Bellrock Offshore Wind Farm

Wind Farm Development Area

Environmental Impact Assessment Report - Volume IV

Appendix 6.2: Stratification Analysis Report

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Term	Definition
Bellrock Offshore Wind Farm (or the Bellrock Project)	An offshore wind farm capable of exporting up to 1.8 GW of renewable energy to the National Electricity Transmission System. The Wind Farm Development Area is located 120 km east of Stonehaven, and will connect to the National Electricity Transmission System at the proposed SSEN Transmission Hurlie substation, west of Stonehaven in Aberdeenshire. The Bellrock Offshore Wind Farm comprises of the following Development Areas: ▪ Wind Farm Development Area; ▪ Offshore Transmission Development Area; and ▪ Onshore Transmission Development Area.
Floating offshore unit	The combined wind turbine generator and floating substructure.
Floating substructure	A floating structure which provides buoyancy and, in conjunction with the station keeping system, supports a superstructure (e.g. wind turbine generator or offshore substation), and maintaining its position within the structure's excursion limit
Potential Energy Anomaly	Is a measure of the strength of stratification. PEA is the amount of work required to fully mix the water column. For a fully mixed (homogenous) water column, PEA is zero; while it becomes increasingly positive as stratification increases.
Wind Farm Development Area	The boundary within which the Wind Farm Infrastructure will be constructed, operated and maintained, and decommissioned.
Wind Farm Infrastructure	Infrastructure located within the Wind Farm Development Area including wind turbine generators; floating substructures, station keeping systems and associated scour protection; inter-array cables and associated cable protection; subsea cable hubs; and ancillary infrastructure including buoys (including activities associated with the Wind Farm Infrastructure construction, operation and maintenance, and decommissioning).
Wind turbine generator	A wind turbine generator converts wind energy into electrical energy. The main components include rotor assembly (composed of three blades and a hub); nacelle (containing the generator, shaft and gearbox, power electronic converter and transformer); and a tower (containing lifting equipment and switchgear).

Glossary of Abbreviations

Term	Definition
EIA	Environmental Impact Assessment Report
FOU	Floating offshore unit
FSS	Floating substructure
OWF	Offshore Wind Farm
PEA	Potential Energy Anomaly
SSM	Scottish Shelf Model
SST	Sea surface temperature
SSW-RS	Scottish Shelf Waters Reanalysis Service
WFDA	Wind Farm Development Area
WTG	Wind turbine generator

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1 Introduction

1. This Bellrock Stratification Analysis Report is an **Appendix** to **Chapter 6: Marine Geology, Oceanography and Physical Processes (Volume II)** of the Bellrock Wind Farm Development Area (WFDA) Environmental Impact Assessment (EIA) Report.

2. Ocean stratification refers to the natural vertical layering of seawater based on seawater density differences, primarily driven by variations in seawater temperature and salinity. This vertical structure regulates global climate and marine health, as it governs the exchange of heat, carbon, and nutrients between water surface and deeper depths. Until recently, offshore wind farms (OWF) were built in shallow waters where stratification is typically absent and these OWFs used fixed bottom foundations such as monopiles or jackets.

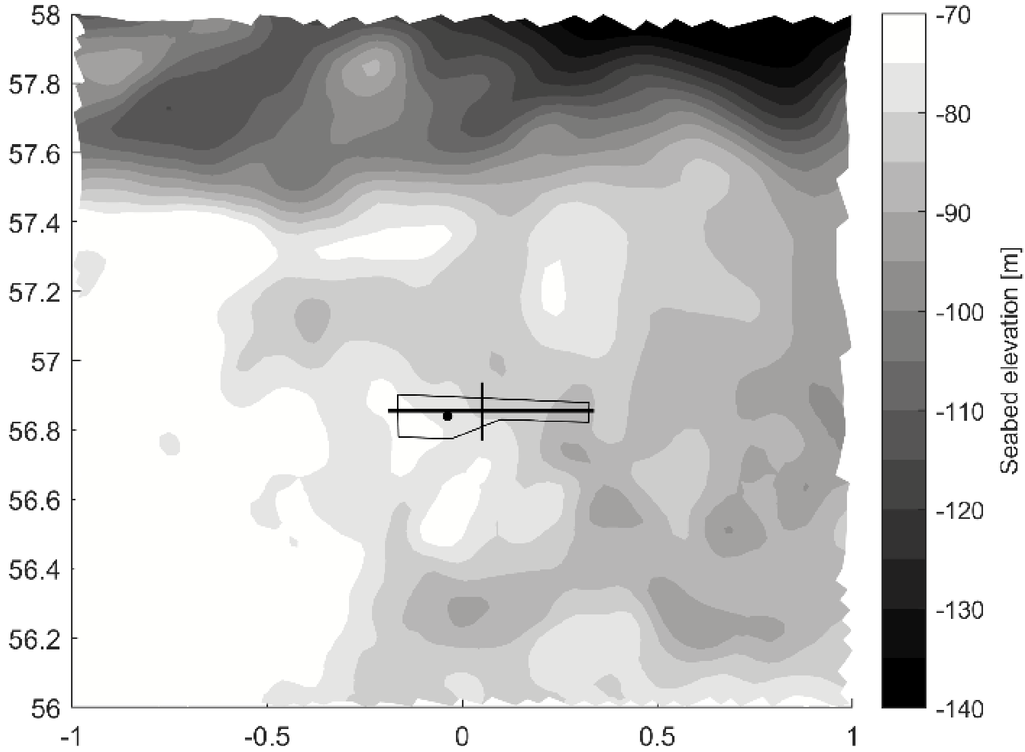
3. With the development of floating offshore wind technologies, OWF projects are being developed in deeper waters within seasonally stratified shelf seas (see Dorrell et al. 2022). However, the introduction of OWFs within seasonally stratified seas has the potential to change water column structure. As tidal currents and oceanic flows interact with the floating substructure (FSS) of the wind turbine generator (WTG), the FSSs generate turbulent wakes that can enhance vertical mixing. A reduction in wind speed at the sea surface due to the presence of the FSSs and associated WTGs has the potential to reduce mixing. Assessing the impact of OWF structures is essential to determine if localised turbulence significantly alters the water column structure, which could, in turn, influence primary productivity, regional biodiversity, and the long-term stability of shelf sea ecosystems.

4. To gain an understanding of the extent and timing of water column stratification, monthly mean sea surface and sea bottom temperature and salinity values, averaged across the Bellrock WFDA, are compared. To assess how sea surface temperature and salinity vary spatially throughout the year, both are plotted in relation to the Bellrock WFDA. Also plotted are vertical profiles showing the difference in both temperature and salinity between the bottom and sea surface layers at Point P (as shown in **Plate 1.1**), again averaged for each month.

