REPORT

Appendix 7.2 Marine Physical Environment Stratification Analysis

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GLOSSARY OF ACRONYMS

Acronym	Definition
MD-SEDD	Marine Directorate – Science Evidence Data and Digital
p	Density
PEA	Potential Energy Anomaly
PSU	Practical Salinity Unit
T	Temperature
SSM	Scottish Shelf Model
SST	Sea Surface Temperature
SSW-RS	Scottish Shelf Waters Reanalysis Service
S	Salinity
WDA	Windfarm Development Area
WTG	Wind turbine generator

1 Introduction

1. Ocean stratification refers to the natural vertical layering of seawater based on density differences, primarily driven by variations in 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.

2. Until recently, offshore windfarms were built in shallow waters where stratification is typically absent and these windfarms used fixed foundations such as monopiles. With changing offshore wind technologies, the sector is moving into deeper waters and building larger wind turbine generator (WTG) foundations within seasonally stratified shelf seas (see Dorrell et al. 2022). The introduction of offshore windfarms within seasonally stratified seas has the potential to change water column structure. As tidal currents and oceanic flows interact with WTG foundations, they generate turbulent wakes that can enhance vertical mixing. A reduction in wind speed at the sea surface due to the presence of the WTGs also has the potential to reduce mixing. Assessing the impact of offshore windfarm 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.

3. To understand how best to assess the impact of offshore windfarm structures on stratification and mixing within the MachairWind Windfarm Development Area (WDA) a focused meeting was held with an expert marine renewables oceanographer from Marine Directorate – Science Evidence Data and Digital (MD-SEDD) on 02 December 2025. This meeting involved discussion around the key topics to be assessed, including how to best simulate the water column structure, how best to show the mobile and spatially varied nature of changes to the water column structure and how to represent these changes against an appropriate timescale. Additionally, the expert from MD-SEDD highlighted the ongoing lack of research associated with understanding the impact of offshore windfarms on mixing and stratification within the water column.[1] This consultation provided the basis for the aims of this technical report.

4. The aims of this technical report are to characterise the baseline timing and strength of stratification and establish tidal mixing front dynamics within the WDA. This analysis supports **Chapter 7 Marine Physical Environment** of the MachairWind WDA Environmental Impact Assessment Report.

2 Methodology

2.1 Data and Information sources

5. The temperature and salinity data used for this analysis was obtained from the Scottish Shelf Waters Reanalysis Service (SSW-RS) (Barton et al., 2022), which gives a reanalysis of the 1993-2019 Scottish Shelf Model (SSM) output. The SSM covers most UK waters, including the area of Scottish Shelf where the WDA is located. The model operates on an unstructured mesh, with higher resolution at the coast and lower resolution at the open ocean boundary. The resolution at the WDA is approximately 2 km. Since water depth within the WDA does not exceed 120 m

[1] It is noted that the Physics-to-Ecosystem Level Assessment of Impacts of Offshore Wind Farms (PELAgIO) project is a UK-based, interdisciplinary research initiative within the ECOWind programme which is looking into the potential effects of offshore wind on stratification.

(**Plate 2.1**), the model has 20 terrain following sigma (depth) layers, each occupying 5% of the water column. For depths of 30-80 m, this gives a vertical resolution ranging between 1.5 to 4 m.

6. For this analysis daily mean outputs of temperature and salinity have been used. At its open boundaries 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.

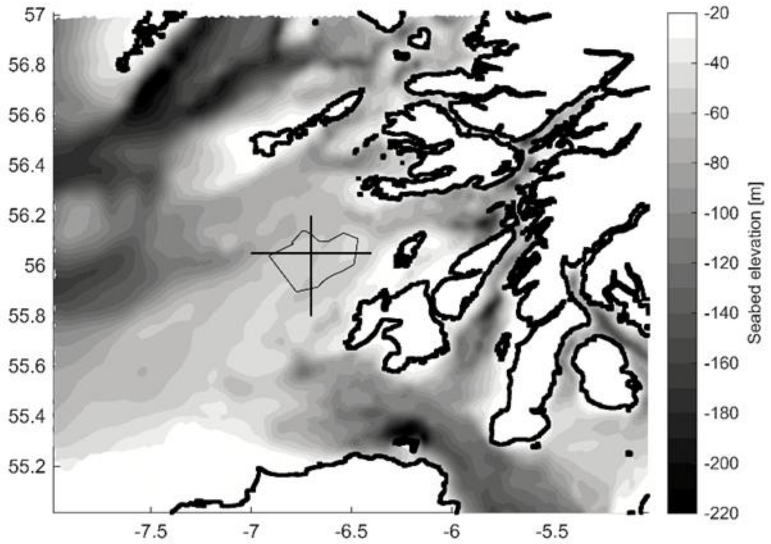

Plate 2.1 Seabed elevation at Machair windfarm array. Horizontal and vertical lines represent the longitudinal and latitudinal transects

7. **Plate 2.1** shows the seabed bathymetry around the WDA and the location of the longitudinal and latitudinal transects used to analyse the spatial distribution of temperature and salinity within the water column.

3 Baseline Characterisation

8. To investigate vertical structure of the water column at the WDA, sea temperature and salinity were analysed. Monthly averaged punctual and spatial profiles of temperature and salinity were investigated to assess how stratification varies spatially and temporally during a representative year (i.e., 2019) across the WDA. The representative year was chosen based on the analysis carried out by ABPMer (2025).

3.1 Temperature

9. **Plate 3.1** shows the monthly averaged sea surface and bottom temperature within the WDA for the year of 2019. Both the water surface and bottom experience an increase in temperature during summer periods. The temperatures are identical from September to March. Both reach peak temperature of 14.5°C in September and minimum temperature of 8.2°C in March. However, the surface temperature increases more rapidly in the summer due to increased sun exposure (i.e., insolation). This difference in temperature from April to August suggests thermal stratification exists during this period, and during other months there is vertical mixing.

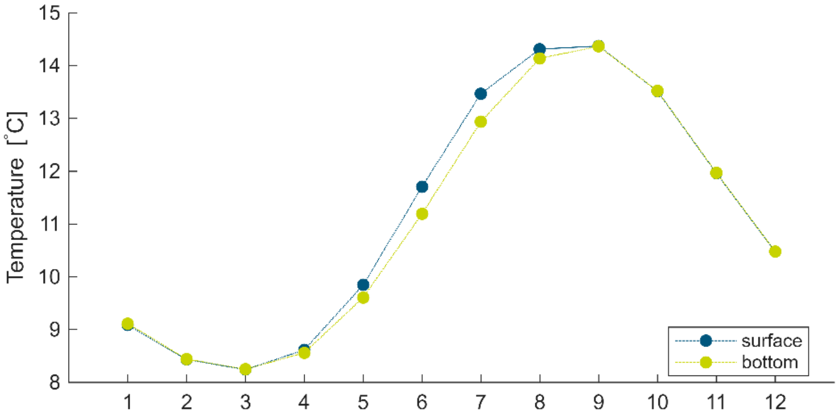

Plate 3.1 Monthly averaged and spatially averaged temperature at water surface and at bottom of the water column

10. Monthly averaged sea surface temperatures in 2019 are given in **Plate 3.2**. Within the WDA, warm surface water approaches from the southwest between April and September. From October to March colder surface water progresses from the northeast through the WDA.

11. Vertical profiles showing the monthly averaged temperature difference between the sea surface and bottom at centre Point P (see **Plate 3.2**) are given in **Plate 3.3**. The data show that a weak thermocline forms in May between the water surface and depths of approximately 20 m, with temperature difference of approximately -0.5 °C, (i.e., water surface is warmer than the deeper waters). By July, the thermocline is fully developed between the surface and 25 m, where the temperature difference reaches -0.6°C. This is still a relatively weak thermocline compared to open ocean conditions on the west of the WDA. In August, the thermocline weakens with temperature difference of -0.25°C between depths of 0m to 15m. No vertical change in temperature is evident at point P during the months of September to March.

