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**Spatial and Temporal Variability of
Pycnocline Formation and Its
Influence on Phytoplankton
Distribution in the Dutch North Sea**

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Abstract

Stratification within the water column is a key process regulating phytoplankton by influencing the vertical distribution of nutrients, light availability, and mixing processes. Within this study, the relationship between pycnocline occurrence and vertical phytoplankton distribution has been investigated. The focus centred around how physical stratification structures shape ecological patterns. Simultaneously the effectiveness of monitoring strategies of Rijkswaterstaat, executive agency of the Dutch Ministry of Infrastructure and Water Management, have been evaluated.

For this study, a data analysis has been conducted on a dataset spanning almost 30 years. Stratification occurrence, pycnocline dynamics, and phytoplankton abundance have been analysed to determine spatial and temporal patterns.

The results showed that pycnocline dynamics significantly influence the vertical phytoplankton distribution. However, pycnocline dynamics cannot fully explain the vertical phytoplankton distribution. Therefore, it is apparent other physical and biological parameters influence phytoplankton abundance and distribution.

The current monitoring strategy does not capture the full complexity within spatial and temporal dynamics of pycnocline occurrence and phytoplankton abundance. The confidence within the data, because of the low resolution, is limited towards understanding ecological dynamics. Strong seasonal patterns have been observed for the pycnocline occurrence within the water column. In general, summers showed clear pycnocline occurrence with lower pycnocline occurrence in winter. The overall findings indicate the need for higher resolution monitoring when stratification is present to better capture pycnocline dynamics and phytoplankton abundance.

Concluding, the study shows the importance of stratification and pycnocline dynamics in influencing phytoplankton distribution. Also, the research reveals the limitations of the current monitoring strategy. Improved monitoring strategies with greater temporal resolution are needed to capture the interaction between physical and biological processes. Overall, this will enhance the understanding of ecological dynamics in stratified shelf seas.

Samenvatting

In de Noordzee staat de waterkwaliteit onder druk door klimaatverandering en menselijke activiteit. Stratificatie, waarbij dichtheidsverschillen in de waterkolom leiden tot een spronglaag, is hierbij een belangrijk proces. De spronglaag beïnvloedt het transport van nutriënten, zuurstof en fytoplankton. Als een gevolg hiervan kan eutrofiering optreden, wat leidt tot zuurstofloosheid.

Rijkswaterstaat monitort deze processen met behulp van kustwachtschepen door op bepaalde locaties in de Noordzee verticale profielen te nemen. Mogelijk kan op basis van oppervlaktewaarnemingen van satellieten de huidige monitoring aangevuld en/of verbeterd worden. Het is hiervoor echter belangrijk om de dynamiek tussen stratificatie en de verticale verspreiding van fytoplankton in de gehele waterkolom te doorgronden.

Binnen dit onderzoek is gebruik gemaakt van een dataset van ruim 29 jaar (1995-2024) aan CTD-profielmetingen van Rijkswaterstaat. De dataset is geanalyseerd om de invloed van spronglagen op de verticale verspreiding van fytoplankton op het Nederlands Continentaal Plat (NCP) te onderzoeken.

Sterke ruimtelijke en seizoensafhankelijke patronen zijn zichtbaar in de resultaten. Spronglagen zijn vooral aanwezig in het voorjaar en de zomer, hierbij ontstaan sterke dichtheidsgradiënten. In de winter zijn deze spronglagen grotendeels afwezig. Daarnaast is vastgesteld dat spronglagen vaker voorkomen op locaties die meer dan 20 kilometer uit de kust liggen. Dichter bij de kust komen spronglagen minder vaak voor door sterkere menging, onder andere als gevolg van getijden en wind. Daarnaast laten de resultaten zien dat de dynamiek van de spronglaag een belangrijke sturende factor is voor de verticale verspreiding van fytoplankton.

Desondanks maakt de beperkte meetfrequentie het moeilijk om de dynamiek in de waterkolom volledig vast te leggen. Hierdoor is ook de interactie tussen fysische en biologische processen lastig betrouwbaar te beoordelen. Dit geldt met name voor gestratificeerde perioden, omdat dan een hoge temporele resolutie nodig is om veranderingen in de waterkolom en de bijbehorende reactie van fytoplankton nauwkeurig te volgen.

Voor Rijkswaterstaat liggen er kansen door in gestratificeerde perioden de meetfrequentie te verhogen. Ook kan voor ondiepere delen van de Noordzee satelliet monitoring een toevoeging vormen. Hiermee kan het begrip van ecosysteemdynamiek worden vergroot, de waterkwaliteit betrouwbaarder worden beoordeeld en zowel intern als voor beleidsdoeleinden een sterkere kennisbasis worden opgebouwd.

List of Abbreviations

CTD = Conductivity, Temperature and Depth (sensor-based vertical measurements)

DCM = Deep Chlorophyll-a Maximum

DCS = Dutch Continental Shelf

MSFD = Marine Strategy Framework Directive

NPQ = non-photochemical quenching

OSPAR = Oslo and Paris Conventions

RMSE = Root Mean Square Error

ROFI = Region Of Freshwater Influence

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1. Introduction

The marine environment provides many goods and services of ecological, economic, and societal relevance, including food provision, recreational opportunities, coastal protection and breaking down organic waste. Therefore, the goods and services derived from marine waters represent substantial value and are critical for human well-being. Maintaining and managing these goods and services is therefore essential for sustainable marine resource use (Eggert & Olsson, 2009; Yadava et al., 2023).

However, marine water quality has become an increasing concern in many coastal and shelf seas (shallow water body) due to climate change and human activities, resulting in nutrient enrichment and pollution (Cadée and Hegeman, 2002). These results can lead to environmental problems, including eutrophication. Eutrophication is caused by excessive nutrient inputs and is characterized by excessive phytoplankton (microalgae) growth. This growth leads to several negative ecological impacts such as oxygen depletion in marine waters and altered marine ecosystem functioning (Ansari et al., 2010; Chislock et al., 2013).

Eutrophication in the North Sea

Across European seas, marine water quality varies considerably, with some regions experiencing persistent eutrophication due to high nutrient inputs from densely populated river catchments (OSPAR Commission, 2023). The North Sea is one of the most intensively used shelf seas in the world (e.g. intensive fishing) and is bordered by several densely populated countries with high agricultural land use, causing surface runoff and nutrient inputs. This, in combination with the discharge from major European rivers such as the Rhine, Elbe, and Thames, cause nutrient enrichment and makes the North Sea particularly vulnerable for eutrophication (Emeis et al., 2015; Mojica et al., 2015).

Natural variability of nutrient concentrations (from interannual to multidecadal time scales) are driven by changes in the North Atlantic. However, the magnitude of these natural fluctuations is minor compared to the impacts of eutrophication caused by human activities. Anthropogenic pressures have historically increased nutrient inputs, driving elevated eutrophication levels, followed by ongoing efforts to mitigate these effects (Emeis et al., 2015). Nevertheless, these mitigation measures are constrained by a lack of precise information on spatial occurrence of eutrophication due to currents and hydrodynamics.

Ecological importance of phytoplankton

Phytoplankton are vital to marine ecosystems, forming the base of the food web and playing a key role in oceanic carbon cycles. However, high algal biomass can lead to hypoxia, which is harmful to the environment. Furthermore, certain phytoplankton species have the ability to form harmful algal blooms (HABs), which can disrupt ecosystems (Berdalet et al., 2017; De Rijcke, 2017; Peperzak, 2003).

Although nutrient inputs have declined over the recent decades and have led to improvement of ecosystems in some offshore areas (OSPAR Commission, 2023). The OSPAR (Oslo and Paris Conventions) and the EU Marine Strategy Framework Directive (MSFD) requires to assess the water quality status of the Greater North Sea (OSPAR Commission, 2023). Indicators such as chlorophyll-a concentrations and phytoplankton dynamics are important signalling parameters to assess this water quality status. Currently, the North Sea does not meet the required water quality standards, making compliance with these regulatory frameworks essential to avoid potential fines or other penalties from the European Union (European Environment Agency, 2024).

The role of stratification in phytoplankton dynamics

Existing literature demonstrates that the inhibition in vertical exchange within the water column (from surface to seabed) also controls nutrient and light distribution within the water column, which are important drivers for phytoplankton growth (van de Poll et al., 2013; Yamaguchi et al., 2019). Therefore, vertical stratification plays a key role in regulating phytoplankton production (Behrenfeld et al. 2006; Huisman et al. 2006; Hoegh-Guldberg and Bruno 2010).

When stratification develops, phytoplankton benefit from increased light and nutrient availability in the surface layer, which can stimulate growth, particularly during the spring bloom (Sharples et al., 2006; van de Poll et al., 2013). However, because mixing of the water is reduced, nutrients at the surface are no longer replenished from deeper water, leading to nutrient depletion in the surface layer. Alternatively, phytoplankton may shift towards the region near the pycnocline, where sufficient light is still available and nutrients are supplied from deeper waters (Cullen, 2015).

Stratification and phytoplankton dynamics

Climate change and human activities keep altering physical and biological processes within European seas (Mojica et al., 2015; van de Poll et al., 2013). Physical processes such as stratification are influenced by climate change, which in turn plays a crucial role in regulating phytoplankton growth and dynamics, thereby affecting eutrophication (Li et al., 2020; Yamaguchi et al., 2019). Understanding these processes can provide a better insight into the eutrophication status of a region.

Stratification is characterized by a density difference between an upper and deeper water layer. The location within the water column where this density difference changes most rapidly is known as the pycnocline, which influences phytoplankton biomass and distribution (Blauw, 2015; Sprintall & Cronin, 2009).

Knowledge gap

Previous studies on the relationship between stratification and phytoplankton have primarily focused on oligotrophic open oceans, where nutrient limitation dominates phytoplankton dynamics (Behrenfeld et al., 2006; Polovina et al., 2008; Dave and Lozier, 2010; Lozier et al., 2011). In contrast, temperate and higher-latitude shelf seas, such as the North Sea, have received less attention.

Therefore, it is crucial to investigate how pycnocline occurrence influences phytoplankton biomass in the Dutch North Sea, using region-specific data. While Deltares, in a recent study, has examined pycnocline occurrence at two monitoring locations in the Dutch North Sea, further detailed analysis across additional monitoring locations is required to better understand spatial and temporal patterns (Hendriks, Blauw, Stolte, & Rautenbach, 2026).

Monitoring marine ecosystems

Changes in the marine environment require corresponding changes in monitoring. To adapt monitoring effectively and support policy implications, it is important to clearly define what needs to be observed (Blauw, 2015). Furthermore, alternative monitoring methods for detecting phytoplankton abundance are being developed, including automated buoys and satellite remote sensing. These methods are increasingly used alongside conventional field observations, such as in-situ sampling and measurements (Blauw, 2015).

Consequently, monitoring capabilities are expanding. However, it remains unclear whether and how these alternative methods can be effectively combined with conventional field observations (Prins & Enserink, 2022). A better understanding of the interactions between physical processes, such as stratification, and phytoplankton dynamics is therefore essential. This knowledge supports the design

of appropriate monitoring programmes and the accurate assessment of marine ecosystem health, including eutrophication.

Policy framework and monitoring requirements

The OSPAR Convention and the European Union Marine Strategy Framework Directive (MSFD) require member states to monitor and evaluate ecosystem health by using standard indicators. Rijkswaterstaat is responsible for managing the Dutch part of the North Sea and assessing the chemical status of Dutch marine waters (European Parliament & Council of the European Union, 2008). By doing so, Rijkswaterstaat is aiming for a good environmental status for the Dutch part of the North Sea according to the MSFD. This assessment is carried out within international and European policy frameworks, including the OSPAR Convention and the EU MSFD, which are implemented nationally through the Dutch Marine Strategy. To comply with these obligations, Rijkswaterstaat monitors and evaluates the eutrophication status of the North Sea and reports on indicators such as chlorophyll-a concentrations and the occurrence of algal blooms (Rijkswaterstaat, n.d.; European Parliament & Council of the European Union, 2008). These indicators are used to assess ecosystem condition and support international efforts to protect marine biodiversity and water quality as this is a goal from the OSPAR agreement (OSPAR Commission, 1992). The monitoring activities are coordinated through the national monitoring program (Rijkswaterstaat, n.d.).

As monitoring strategies are evolving, understanding the relationship between stratification and phytoplankton dynamics is getting increasingly more important. Greater understanding will result in more effective assessment of eutrophication in future monitoring strategies.

Research aim and research questions

In 2026, a revised monitoring strategy will be introduced by Rijkswaterstaat, with an increased emphasis on remote-sensing techniques. As monitoring shifts toward surface-focused remote sensing, understanding the vertical structure of the water column becomes increasingly important. To avoid missing key information and dynamics occurring below the surface, it is essential to know when, where, and at which depths phytoplankton should be monitored in relation to pycnocline dynamics. This study therefore uses a long-term dataset, using CTD (Conductivity, Temperature and Depth) measurements, to identify spatial and temporal patterns in pycnocline formation and phytoplankton distribution. These insights will contribute to a broader understanding of North Sea ecosystem functioning and support more effective ecosystem assessment. By linking scientific understanding to practical application, the results can support the development of a more effective monitoring strategy.

To be able to give input towards an improved monitoring strategy for chemical and biological water quality measurements, a research question and several sub-questions (SQ) need to be answered.

Main research question:

How have spatial and temporal patterns of pycnocline formation altered the vertical distribution of phytoplankton on the Dutch continental shelf between 1995 and 2024?

SQ1: What are the spatial and temporal patterns of pycnocline occurrence on the Dutch continental shelf between 1995 and 2024 as predicted by CTD data?

Hypothesis: Pycnoclines occur predominantly during late spring and summer when solar heating exceeds vertical mixing, where stratification will occur more frequently in offshore regions of the Dutch continental shelf compared to shallow coastal zones due to weaker tidal mixing (Holt & Umlauf, 2008; van Leeuwen et al., 2015).

SQ2: How does pycnocline formation influence the vertical distribution and abundance of phytoplankton across seasons and locations between 1995 and 2024?

Hypothesis: Pycnocline formation promotes the development of a subsurface chlorophyll maximum near the pycnocline (Mojica et al., 2015; Tweddle et al., 2013).

SQ3: What do the identified spatial and temporal patterns of pycnocline occurrence and phytoplankton distribution imply for the representativeness and future outlook of current vertical sampling strategies?

Hypothesis: Current sampling strategies do not adequately capture these spatial and temporal patterns and lack sufficient coverage to provide a comprehensive assessment of water quality status in line with international agreements.

Study Area - North Sea

In this section the characteristics of the study area will be explained. This study focuses on the Dutch Continental Shelf (DCS). This area can be seen in Figure 1 below.