5. This allows for a detailed assessment of the structure and strength of water column stratification throughout the year. To assess how stratification varies spatially across the Bellrock WFDA at different points in the year, monthly difference plots of surface to bottom temperature and salinity were analysed and variations in the structure of stratification across the Bellrock WFDA was identified using longitudinal and latitudinal transects.

6. Finally, salinity and temperature data were used to calculate the Potential Energy Anomaly (PEA), which is then used to assess the stratification strength inside the Bellrock WFDA.

Plate 1.1: Seabed Elevation at Bellrock WFDA (Dot Represents Point P for Punctual Analysis. Horizontal and Vertical Lines Represent the Longitudinal and Latitudinal Transects



2 Data and Information Sources

7. The temperature and salinity data used for this analysis were obtained from the Scottish Shelf Waters Reanalysis Service (SSW-RS) (Barton et al. 2022), which gives a reanalysis of the 1993 to 2019 Scottish Shelf Model (SSM) outputs. The SSM covers most UK waters, including the area of Scottish Shelf where the WFDA is located.

8. The model operates on an unstructured mesh in latitude longitude plane, with higher resolution at the coast and lower resolution further offshore. Hereafter data are reported in latitude-longitude coordinates. The resolution at the Bellrock WFDA is approximately 2 km. Since the water depth at the Bellrock WFDA does not exceed 120 m (**Plate 1.1**), the model has 20 vertical layers (sigma layers). For depths of 70 – 90 m, this gives a vertical resolution ranging between 3.5 – 4.5 m. For this analysis daily mean outputs of temperature and salinity have been used.

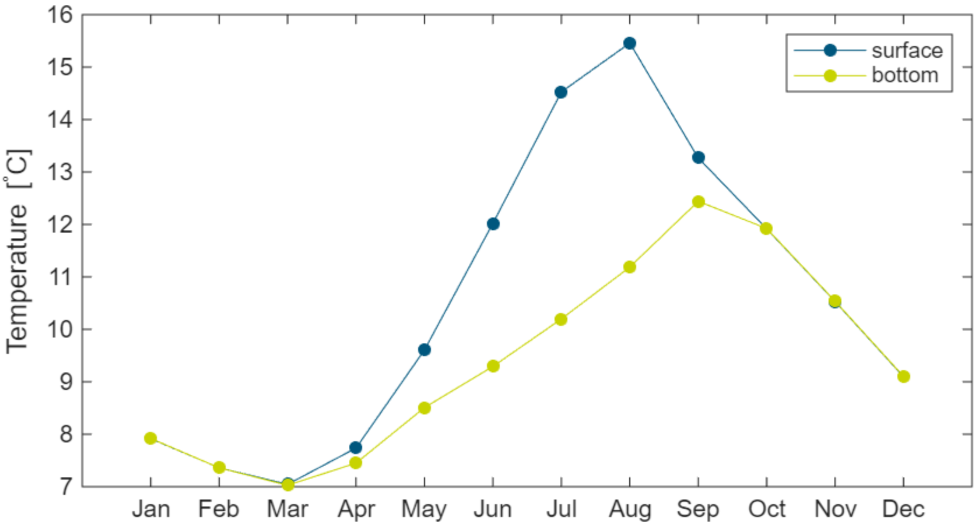
9. Further offshore the SSM is forced by the Copernicus Marine Environment Monitoring Service products: Atlantic – European North West Shelf – Ocean Physics Reanalysis and Baltic Sea Physics Reanalysis. Atmospheric forcing derives from European Centre for Medium-Range Weather Forecasts ERA 5 data. Data assimilation is conducted with ODYSSEA L3 sea surface temperature (SST) data.

3 Baseline Characterisation

3.1 Temperature

10. **Plate 3.1** shows the monthly averaged temperature at the surface and bottom of the water column within the Bellrock WFDA for 2019. Both water surface and bottom temperature increase during the summer period (June to August). However, due to more direct exposure to insolation, the water surface reaches peaks of 16 °C, while the bottom of the water column reaches peaks of 12 °C. Such a difference between peak temperature at the surface and bottom of the water column suggests stratification may occur during summer. The outputs show there is no difference between surface and bottom of the water column temperature from October through to March, suggesting the water column is mixed during these months.

Plate 3.1: Monthly Averaged and Spatially Averaged Temperature at Water Surface and at Bottom of the Water Column



11. **Plate 3.2** shows the monthly average surface temperature in 2019. Between January and May, the surface temperature across the Bellrock WFDA is constant, while from June to September the surface temperature southeast of the Bellrock WFDA is warmer than in the northwest, causing a temperature gradient in the water surface which may indicate the position of an ocean front.

12. **Plate 3.3** shows the difference between the monthly surface temperature and bottom of the water column temperature at Point P (see **Plate 1.1**).

13. The outputs shows that the thermocline starts to form in May between the water surface and depths of approximately 20 m, with a temperature difference of -1 °C, (i.e. the water surface is warmer than the deeper waters). A fully developed thermocline at depths between 10 m to 20 m is evident during the months of June to August, where the temperature difference reaches -4 °C. In September, the thermocline weakens with temperature difference of -1 °C between depths of 20 m

to 30 m. No vertical change in temperature is evident at Point P during the months of October to December indicating it is well mixed.

14. To investigate further the water column structure within the Bellrock WFDA, **Plate 3.4** shows the monthly averaged spatial distribution of the temperature difference between surface and bottom waters for 2019. Although the outputs do not provide information on the depths of the thermocline, it identifies the periods and the locations within the Bellrock WFDA where thermal stratification happens. In **Plate 3.4** values between ±0.25 °C have been blanked out, meaning that within this range of values, temperature can be considered constant.

15. From October to March the plate shows no difference between surface and bottom water temperature within the Bellrock WFDA. In April, weak stratification starts to develop in the eastern part of the Bellrock WFDA, where the bottom temperature is 0.5 °C colder than the surface water. From May to August the outputs show steadily increasing thermocline development with the temperature difference between surface and bottom waters reaching peaks of -5 °C. The thermocline starts to weaken in September with surface to bottom water temperature differences within the Bellrock WFDA spatially changing between -2 °C and -0.5 °C.

16. Vertical profiles of monthly averaged water temperature were extracted along the transects in **Plate 1.1** to investigate the thermal stratification within the Bellrock WFDA. **Plate 3.5** shows vertical profiles of monthly averaged temperature for 2019 along the latitudinal. From January to March no thermocline is noticeable along the transect. In March the thermocline starts to build up everywhere along the transect. In April, **Plate 3.5** clearly shows a layer of warmer waters near the surface (depthless than 20 m) and a slightly colder layer at depths below 30 m, creating a thermocline between 20 m and 30 m water depth. As the water surface temperature gets warmer the thermocline is more evident between the upper part and the lower part of the water column.