12. To further investigate the stratification effects within the WDA, **Plate 3.4** shows the monthly averaged spatial distribution of the temperature difference between surface and bottom waters for the year 2019. Although the figure does not provide information on the depths of the thermocline, it identifies the periods and the locations inside the WDA where stratification occurs. In **Plate 3.4**, differences of ±0.125 °C are blanked as they are too small to indicate stratification and the water column is considered to be well-mixed. From September to April there is no difference between surface and bottom temperature within the WDA. In May weak stratification starts to develop from the north, where the bottom temperature is approximately 0.25°C colder than the surface water. In June and July stratification in the WDA is strongest with a surface to bottom temperature difference of -0.75°C. This is a relatively small temperature difference compared to strongly stratified open ocean conditions. The strongest temperature difference is in the north of the WDA, becoming weaker in the south (-0.125°C difference). In August, the stratification weakens in the south.

13. Vertical profiles of monthly averaged water temperature were extracted along the transects in **Plate 2.1** to determine the longitudinal variation of thermal stratification within the WDA. **Plate 3.5** shows vertical profiles of monthly average temperature along the longitudinal transect. From September to April, no vertical stratification is noticeable along the longitudinal transect. In May, the water at approximately 20 m depth is slightly warmer (0.25°C) than that at greater depth, creating two layers along the length of the transect. **Plate 3.5** indicates that in June there is a stronger temperature gradient of 0.75°C between the surface and 20 m depth. This temperature

gradient is strongest in the east, whereas in the west the warmer water penetrates deeper. In July weak stratification persists in the east but there is a greater degree of homogeneity around -6.9° and -6.7° longitude (within the WDA). The thermal stratification weakens in August, with surface and bottom temperatures both at 14.5°C in the WDA.

14. **Plate 3.6** shows the vertical profiles of monthly averaged temperature along the latitudinal transect. As with the longitudinal transect (**Plate 3.5**), no thermal stratification is present between September and April, as expected. In May, a layer of warmer water develops in the north of the WDA, in the south of the WDA the water column remains homogenous. In June, the strength of the stratification is increased, with a temperature drop between the water surface and 20 m depths from 12°C to 11°C. In the south, no stratification is present. In July, the stratification is still limited to the north only, where there is a temperature difference between surface and bottom waters of 1°C. South of the WDA no stratification is present. In August, no stratification is present within WDA.

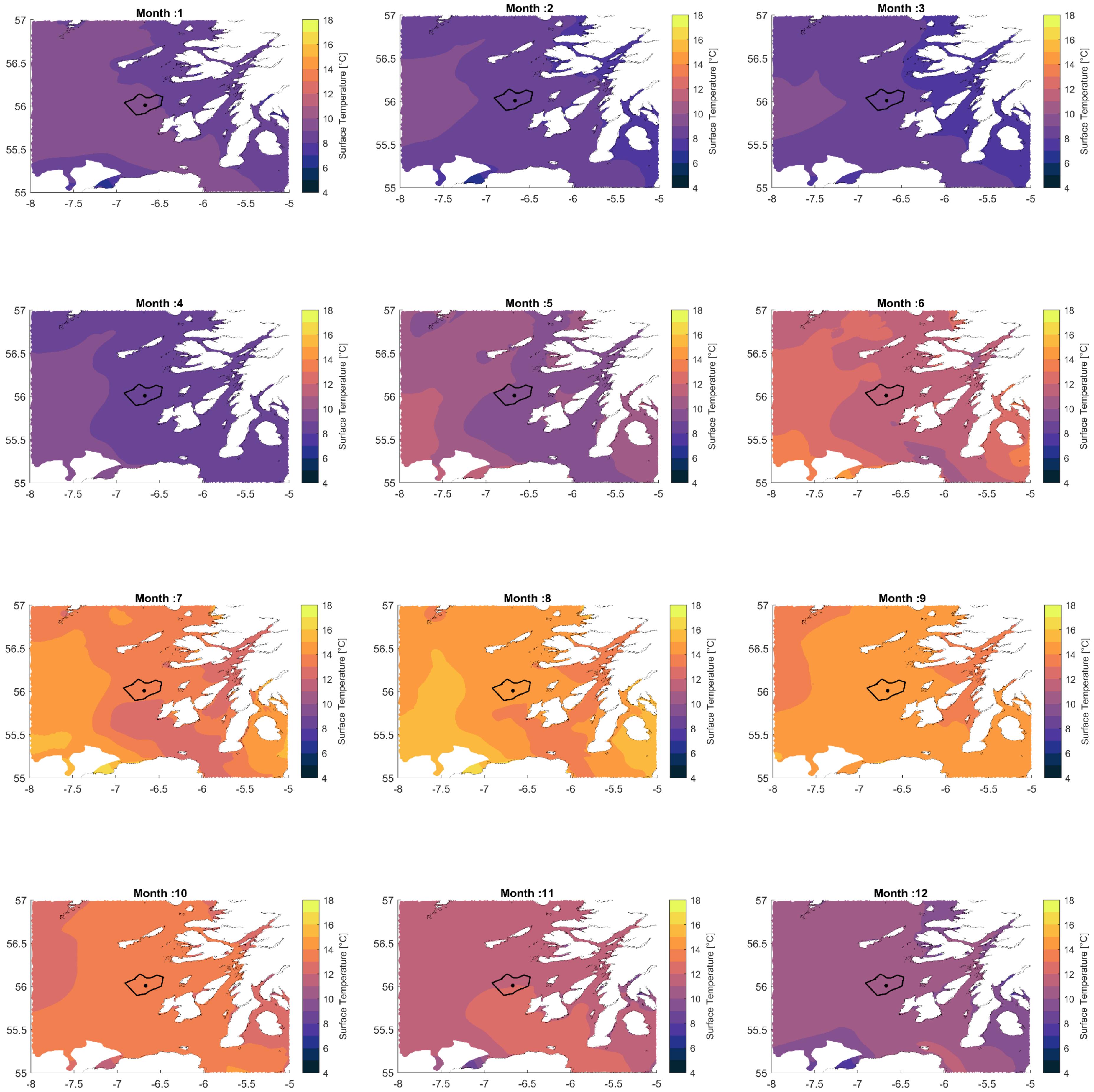

Plate 3.2 Monthly averaged surface temperature at the WDA (black polygon), black dot representing Point P