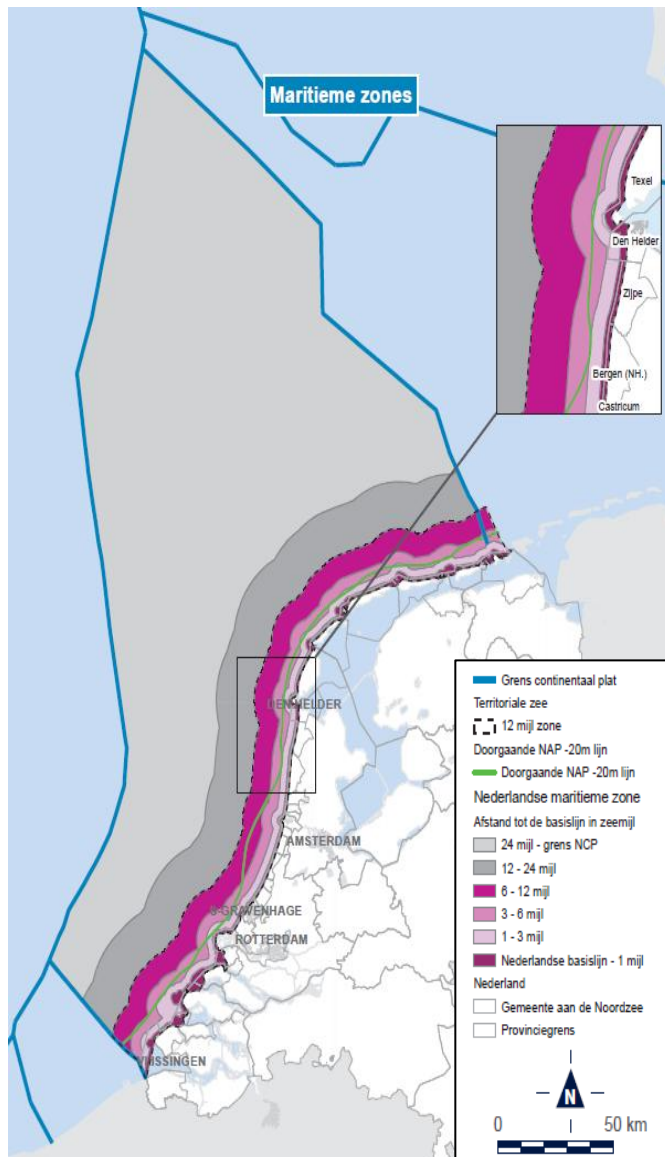


Figure 1: Maritime zones in the Dutch North Sea: Netherlands Continental Shelf (NCS) and Exclusive Economic Zone (EEZ) (Rijkswaterstaat, 2025-b).

The DCS is characterised by a relatively shallow marine environment and covers an area of approximately 57,000 km². Bathymetry data, visualised by Doornenbal and Heteren (n.d.), shows that the DCS is logically shallow when proximate to the coastline and becomes deeper further from the coast (see Figure 2). However, sand banks within the DCS can create shallower areas further from the coast. Depths range from 2.70 to 71 metres. These geomorphic features influence local conditions towards stratification, as seen in Figure 2.

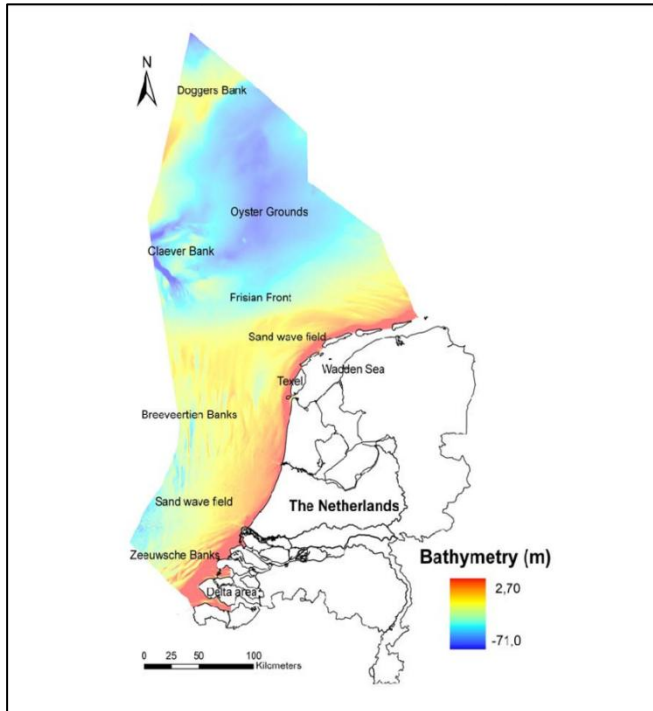


Figure 2: Bathymetric map of the Dutch Continental Shelf (DCS) (Doornenbal & Heteren, n.d.).

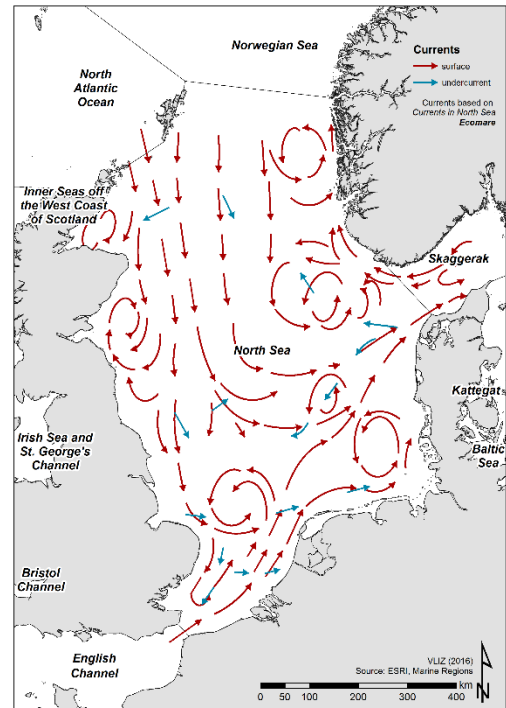


Figure 3: Currents of the North Sea (De Hauwère, 2016).

Hydrodynamic conditions within the DCS are primarily influenced by tidal currents, wind, and freshwater input. Tidal currents are more dominant in controlling vertical mixing of nutrients in shallower parts, near the coastline or in the southern part (Holt & Umlauf, 2008; Sündermann & Pohlmann, 2011; van Leeuwen et al., 2015), as seen in Figure 3. Due to these currents, water columns are mixed throughout the year (van Leeuwen et al., 2015). On the other hand, deeper areas in the northeast part of the DCS experience seasonal thermal stratification due to solar heating (Sündermann & Pohlmann, 2011; van Leeuwen et al., 2015). Wind can enhance vertical mixing, especially when stronger winds occur. In addition, freshwater influences from the Rhine and Meuse can alter local salinity patterns and this can influence stratification (van Leeuwen et al., 2015).

2. Theory

Phytoplankton dynamics are shaped by various physical and biological factors, including light, temperature, and nutrient availability. These factors, often referred to as drivers, can have either positive or negative effect on phytoplankton biomass. Vertical mixing and stratification of the water column is one of the drivers and could modulate how the other drivers influence phytoplankton biomass growth. Additionally, these drivers can be enhanced by climate change as temperatures rise. Understanding the interaction between all the drivers and corresponding processes, stratification and phytoplankton dynamics, is essential to clarify the effect of phytoplankton dynamics and stratification on temporal and spatial scale. Beneath phytoplankton dynamics, stratification processes, and the relationship between phytoplankton and stratification are explained.

2.1 Phytoplankton dynamics

Definition of phytoplankton

Phytoplankton, microscopic organisms (micro algae), forms the base of the marine food web and plays a crucial role in global carbon cycling and carbon fixation (Geider et al., 2001; Jahan & Singh, 2023). Through photosynthesis, phytoplankton convert sunlight, carbon dioxide and nutrients (e.g. nitrate and phosphate) into organic matter (Jahan & Singh, 2023). This organic matter partly provides food for zooplankton and fish. Phytoplankton has specialized pigment molecules, chlorophyll-a molecules, which can be detected by chlorophyll-a fluorescence (Althuis et al., 1994). Chlorophyll-a fluorescence represents the fraction of absorbed light energy that is re-emitted as light by chlorophyll-a molecules during photosynthesis (Althuis et al., 1994). Consequently, measurements of chlorophyll-a fluorescence are widely used as a proxy for phytoplankton biomass (Althuis et al., 1994).

Drivers of phytoplankton

There are different drivers which can influence phytoplankton biomass in a positive and negative way. Both biological and physical drivers can affect phytoplankton biomass. Figure 4 shows the different drivers which influence phytoplankton growth. Physical drivers such as wind and temperature can influence the abundance of phytoplankton directly or indirectly. Biological drivers, such as zooplankton, can also influence the abundance of phytoplankton. In this subsection the various drivers are discussed.

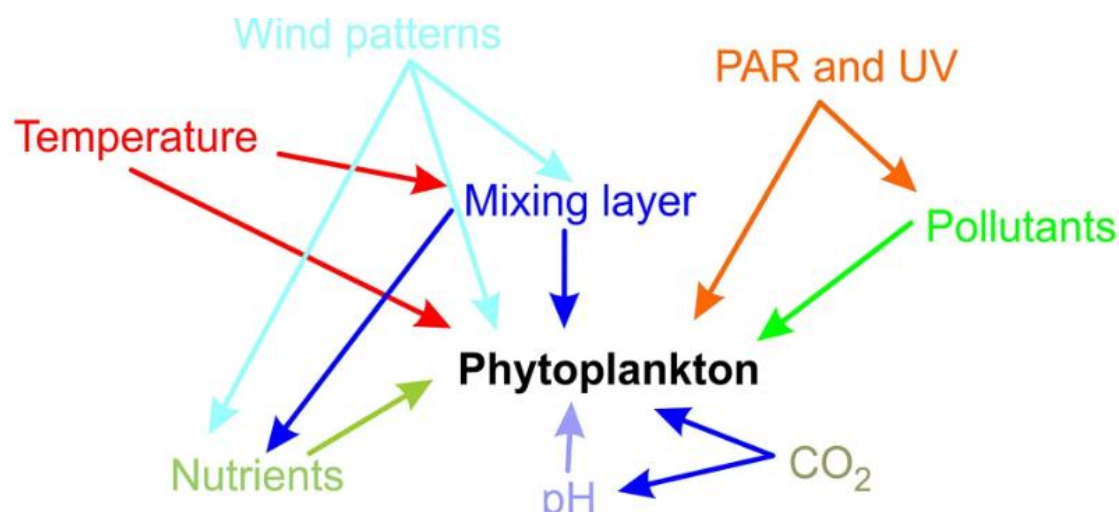


Figure 4: Drivers of phytoplankton biomass (Häder & Gao, 2015).

Phytoplankton abundance can be negatively affected by several drivers that cause losses in biomass. Predation by zooplankton and sedimentation, where cells sink through the water column, are common sources of phytoplankton loss (van de Poll et al., 2013). Another important mechanism is lysis, which refers to the destruction of cells. Lysis can result from viral infections, bacterial activity, or environmental stresses, such as intense sunlight, prolonged darkness, or nutrient depletion (Baudoux et al., 2008; van de Poll et al., 2013).

Temperature, a physical driver, influences the growth of phytoplankton due to the enzymatic activity and photosynthesis (Lewandowska et al., 2014; Gao et al., 2012). As a result of temperature increase surface water temperature can rise, this in part causing phytoplankton blooms (Duteil, Macias, Stips, & Polimene, 2024). A phytoplankton bloom is a rapid increase in phytoplankton biomass (Peperzak, 2003). Climate change, logically, has made the conditions more beneficial for phytoplankton blooms as ocean temperatures rise (Peperzak, 2003).

Furthermore, light availability is essential for photosynthesis and therefore an important factor for influencing phytoplankton growth (Singh et al., 2008). Light is most abundant at the surface, where penetration is less obstructed. However, sediment or organic matter can attenuate light, reducing light availability in deeper water layers (Wood & Smith, 2022). Conversely, excessive UV radiation can damage photosynthetic machinery, which could negatively affect phytoplankton growth (Singh et al., 2008).

To be able to facilitate growth, nutrients are needed such as nitrogen, phosphorus, and iron. Nutrients are one of the main limiting factors for phytoplankton growth (Duteil, Macias, Stips, & Polimene, 2024). Beman et al. (2005) and Hutchins et al. (2010) demonstrated that phytoplankton growth rates increase when nutrients are sufficiently available. This positive correlation indicates that phytoplankton growth rates decrease under lower nutrient availability conditions. Discharges of rivers are an important source of nutrients. On large spatial and temporal scales, greater phytoplankton abundance usually indicates increased nutrient availability (Blauw, 2015). Additionally, Beman et al. (2005) and Hutchins et al. (2010) explain how nutrient availability can influence light abundance within the water column, as explained above, having a negative effect on phytoplankton growth.

Additionally, some drivers have smaller influences but do need to be taken into consideration. Pollution, for example, heavy metals, organic pollution, or oil spills, usually inhibit growth (Huang et al., 2011). This inhibition of growth is strengthened by increased UV exposure and higher temperatures (Echeveste et al., 2011). Also, water chemistry and ocean acidification have an influence on the rate of growth for certain species, impairing some and benefitting others based on light and temperature conditions (Gao & Campbell, 2014).

All drivers are influenced by the extent of vertical mixing of the water column. When mixing is inhibited, stratification occurs. Stratification can affect phytoplankton growth and biomass by controlling the light supply for photosynthesis and nutrient supply from the subsurface ocean (Yamaguchi et al., 2019). Strengthened stratification may produce better light availability for the phytoplankton by creating a lighter, well-lit upper layer, but it also prevents vertical nutrient supply to the surface, which decreases surface nutrient availability (Doney, 2007).

Seasonality of phytoplankton

During the year, different conditions occur influencing phytoplankton biomass. Therefore, phytoplankton growth depends on seasonal and interannual climatological cycles which determine availability in nutrients and light (van de Poll et al., 2013).

In the spring, when temperatures rise and eutrophic conditions are present, phytoplankton blooms occur, also known as spring blooms (Brussaard et al., 1996). Rapid consumption of nutrients during spring blooms drives the system toward a more oligotrophic (nutrient-poor) state by summer (Kuipers & Witte 1999). Consequently, Kuiper and Witte (1999) report that smaller-sized phytoplankton dominate in summer, due to reduced nutrient availability and are controlled by grazing of microzooplankton, thereby limiting the increase of phytoplankton biomass.

In the winter, phytoplankton biomass is generally lower due to several environmental conditions as explained by Behrenfeld & Boss (2014) and Sverdrup (1953). They explain how lower light availability reduces photosynthetically active radiation and limits photosynthesis. Also, lower temperatures slow metabolic and growth rates of phytoplankton. Additionally, nutrient distribution due to mixing causes constant vertical displacement, preventing phytoplankton from efficiently accessing nutrients. Lastly, strong vertical mixing, due to storms and wind driven turbulence, mix phytoplankton throughout the water column, including deeper, darker layers, reducing the time phytoplankton cells spend in the light-rich surface (van de Poll et al., 2013).

2.2 Stratification processes

Definition of stratification and pycnocline

Stratification is an important physical process within marine ecosystems that influences vertical mixing within the water column. Vertical mixing regulates light and nutrient availability in the different layers of the water column. Temperature variation is one indicator of stratification. Zones with sharp temperature gradients are called thermoclines, with greater gradients indicating greater stratification (Fiedler, 2010). According to Blauw (2015), stratification is present when the water column can be divided into different layers. Typically, the water column can be divided into three layers. The upper layer, the epilimnion, is well-mixed and layered. As explained by Blauw (2015), the bottom layer, or hypolimnion, is colder and denser. Between the hypolimnion and the surface layer lies the transition layer, the metalimnion, which is commonly referred to as the pycnocline, defined by density differences.