17. From June to August the thermocline remains at water depths between 10 m and 30 m everywhere along the transect, with larger temperature differences in the eastern part than on the western part of the transect (see **Plate 3.5**). Vertical stratification is strongest in July and August when the temperature changes by 3.5 °C between 10 m and 20 m depth. Then in September the water surface cools and the thermocline is limited to depths between 20 m to 30 m. On the western part of the transect the thermocline is absent, while on the eastern part of the transect the temperature difference between water surface and rest of the water column is 2 °C. No thermocline is evident from October onwards despite the change in water temperature along the transect.

18. **Plate 3.6** shows the vertical profiles of monthly averaged temperature along the longitudinal transect. Similar considerations to those for the latitudinal transect (**Plate 3.6**) can be made for the longitudinal transect. Of interest, from June to September the water temperature below roughly 20 m depth is more consistent along the longitudinal transect than along the latitudinal transect, this is possibly due to the deeper water at the eastern end of the latitudinal transect being less affected by increased surface temperatures. Another possibility is that the longitudinal transect is too short to pick up the larger scale variation in temperature in the water column.

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Plate 3.2: Monthly Averaged Surface Temperature at Bellrock

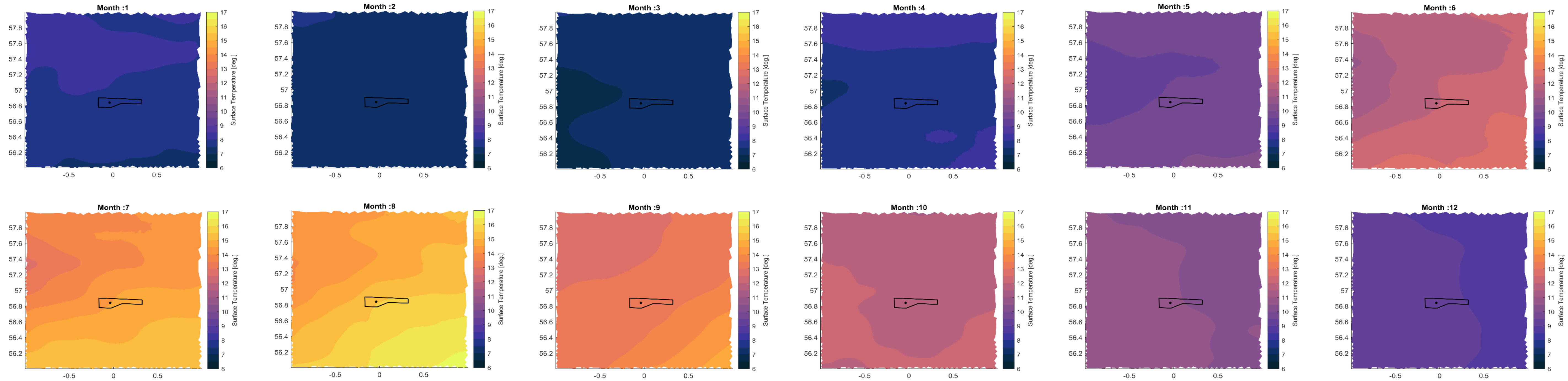


Plate 3.3: Temperature Difference Between Monthly Averaged Surface and Bottom of Water Column at Point P (Negative Values Mean Colder Bottom Water Column than Surface, and Positive Values Vice Versa)

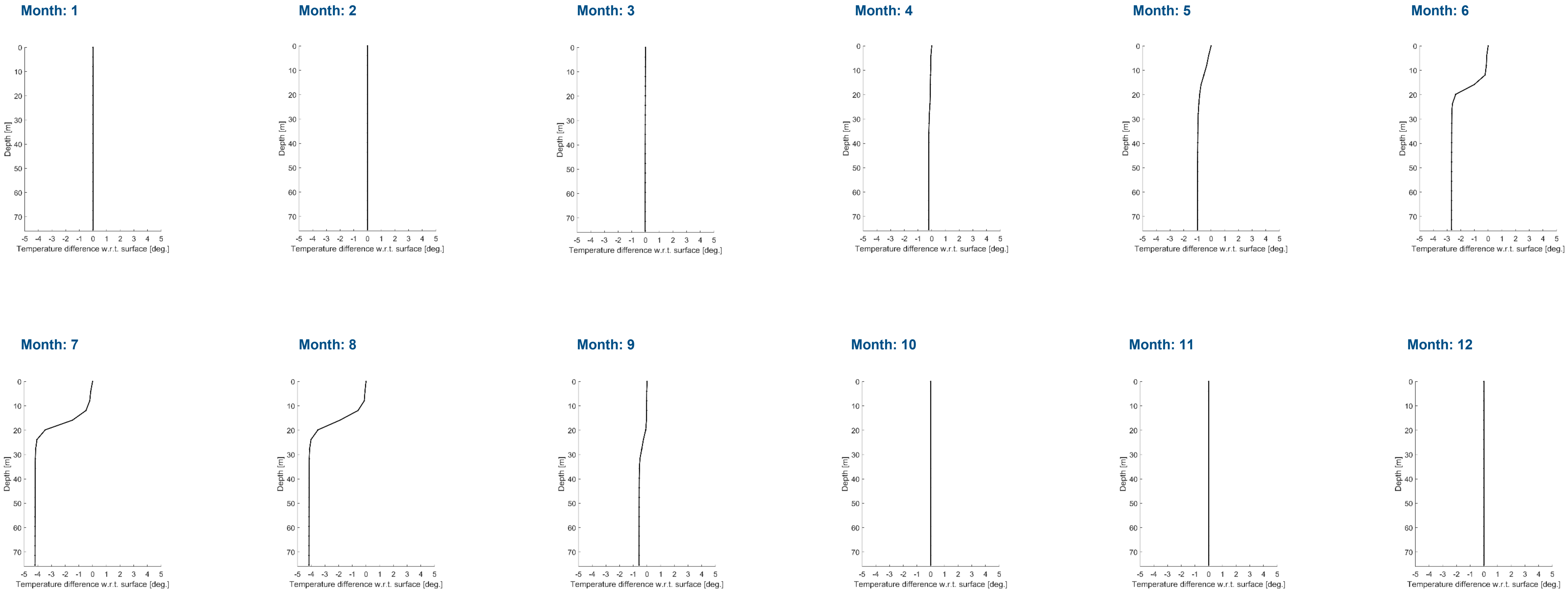


Plate 3.4: Temperature Difference Between Surface and Seabed (Negative Values Mean Seabed Colder than Surface and Positive Values Vice Versa)