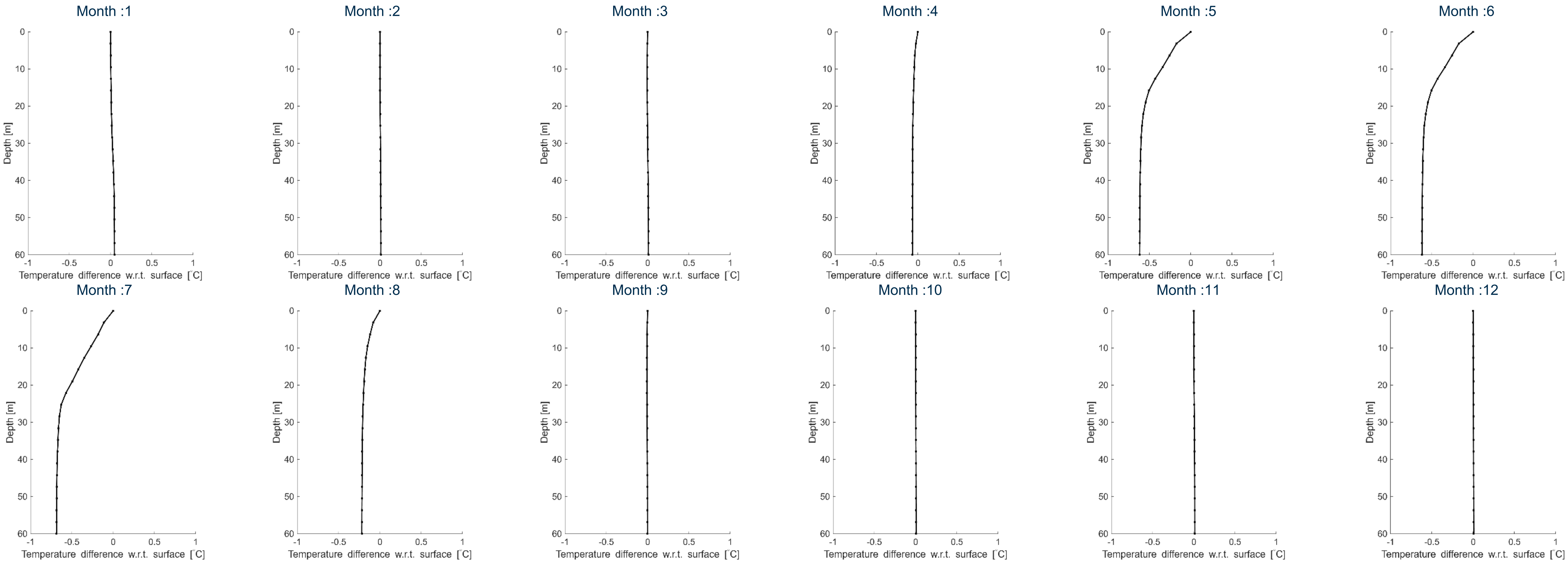

Plate 3.3 Temperature difference between monthly averaged surface and bottom of water column at point P, Negative values mean colder bottom water column than surface, and positive values vice versa

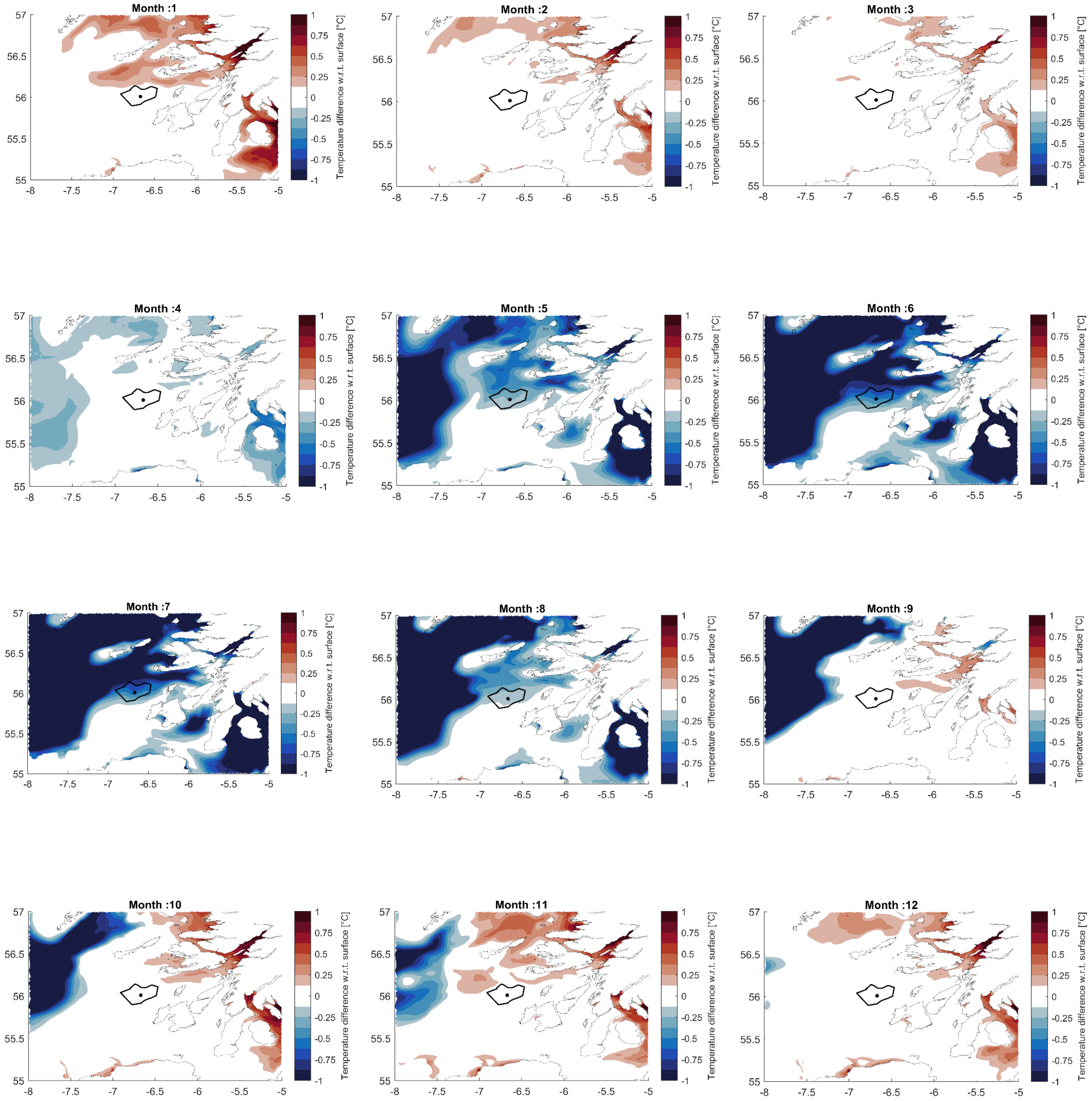

Plate 3.4 Temperature difference between surface and seabed. Negative values mean the seabed is colder than the sea surface and positive values vice versa. Black polygon is the WDA boundary, and black dot is point P.