Density differences can also occur due to temperature and salinity differences. Solar radiation absorbed by the upper layer can cause temperature differences between upper and lower layers. As warm water is less dense, a temperature driven stratification, thermocline can occur (Zhang et al., 2023). Density differences, with heavier, more saline water near the bottom and lighter, less saline water near the surface, induce temporary salinity stratification (Li et al., 2020). According to Sprintall and Cronin (2009), a thermocline is the transition layer defined by temperature gradients, while a halocline is defined by salinity gradients. The pycnocline, based on density gradients, represents the layer in the water column where density increases most rapidly with depth, as illustrated in Figure 5. Identification of the pycnocline follows a set protocol, which will be explained in the methodology section. However, finding a specific threshold value to determine a pycnocline is still a challenge.

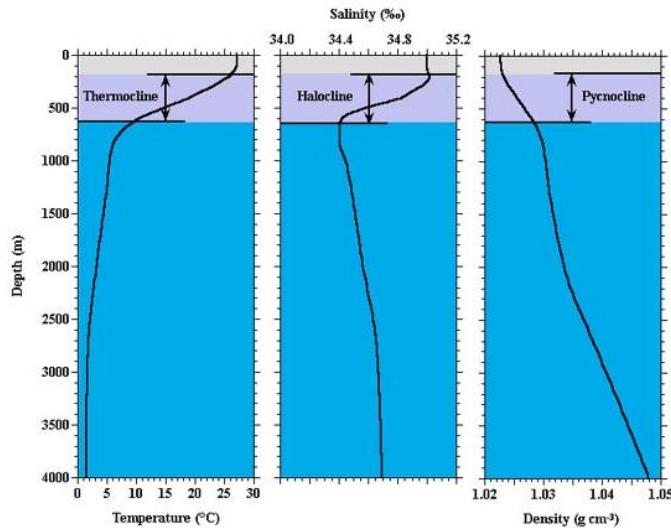


Figure 5: Vertical profiles showing changes in temperature, salinity, and density with depth, illustrating the thermocline, halocline, and pycnocline based on the corresponding gradients (Flanders Marine Institute, 2008).

These stratified configurations can act as a barrier to water mixing which impact the efficiency of vertical exchange of heat, nutrients, oxygen and carbon (Li et al., 2020). This in part can influence the growth of phytoplankton. The relationship between stratification and phytoplankton is explained in section 2.3.

Seasonal stratification occurs in the deeper areas of the Dutch Continental Shelf during spring and summer. This type of stratification is common in shelf-seas like the North Sea (Holt & Umlauf, 2008). Due to solar heating, when heating is significant enough to overcome mixing forces, the surface layer increases in temperature (Sharples et al., 2006; Holt & Umlauf, 2008). Simpson & Hunter (1974) propose that when the depth of a water column is small enough or vertical velocity is great enough, mixing will occur. The southern part of the North Sea is relatively shallow and has relatively large tidal ranges. Towards the north, the sea becomes gradually deeper, with lower tidal ranges. Therefore, the southern part of the North Sea can develop vertical mixing year-round, whereas the northern part can develop seasonal stratification (van Leeuwen et al., 2015). Modelled stratification zones within the North Sea can be seen in Figure 6.

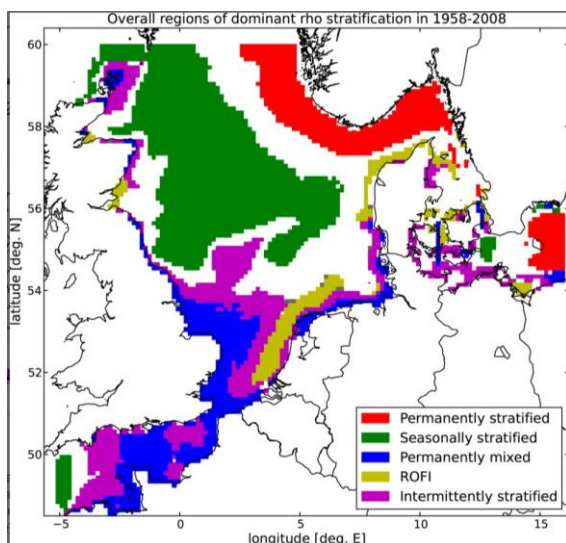


Figure 6: Modelled stratification zones dominated by density-based (ρ) stratification, where ROFI stands for Region of Freshwater Influence (van Leeuwen et al., 2015).

In Figure 6, the various stratification zones dominated by density (ρ) is shown. In the ROFI zone (Region Of Freshwater Influence), a plume occurs along the shallow Dutch coast. This plume causes temporary salinity stratification due to the input of nutrients discharged from the rivers (van Leeuwen et al., 2015). For offshore locations, stratification is driven by temperature (Simpson et al., 1993; De Boer et al., 2009).

Seasonality of stratification

Thermo- and haloclines, density difference in the water column, are influenced by temperature and river discharge, and the seasonality of these parameters explains the observed patterns of pycnocline occurrence. Stratification begins in spring and strengthens during summer due to higher summer temperatures, with deeper parts of the shelf seas becoming thermally stratified (Ruudij, Van Haren, & Ridderinkhof, 1997; van de Poll et al., 2013). Stratification usually occurs until autumn, when temperatures drop and wind-driven mixing increases. The spring wind regime can advance or delay the onset of stratification (Ruudij, Van Haren, & Ridderinkhof, 1997). In addition, significant warming resulting from global climate change is expected to continue over the coming decades. This warming has already caused a global increase in stratification in oceans in recent decades, primarily due to temperature changes, although local variations in salinity also play an important role in increased stratification (Li et al., 2020; van de Poll et al., 2013).

2.3 Relationship between phytoplankton and stratification

The concepts of phytoplankton growth and stratification occurrence have been discussed separately. However, their interaction is crucial to understanding the dynamics studied in this research. When a pycnocline is present, the water column can be divided into three layers: the surface layer, the pycnocline (or thermocline), and the deep-water layer as seen in Figure 7. When stratification occurs the convection between surface and deeper layers is inhibited (van de Poll et al., 2013). A stable upper layer allows phytoplankton to remain in well-lit and nutrient-rich surface layer, where light exposure and nutrient availability promotes photosynthesis and rapid growth, initiating the spring bloom (Sharples et al., 2006; van de Poll et al., 2013).

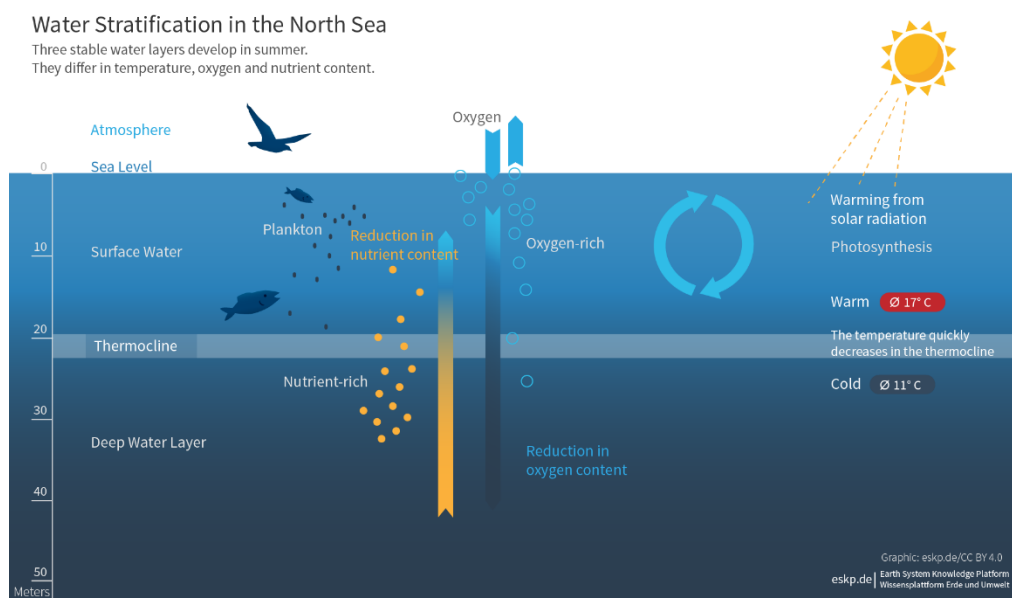


Figure 7: Water stratification in the North Sea, showing three distinct layers, each with their own characteristic properties. The exchange of nutrients, phytoplankton, and oxygen between them is illustrated (Earth System Knowledge Platform [ESKP], n.d.).

Additionally, stratification inhibits the exchange of nutrients between deeper-water layers and the surface water layer (Li et al., 2020; Sverdrup, 1953). As a consequence, phytoplankton at the surface will deplete the availability of nutrients due to their consumption (Ruurdij, Van Haren, & Ridderinkhof, 1997; Sverdrup, 1953), as illustrated in Figure 7.

When nutrients are not sufficiently available in the surface water layer, phytoplankton will migrate towards a location in the water column where an optimal balance between light and nutrient availability is present (Cullen, 2015). This can result in a subsurface chlorophyll-a maximum, commonly referred to as a Deep Chlorophyll Maximum (DCM). The DCM often forms at a depth where nutrient availability and light are sufficient for photosynthesis, which typically occur near the pycnocline (Cullen, 2015). Therefore, the DCM is a result of the occurrence of pycnocline formation. Phytoplankton can cross through sinking or active motility (Pan, 2022). DCM can be a combination of active positing by living phytoplankton and settling sinking dead cells.

In the deeper layers of the water column, oxygen depletion can occur in stratified areas as oxygen exchange is not possible from surface to deeper layers due to the presence of the pycnocline, as illustrated in Figure 7 (Dominović et al., 2023; Emeis et al., 2015). Moreover, dead phytoplankton in the deeper water layer also lead to oxygen depletion as bacteria degrading dead phytoplankton into organic matter consume oxygen (Dominović et al., 2023; Huthnance et al., 2016).

3. Methodology

This study used sensor data from vertical CTD profiles collected as part of the Rijkswaterstaat monitoring programme. The CTD profiles provided measurements of temperature, salinity, and chlorophyll-a fluorescence throughout the water column. First, these measurements were processed to calculate seawater density from temperature and salinity. Subsequently, area-specific density gradient thresholds were determined to distinguish stratified from non-stratified conditions. These thresholds were then used to identify pycnoclines based on the maximum density gradient and to determine chlorophyll-a maxima. Following data preparation, quality control, and threshold determination, the processed profiles were analysed to investigate the spatial and temporal variability of stratification and phytoplankton dynamics. Three analyses were subsequently performed. First, pycnocline occurrence and depth were quantified to describe patterns in water column stratification for the profiles observed. Second, chlorophyll-a maxima and their relationship with pycnocline depth were investigated in profiles containing a pycnocline. Finally, a sensitivity analysis was performed to evaluate whether near-surface chlorophyll-a concentrations could represent subsurface chlorophyll-a maxima. Based on these results, the representativeness of the current vertical CTD measurements and sampling strategy and the applicability of satellite-based monitoring were assessed.

3.1 Study area and monitoring programme

Monitoring locations

Rijkswaterstaat conducts measurements at various locations on the Dutch Continental Shelf (DCS). Figure 8 shows the different measurements locations included in this study. These locations are part of the DCS monitoring network and provide the observational data used in this study.



Figure 8: Rijkswaterstaat monitoring locations on the Dutch Continental Shelf, showing the different measurements and their respective annual (sampling) frequencies (indicated with 1 and 2) at each monitoring location. Blue indicates routine CTD vertical profiling/measurements and surface water sampling conducted at all locations. Orange indicates additional water sampling, which is performed only when a pycnocline is detected at the offshore TERSLG stations (TS50–TS235).

Throughout this study, abbreviated location codes are used instead of the full monitoring location names shown in Figure 8. Table 1 provides an overview of the monitoring location names, the corresponding location codes, and their meanings.

Table 1: overview of the monitoring location names, the corresponding location codes, and their meanings.

Location name	Location code	Meaning
WALCRN2	WC2	Walcheren, 2 km offshore
WALCRN20	WC20	Walcheren, 20 km offshore
WALCRN70	WC70	Walcheren, 70 km offshore
SCHOUWN10	SW10	Schouwen, 10 km offshore
GOERE2	GR2	Goeree, 2 km offshore
GOERE6	GR6	Goeree, 6 km offshore
NOORDWK2	NW2	Noordwijk, 2 km offshore
NOORDWK10	NW10	Noordwijk, 10 km offshore
NOORDWK20	NW20	Noordwijk, 20 km offshore
NOORDWK70	NW70	Noordwijk, 70 km offshore
TERSLG10	TS10	Terschelling, 10 km offshore
TERSLG50	TS50	Terschelling, 50 km offshore
TERSLG100	TS100	Terschelling, 100 km offshore
TERSLG135	TS135	Terschelling, 135 km offshore
TERSLG175	TS175	Terschelling, 175 km offshore
TERSLG235	TS235	Terschelling, 235 km offshore

Data collection

Rijkswaterstaat uses two measurement methods to determine phytoplankton abundance (i.e., phytoplankton biomass). Abundance is determined using chlorophyll-a fluorescence, which is measured by a sensor (fluorometer). Alternatively, the analytical chlorophyll-a concentration can be determined by analysing water samples in the lab using glass fibre filters. Both methods are conducted with a research vessel locally, also known as in-situ.

According to the standard monitoring protocols of Rijkswaterstaat¹² (Rijkswaterstaat, 2025-a), vertical measurements (throughout the whole water column) are carried out at each monitoring location using a CTD (Conductivity, Temperature, Depth) profiling system (indicated with blue symbols in Figure 8). A SeaBird CTD system, including different sensors, is used to record various physical and biogeochemical parameters, such as temperature, depth, conductivity, chlorophyll fluorescence, and dissolved oxygen. Seabird CTD measurements are collected alongside light attenuation measurements, where vertical profiles of different parameters are automatically recorded as part of the light attenuation measurement procedure of Rijkswaterstaat. In addition, water samples are collected at approximately 3.5 meter below the water surface at all locations using Niskin bottles. These samples are analysed in the laboratory, where chlorophyll-a concentrations are determined by laboratory analysis of the material retained on glass fibre filters following filtration of the water samples using high-performance liquid chromatography (HPLC).

At a subset of the monitoring locations, additional sampling is performed when a pycnocline is present (indicated with orange symbols in Figure 8). The presence of a pycnocline is identified during the sampling by visual examination of the vertical temperature profile obtained from the vertical CTD measurements. A peak in the in-situ fluorescence profile, measured by the CTD-mounted fluorometer, is used to identify the depth at which a water sample is collected using Niskin bottles attached to a rosette sampler. When stratification occurs, an additional sample is taken approximately 3 meters above the seabed. Visualizations of the monitoring procedure described above are provided in Appendix 1.

All data used in this study were retrieved from the Rijkswaterstaat data archive system (WADAR). Data collection was conducted prior to this research by Rijkswaterstaat as part of its long-term monitoring programme as explained above. Consequently, no field measurements were carried out specifically for this study. The CTD profiles and associated chlorophyll-a fluorescence measurements collected through this monitoring programme form the basis of the dataset used in this study. The composition and characteristics of this dataset are described in the following section (section 3.2).