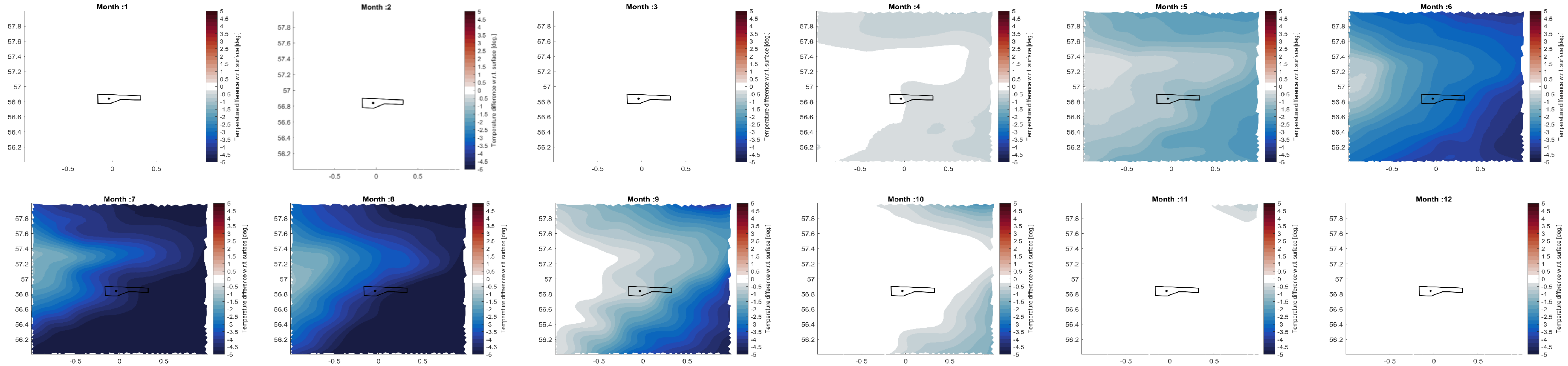


Plate 3.5: Monthly Averaged Vertical Profile of Temperature Along Latitudinal (East – West) Transect

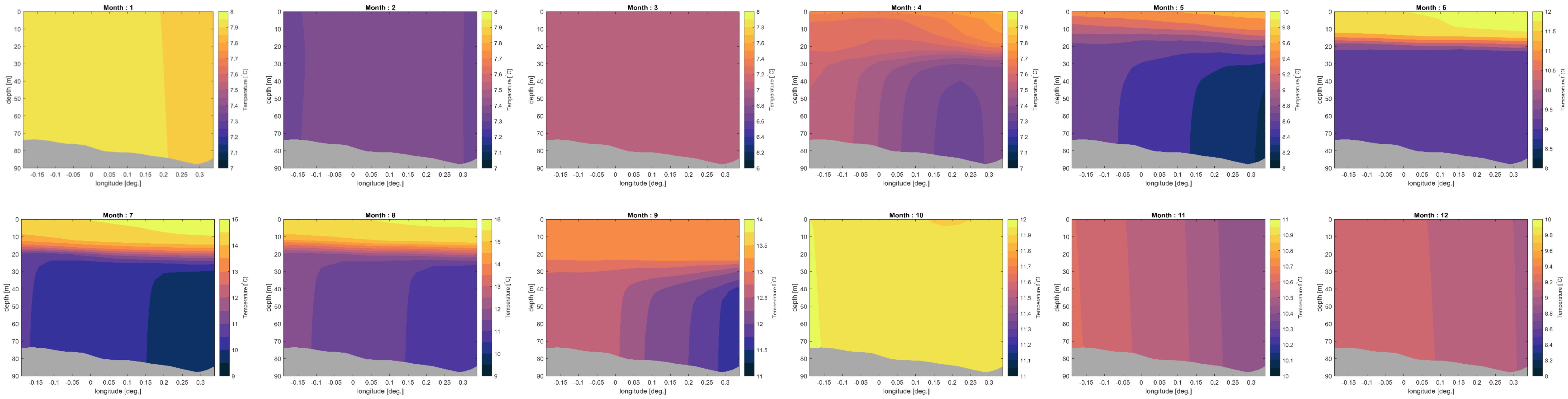
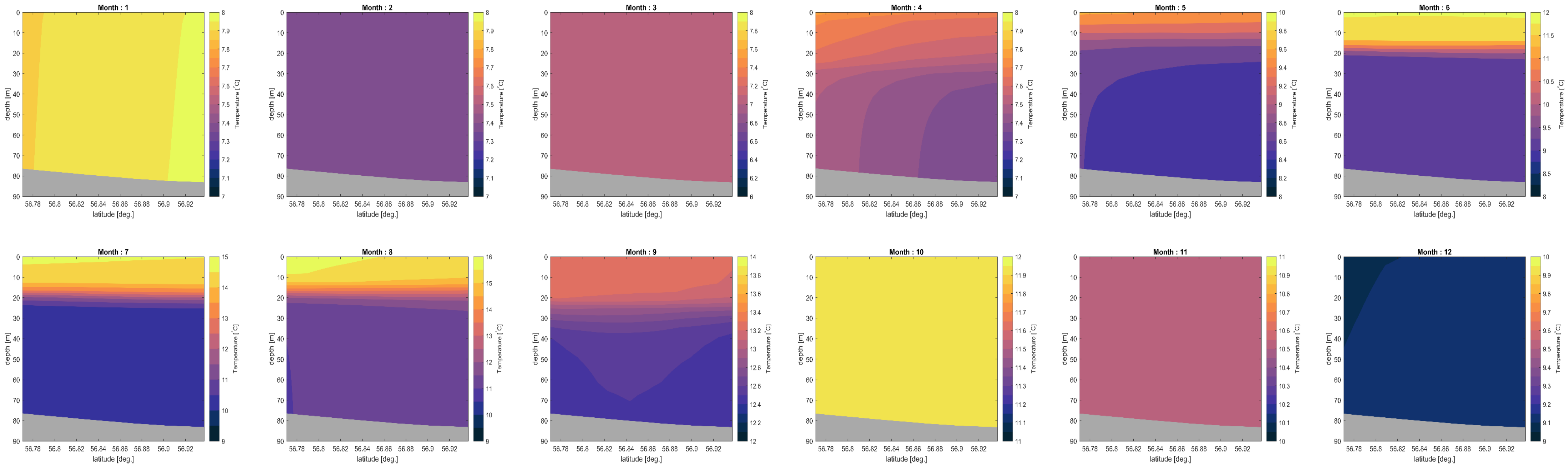


