Bellrock Offshore Wind Farm

Wind Farm Development Area

Environmental Impact Assessment Report - Volume IV

Appendix 6.1: Bellrock WFDA Stratification Baseline

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Shelf sea stratification, nutrient fluxes and primary production baseline for Bellrock Wind Farm Development Area

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Acronyms & Abbreviations

BODC	British Oceanographic Data Centre
GEBCO	General Bathymetric Chart of the Oceans
ICES	International Council for the Exploration of the Sea
LAT	Lowest Astronomical Tide
NSBC	North Sea Biogeochemical Climatology
SAMS	Scottish Association for Marine Science
SAMS Enterprise	SAMS Applied Marine Science Enterprise Ltd.
SCM	Subsurface Chlorophyll Maximum
TKE	Turbulent Kinetic Energy
WFDA	Wind Farm Development Area
WOD	World Ocean Database
WODC	World Ocean Data Centre

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1 INTRODUCTION

1.1 Project Background

1.1.1 Bellrock Offshore Wind Farm Limited (the Applicant) is developing the Bellrock Offshore Wind Farm (Bellrock Project) under the first ScotWind leasing round. The Bellrock Wind Farm Development Area (WFDA) is located 120 km east of Stonehaven (116 km southeast of Peterhead), Aberdeenshire, Scotland, and covers an area of 280 km^2.

1.1.2 Most offshore wind farms to date have been built in shallow (nearshore) and often unstratified (well-mixed) seas and tended to use fixed foundations. With the development of floating offshore wind technologies, the sector is moving into deeper waters and building larger floating turbine foundations within seasonally stratified shelf seas (see Dorrell et al. 2022). Stratified seas play a key role in primary production (the synthesis of organic compounds by primary producers). In the ocean, primary production is carried out primarily by photoautotrophs in the sunlit surface layer, and is linked to biogeochemical cycles. Introducing structures into these environments can artificially increase mixing of stratified waters leading to enhanced nutrient supply. In turn, this may have profound impacts on the marine ecosystem.

1.1.3 The purpose of this report is to provide baseline information on sea stratification, nutrient fluxes and primary production for the Bellrock WFDA.

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 (Fig. 1), 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, typically nearshore (Huthnance, 1991). The North Sea is generally deeper in the north, with the deepest area (exceeding 150 m) north of 57.5°N and between 0°E and 1.5°E.

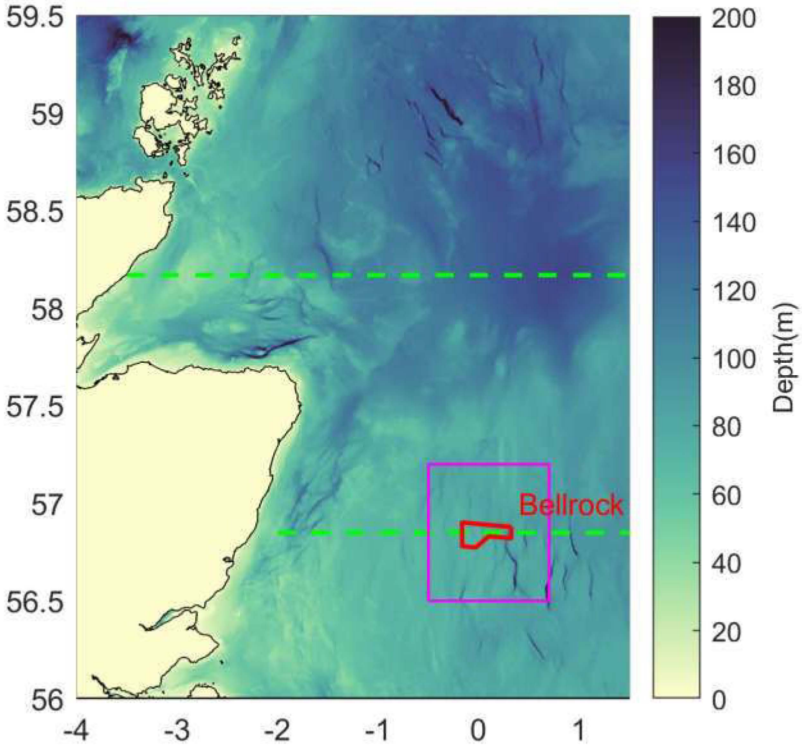

***Figure 1.** Bathymetry (General Bathymetric Chart of the Oceans, GEBCO) (depth in m) of the northern North Sea in relation to the Bellrock WFDA. The green east-west transects are discussed elsewhere.*

2.1.2 Bellrock WFDA is located in the central North Sea to the south of the deepest area, in water depths of 69 to 121 m below Lowest Astronomical Tide (LAT).