3.2 Dataset

The data of the CTD vertical measurements are stored in CSV format following preprocessing into a cleaned and compiled dataset provided by Rijkswaterstaat. A separate file is available for each monitoring location, covering the period 1995–2024 (measurement frequency ranges from once to 33 times per year). These files contain multiple parameters, including temperature, salinity, depth, and chlorophyll-a fluorescence, measured at various depths relative to the water surface. This continuous monitoring results in a vertical profile for each location. A vertical profile consists of a series of

¹ Standard monitoring protocol for chemical measurements: *rwsv_913-00-w015_bepaling_fysisch-chemische_veldparameters_v4* (2025); *rwsv_913-00-w016_monsterneming_van_steekmonsters_oppervlaktewater_met_een_niskin-fles_of_rosette* (2024)

² Standard monitoring protocol for biological measurements: *rwsv-913-00-b070-bemonstering-fytoplankton-zout-en-brak* (2025)

measurements collected throughout the water column, from the surface to the seabed, at a specific location and point in time. It describes how a particular water property, such as temperature, salinity, or chlorophyll-a fluorescence, varies with depth. These measurements can be visualized by plotting the parameter values against depth. Figure 9 presents an example of vertical profiles for temperature, salinity, density, and chlorophyll-a fluorescence.

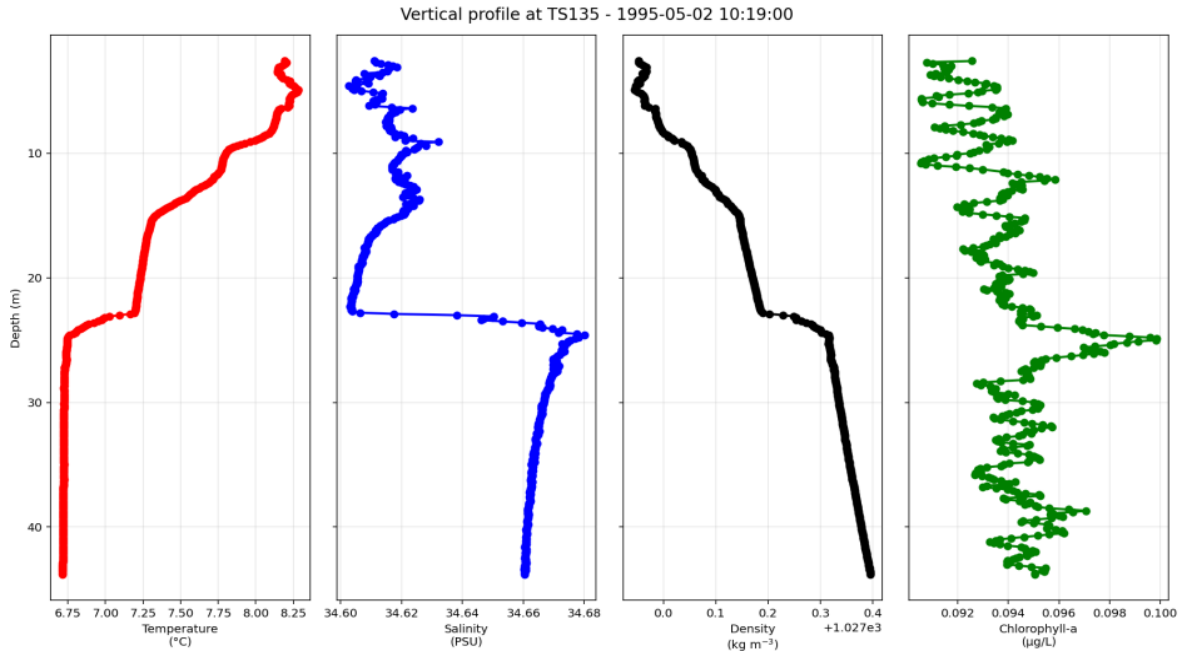


Figure 9: Example of a vertical CTD profile at station Terschelling 135, displaying temperature ($^{\circ}\text{C}$), salinity (PSU), density (kg/m^3) and chlorophyll-a fluorescence ($\mu\text{g}/\text{L}$) against depth (m).

The frequency of measurements varies considerably between monitoring locations and over time. Figure 10 shows the number of available vertical profiles collected at each monitoring location per year. Substantial variation in data availability can be observed, with some locations and years being represented considerably more than others. Figure 10 presents the measurement frequency for temperature profiles. Equivalent figures for salinity and chlorophyll-a fluorescence are provided in Appendix 2. Although minor differences exist between these datasets, they exhibit similar patterns in measurement frequency and data availability.

year	GR2	G6	NW10	NW20	NW2	NW70	SW10	TS100	TS10	TS135	TS175	TS235	TS50	WC20	WC2	WC70
1995			13	5	5	7	3	11	9	10	11	8	7	6	5	1
1996			28	9	16	9	2	12	6	12	12	10	3	3	3	2
1997			33	13	17	16		12	6	14	12	11	2	3	6	3
1998		3	22	8	9	9		9	4	12	9	8	2	2	4	1
1999																
2000																
2001																
2002																
2003		12	21	9	11	6	5	7	7	10	8	6	5	5	7	2
2004		5	18	9	12	9	3	9	3	11	10	10	1	2	4	5
2005		3	15	6	8	7	3	9	6	9	7	8	3	2	3	3
2006		5	11	7	8	3	3	10	4	10	9	7	2	2	3	1
2007																
2008	3	3	13	9	6	9	3	11	3	13	12	9	4	2	3	2
2009			3		1	1		7	1	11	7	8				
2010			2	1	1			3	1	4	2	2	1			
2011			1		2			5		5	3	3	1			1
2012								4		4	3	3				
2013	2	1	6	6	5	4	3	3	4	4	1	1	5		1	2
2014	1	2	7	11	7	5	5	9	8	7	2	2	9	2	1	4
2015	1	1	9	12	5	7	2	7	4	6	4	1	5	1	1	2
2016	4	3	12	10	8	7	7	5	7	3	1	1	8		3	3
2017			2	1			2	1	1				1		1	
2018	1	1	3	4	3	1	1	1	1	1	1		1			
2019	1		15	16	16	6	5	5	8	7	2	3	8	2	1	5
2020	7	6	7	7	7	1	6	5	3	2		1	5		4	1
2021	8	8	12	12	15	6	6	2	4	4	2	2	7		7	4
2022	3	4	11	10	9	4	3	4	4				5		3	2
2023	3	2	7	7	6	1	3	3	2	4		1	4		3	1
2024	5	4	6	5	7	6	3	2	3	2	1	1	5	1	2	2

Figure 10: Measurement frequency (number of available vertical profiles) of temperature profiles at each monitoring location per year.

3.3 Data preparation

Data preprocessing

Prior to analysis, the CTD vertical measurement data were imported into Spyder/Python (version 6) from 16 individual CSV files. The dataset was then pre-processed to ensure consistency and reliability. The steps were as follows:

- Variables such as date, location, depth, temperature, salinity, and chlorophyll-a fluorescence were standardised and harmonised to ensure comparability across measurements.
- Additional variables, including year, month, and season, were derived from the sampling date to enable temporal analysis.
- Quality control procedures were applied to identify unrealistic measurements, and potential outliers, as described in the data filtering section below.

Data filtering

Vertical profiles containing unrealistic measurements (e.g. too high) were removed based on predefined filtering criteria adapted from a comparable CTD-based study by Deltarees that investigated pycnocline depth at two monitoring locations (Hendriks et al., 2020). Vertical profiles were excluded when more than 10% of salinity measurements exceeded 50 PSU or when more than 10% of temperature measurements exceeded 30 °C. In addition, profiles with a total depth of less than 5 m were removed, as these profiles provide limited information on vertical water column structure. The number of removed profiles are provided in Appendix 3.

Spatial classification

To characterise the distribution of environmental conditions across monitoring locations, exploratory boxplots of median salinity, temperature, and chlorophyll-a fluorescence values were constructed. For each vertical profile, the median value of each parameter was calculated and subsequently visualised using boxplots. The median was calculated because it provides a robust measure of the central tendency and is less affected by extreme values or outliers than the mean. These boxplots were used to identify broad spatial patterns within the dataset and to distinguish coastal from offshore

monitoring locations. This distinction resulted in two subsets, which were used for the subsequent data analysis. This spatial classification was primarily based on differences in salinity and chlorophyll-a fluorescence distribution.

Density calculation

For profiles containing both temperature and salinity measurements, seawater density was calculated using the Gibbs SeaWater (GSW) Python toolbox, which implements the Thermodynamic Equation of Seawater 2010 (TEOS-10). Prior to the density calculations, depth measurements were converted from centimetres to metres to ensure consistency in the analysis. The resulting density profiles were used to investigate vertical stratification patterns and to identify pycnoclines throughout the study area. Density was selected as the primary indicator of stratification because density gradients are widely used to detect stratification and pycnocline formation in marine environments (de Boyer Montégut et al., 2004; Kara et al., 2000). Profiles lacking either temperature or salinity measurements were not used for density calculations and were therefore excluded from subsequent analyses. An overview of the excluded profiles is provided in Appendix 4. The distribution of calculated density values across monitoring locations is also presented in Appendix 4.

3.4 Threshold determination

Thresholds for pycnocline occurrence were derived from the dataset using a literature-based stratification indicator as an initial step towards defining an exploratory threshold, as no universally applicable thresholds are available in the literature for the specific study area. First, vertical density variability was calculated for each profile as the difference between the 95th and 5th percentiles, thereby reducing the influence of extreme values in the upper and lower tails of the distribution. Based on this measure, profiles were classified as either stratified or mixed using a threshold value of 0.086 kg m^{-3} , adopted from Van Leeuwen et al. (2015). Profiles below this threshold were considered non-stratified and were excluded from further threshold determination.

For the remaining stratified profiles, the maximum density gradient was calculated for each vertical profile as:

$$X = \max\left(\frac{d\rho}{dz}\right)$$

This represents the point in the water column where density changes ($d\rho$) most rapidly with depth (dz) and is used to identify the position and intensity of the pycnocline (de Boyer Montégut et al., 2004; Kara et al., 2000). The approach follows methods adapted from a comparable CTD-based study by Deltare and is consistent with existing literature. To reduce noise in the vertical density profiles, a Savitzky–Golay filter (Orfanidis, 1996) was applied using a 30-point moving window and a third-order polynomial, following Gregor et al. (2019).

The Savitzky–Golay filter is a smoothing technique that preserves the overall shape of the profile while reducing measurement noise. Unlike a moving average, the filter fits a polynomial to a moving window of data points and uses this polynomial to estimate smoothed values. Without smoothing, small measurement errors can generate artificial gradients, potentially leading to incorrect identification of pycnoclines. After smoothing, the derivative ($d\rho/dz$) was calculated from the fitted polynomial, representing the local slope of the smoothed density profile. This resulted in a large number of density gradient values along each individual vertical profile. The maximum density gradient was then extracted from each profile and used to quantify the strength and vertical position of the pycnocline.

For both subsets, coastal and offshore, distributions of maximum density gradients were examined. As the distributions were skewed, outliers were removed and the distributions were reassessed (Appendix 5). Finally, sensitivity analyses were performed using lower percentile thresholds (based on 2.5th percentile, 5th percentile, 10th percentile, and 20th percentile) to evaluate the robustness of the classification (see Table 2). Based on these analyses, final threshold values were defined as 0.029 kg m⁻³ for coastal stations and 0.006 kg m⁻³ for offshore stations. Validation of these thresholds took place by expert visual inspection and checking vertical profiles.

Table 2 Percentile-based threshold values (kg m⁻³) derived from the distributions of maximum density gradients for coastal and offshore dataset after outlier removal.

Dataset	P2.5	P5	P10	P20
Coastal	0.014	0.019	0.029	0.048
Offshore	0.005	0.005	0.006	0.009

3.5 Data analysis

Pycnocline occurrence

The determined threshold values were applied to the calculated max density gradients, and a Boolean index (true or false) was used to determine whether a pycnocline was present or not. Based on this classification, the percentage of pycnocline occurrence was calculated per month and per monitoring location. This involved counting the number of profiles classified as True (indicating the presence of a pycnocline) for each month per location. The percentage of pycnocline occurrence was then calculated relative to the total number of profiles per month per location visualized by bubble plots. Furthermore, additional maps were created to visualize the spatial differences in pycnocline occurrence between locations based on quartiles. The same method used to calculate the monthly percentage of pycnocline occurrence was applied, but here it was performed separately for each quartile. This approach allowed for the analysis of spatial and temporal differences between monitoring locations and months.

Pycnocline depth

The pycnocline is a depth range within the water column. However, for this analysis the pycnocline depth was defined, as one position. The pycnocline depth used is the depth at which the maximum density gradient occurs, representing the location within the water column where density changes most rapidly with depth. This value was determined for each individual vertical profile. Mean pycnocline depths were then calculated per month for each monitoring location in order to analyse spatial and temporal patterns in pycnocline depth.

Maximum chlorophyll-a concentration and depth

Chlorophyll-a maxima, also referred to as the DCM, were determined for each vertical profile using chlorophyll-a fluorescence data. Only profiles containing a pycnocline were considered for this analysis. For each selected profile, the maximum chlorophyll-a concentration was extracted, resulting in a single value per profile. This approach allowed a consistent quantification of the DCM associated with stratified conditions. Maximum chlorophyll-a concentrations were aggregated on a monthly basis per monitoring location to calculate monthly mean values. This data was used to enable spatial comparisons between monitoring locations and seasonal analyses of maximum chlorophyll-a variability.

Chlorophyll-a depth was defined as the depth corresponding to the maximum chlorophyll-a concentration within each vertical profile. Mean maximum chlorophyll-a depth was then calculated

per month for each monitoring location in order to analyse spatial and temporal patterns in maximum chlorophyll-a depth.

Correlation pycnocline depth and maximum chlorophyll-a depth

Spearman's rank correlation was used to assess the relationship between maximum chlorophyll-a depth and pycnocline depth, as a linear relationship was not assumed and the data were not normally distributed. Scatterplots were used to visualize the data. In addition, linear regression was applied to evaluate whether chlorophyll-a maxima occur above or below the pycnocline and to quantify the directional relationship between both variables. Due to potential non-linearities, this linear regression should be interpreted as a first-order approximation of the relationship.

In addition, boxplots were made to illustrate the depth difference between the pycnocline depth and maximum chlorophyll-a depth (DCM depth). The depth difference was calculated and plotted for each quartile and for each monitoring location.

Pairwise similarity matrices

Pairwise similarity matrices have been constructed to compare monitoring locations based on their mean maximum chlorophyll-a depth and mean pycnocline depth. The matrix was used to assess if patterns are consistent across locations, as described by Mazurek (2023). The pairwise similarity matrix has been used to show similarity of general spatial patterns in mean maximum chlorophyll-a depth and mean pycnocline depth across monitoring locations.