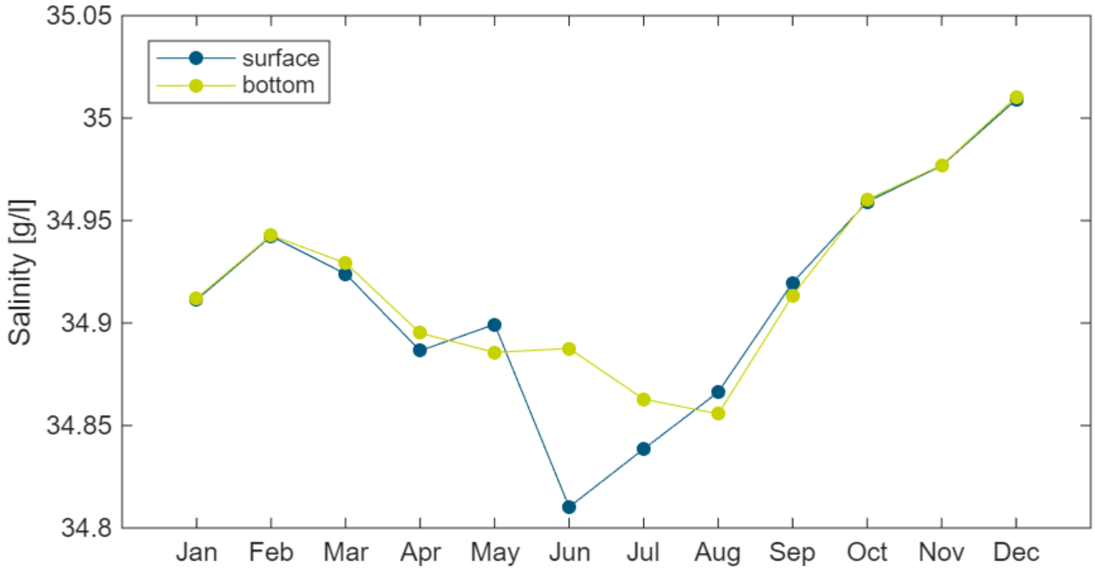
Plate 3.6: Monthly Averaged Vertical Profile of Temperature Along Longitudinal (North – South) Transect



3.2 Salinity

19. Salinity concentration in open ocean waters normally ranges between 33 PSU to 35 PSU. Given the narrow range of salinity concentrations discussed within the Bellrock WFDA, intervals have been defined to define the strength of the halocline. Salinity differences between the top and bottom of the water column that exceed 0.5 g/l (~0.5 PSU) are considered to define areas with strong halocline. Values between 0.1 g/l to 0.5 g/l define areas with moderate halocline, and values below 0.05 g/l define areas with a weak/absent halocline. **Plate 3.7** shows the monthly averaged surface and bottom salinity concentration within the Bellrock WFDA for 2019. Both water surface and bottom experience a decrease in salinity during summer periods. Although the difference in surface and bottom salinity is the largest in June, this is only 0.1 g/l suggesting that a medium strength halocline develops during summer months.

Plate 3.7: Monthly Averaged and Spatially Averaged Salinity at Water Surface and at Bottom of the Water Column



20. **Plate 3.8** shows monthly averaged surface salinity concentration during 2019 within the Bellrock WFDA. While a spatial distribution of salinity concentration is noticeable throughout the year, the salinity values do not fall below 34 g/l. Throughout the year, salinity concentrations around the Bellrock WFDA region range between 34 g/l to 36 g/l, with higher concentrations on the eastern side of the WFDA than on the western side. **Plate 3.9** shows vertical profiles of salinity concentration difference within the water column at point P (**see Plate 1.1**). From January to April the halocline is absent throughout the water column. In April a weak halocline starts to build up at depths between 10 m and 20 m and fully develops by May when the concentration at the bottom of the water column becomes 0.05 g/l higher than those at surface. During July and August the halocline strength decreases but interestingly a veneer of higher concentration remains at 15 m below surface. No halocline is noticeable from September onwards.

21. To investigate further the water column structure within the Bellrock WFDA, **Plate 3.10** shows the monthly averaged spatial distribution of the salinity concentration difference between the surface and bottom of the water column for 2019. Although the outputs do not provide information on the depths of the halocline, they identify the periods and the locations inside the WFDA where stratification occurs. The outputs show that from April to September waters around the WFDA are at higher concentration (+0.05 g/l) than at the bottom of the water column, whilst the rest of the WFDA does not experience such a change. In May the surface waters in the eastern part of the WFDA are at lower concentrations (-0.05 g/l) than the bottom of the water column. In June, a halocline develops across the entire WFDA, of which the strength varies from moderate to weak from west to east.

22. The surface waters in the eastern part of the WFDA experience a moderate halocline with a surface water salinity concentration 0.125 g/l higher than the salinity at the bottom of the water column. This halocline gradually decreases in strength from east to west, with surface water on the western side of the array at a slightly higher concentration (0.05 g/l) than the bottom waters. **Plate 3.10** shows that in July the eastern part of the WFDA experiences no difference in salinity though the water column and only a small difference persists in the western part of the WFDA. However, **Plate 3.9** shows that possibly a veneer of high salinity concentration remains along the water column which is not captured by analysis of only surface and bottom layers of the water column. In August and September the surface waters in the eastern part of the WFDA have a slightly lower concentration (0.05 g/l) than at the bottom of the water column and from October onwards, the water column surface and bottom waters within the WFDA do not experience differences in salinity concentration.

23. Vertical profiles of monthly averaged salinity concentration from 2019 were extracted along the transects in **Plate 1.1** to investigate the stratification inside the WFDA. **Plate 3.11** shows vertical profiles of monthly averaged salinity concentration along the longitudinal transect. The plate shows that between January and March the salinity concentration of the water column along the transect remains constant. From April to May the plate shows the buildup of the halocline, which reaches its maximum strength in June. During September and October the outputs clearly show the veneer of higher salinity concentration between 10 m and 20 m which disappears after November. Salinity concentration is the lowest during the months of November and December.

24. **Plate 3.12** shows vertical profiles of monthly averaged salinity concentration along the latitudinal transect. Along this transect the salinity concentration is much more constant than along the longitudinal transect. During July and August it is possible to notice the veneer at higher concentration between 10 m and 20 m.