2.1.3 In winter, the North Sea is only stratified by salinity where coastal freshwater influence is significant (Huthnance, 1991). Elsewhere, water properties are uniform from the top to the bottom of the water column. Most of the northern North Sea is seasonally stratified, however, so solar heating in spring overcomes tidal stirring and the water column stratifies.

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 Fig. 2; Hill et al. 2008). More coastal or shallow 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 in the area east of Orkney and the outer Moray Firth, and then east into the central North Sea as the Dooley Current. Bellrock WFDA lies to the south of the Dooley Current, on the shallow side of this gradient, so it shows seasonality in bottom conditions.

Figure 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.*

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 International Council for the Exploration of the Sea (ICES)/ World Ocean Data Centre (WODC) climatology of surface and near-bed temperature and salinity (Berx and Hughes, 2009). These represents average values for the period 1971-2000 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 vertical profiles of temperature and salinity (next section).

2.2.3 At Bellrock WFDA (Fig. 3), surface and bottom temperatures are lowest in March. Stratification (surface to bed difference) is first significant in May. Surface temperature and stratification peak in August, when the top to bottom temperature difference exceeds 6°C, before falling rapidly until there is no longer significant stratification in November.

(a) (b)

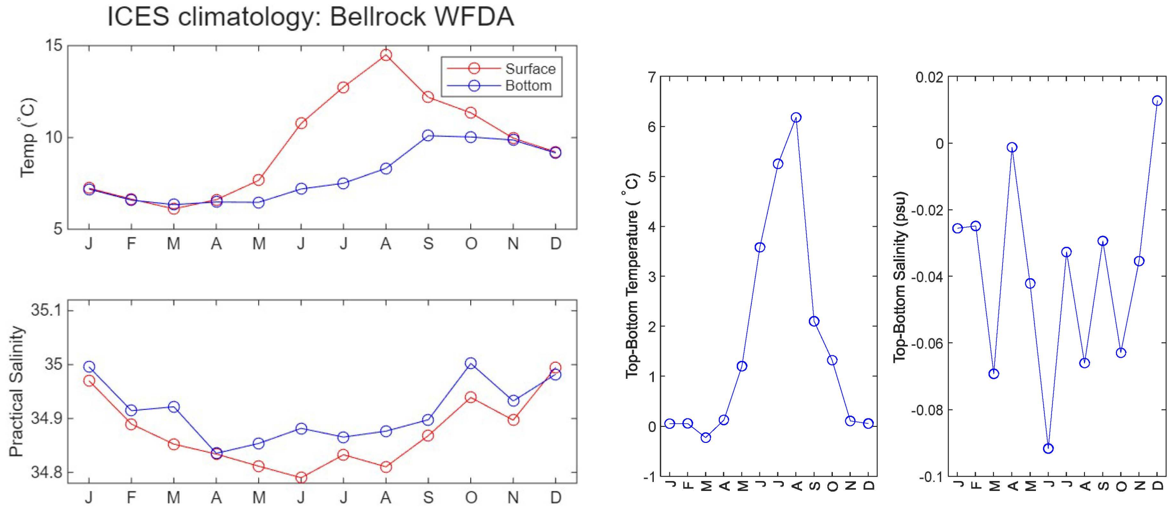

Figure 3. *(a) Monthly ICES climatological values for surface (red) and bottom (blue) temperature and salinity at Bellrock WFDA. (b) Monthly top to bottom difference in ICES climatological temperature and salinity at Bellrock WFDA.*

2.2.4 West-east transects through the Bellrock WFDA at varying times of year (Fig. 4) show a horizontal gradient of water properties from coastal waters in the west that are more weakly stratified in summer, to those that are more strongly stratified in the central North Sea.