Due to variability in the data, a standardization was applied using z-scores. The formula used is shown below.

$$z_{ik} = \frac{X_{ik} - \bar{X}_k}{\sigma_k}$$

Within the formula, z_{ik} represents the standardized score calculated for each depth. X_{ik} is the mean value of parameter k , as there are two parameters, at location i . $\bar{X}_k$ is the mean for each parameter k . σ_k is the standard deviation for parameter k . By applying standardization each parameter contributed equally towards the comparison between locations. For each pair of locations, the distance between the mean maximum chlorophyll-a depth and the mean pycnocline depth was calculated. The pairwise similarity score was used to assess the similarity of the calculated distances across all locations. The similarity score is between 0 and 1, respectively low and high similarity.

Vertical distribution analysis

Using near-surface chlorophyll-a concentrations could be helpful within monitoring strategies, particularly because satellite remote sensing mainly provides information about chlorophyll-a concentrations in the upper part of the water column. For each location, a sensitivity analysis was conducted to assess how well mean chlorophyll-a concentrations in the upper water column represented the maximum chlorophyll-a concentration observed across the full water column. The upper-water-column layers assessed within the sensitivity analysis were 0–1 m, 0–2 m, 0–3.5 m, and 0–5 m. First, the mean chlorophyll-a concentration within each selected depth range of the upper-water column was calculated for every profile. Next, the maximum chlorophyll-a concentration within each profile was determined. These values were compared using Spearman's ρ , the corresponding p-value, R^2 , root mean square error (RMSE), and mean bias error. The results were presented in a table for all locations. This analysis indicated where and to what extent near-surface chlorophyll-a measurements could serve as a proxy for the maximum chlorophyll-a concentration, thereby providing insight into the applicability and limitations of satellite-based monitoring.

4. Results

In this section the results of the research are shown and explained.

4.1 Spatial classification

Figure 11 shows the distribution of the median salinity per vertical profile for each monitoring location. Median salinity increased gradually from the coastal towards the offshore locations, ranging from approximately 30 PSU at NW2 to around 35 PSU at the most offshore stations (TS235, WC70 and NW70). The spread in median salinity was largest at the coastal locations and became progressively smaller offshore, as reflected by the decreasing interquartile ranges and whisker lengths. Outliers occurred at most monitoring locations but were more frequent and more extreme at the coastal locations than at the offshore locations.

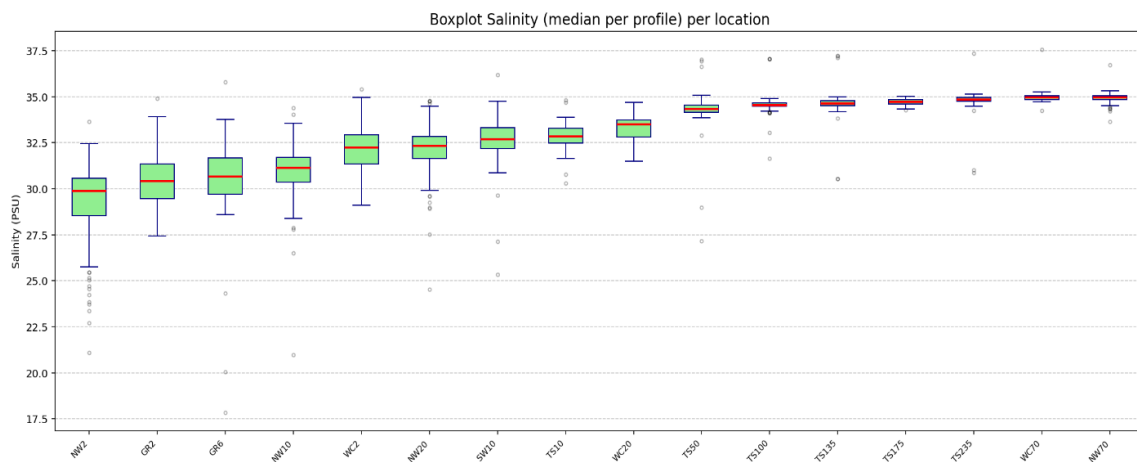


Figure 11: Distribution of median salinity values per vertical profile across monitoring locations. Boxplots show the median (red line), interquartile range (box), whiskers, and outliers of salinity measurements (PSU) for each location. Monitoring locations are ordered according to increasing median salinity.

Figure 12 shows the distribution of the median chlorophyll-*a* concentration per vertical profile for each monitoring location. Median chlorophyll-*a* concentrations are lower at offshore locations and increase towards the coastal locations, with the lowest median values observed at the offshore Terschelling locations and the highest median values at GR2, GR6 and NW20. The variability in chlorophyll-*a* concentrations also increased towards the coast, as reflected by wider interquartile ranges, and longer whiskers. While outliers occurred throughout the monitoring network, the largest values ($>20 \mu\text{g L}^{-1}$) are restricted to the coastal locations.

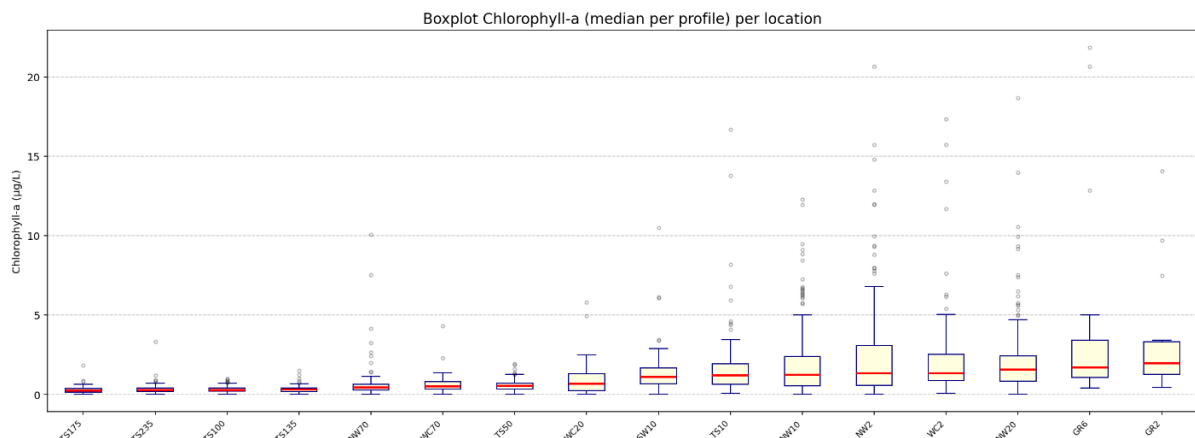


Figure 12: Distribution of median chlorophyll-*a* values per vertical profile across monitoring locations. Boxplots show the median (red line), interquartile range (box), whiskers, and outliers of chlorophyll-*a* measurements ($\mu\text{g/L}$) for each location. Monitoring locations are ordered according to increasing median chlorophyll-*a*.

Figure 13 presents the spatial classification of the monitoring locations used in this study. Based on the spatial patterns observed in the salinity and chlorophyll-*a* boxplots (Figures 11 and 12), a jump can be observed. The monitoring locations were classified into coastal and offshore groups. Locations within 20 km of the coastline were classified as coastal, whereas locations located more than 20 km offshore were classified as offshore. This classification was used in all subsequent analyses. The distribution of the median temperature per vertical profile for each monitoring location can be found in Appendix 6.



Figure 13: Spatial classification of coastal and offshore measurement locations on the Dutch Continental shelf. Orange represents the coastal locations and purple the offshore locations.

4.2 Pycnocline occurrence

Figure 14 shows the pycnocline occurrence at coastal locations. Pycnoclines are observed in 80–100% of profiles at several locations. Larger bubbles indicate a greater number of available profiles and therefore a more robust estimate of occurrence. NW10, NW20, and NW2 generally exhibit high pycnocline occurrence throughout the year, whereas GR2, GR6, WC2, and WC20 show lower and more variable occurrence. Across all locations, pycnocline occurrence is lowest during winter and highest during summer months.

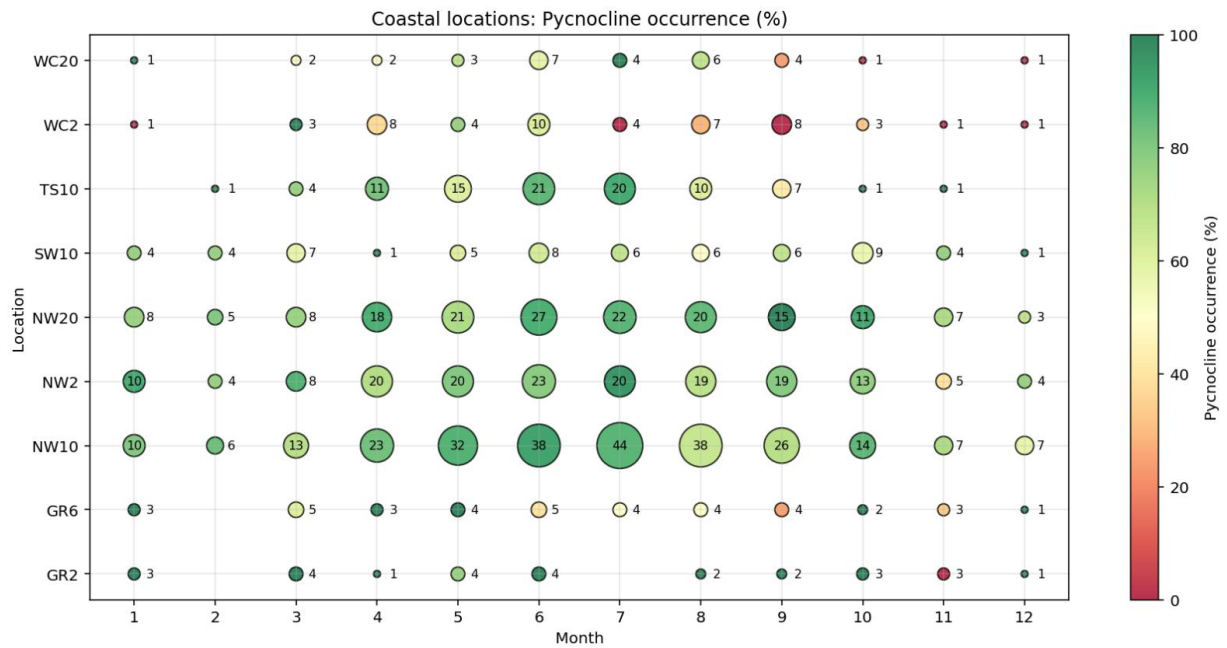


Figure 14: Monthly pycnocline occurrence (%) at coastal monitoring locations. Bubble colour indicates the percentage of profiles containing a pycnocline, ranging from low occurrence (red) to high occurrence (green). The bubble size represents the number of available profiles and the robustness of the occurrence estimation. The exact number of profiles is shown within or next to each bubble. Months 1 to 12 correspond to January through December.

Figure 15 shows the monthly pycnocline occurrence at offshore monitoring locations. Most offshore stations exhibit pycnoclines in nearly all profiles during the summer months, with occurrence values frequently approaching 100%. Across all offshore locations, pycnocline occurrence is lowest during winter and highest during summer. The highest occurrence values are observed at TS100, TS135, TS175, and TS235, whereas WC70 and NW70 generally show lower occurrence. Compared to the coastal stations, offshore locations exhibit higher pycnocline occurrence overall, particularly during the summer months.

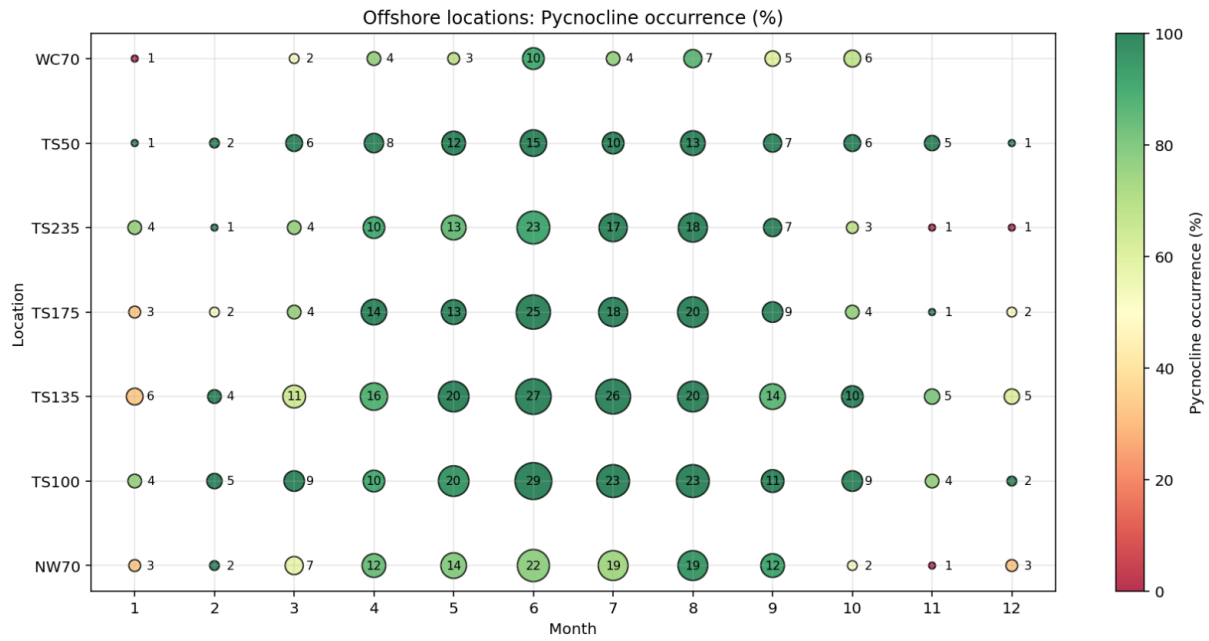
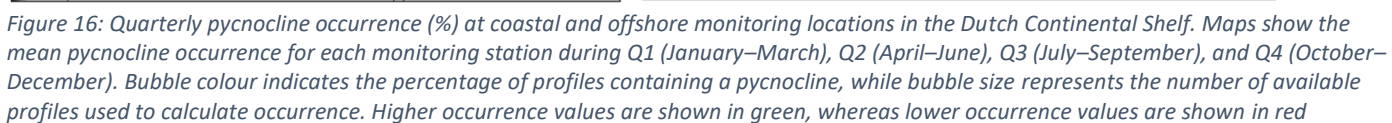


Figure 15: Monthly pycnocline occurrence (%) at offshore monitoring locations. Bubble colour indicates the percentage of profiles containing a pycnocline, ranging from low occurrence (red) to high occurrence (green). The bubble size represents the number of available profiles. The exact number of profiles is shown within or next to each bubble. Months 1 to 12 correspond to January through December.

During Q1 and Q4, pycnocline occurrence was generally lower and more variable among locations. In Q4, relatively high occurrence remained visible at TS50, TS100 and TS135, while lower values occurred at TS175, TS235, NW70 and several coastal stations. The number of available profiles also varied among quarters, with generally fewer observations in Q1 and Q4 than in Q2 and Q3.



4.3 Pycnocline depth

Figure 17 shows the monthly mean pycnocline depth, from the surface, at coastal monitoring locations. Pycnocline depths at coastal locations generally range between approximately 2 and 10 metres below the water surface. Temporal variability is relatively limited, although some seasonal fluctuations are observed between locations. The magnitude and timing of these fluctuations vary among locations.