Plate 3.8: Monthly Averaged Surface Salinity at Bellrock WFDA

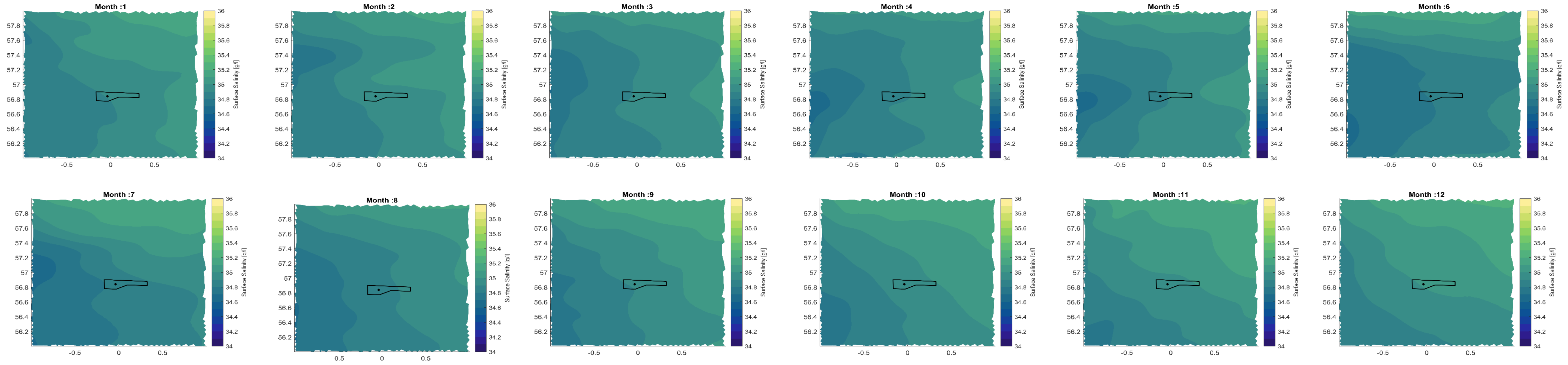


Plate 3.9: Salinity Difference Between Monthly Averaged Surface and Bottom of Water Column at Point P (Negative Values Mean Higher Concentration at Bottom Water Column than Surface, and Positive Values Vice Versa)

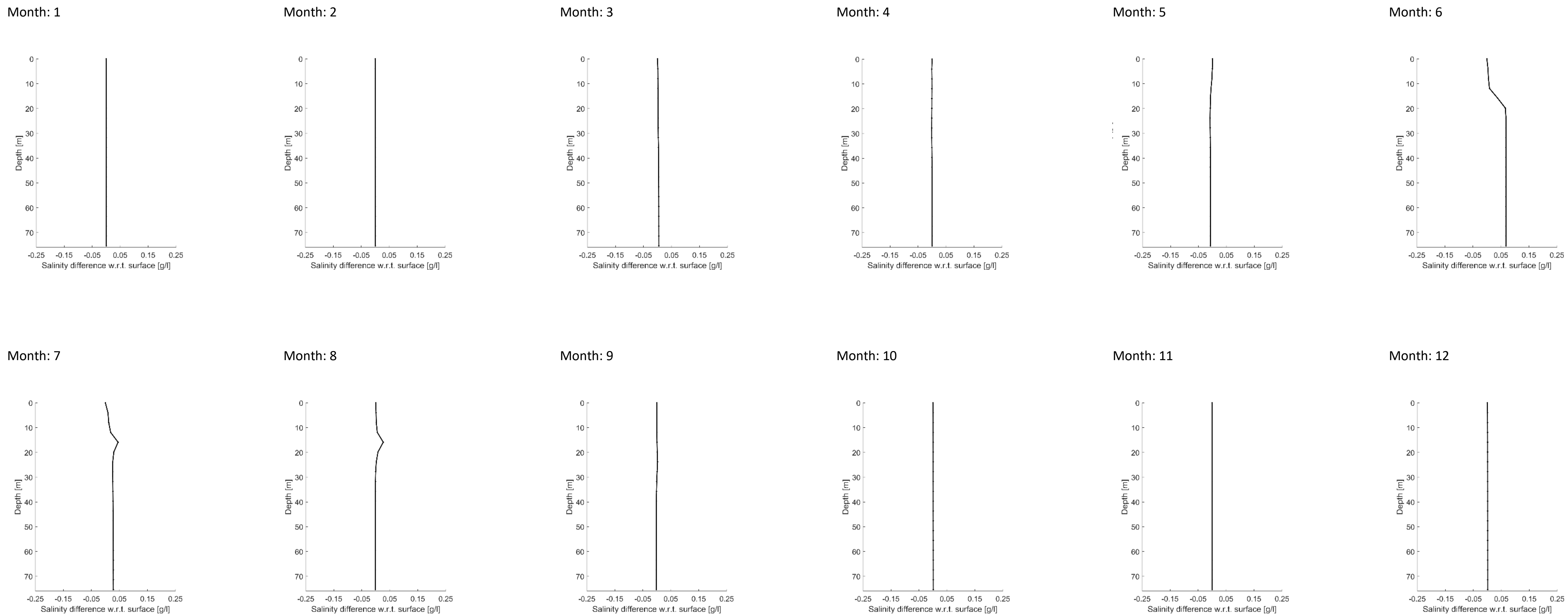


Plate 3.10: Monthly Averaged Vertica Profile of Salinity Concentration Along Longitudinal Transect

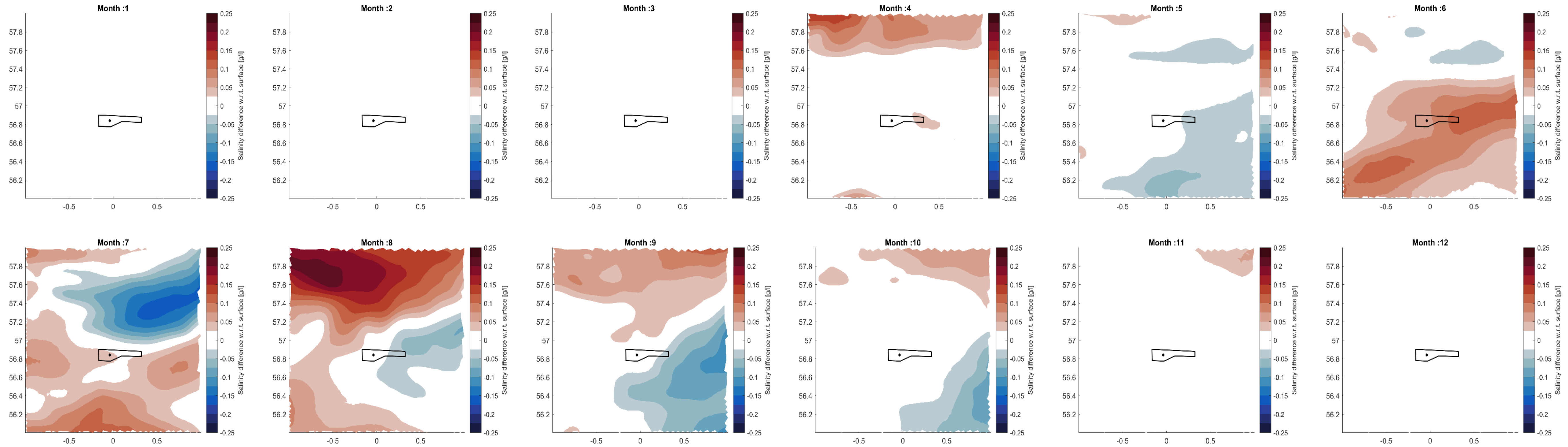


Plate 3.11: Salinity Difference Between Surface and Seabed (Negative Values Mean Higher Concentration at Seabed than Surface and Positive Values Vice Versa)