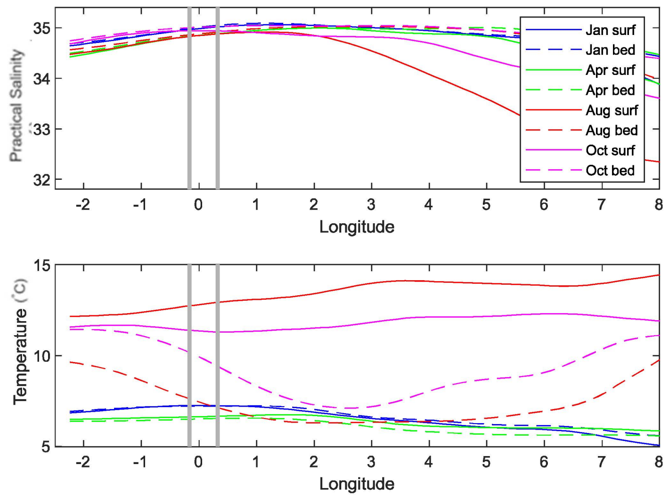

Figure 4. *West-east transects of surface and bed temperature and salinity at the latitude of Bellrock WFDA (56.85°N), from ICES climatology. The longitude range of the Bellrock WFDA is indicated by the vertical grey bars.*

2.3 Historical water column profiles

2.3.1 Directly measured vertical profiles of temperature and salinity have been accessed via the British Oceanographic Data Centre (BODC) (British Oceanographic Data Centre, n.d.) and the World Ocean Database (WOD) (National Centers for Environmental Information, n.d.). These provide good coverage of the region and an indication of the variability expected in conditions at the time of measurement.

2.3.2 Profiles were aggregated within a box-shaped region containing the Bellrock WFDA (Fig. 2). The box contained 574 historical profiles reflecting acceptable year-round coverage.

2.3.3 Stratification was first assessed by taking the difference between the surface and bottom density in each profile (Fig. 5). This measure was directly compared with the ICES climatological values.

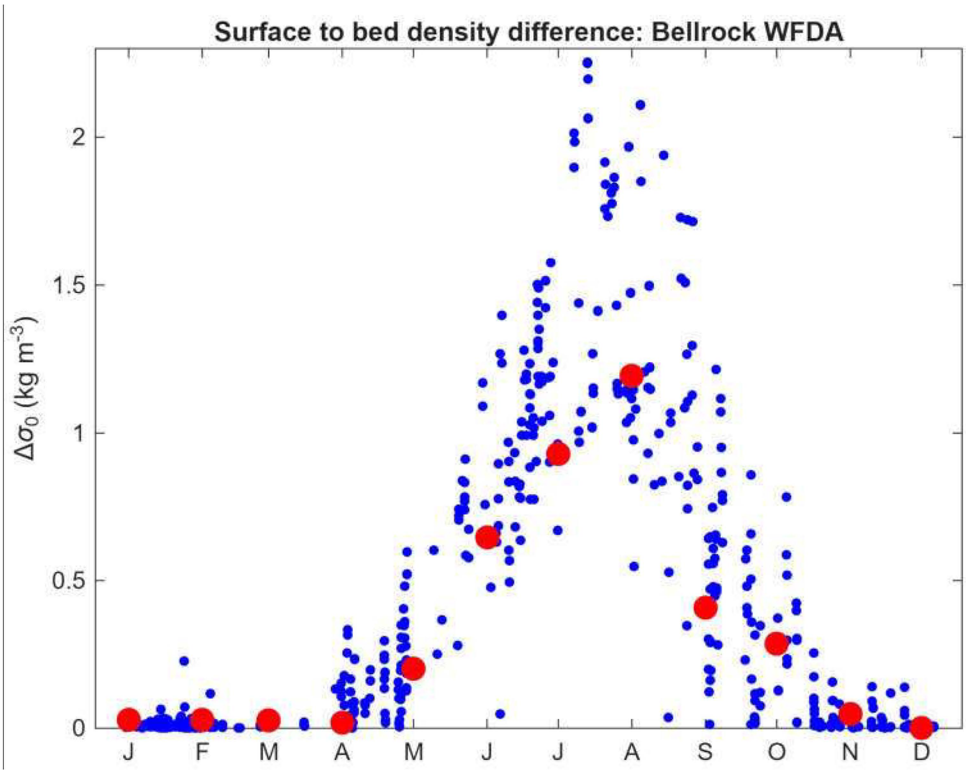

Figure 5. *The annual cycle of stratification at the Bellrock WFDA expressed as the difference in potential density between the surface and the bed. Each dot (blue) shows a single measured profile obtained from BODC or WOD. ICES climatological values are shown as larger discs (red).*

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

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

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). This has been calculated over the available profile depth (Fig. 6) and 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.

2.3.5 The potential energy anomaly has also been calculated using the observed salinity profile but a depth-mean for the temperature. This salinity-only anomaly is shown red in Fig. 6 and separates the salinity influence on stratification from the temperature influence. The salinity contribution to Ø is generally small compared to the temperature contribution.