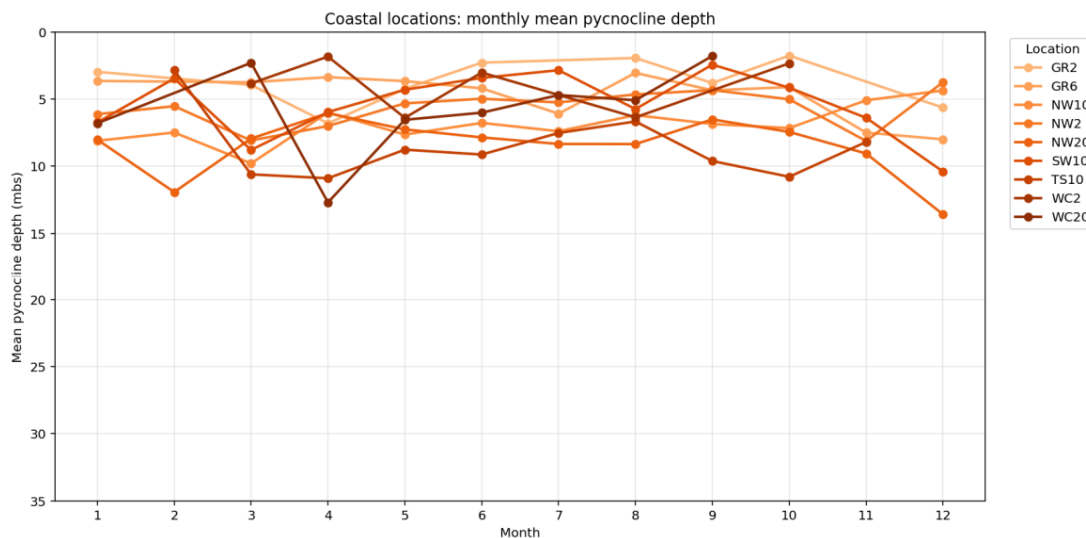


Figure 17: Monthly mean pycnocline depth in metres below the surface (mbs) at coastal monitoring locations. Each line represents a monitoring location and points indicate the mean pycnocline depth calculated from all profiles containing a pycnocline within a given month. Months 1 to 12 correspond to January through December.

Figure 18 shows the monthly mean pycnocline depth at offshore monitoring locations. Offshore monitoring locations generally exhibit substantially deeper pycnoclines than coastal locations, with depths frequently exceeding 20 metres and reaching approximately 30 metres at several locations. In addition, offshore locations show greater temporal variability in pycnocline depth throughout the year and a clear distinction between locations during the summer months. Some locations, including TS100, TS135, and TS175, exhibit deeper pycnoclines during the summer months, whereas locations including TS235, TS50, WC70, and NW70 show generally shallower pycnocline depths during the summer.

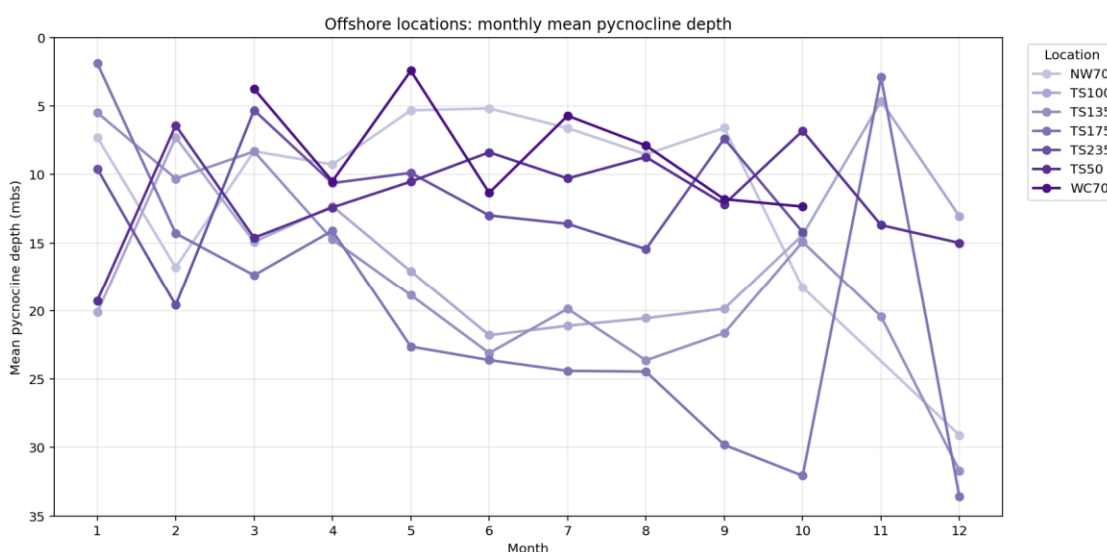


Figure 18: Monthly mean pycnocline depth in metres below the surface (mbs) at offshore monitoring locations. Each line represents a monitoring location and points indicate the mean pycnocline depth calculated from all profiles containing a pycnocline within a given month. Months 1 to 12 correspond to January through December.

Comparing coastal and offshore locations reveals clear differences in pycnocline depth. Offshore locations consistently exhibit deeper pycnoclines than coastal measurement locations. Furthermore, seasonal fluctuations in pycnocline depth are generally more pronounced at offshore locations than at coastal locations.

4.4 Maximum chlorophyll-a concentration

Figure 19 shows the monthly mean maximum chlorophyll-a concentration at coastal monitoring locations. Chlorophyll-a concentrations varied considerably throughout the year and are characterized by a pronounced peak during spring. Most locations exhibit their highest concentrations between April and May, with maximum values reaching approximately 15–20 $\mu\text{g L}^{-1}$ at several locations, including GR2, GR6, and WC2. Following this spring peak, concentrations decline and remain relatively low during the rest of the year.

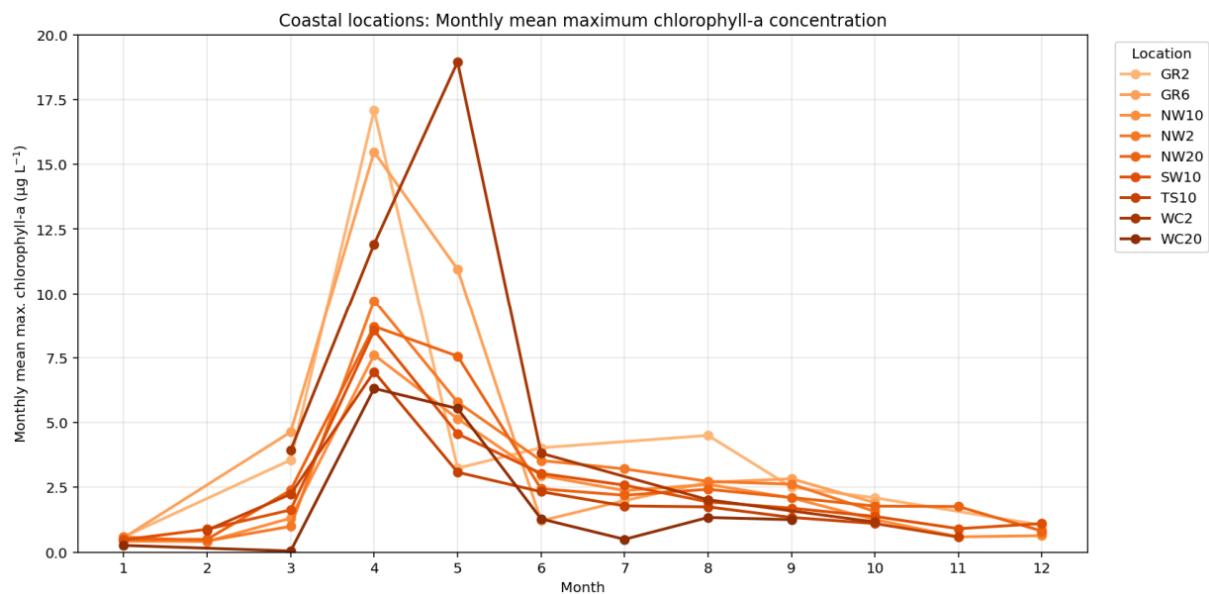


Figure 19: Monthly mean maximum chlorophyll-a concentration ($\mu\text{g L}^{-1}$) at coastal monitoring locations. Lines represent individual monitoring locations, and points indicate the monthly mean of the maximum chlorophyll-a concentration from all profiles containing a pycnocline within a given month. Concentrations are expressed in micrograms per litre ($\mu\text{g L}^{-1}$). Months 1 to 12 correspond to January through December.

Figure 20 shows the monthly mean maximum chlorophyll-a concentration at offshore monitoring locations. In contrast to the coastal locations, offshore locations generally exhibit lower chlorophyll-a concentrations throughout the year. Seasonal fluctuations are less pronounced, and maximum concentrations remain substantially below those observed at coastal locations. Although some locations, including NW70, TS50, and WC70, show elevated concentrations during spring and summer (April-May), with maximum values reaching approximately 2.5–5 $\mu\text{g L}^{-1}$. However, the magnitude of this peak is substantially lower than that observed at the coastal locations.

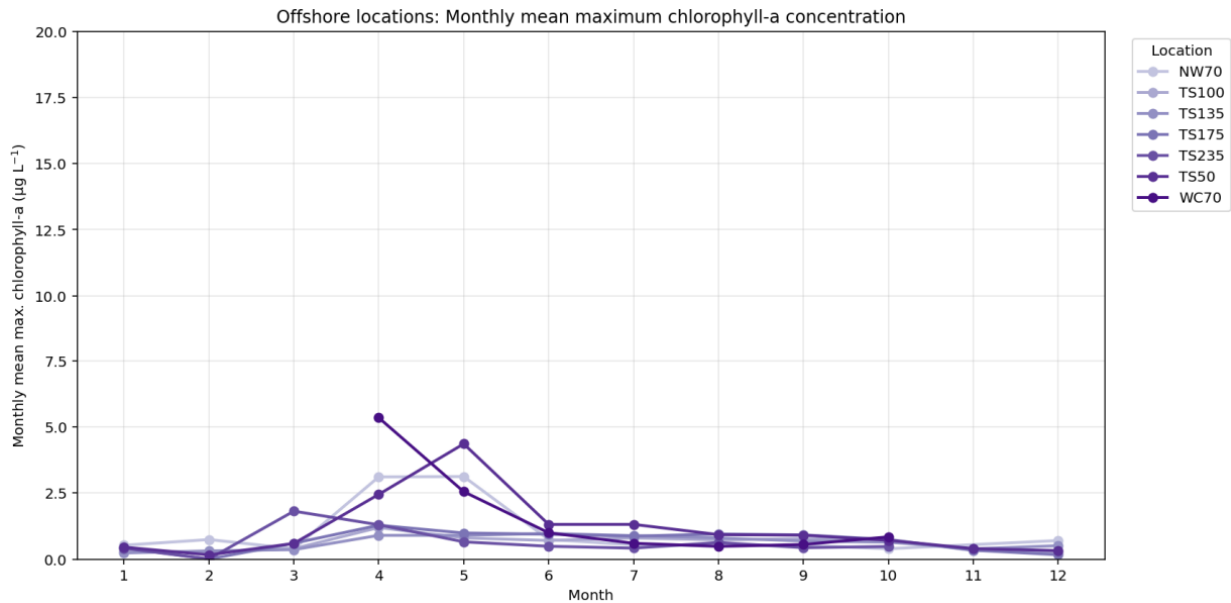


Figure 20: Monthly mean maximum chlorophyll-a concentration ($\mu\text{g L}^{-1}$) at offshore monitoring locations. Lines represent individual monitoring locations, and points indicate the monthly mean of the maximum chlorophyll-a concentration from all profiles containing a pycnocline within a given month. Concentrations are expressed in micrograms per litre ($\mu\text{g L}^{-1}$). Months 1 to 12 correspond to January through December.

4.5 Maximum chlorophyll-a depth

Figure 21 shows the monthly mean depth of the maximum chlorophyll-a concentration at coastal monitoring locations. The chlorophyll maximum is generally located at relatively shallow depths, typically between 5 and 15 metres below the water surface. Although some temporal variation is observed between locations and months, the depth of the chlorophyll maximum remain relatively shallow throughout the year.

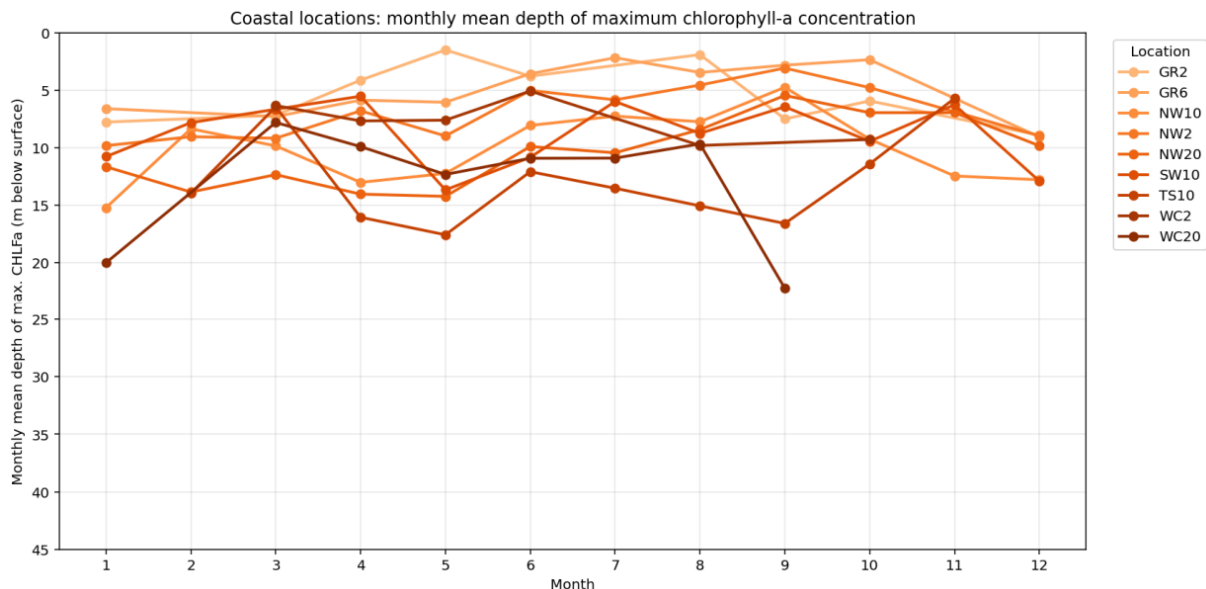


Figure 21: Monthly mean depth of maximum chlorophyll-a concentration in metres below the surface (mbs) at coastal monitoring locations. Each line represents a monitoring locations, while points indicate the monthly mean depth of the chlorophyll maximum. Months 1 to 12 correspond to January through December.

Figure 22 shows the monthly mean depth of the maximum chlorophyll-a concentration at offshore monitoring locations. Offshore chlorophyll maxima generally occur at greater depths than those observed at coastal locations. At several locations, the chlorophyll maximum was frequently observed between approximately 15 and 35 metres below the surface. Seasonal fluctuations in chlorophyll maximum depth are also more pronounced at offshore locations. At most locations, the depth of the chlorophyll maximum is generally shallower during winter and autumn and deeper during spring and summer.