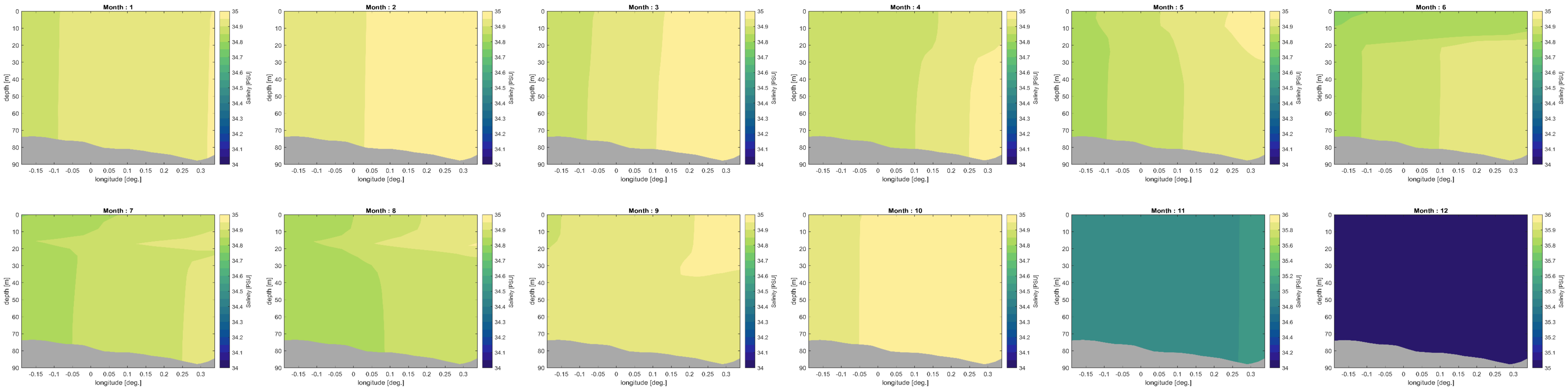
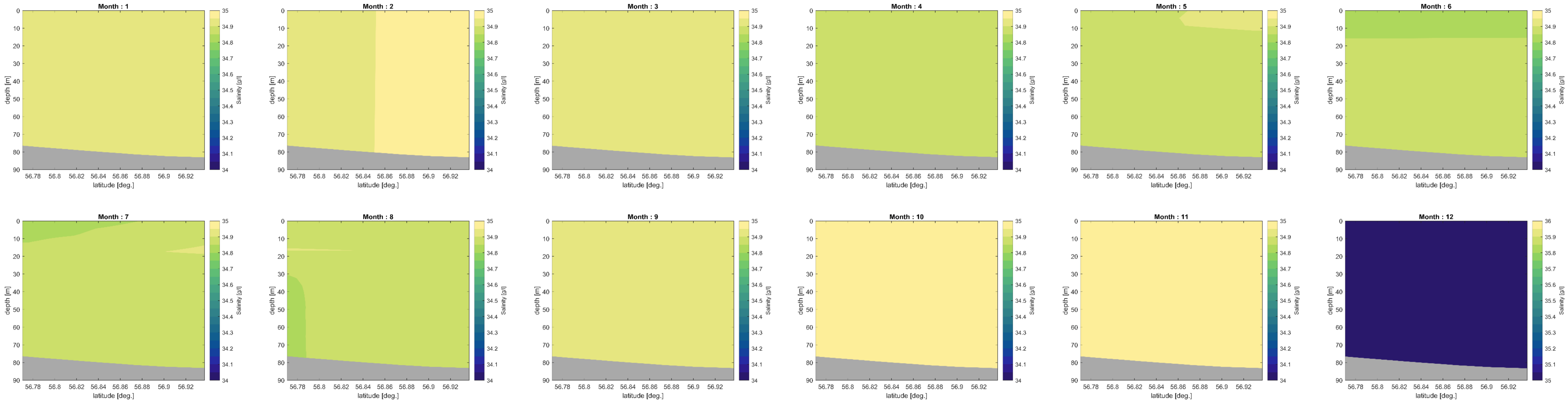


Plate 3.12: Monthly Averaged Vertical Profile of Salinity Concentration Along Latitudinal Transect



3.3 Potential Energy Anomaly

25. Seawater density is fundamentally a function of its equation of state, where density (ρ) increases as temperature (T) decreases and salinity (S) increases. In a typical stratified environment, solar heating at the surface creates a warm, buoyant upper layer, while colder, saltier - and thus denser - water occupies the depths. This vertical density gradient establishes the gravitational potential energy distribution of the water column. To disrupt this state and mix the layers, external work must be performed. This is often quantified by the PEA (ϕ), which represents the mechanical energy per unit volume (in Joules per cubic metre, J/m³) required to fully mix the water column. In the context of offshore wind energy, submerged structures act as a source of this mechanical energy, converting kinetic energy from tides and currents into turbulence that "lifts" the denser bottom water, thereby increasing the total potential energy of the system and weakening the stratification.