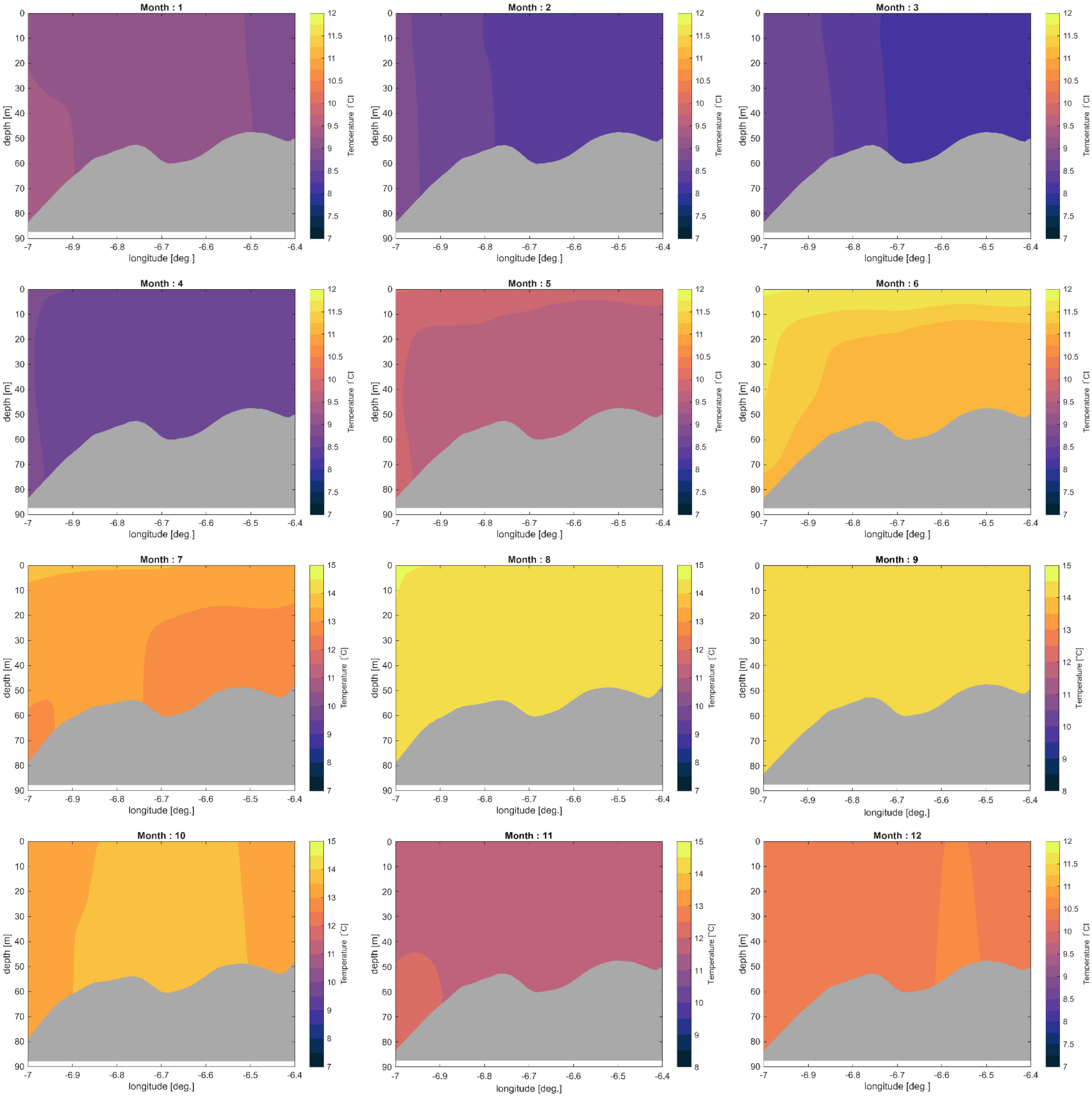

Plate 3.5 Monthly averaged vertical profile of temperature along longitudinal transect

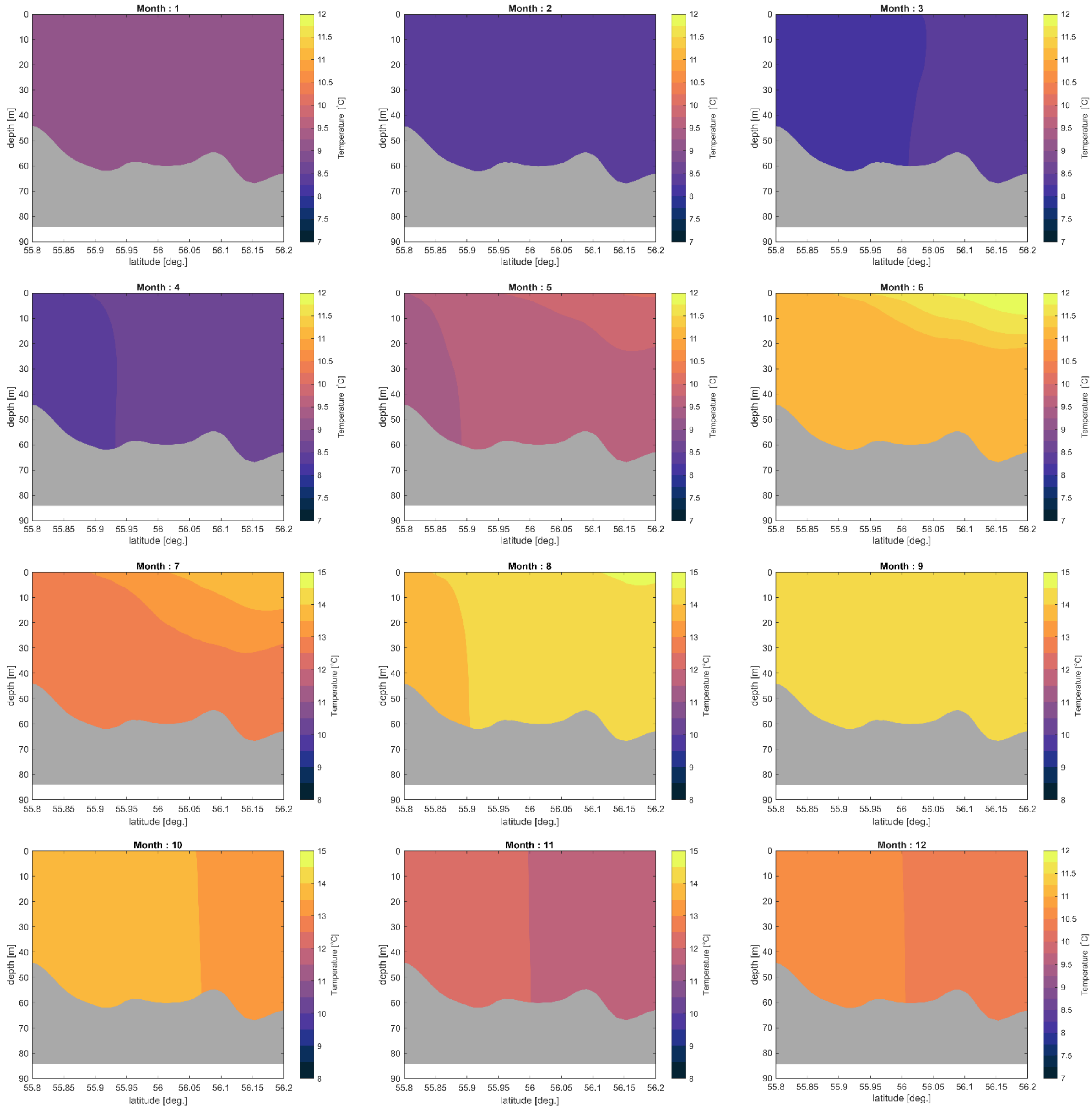

Plate 3.6 Monthly averaged vertical profile of temperature along latitudinal transect

3.2 Salinity

15. Salinity concentration in open ocean waters normally ranges between 33 Practical Salinity Unit (PSU) to 35 PSU. Given the narrow range of salinity concentrations discussed here, intervals have been defined with respect to 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 a strong halocline. Values between 0.1 g/l to 0.5 g/l define areas with a moderate halocline, and values below 0.05 g/l define areas with a weak/absent halocline.

16. **Plate 3.7** shows the monthly averaged surface and bottom salinity concentration within the WDA for 2019 (for the location shown on **Plate 2.1**). Both the water surface and bottom have relatively low salinity between May and December. The difference in sea surface and bottom salinity is low throughout the year, with the greatest differences observed between January and July. During this period, the bottom has higher salinity than the surface, reaching a maximum difference in July of approximately 0.05 g/l. This indicates the development of a weak halocline.

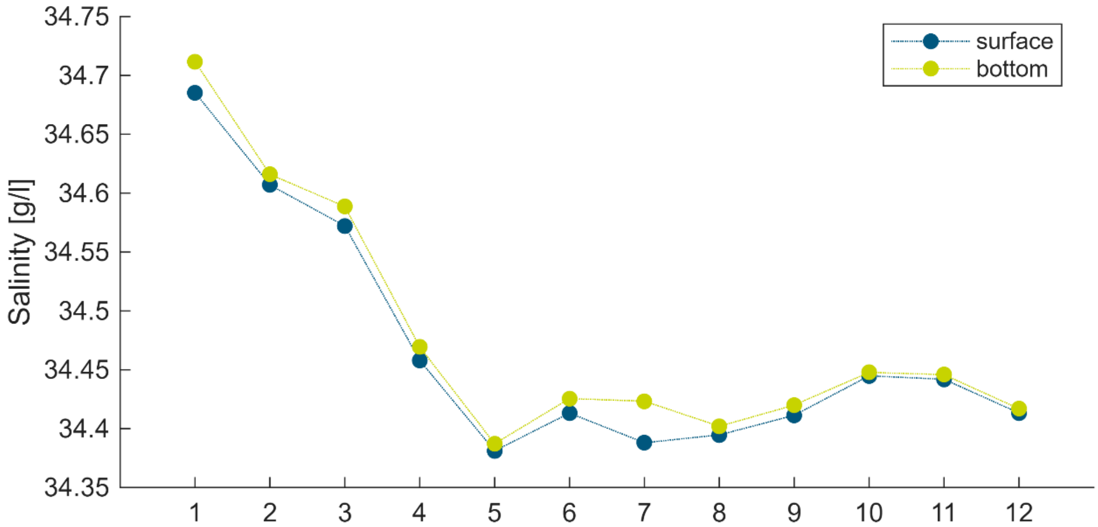

Plate 3.7 Monthly averaged and spatially averaged salinity at water surface and at bottom of the water column.