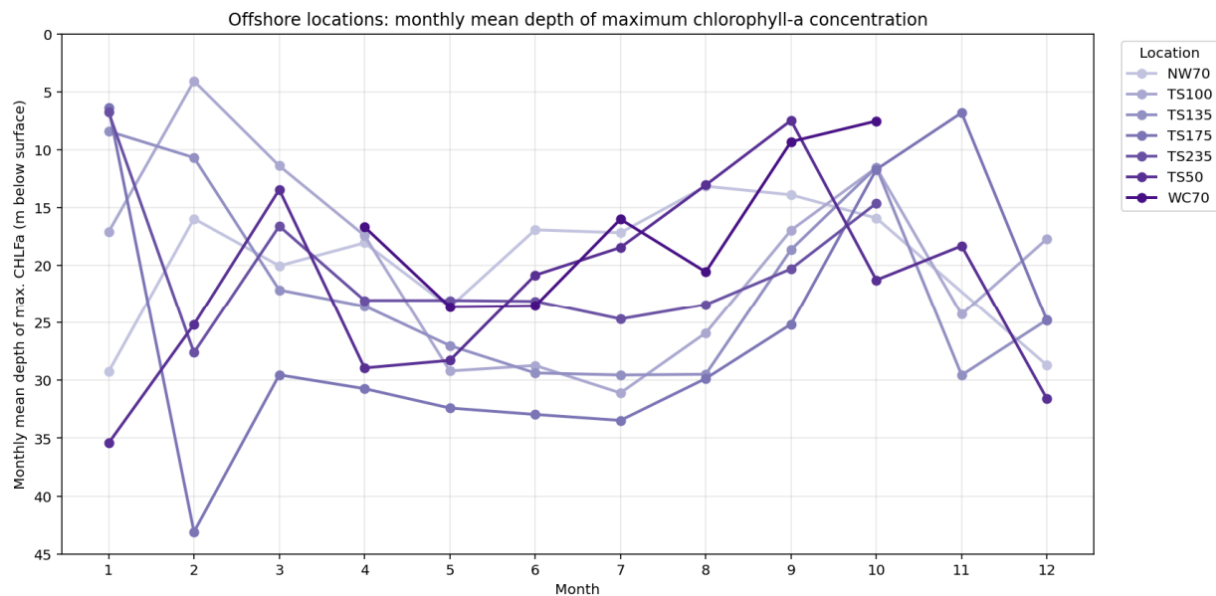


Figure 22: Monthly mean depth of maximum chlorophyll-a concentration in metres below the surface (mbs) at offshore monitoring locations. Each line represents a monitoring locations, while points indicate the monthly mean depth of the chlorophyll maximum. Months 1 to 12 correspond to January through December.

4.6 Correlation and pairwise similarity matrix

The relationship between pycnocline depth and the depth of the maximum chlorophyll-a concentration at coastal and offshore monitoring locations are visualised using scatterplots, which are presented in Appendix 7. At most coastal and offshore monitoring locations, the chlorophyll maximum occurs at or below the pycnocline, as indicated by most observations falling below the 1:1 line. Positive Spearman correlation coefficients are observed at most locations, indicating that deeper pycnoclines are generally associated with deeper chlorophyll-a maxima.

However, only weak statistically significant relationships are observed at a limited number of locations. Despite the positive relationships, coefficients of determination (R^2) remain low across both coastal and offshore locations, with most values ranging between 0.00 and 0.16. Several locations also show weak negative relationships between pycnocline depth and maximum chlorophyll-a depth. The boxplots in Appendix 7 show an example of greater seasonal variability at offshore locations than coastal locations across the four quarters during the year.

Overall, the observed relationships are generally weak, with pycnocline depth explaining only a limited proportion of the variability in maximum chlorophyll-a depth at both coastal and offshore monitoring locations. Additional analysis is needed to determine stronger relationships. To be able to do this, a pairwise similarity is made to be able to identify locations with similar pycnocline depth and the depth of the maximum chlorophyll-a concentration.

Figure 23 presents the pairwise similarity between monitoring locations based on their difference between mean pycnocline depth and mean depth of maximum chlorophyll-a concentration. Higher values indicate that two locations have more similarity, whereas lower values indicate greater differences between locations. The diagonal contains values of 1 because each location is compared with itself.

A general separation between coastal and offshore locations is visible. In particular, TS100, TS135 and TS175 show low similarity with the coastal locations, with values ranging approximately from 0.18 to 0.33. When all offshore locations are considered, similarities with the coastal locations range from 0.18 to 0.69, indicating that some offshore locations, particularly WC70 and NW70, are more comparable to the coastal group than TS100, TS135 and TS175.

Relatively high similarities occur within the coastal group. Examples include GR2–GR6 (0.88), GR2–WC2 (0.85), WC2–GR6 (0.83), and NW10–NW20 (0.86). Within the offshore group, WC70 and NW70 show a particularly high similarity of 0.88, while TS100 and TS135 show a similarity of 0.80. In contrast, TS175 and TS235 show relatively low similarity, with a value of 0.34. Appendix 8 presents additional pairwise similarity matrices for each zone, with locations grouped according to their location-code letters.

Overall, pairwise similarity values were generally lower between coastal and offshore locations. Higher values occurred more frequently between locations within the same group, although similarity values varied within both groups.

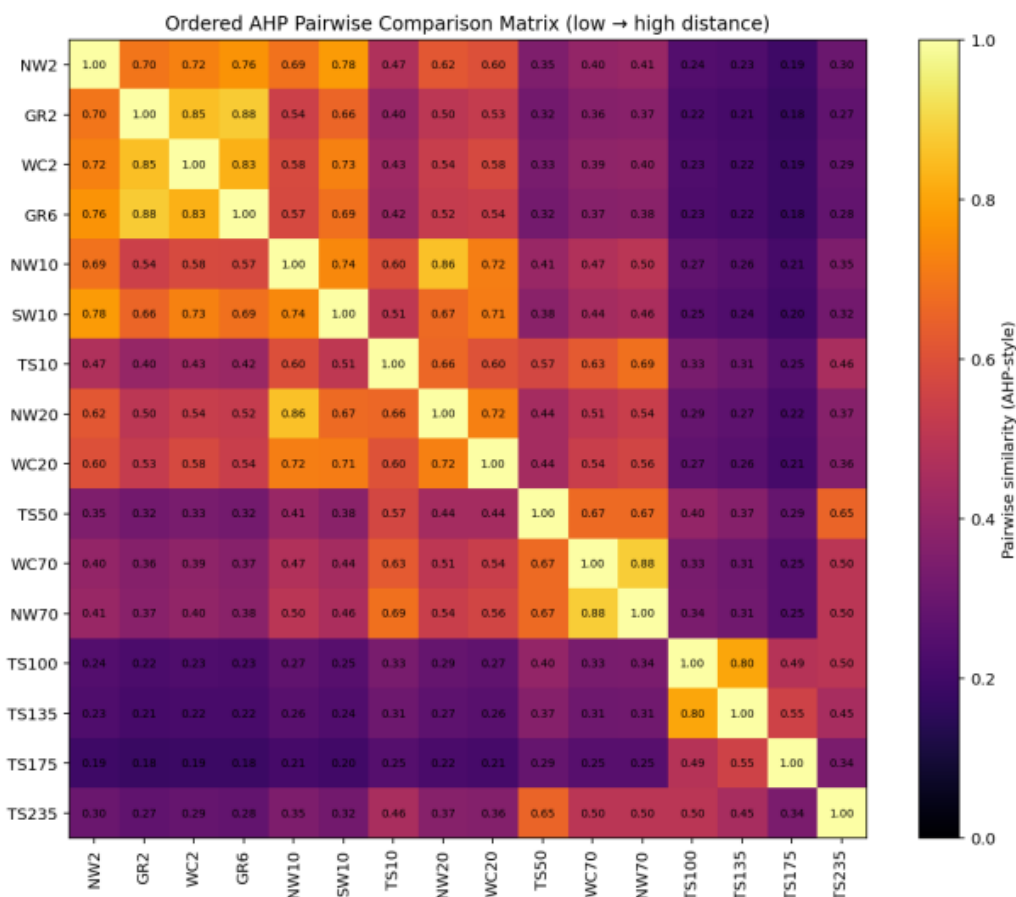


Figure 23: The pairwise similarity matrix compares monitoring locations based on their mean pycnocline depth and mean depth of maximum chlorophyll-a concentration. The x- and y-axes show the monitoring location codes. The coloured cells represent the degree of similarity between each pair of locations, while the numerical values within the cells show the corresponding pairwise similarity scores, ranging from 0 to 1. Higher values indicate greater similarity between locations, whereas lower values indicate greater dissimilarity.

4.8 Vertical distribution analysis

The vertical distribution analysis compares chlorophyll-a concentrations in the upper water column with maximum chlorophyll-a concentrations, generally showing a positive correlation. The strongest correlations occur at coastal locations (GR2, GR6, NW2, SW10, WC2, and WC20), with Spearman's rho values above 0.8. In contrast, offshore locations (TS100, TS135, TS175, and TS50) exhibit weaker correlations, often below 0.5. Correlations generally increase when larger upper-water-column depth ranges are considered. The strongest correlations are observed using 0–3.5 meter and 0–5 meter ranges. These results suggest that, in coastal areas, surface measurements can provide a reasonable estimate of maximum chlorophyll-a concentrations, whereas offshore, surface layers are less representative of the deeper maximum chlorophyll-a concentration.

Based on Table 3, surface chlorophyll-a concentrations generally show a strong and significant correlation with the maximum chlorophyll-a concentration at most locations. This is indicated by low p-values. R^2 values are typically higher at coastal locations, reflecting a closer correspondence between surface and maximum chlorophyll-a concentrations. Offshore locations show lower R^2 values, indicating a lower correspondence. RMSE values are larger for some offshore locations, suggesting greater variability or uncertainty in predicting maximum concentrations from surface values. Mean bias values are generally small and negative, implying a slight underestimation of maximum chlorophyll-a by surface measurements.

Table 3: Vertical distribution analysis.

Location	Surface depth	n	Spearman rho	p-value	R^2	RMSE	Mean bias
GR2	2m	12	0.99	<0.001	0.91	2.69	-1.4
GR2	3.5m	13	0.99	<0.001	0.93	2.22	-1.1
GR2	5m	13	0.97	<0.001	0.97	1.8	-1
GR6	2m	11	0.79	0.004	0.56	6.08	-3.02
GR6	3.5m	17	0.99	<0.001	0.86	4.5	-2.18
GR6	5m	17	0.99	<0.001	0.92	3.73	-1.85
NW10	1m	6	0.71	0.111	0.39	1.31	-0.91
NW10	2m	70	0.8	<0.001	0.42	3.58	-1.61
NW10	3.5m	173	0.84	<0.001	0.44	3.02	-1.32
NW10	5m	179	0.88	<0.001	0.47	2.89	-1.23
NW2	2m	58	0.88	<0.001	0.51	3.78	-1.42
NW2	3.5m	104	0.94	<0.001	0.66	2.95	-1.03
NW2	5m	104	0.96	<0.001	0.7	2.79	-0.99
NW20	1m	10	0.61	0.06	0.85	1.57	-1.15
NW20	2m	63	0.81	<0.001	0.37	3.94	-1.83
NW20	3.5m	110	0.77	<0.001	0.27	4.54	-1.93
NW20	5m	112	0.78	<0.001	0.28	4.45	-1.85
NW70	2m	31	0.78	<0.001	0.69	1.41	-0.74
NW70	3.5m	76	0.76	<0.001	0.87	1.42	-0.64
NW70	5m	78	0.76	<0.001	0.88	1.32	-0.6
SW10	2m	18	0.89	<0.001	0.78	1.57	-0.88
SW10	3.5m	31	0.78	<0.001	0.65	1.42	-0.75
SW10	5m	31	0.82	<0.001	0.7	1.29	-0.68

TS10	1m	7	0.21	0.645	0.2	1.97	-1.34
TS10	2m	33	0.71	<0.001	0.69	1.73	-1.12
TS10	3.5m	59	0.8	<0.001	0.79	2.13	-1.26
TS10	5m	59	0.83	<0.001	0.8	2.1	-1.23
TS100	2m	23	0.49	0.017	0.82	0.58	-0.42
TS100	3.5m	107	0.47	<0.001	0.55	0.57	-0.42
TS100	5m	118	0.46	<0.001	0.52	0.59	-0.42
TS135	1m	6	0.49	0.329	0.55	0.63	-0.51
TS135	2m	34	0.5	0.002	0.2	0.5	-0.36
TS135	3.5m	109	0.22	0.019	0	0.84	-0.54
TS135	5m	126	0.21	0.017	0	0.84	-0.57
TS175	2m	17	-0.09	0.722	0.03	1.05	-0.71
TS175	3.5m	87	0.06	0.572	0	0.96	-0.71
TS175	5m	97	0.03	0.769	0	0.97	-0.72
TS235	2m	19	0.78	<0.001	0.56	0.95	-0.6
TS235	3.5m	71	0.53	<0.001	0.45	0.65	-0.41
TS235	5m	83	0.48	<0.001	0.41	0.63	-0.39
TS50	1m	8	-0.21	0.61	0	5.67	-3.13
TS50	2m	33	0.33	0.062	0.02	3.15	-1.37
TS50	3.5m	62	0.34	0.007	0	2.77	-1.17
TS50	5m	67	0.37	0.002	0.01	2.66	-1.11
WC2	2m	6	0.66	0.156	0.6	2.94	-2.29
WC2	3.5m	12	0.95	<0.001	0.93	2.32	-1.58
WC2	5m	12	0.96	<0.001	0.94	2.11	-1.45
WC20	2m	9	0.95	<0.001	0.86	2.06	-1.18
WC20	3.5m	18	0.99	<0.001	0.9	1.49	-0.81
WC20	5m	18	0.99	<0.001	0.94	1.28	-0.72
WC70	2m	11	0.6	0.051	0.96	1.57	-0.86
WC70	3.5m	24	0.82	<0.001	0.93	1.23	-0.7
WC70	5m	24	0.82	<0.001	0.93	1.23	-0.69

5. Discussion

5.1 Limitations

Limitations of dataset and data collection

Several limitations should be considered when interpreting the results of this study. First, the analysis relies primarily on in-situ sensor-based chlorophyll-a fluorescence data rather than laboratory-derived chlorophyll-a concentrations, due to limited availability of sampled and lab-derived data. Previous studies have shown that the relationship between in-situ chlorophyll-a fluorescence measurements and laboratory-derived chlorophyll-a concentrations becomes less robust during winter and spring (Althuis et al., 1994). During these seasons, chlorophyll-a degradation products associated with phytoplankton decay, as well as scattering by non-algal suspended matter, introduce additional uncertainty. This uncertainty may lead to an overestimation of actual chlorophyll-a concentrations. In addition, non-photochemical quenching (NPQ) can reduce the fluorescence signal under high-light conditions without changes in actual chlorophyll-a concentration (Ruban, 2016). This NPQ can cause an underestimation and may weaken the relationship between sensor-based measurements and actual phytoplankton biomass.