26. To assess if the floating offshore unit (FOUs) can change water column structure, within the WFDA, instantaneous vertical profiles of water temperature and salinity were used to calculate instantaneous vertical profiles of water density. These density profiles were used to determine the stratification strength of the water column through the PEA which is calculated as:

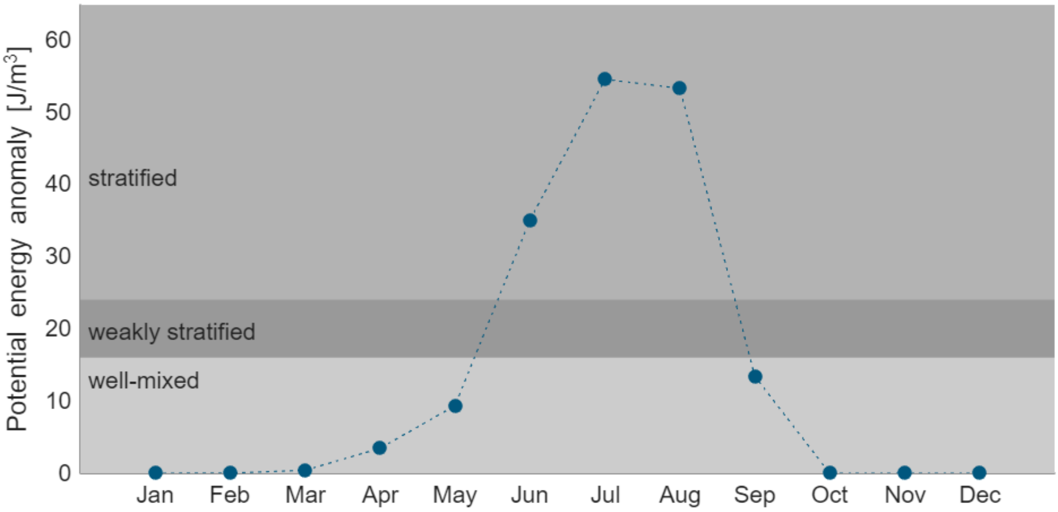
$$\phi(t) = \frac{1}{H}\int_0^H (\rho(z,t) - \rho_0) g z \, \mathrm{d}z$$

where ϕ is the PEA, g is gravity, ρ is the instantaneous density profile, ρ_0 is the well-mixed density profile, z is the vertical elevation, and H is the water depth.

27. A PEA of zero indicates a fully mixed column, while positive values indicate varying degrees of stratification. Following the Scottish Government Guidance, a PEA value of 20 J/m³ or higher suggests significant stratification, which can impact nutrient availability and oxygen levels in aquatic environments (Scottish Government, 2020).

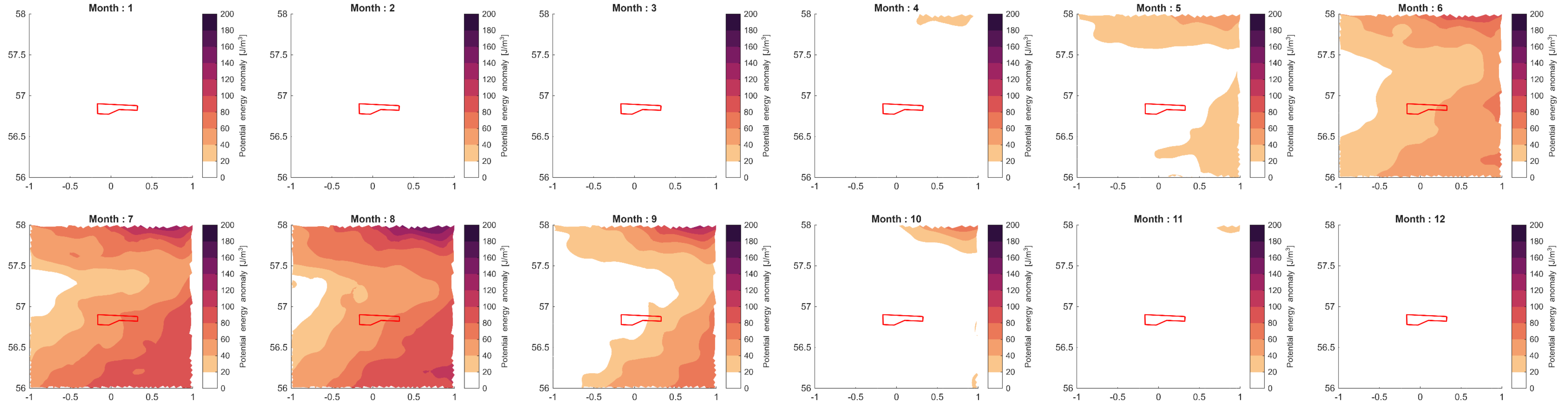
28. **Plate 3.13** shows the monthly averaged PEA inside the Bellrock WFDA. A ±20% band around the 20 J/m³ threshold was used to define: a weakly stratified water column when 16 J/m³ $< \phi <$ 24 J/m³, a stratified water column when $\phi \geq$ 24 J/m³, and well mixed water column when $\phi \leq$ 16 J/m³. The plate shows that during summer months (June, July, August) a strong stratification develops inside the Bellrock WFDA.

Plate 3.13: Monthly and Spatially Averaged Potential Energy Anomaly Inside the Bellrock WFDA



29. **Plate 3.14** shows the PEA spatial distribution around the Bellrock WFDA. Location of mixed water column (PEA<20 J/m^3) have been blanked. Stratification starts developing in May in the east of the Bellrock WFDA. In June a weak stratification develops within most of the Bellrock WFDA with slightly larger PEA values in the east. In July and August the stratification is the strongest and comprises most of the Bellrock WFDA. After August stratification starts to weaken meaning that the water column becomes well mixed. However, due to the persistently higher PEA values on the east, the water column in the Bellrock WFDA becomes fully mixed by October.

Plate 3.14: Monthly Averaged Potential Energy Anomaly Maps



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4 Conclusion

30. Temperature and salinity data from the SSW-RS (Barton et al. 2022) were used to analyse the vertical structure of temperature and salinity, and to calculate the PEA within the WFDA.

31. Analysis of the temperature data reveal that thermic stratification within the Bellrock WFDA occurs during summer months due to insolation. The thermocline develops due to warmer surface waters compared to rest of the water column. Vertical profiles of water temperature in the longitudinal and latitudinal direction show that the thermocline develops between April and September at depths between 10 m and 20 m. The thermocline is strongest during July and August when the difference in surface and bottom temperature is 5 °C.

32. Analysis of salinity concentration in the water column reveal weak stratification within the Bellrock WFDA. The halocline is always stronger to the east of the WFDA when compared to the west. The maximum difference between surface concentration and the bottom of the water column is 0.125 g/l (moderate halocline). This largest value occurs only during June, while during the rest of the year the halocline is weak (differences less than 0.05 g/l). Vertical profiles of salinity concentration along a longitudinal and latitudinal transect reveal that the halocline develops at depths between 15 m to 20 m. During July and August the vertical profiles reveal a veneer of high concentration water around 15 m to 25 m below surface.

33. Instantaneous vertical profiles of water temperature and salinity were used to calculate instantaneous vertical profiles of water density. These were used to calculate the PEA, which represents the energy required to break the stratification and fully mix the water column. Analysis of the PEA shows that the Bellrock WFDA is strongly stratified (PEA> 24 J/m^3) during June, July, and August, while it is well mixed during the rest of the year (PEA< 16 J/m^3). Spatial variation of PEA shows that stratification is stronger on the east side of the Bellrock WFDA.

5 References

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