17. **Plate 3.8** shows monthly averaged sea surface salinity concentrations within the WDA throughout 2019. Throughout the year, salinity around the WDA ranges between 34.35g/l to 34.75g/l, with higher concentrations on the western side of the WDA. To the east, the coastal areas have lower surface salinity due to freshwater input from fluvial sources (Barton et al., 2024). Winter salinity concentrations are higher within the WDA than in the summer.

18. **Plate 3.9** shows vertical profiles of salinity concentration difference within the water column at the centre of the WDA (**Plate 3.8**). There is no halocline present between February and June or August and December, with a maximum difference during these periods of < 0.05g/l. In January, the surface is more saline than the bottom by 0.05g/l, indicating weak stratification. The salinity lowers gradually from approximately 30 m to 40 m depth. The salinity difference between surface and bottom waters is similar in July, however at this time the salinity lowers between approximately 5 m and 15 m depth.

19. To further investigate the stratification within the WDA, **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 **Plate 3.10** does not provide information on the depths of the halocline, it identifies the periods and the locations inside the WDA where stratification could occur.

20. **Plate 3.10** shows that from February to June and from August to December there is little or no difference between surface and bottom salinity within the WDA. In January and July, the difference is greatest and covers most of the WDA. In these months, the salinity at the bottom is on average between 0.05g/l and 0.1g/l lower than at the surface. Throughout the year, to the north of the WDA, the figure indicates the salinity at the bottom is significantly lower than at the surface by >0.25g/l. This is possibly due to freshwater input from the nearby coast before mixing can occur.

21. Vertical profiles of monthly averaged salinity concentration were extracted along transects across the centre of the WDA, from north to south and east to west, to investigate stratification inside the WDA (as shown on **Plate 2.1**). **Plate 3.11** shows vertical profiles of monthly averaged salinity concentration along the longitudinal transect. For all months except July, the salinity concentration through the water column along the transect remains constant. The salinity is stronger in the west than the east throughout the year, with January to March being overall stronger than the rest of the year. In July, a layer of weak salinity is present on the east of the transect between 0 m and 10 m depth however, the extent and duration is limited, suggesting the presence of an ephemeral salinity front rather than a systematic trend.

22. **Plate 3.12** shows vertical profiles of monthly averaged salinity concentration along the latitudinal transect (**Plate 2.1**). The figure shows there is a persistent area of higher salinity in the north of the transect. From February to November, the bottom salinity is marginally higher than the surface salinity, indicating some stratification proximal to the WDA. This is strongest in April and May where the salinity increases by approximately 0.1g/l from 15 m to 25 m depth. As with the longitudinal transect, the main variation in salinity is likely due to salinity frontal positions.

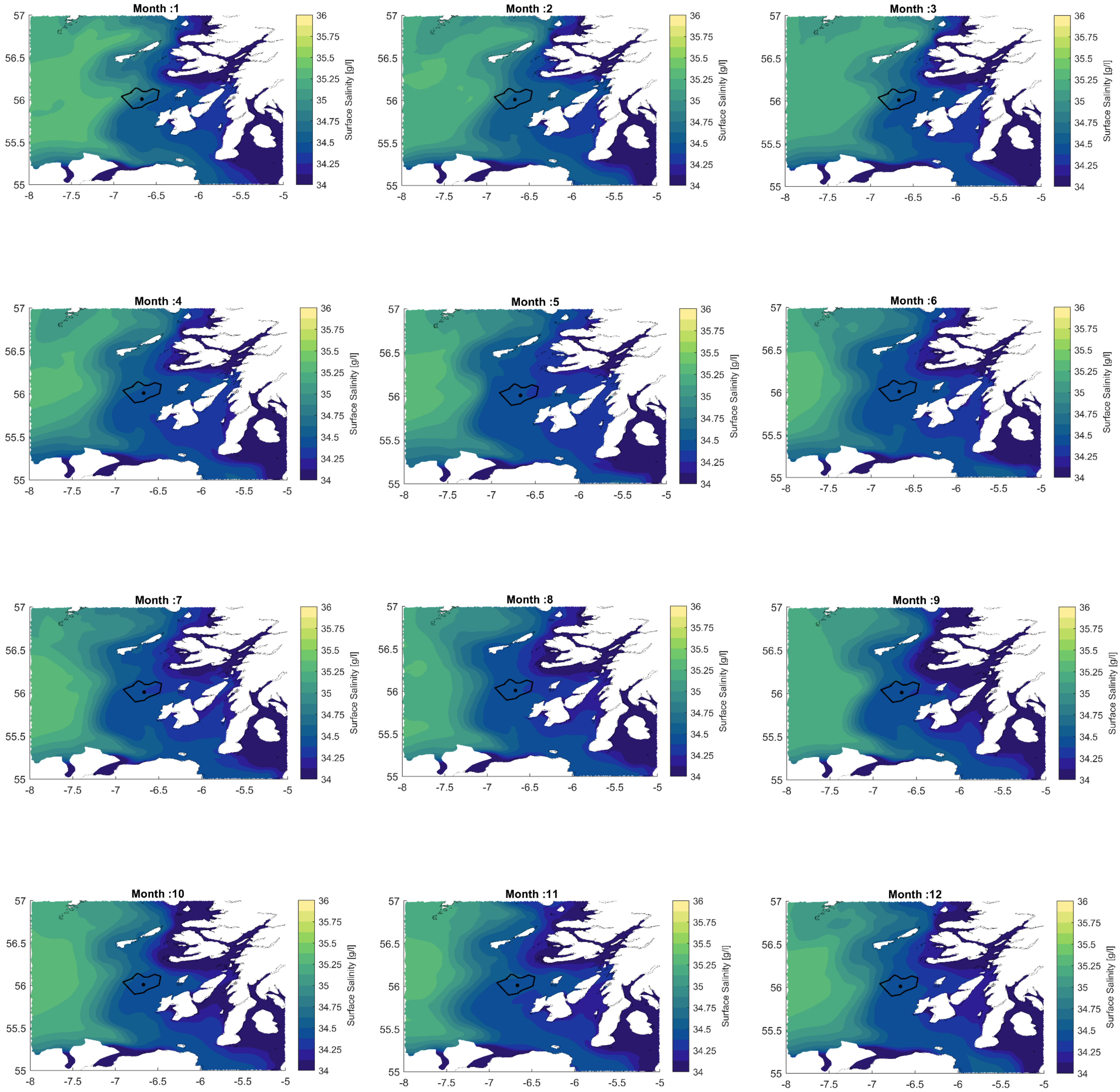

Plate 3.8 Monthly averaged surface salinity at the Machair WDA. Black polygon for the WDA boundary, black dot for point P.