2.3.6 The depth of the thermocline has also been estimated from actual profiles (Fig. 7). The simple method used was to identify the maximum and minimum temperatures in a profile, average them, then look 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.

2.3.7 At the Bellrock WFDA, 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 10-40 m range (Fig. 7). From August to November, the depth of the thermocline increases, approaching the seabed as winter mixed conditions develop.

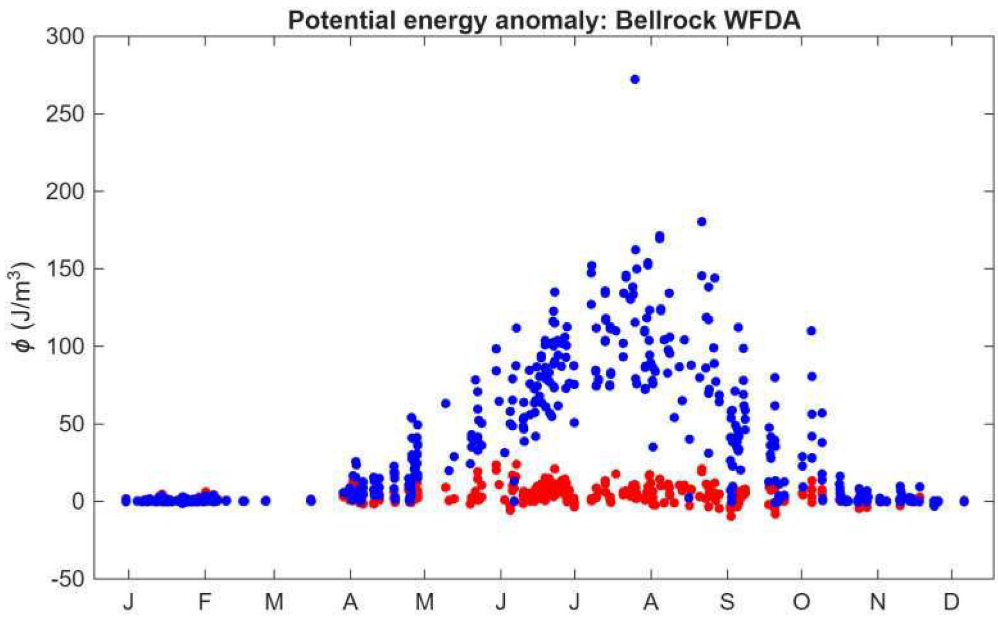

Figure 6. *The annual cycle of the potential energy anomaly (∅) of stratification in the box containing the Bellrock WFDA. Each blue dot represents ∅ for a single measured profile obtained from BODC or WOD. Red dots show the contribution of salinity stratification to ∅.*

