those considered by Christiansen *et al.* (2022). Based on this, any associated wind wake effects are therefore only expected to have a very limited aggregated spatial footprint. The potential for widespread changes in the rate of surface mixing and associated water column stratification is therefore considered to be low.

5.5.3 Whilst Christiansen *et al.* (2022) provides some evidence on the effects of Wind Turbines on near surface wind speeds and water column mixing. It is noted that this work focused on a region of the North Sea that does not strongly seasonally stratify, so is not completely analogous to the location of the Array Area. Other literature and methodology focusing on this wind wake effect is limited. Therefore, the potential impact is associated with considerable uncertainty.

6 Summary

6.1.1 The assessment of potential changes to stratification and frontal systems caused by the Proposed Development indicates that the Bowdun OWF will have minimal impacts, with effects generally falling within the range of natural variability.

6.1.2 The baseline conditions show that the Array Area experiences only relatively weak stratification, with significant seasonal and inter-annual variability. Stratification typically peaks during mid-summer when warmer surface waters are separated from colder bottom waters by a thermocline (temperature gradient) and associated pycnocline (density gradient). The region to the east of the Array Area experiences relatively stronger and more persistent stratification, which supports higher levels of PP. In contrast, the Array Area itself is characterised by more transient stratification and lower levels of PP.

6.1.3 The installation of Wind Turbine structures (fixed jacket foundations) will generate additional turbulence alongside naturally occurring turbulence generated at the seabed by tidal currents and the surface by wind/wave action. The foundation induced TKE will enhance vertical mixing of the water column, acting to break down stratification. However, this mixing effect is expected to be spatially limited.

6.1.4 Mixing timescales for a range of stratification strengths observed in the Array Area have been calculated. The shortest estimated mixing timescale, associated with a year of weaker stratification (2015) is 20.1 days. A parcel of water within the Array Area is likely to experience enhanced turbulent mixing induced by the OWF structures for 13.9 days. Therefore, a parcel of water is not exposed to the elevated TKE from OWF structures for a sufficiently long time to completely break down the stratification present in the water column, even for more weakly stratified years such as 2015.

6.1.5 The calculated mixing timescales presented here are based on a conservative description of the Wind Turbine foundations, including all elements – scour protection and primary and secondary jacket member.

6.1.6 The Proposed Development is not expected to significantly influence the timing of seasonal stratification or the positioning of tidal mixing fronts. While additional mixing may theoretically delay the onset of stratification in spring or accelerate its breakdown in autumn, any changes would be subtle and fall within the bounds of natural variability. Similarly, shifts in frontal systems—regions where mixed and stratified waters meet—are expected to be highly localised.

6.1.7 Impacts on PP and the wider ecosystem are also expected to be minimal. The most productive area, located east of the Array Area within the more strongly stratified waters, is located outside the direct influence of the Array Area.

6.1.8 Finally, while changes in near-surface wind speeds due to the Proposed Development could theoretically influence water column mixing, the scale of these effects is expected to be small. Large-scale wind farms have been shown to reduce surface mixing and enhance stratification in some studies, but the comparatively small size of the Proposed Development makes widespread impacts unlikely. However, literature focusing on this wind wake effect is limited. Therefore, this potential impact is associated with some uncertainty.

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