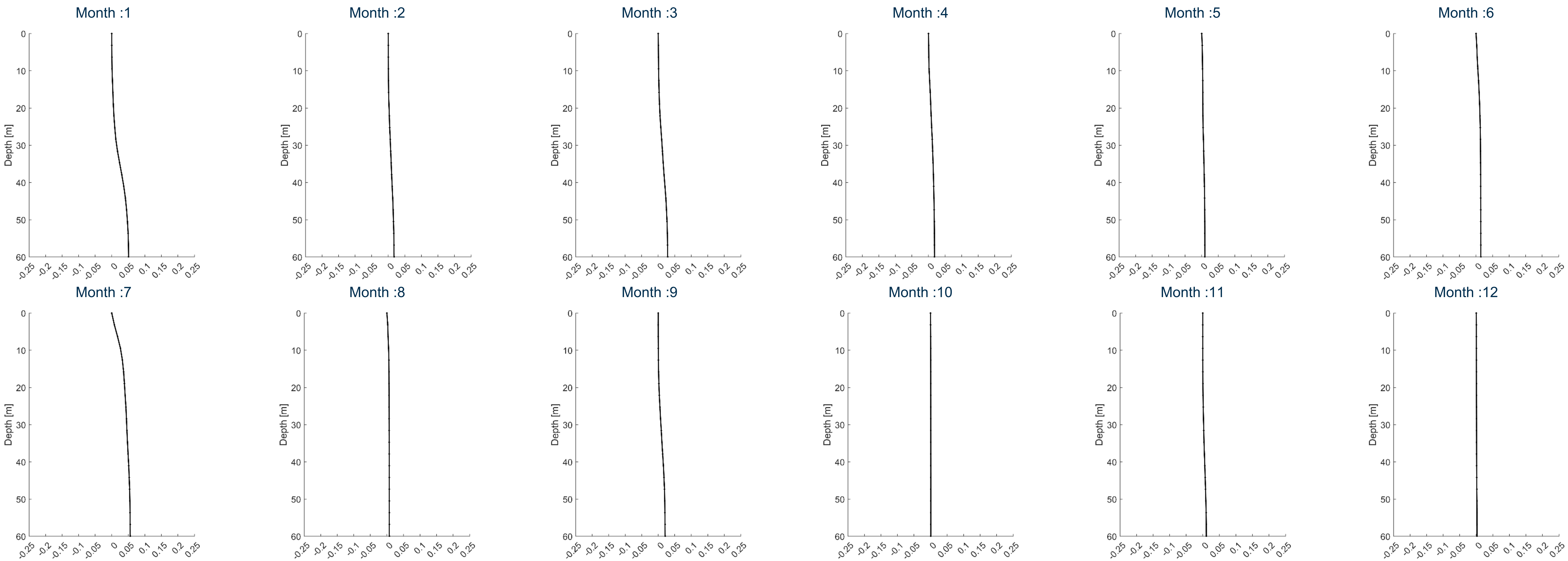

Plate 3.9 Salinity difference between monthly averaged surface and bottom of water column at point P, Negative values mean higher concentration at bottom water column than surface, and positive values vice versa

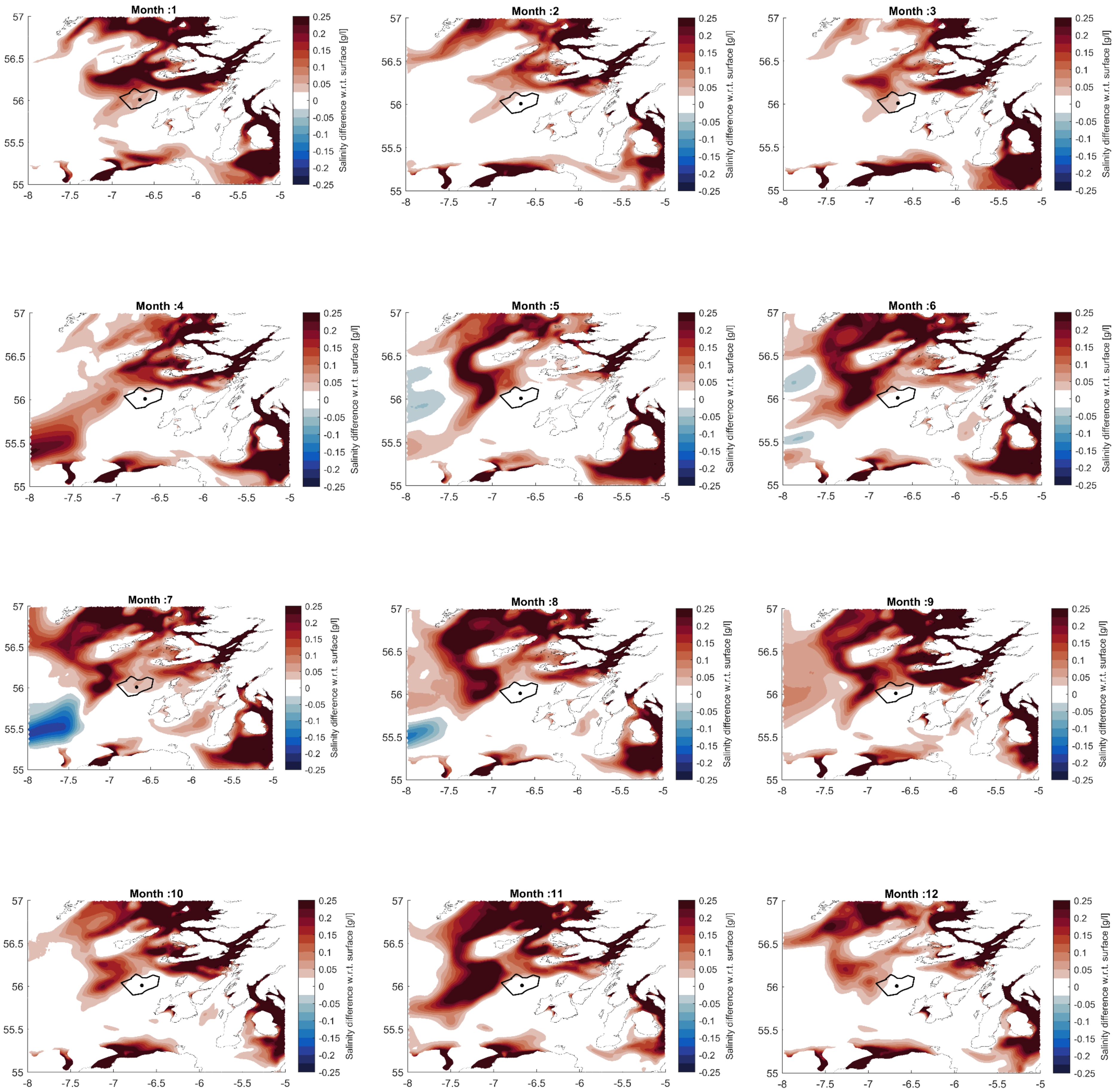

Plate 3.10 Salinity difference between surface and seabed. Negative values mean higher concentration at seabed than surface and positive values vice versa. Black polygon is the WDA boundary, and black dot is point P.