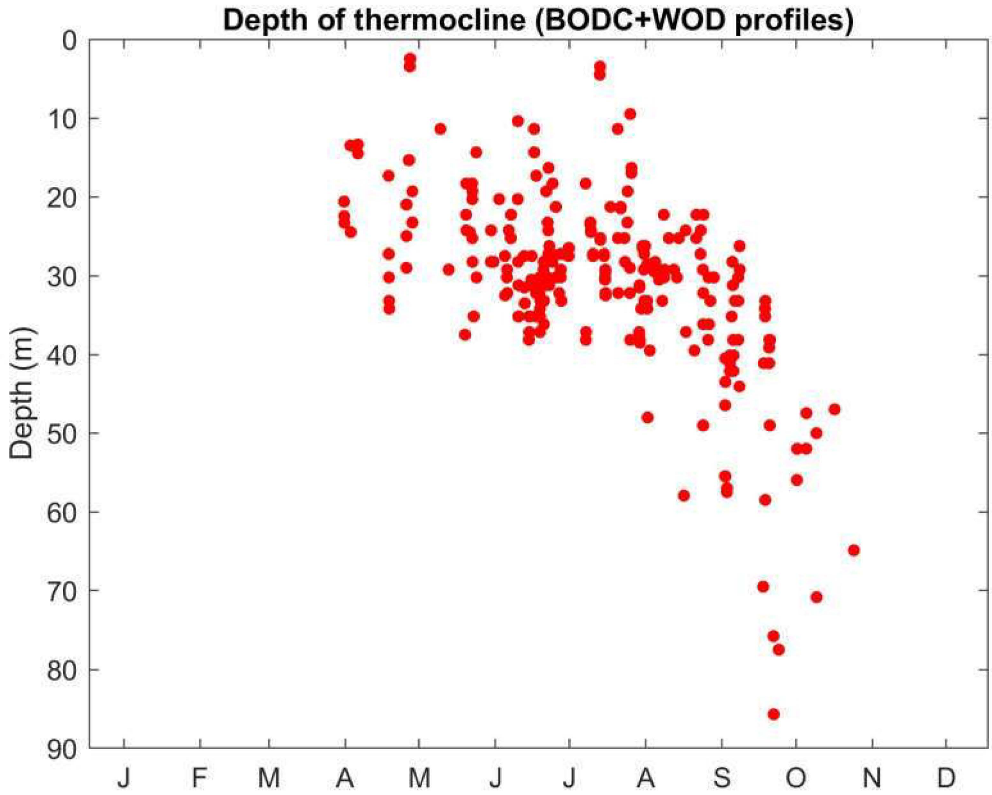

Figure 7. *Depth of the thermocline at varying times of year from historical vertical profiles in the vicinity of the Bellrock WFDA. The thermocline depth has been estimated as the depth of the mid-point of the profile temperature range, with a threshold gradient used to eliminate well-mixed or only weakly stratified cases.*

3 NUTRIENT BIOGEOCHEMISTRY AND PRIMARY PRODUCTION

3.1 Methods

3.1.1 To investigate the biogeochemistry of the study region, nutrient (nitrate, ammonium, phosphate, silicate), chlorophyll and oxygen data were extracted from the North Sea Biogeochemical Climatology (NSBC) (Hinrichs et al. 2017). The climatology contains 3D fields of monthly and annually averaged biogeochemical parameters on a 0.25° x 0.25 grid. The dataset has only sparse coverage of the NW North Sea, close to the Bellrock WFDA which has limited some of the conclusions drawn in this section.

3.2 Nutrient and chlorophyll profiles at Bellrock WFDA

3.2.1 In winter the water column at all sites is well-mixed and there is a relatively even vertical distribution of chemical tracers (nutrients, oxygen). When the water column is well-mixed, any enhancement in TKE will result in no change to the vertical distribution of nutrients.

3.2.2 In summer months, surface waters become thermally stratified from the higher nutrient waters below. Surface maps (5 m) of the region show concentrations of 0-1 mmol m^{-3} at Bellrock WFDA (Fig. 8). In depth profiles where surface temperature is lower (and therefore there is weaker stratification), there is a higher concentration of nitrate and higher chlorophyll-a concentrations (a proxy for primary production) in the surface layer (Fig. 9).

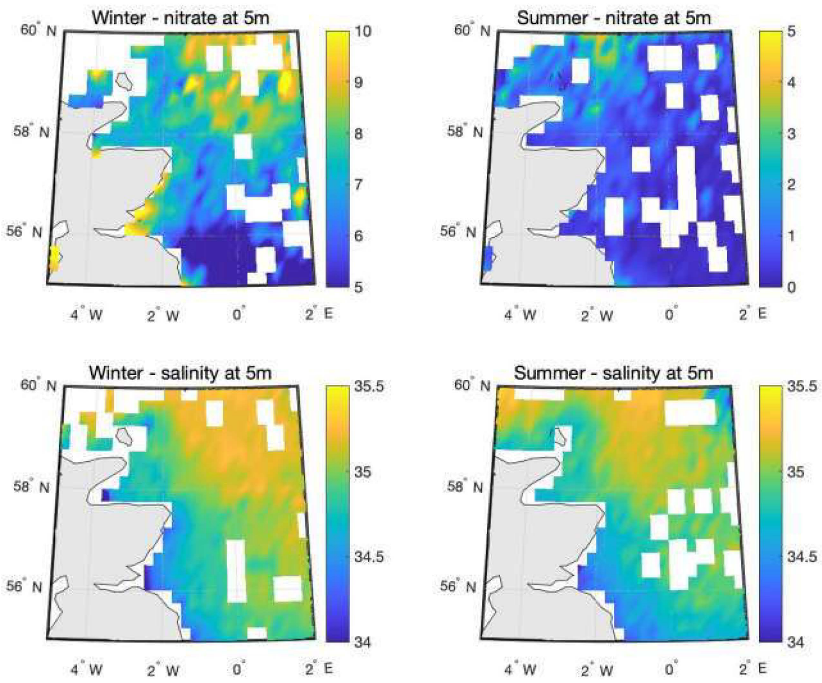

Figure 8. *Surface maps (5m) of nitrate, in mmol m^{-3}, (upper panel) and salinity (lower panel) in winter (left) and summer (right).*