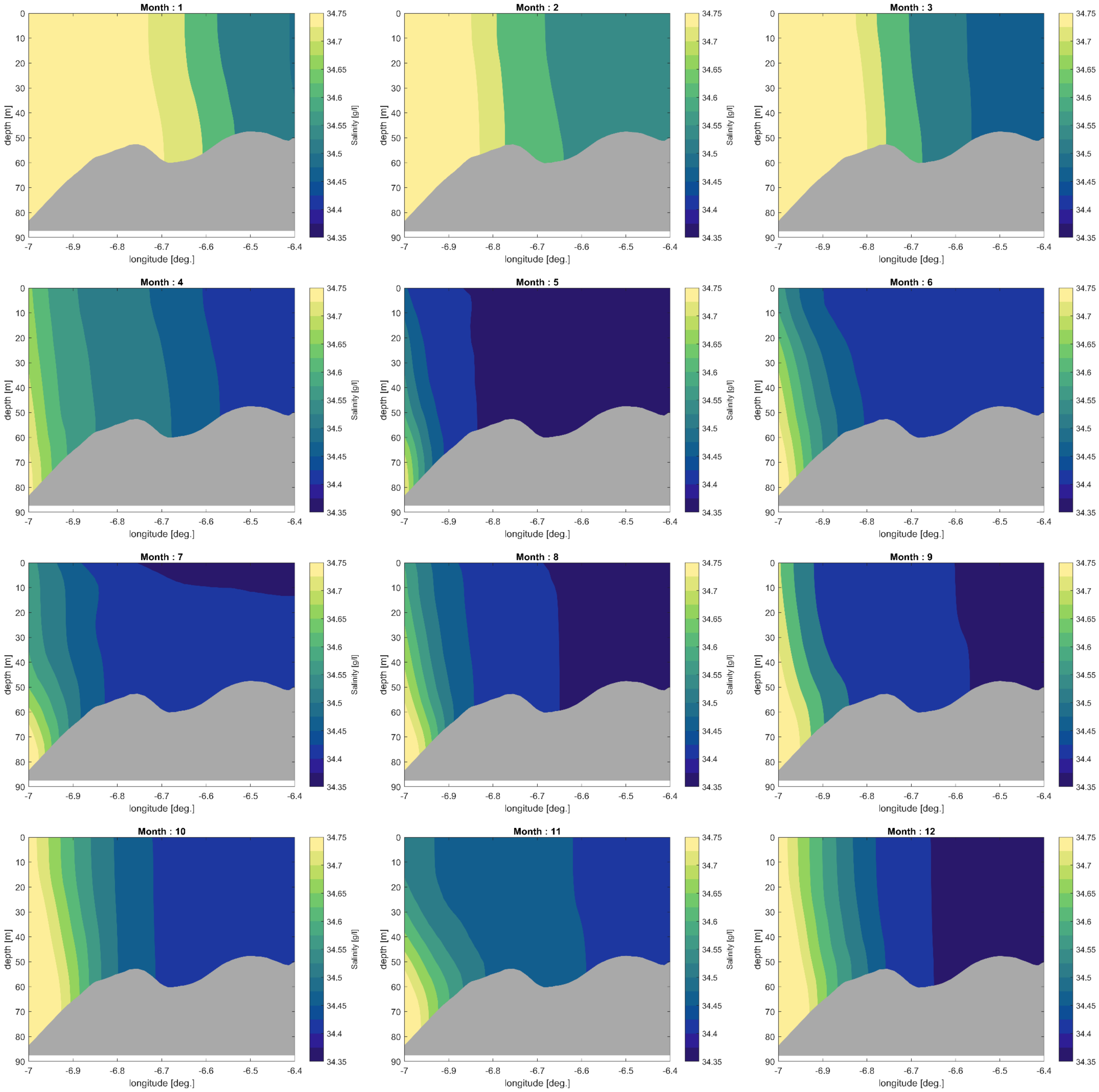

Plate 3.11 Monthly averaged vertical profile of salinity concentration along longitudinal transect

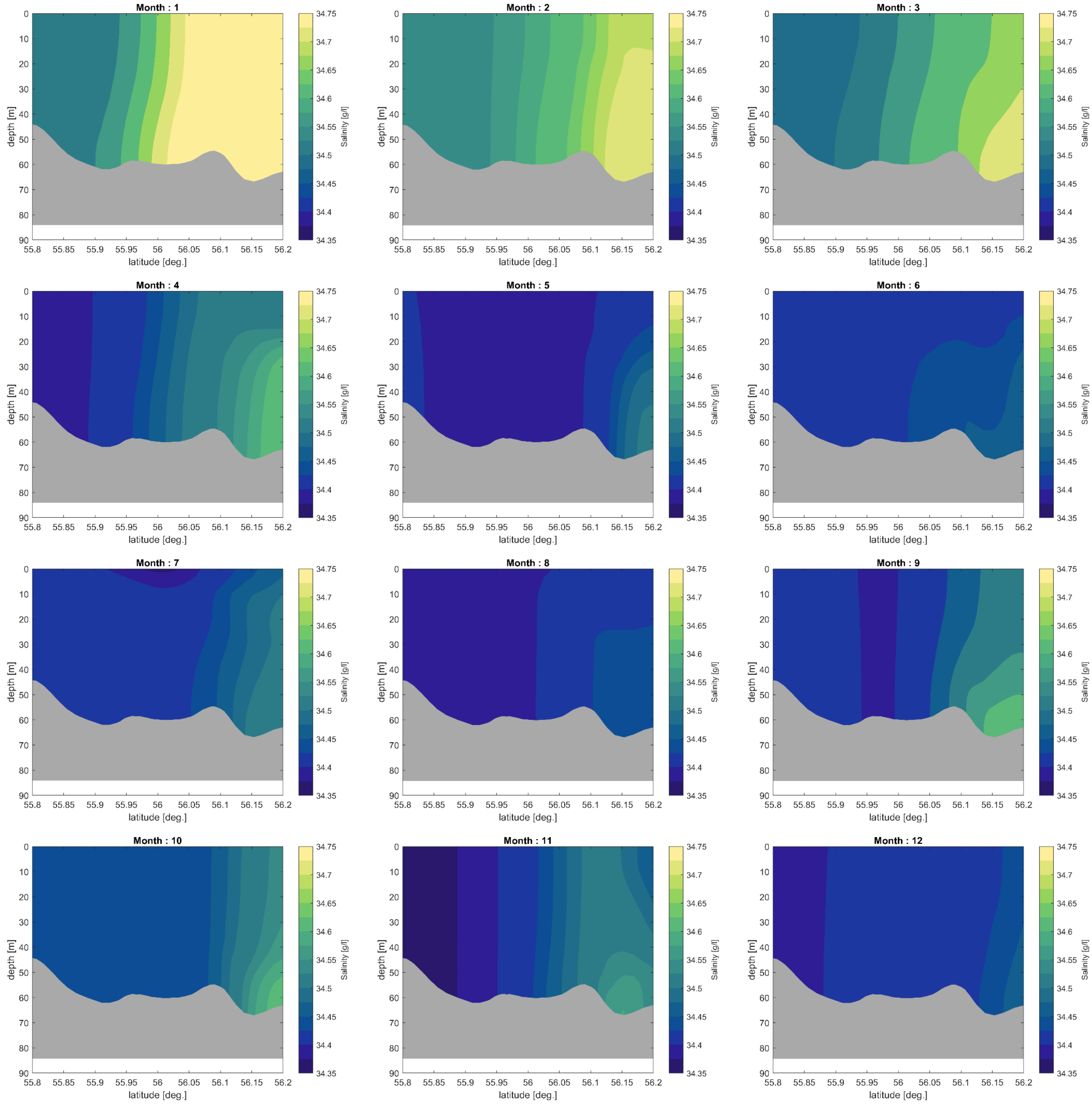

Plate 3.12 Monthly averaged vertical profile of salinity concentration along latitudinal transect

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3.3 Potential Energy Anomaly

23. 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 Potential Energy Anomaly (Φ), which represents the mechanical energy per unit volume (in Joules per cubic meter, J/m³) required to fully mix the water column. In the context of offshore wind energy, the WTG foundations 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.

24. 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 Potential Energy Anomaly (PEA). PEA is calculated as:

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

25. Where ϕ is the PEA, g is gravity, ρ is the instantaneous density profile, ρ_0 is the time-averaged density profile, z is the vertical elevation, and H is the water depth. A PEA of zero indicates a fully mixed column, while positive values indicate varying degrees of stratification. Following the Scottish Government Guidance (Berx and Hindson, 2020), a PEA value of 20 J/m³ or higher is used here to determine if the water column is stratified.

26. **Plate 3.13** shows the monthly averaged PEA inside the WDA. It shows that throughout the year the PEA is below the 20 J/m³ threshold and therefore the water column is well-mixed within the WDA.

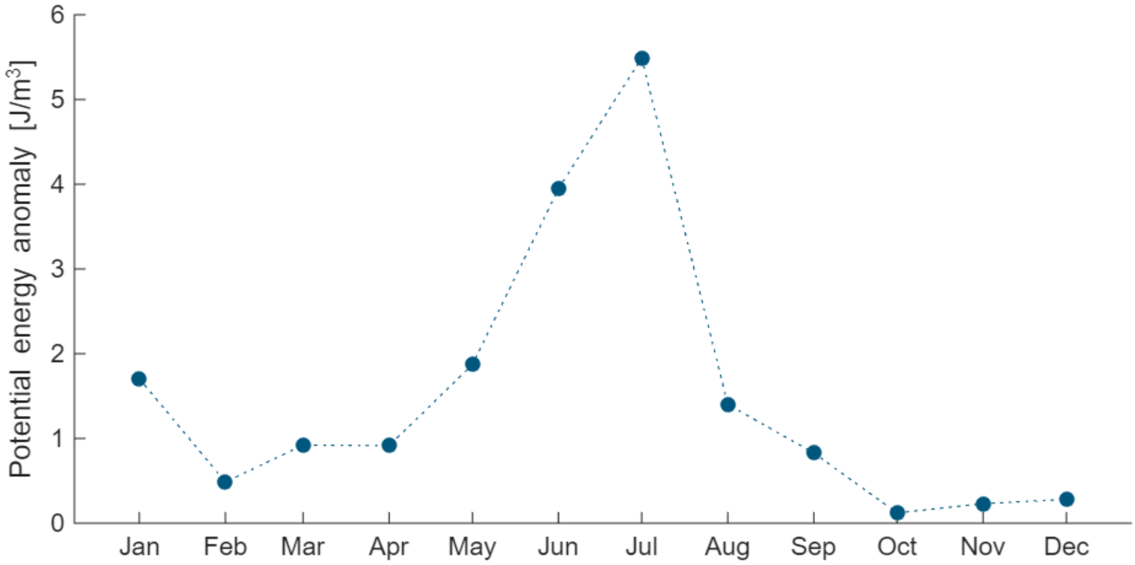

Plate 3.13 Monthly and spatially averaged Potential Energy Anomaly inside the WDA

27. **Plate 3.14** shows the PEA spatial distribution around the WDA. Areas where the water column is mixed (PEA<20 J/m^3) have been blanked. Stratification starts developing in May to the north of the WDA, which is strongest and most extensive in July and largely persists through to September. At no point does the water column within or immediately surrounding the WDA become stratified.

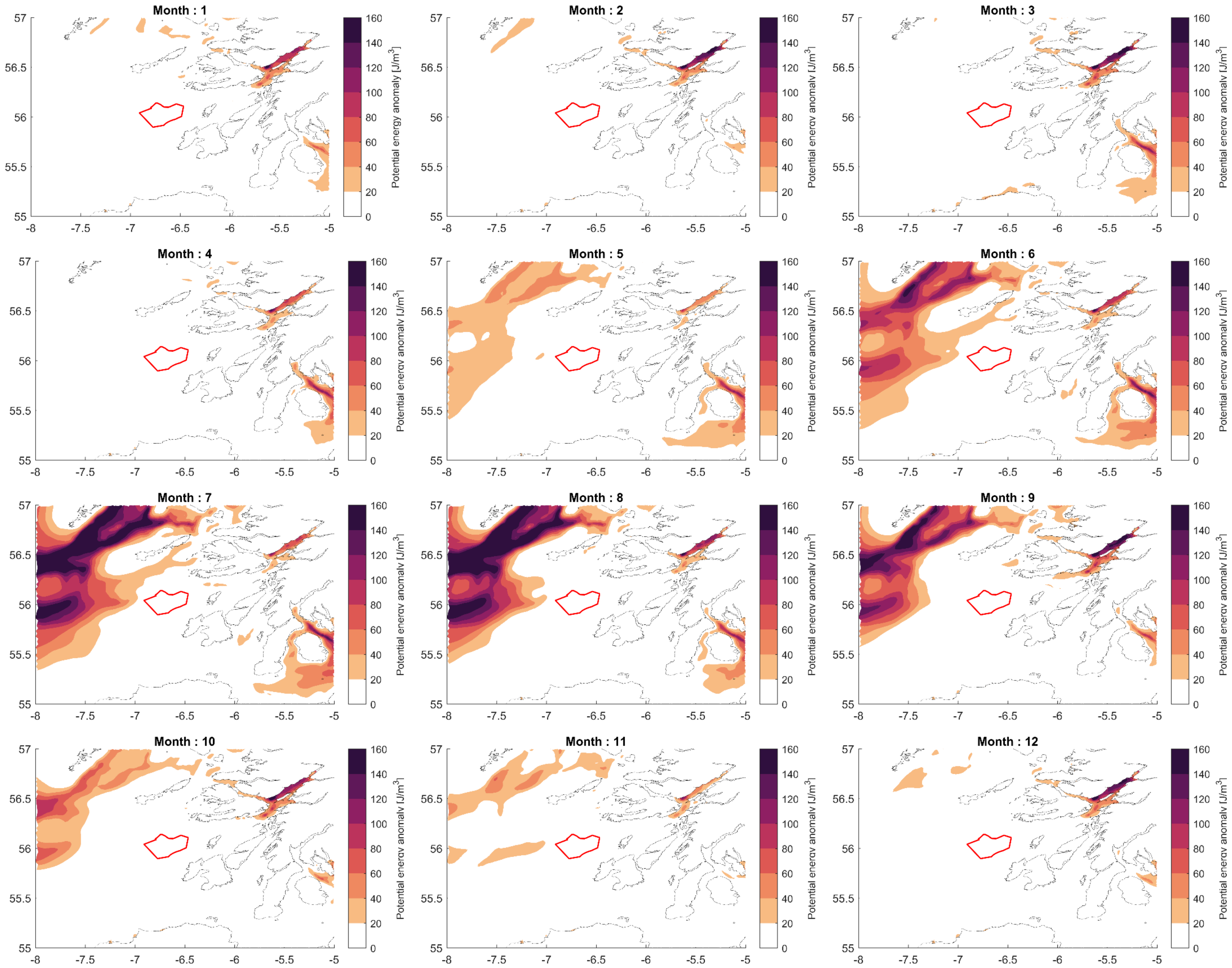

Plate 3.14 Monthly averaged Potential Energy Anomaly at the Machair WDA. Red polygon is the WDA boundaryA

3.4 Summary

28. This study aims to characterise the baseline water column stratification to inform assessment of the potential impact on water column structure from the presence of the WDA infrastructure which is provided in **Chapter 7 Marine Physical Environment**. To characterise the baseline water column stratification, both sea temperature and salinity were analysed within the WDA for the year 2019 to investigate potential stratification effects, resulting in the following conclusions:

<u>Thermocline:</u>

29. Monthly averaged sea surface temperatures indicate a seasonal trend, with warmer waters entering from the southwest between April and September, and colder waters entering from the northeast between October and March. Very weak thermal stratification begins in May, with a thermocline forming at 20 m depth and intensifying through June and July, reaching a maximum temperature difference of -0.75 °C (water surface warmer than that at greater depths). This stratification is strongest in the northern part of the WDA and weakens progressively southward from August. From September to April, the water column remains well-mixed with negligible vertical temperature gradients. Longitudinal and latitudinal transects confirm that stratification is spatially variable, developing primarily in the northern and eastern regions of the WDA during the summer months, while the southern areas remain largely mixed. The thermal stratification around the WDA is weak with a maximum temperature change of 0.75°C through the water column.

<u>Halocline:</u>

30. Analysis of salinity concentration in the water column reveals sporadic weak stratification effects around the WDA, from the 2019 data, it is not clear that any seasonal trend occurs. A halocline is always present to the north of the WDA. The maximum difference between surface concentration and the rest of the water column within the WDA is 0.05g/l (weak halocline). These largest values occur during January and July, while during the rest of the year the water column is well mixed (differences less than 0.05g/l). Vertical profiles of salinity concentration along a longitudinal and latitudinal transect reveal that the halocline develops between 0 m and 25 m depth.

<u>Potential energy anomaly:</u>

31. Instantaneous vertical profiles of water temperature and salinity were used to calculate instantaneous vertical profiles of water density. These density profiles 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 WDA is well mixed throughout the year (PEA<20 J/m3). Spatial variation of PEA shows the area approximately 6-7 km to the west of the WDA experiences some stratification during the summer. These results are consistent with those reported by Berx and Hindson (2020), who found an area of well-mixed water around the WDA in August, with more stratified water to the northwest.

3.5 References

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