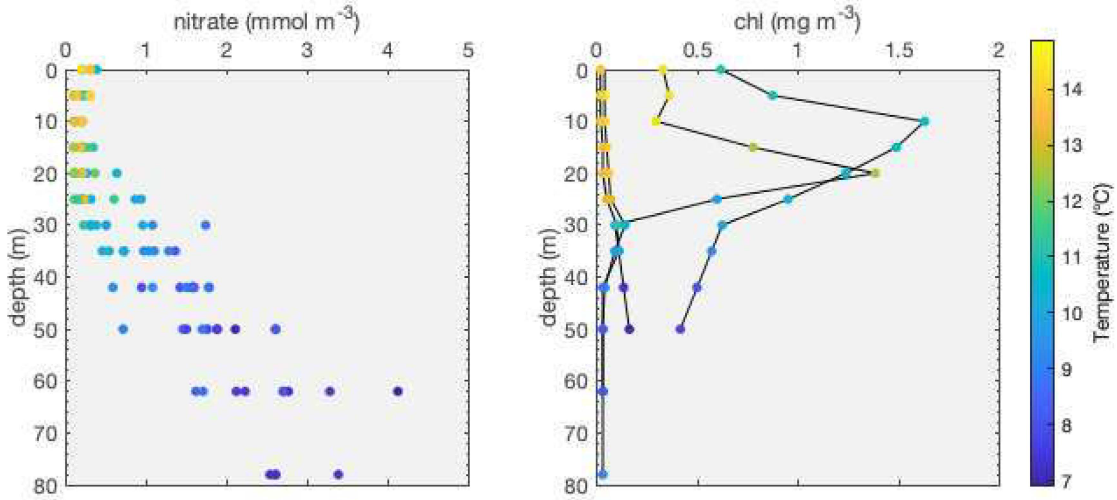

Figure 9. *(a) Nitrate and (b) chlorophyll profiles at Bellrock WFDA in July with temperature shown in colour.*

3.2.3 The temperature difference between surface and bottom waters increases during summer months (section 2.2.3), which separates nutrient rich deep waters from the surface where nutrients are consumed by phytoplankton. Nitrate concentrations are drawn down to near zero concentrations in surface waters when temperatures increase (Fig 9a). These low nitrate surface waters are typical for the upper 20m for summer months (Fig 10).

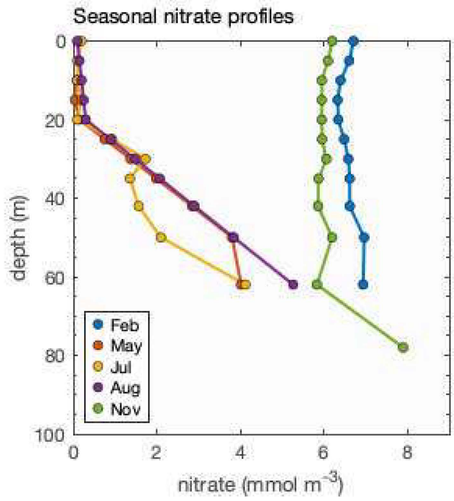

Figure 10. *Seasonal nitrate profiles at the Bellrock WFDA for February, May, July, August and November.*

3.2.4 The Bellrock WFDA develops an SCM in summer months where surface waters are thermally stratified and nutrient availability is likely limiting primary production in the upper 20 m (demonstrated by low chlorophyll concentrations, Fig 9b).

4 CONCLUSIONS

4.1 Characteristics of the site

4.1.1 This report has looked at the physical conditions (stratification and currents) and nutrient dynamics of the Bellrock WFDA.

4.1.2 Characteristics of the Bellrock WFDA are:

- Winter conditions are unstratified.
- Stratification develops seasonally (spring-autumn) and is largely thermal.
- Surface waters become nutrient-depleted in summer so increased mixing and fluxes across the thermocline would directly supply nutrients which drive increased production.
- There is relatively little background flow, so the influence of enhanced mixing would be retained more locally than if there was significant background flow. This also means that the net effect on the local water column would be greater than if the impact was exported to adjoining waters.

4.1.3 Extensive historical water column profiles and climatologies are available for the area around the Bellrock WFDA so there is a high level of confidence in our understanding of the seasonal evolution of the water column.

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