The above mentioned limitations may introduce uncertainty and reduce the accuracy of absolute values of phytoplankton biomass estimates. Despite this, the main spatial and seasonal patterns remain robust, providing confidence in the observed patterns.

Limitations of the data analysis

Several methodological limitations should be considered. Inconsistent measurement frequencies, leading to irregular vertical profile coverage, may affect the robustness of temporal and spatial patterns. The approach of determining a threshold value for pycnocline detection also introduces uncertainty, as it is a dataset-specific threshold and should therefore be considered an approximation. Alternative threshold values could lead to different estimates of pycnocline occurrence. Furthermore, the method used to calculate maximum density gradients and the selection of Savitzky–Golay filter parameters (e.g. window size) may affect the identification of small-scale vertical structures. Larger windows reduce noise but may also smooth out relevant small-scale vertical structures or weak pycnoclines, potentially affecting the calculated pycnocline occurrence percentages. Despite these limitations, the observed spatial and seasonal patterns remain clear, providing confidence in the results.

In addition, the pairwise similarity matrix was calculated only using the mean difference in pycnocline depth and maximum chlorophyll-a depth. Other potentially relevant parameters, such as percentage of pycnocline occurrence, maximum chlorophyll-a concentration, and temporal variability, were not included due to time constraints. While it does not capture the full complexity of pycnocline occurrence and phytoplankton patterns, this approach effectively highlights the mean spatial distinction between coastal and offshore monitoring locations.

Lastly, only in-situ data were used to compare surface layer chlorophyll-a concentrations with maximum chlorophyll-a concentrations. Satellite-derived data was not incorporated, and the potential performance limitations of satellite monitoring (e.g., penetration depth and weather conditions) were not considered. As a result, the sensitivity analysis may not fully capture the actual performance and detection capabilities of satellite-based monitoring. Nonetheless, the analysis shows a clear distinction between offshore and coastal locations, and can therefore be considered a first approximation.

5.2 Comparison of observed patterns with literature

Spatial patterns

The results reveal clear spatial differences in pycnocline occurrence between coastal and offshore monitoring locations. Offshore locations exhibit high pycnocline occurrence, particularly during the summer months, reaching values of up to 100%. This suggests a strong and consistent seasonal stratification pattern. Conversely, coastal monitoring locations show lower and more consistent pycnocline occurrence throughout the year, with less pronounced seasonal structure. These patterns align with the stratification zones of the North Sea as described by Van Leeuwen et al. (2015). According to Van Leeuwen et al. (2015), the southern, nearshore North Sea is relatively shallow and experiences large tidal ranges, whereas the northern, offshore regions are gradually deeper with lower tidal ranges. Simpson and Hunter (1974) noted that when the water column is shallow or vertical velocities are sufficiently high, enhanced mixing occurs. This explains why coastal monitoring locations exhibit lower pycnocline occurrences and weaker stratification, due to enhanced mixing. In contrast, deeper offshore locations experience less mixing, resulting in higher pycnocline occurrences and stronger stratification. These patterns are further supported by the pairwise similarity matrix, which clearly distinguishes coastal and offshore locations. Monitoring locations within the same group, coastal or offshore, show the highest similarity, while comparisons between groups reveal much lower similarity. This reflects the pronounced differences in stratification and pycnocline occurrence patterns between coastal and offshore locations.

Differences in pycnocline depth further support the spatial distinction between coastal and offshore monitoring locations. Consistent with previous studies, offshore locations generally show deeper and more fluctuated pycnocline depths, while coastal locations are characterized by shallower and more stable pycnocline depths (Holt & Umlauf, 2008; van Leeuwen et al., 2015). However, some spatial variability is observed within offshore locations, where shallower pycnoclines occur at monitoring locations such as TS235, TS50, WC70, and NW70. This can partly be explained by local bathymetry (Tweddle et al., 2013). For example, at Dogger Bank near TS235, reduced water depth limits the development of deep stratification.

A clear spatial pattern can also be observed between coastal and offshore locations based on maximum chlorophyll-a concentration. Coastal locations are characterized by relatively high maximum chlorophyll-a concentrations, while offshore locations show lower maximum chlorophyll-a levels. Higher chlorophyll-a concentrations in coastal waters are likely linked to enhanced nutrient inputs from rivers associated with the ROFI-zone which promotes higher phytoplankton biomass (Emeis et al., 2015; Mojica et al., 2015). Additionally, at coastal locations, the shallow bathymetry allows for a strong correlation between surface chlorophyll-a concentrations in the upper water layer and the maximum chlorophyll-a concentration.

Furthermore, the relationship between pycnocline depth and maximum chlorophyll-a depth exhibits a similar spatial pattern across both coastal and offshore locations. At coastal locations, pycnocline depth closely aligns with the depth of maximum chlorophyll-a concentration, with both remaining shallow and relatively stable. A similar correspondence is observed for offshore locations, where both pycnocline and maximum chlorophyll-a depths are deeper and display greater temporal variability. This aligns with literature, which states that the maximum chlorophyll-a concentration, commonly known as DCM, typically occur near the pycnocline (Cullen, 2015). This similarity between pycnocline depth and maximum chlorophyll-a depth further suggests that stratification plays an important role in controlling the vertical distribution of phytoplankton. However, the relatively low R^2 values indicate that pycnocline depth alone only explains a limited proportion of the variability in maximum

chlorophyll-a depth, suggesting that additional processes such as light availability and nutrient dynamics are also important drivers (Duteil, Macias, Stips, & Polimene, 2024; Singh et al., 2008).

Seasonal and temporal patterns

Across all locations, pycnocline occurrence is lowest during winter and highest during summer. This seasonal pattern is consistent with previous studies, where Ruardij, Van Haren, & Ridderinkhof (1997) and Van de Poll et al. (2013) demonstrated that stratification begins in spring and strengthens throughout the summer due to higher temperatures. Stratification typically persists until autumn, when decreasing temperatures and increased wind-driven mixing weaken pycnocline occurrence.

Regarding the maximum chlorophyll-a concentration, a clear seasonal pattern is observed. The results show a spring peak in maximum chlorophyll-a concentration, followed by a decline in summer, and low concentrations during autumn and winter. These findings are consistent with previous studies, which report that phytoplankton blooms are initiated in spring due to rising temperatures and nutrient-rich conditions (Brussaard et al., 1996; Sharples et al., 2006; Van de Poll et al., 2013). Following the spring bloom, phytoplankton biomass declines during summer as nutrients are depleted and grazing by zooplankton increases (Kuipers & Witte, 1999). During winter, phytoplankton biomass is generally lower due to reduced light availability, lower temperatures, and enhanced vertical mixing (Behrenfeld & Boss, 2014; Sverdrup, 1953; Van de Poll et al., 2013).

5.3 Recommendations for further research

Several topics for further research emerge from the limitations. Trend analyses examining interannual variability have not been included due to limited spatial and temporal coverage of vertical profiles and inconsistent measurement frequencies. Despite this, such (historical data) analyses could provide valuable insights into long-term system behaviour. Understanding these trends in the North Sea is especially relevant because of increasing pressures driving patterns, phytoplankton dynamics, and eutrophication processes. Various studies have showed an increase in stratification globally (Li et al., 2020; Sharples et al., 2006; van de Poll et al., 2013). On the other hand, Jardine et al. (2023) highlights that interannual variability, driven by weather or climate change, is poorly understood in shelf seas. This indicates the need for additional research. The main limitation, consistent with this study, is the lack of historical data with sufficient spatial and temporal resolution, which limits the ability to assess year-round trends.

Additionally, further research could improve the accuracy of chlorophyll-a estimates. Increasing accuracy can be achieved by comparing in-situ chlorophyll-a fluorescence concentrations with laboratory-derived chlorophyll-a concentrations. As a result, calibration can improve the reliability of chlorophyll-a fluorescence-based datasets. Furthermore, further research is needed to refine pairwise similarity analysis by adding additional variables, such as pycnocline occurrence, chlorophyll-a concentration variability, and temporal dynamics. As a result, it would improve the identification of representative monitoring locations for extrapolation.

Further validation using satellite data is needed to assess how well surface measurements represent deeper chlorophyll-a distributions. Harvey et al. (2015) has shown how satellite monitoring can add towards monitoring strategies next to in-situ monitoring. Therefore, investigating satellite performance under different environmental conditions would enhance the reliability of monitoring strategies and clarify when in-situ measurements at depth remain necessary.

Several potential directions for further research also emerge based on the scope and findings of this study. This study uses chlorophyll-a as a proxy for phytoplankton biomass. However, it does not include pheophytin-a (pheo-a), the degradation product of chlorophyll-a, as in-situ chlorophyll-a fluorescence

measurements cannot distinguish between living chlorophyll-a and its degradation products. The ratio between chlorophyll-a and pheophytin-a can provide important insight into the balance between phytoplankton growth and decay, which is a key component of eutrophication processes. Since eutrophication is not only driven by biomass accumulation but also by decomposition processes that can contribute to oxygen depletion further research could incorporate pheophytin-a. As a result, it allows for better understanding of bloom dynamics and ecosystem functioning.

Furthermore, this study focuses on phytoplankton abundance and does not consider the composition of species. Within these combinations potentially harmful algal species can be present. Expanding the analysis to include species-level information would improve understanding of ecological risks associated with bloom development. Moreover, oxygen dynamics were not included in this study due to the scope of this research. However, dissolved oxygen is closely linked to phytoplankton production and decomposition processes, as oxygen is consumed during the microbial breakdown of phytoplankton (Häder & Gao, 2015). Further research could therefore explicitly investigate the relationship between chlorophyll-a dynamics, stratification, and oxygen depletion to improve the understanding of ecosystem behaviour to eutrophication. Such analyses would also be relevant in the context of reporting requirements under the MSFD.

Lastly, this research does not include the potential impact of offshore wind farms on North Sea stratification, and chlorophyll-a dynamics. With increasing presence of wind farms, further research could examine their impact on local water mixing and phytoplankton distribution

5.4 Implications

Broader societal implications

The findings of this study have broader implications beyond the scientific results. Pycnocline formation and phytoplankton distribution influence nutrient cycling and oxygen dynamics, affecting the ecological functioning of the North Sea (Ansari et al., 2010; Chislock et al., 2013). These processes are directly relevant to long-term ocean health, which supports fisheries, recreation, and coastal protection (Eggert & Olsson, 2009; Yadava et al., 2023). Understanding these dynamics can improve monitoring strategies and inform mitigation measures.

Furthermore, the observed patterns in pycnocline dynamics and phytoplankton distribution support evidence-based reporting under the MSFD, helping authorities assess eutrophication and water quality at European scales (OSPAR Commission, 2023; European Parliament & Council of the European Union, 2008). Furthermore, ongoing climate change (Li et al., 2020; van de Poll et al., 2013) and increasing nutrient inputs from human activities (Emeis et al., 2015; Mojica et al., 2015) highlight the need for adaptive monitoring and management to ensure sustainable use of the North Sea ecosystem.

Implications for management and policy

The findings of this study have several implications for management and policy to improve the current monitoring strategy of Rijkswaterstaat. These implications/recommendations are the following:

1. Satellite monitoring versus in-situ measurements

Satellite monitoring could be a complementary monitoring strategy with their high spatial and temporal coverage, but cannot replace in-situ measurements on the DCS. For coastal monitoring locations, where chlorophyll-a concentrations are near the surface, satellite monitoring could serve as a reliable monitoring method to determine chlorophyll-a concentrations and assess eutrophication. In contrast, in-situ measurements remain essential for offshore locations to capture phytoplankton concentrations in deeper water layers. Further research on satellite performance under varying environmental conditions,

such as cloud cover, water turbidity, and sedimentation, is recommended, particularly for coastal waters. Additionally, in-situ measurements should be maintained to validate satellite-derived chlorophyll-a concentrations.

2. Selection of monitoring locations

Prioritizing offshore locations, due to their consistently high pycnocline occurrence, is recommended. This is crucial for capturing stratification and phytoplankton dynamics. Within the current monitoring strategy several offshore locations are already included. However, several coastal locations, including NW2, NW10, NW20, and TS10, also show relatively high pycnocline occurrence and are therefore valuable locations for monitoring.

3. Implement continuous monitoring at selected reference locations

Continuous monitoring can be added to the current monitoring strategy at a limited number of representative locations based on the pairwise similarity matrix. For instance, high similarity is observed among coastal locations GR2, GR6, WC2, and NW2, as well as between offshore locations TS100 and TS135. This continuous monitoring could provide high-resolution insight into temporal dynamics. These monitoring locations could serve as reference locations for extrapolating patterns to other locations or areas within the DCS. This could be done with bouys, ultimately saving resources to collect high resolution data.

4. Increase consistency and frequency of vertical profile measurements

To improve the detection of long-term trends, it is recommended to increase the frequency and consistency of vertical profile measurements. This can be achieved by adjusting the sampling design. Varying the order of sampling locations along survey routes could reduce systematic bias between monitoring locations and minimize reliance on nighttime sampling, as CTD measurements are collected together with light attenuation measurements. Future monitoring should prioritize CTD measurements rather than relying solely on light-dependent measurements. Also, continuous monitoring, as mentioned above, can increase vertical profile measurements to improve the detection of long-term trends.

5. Prioritize monitoring during spring and summer months

The results indicate that the most informative period for capturing variability in stratification and phytoplankton dynamics spans from spring to summer, roughly March to October. During this period, chlorophyll-a variability and vertical stratification and pycnocline formation are most pronounced. Increasing measurement frequency during this period would improve process understanding.

6. Use maximum chlorophyll-a concentration

The peak fluorescence signal below the pycnocline is currently applied in the monitoring strategy. Methodologically, it is recommended to use the maximum chlorophyll-a concentration instead of relying solely on the peak fluorescence signal below the pycnocline. Maximum chlorophyll-a concentration provides a more robust representation of phytoplankton biomass distribution and aligns with findings in the scientific literature. However, both metrics may occur at different depths within the same vertical profile. An example of this is provided in Appendix 9. The underlying mechanisms for these vertical differences are not yet fully understood. Therefore, further research is recommended to improve interpretation of vertical phytoplankton distributions.

7. Clarify purpose of sampling design

At present, the rationale behind the selection of sampling locations and chlorophyll-a measurements is not always clear. It is often uncertain whether the goal is to characterize stratification and pycnocline conditions, quantify chlorophyll-a concentrations throughout the water column, or both. Establishing clear sampling objectives, standardized protocols, and coordinated communication between Mobiel Meten, commissioning party, and contractors is recommended to improve consistency and data usability.

8. Automatic data archiving in WADAR

Currently, data are not automatically stored in WADAR. It is recommended to establish and implement a standardized protocol to ensure that all data are securely archived. By doing this, potential data loss can be prevented and future analyses can be facilitated.

6. Conclusion

This study investigated how spatial and temporal patterns of pycnocline formation influence the vertical distribution of phytoplankton on the Dutch Continental Shelf between 1995 and 2024. Based on the findings, clear spatial and temporal patterns have been found. Coastal locations show weaker and more stable pycnocline occurrence throughout the year, while offshore locations show strong and persistent pycnocline formation during spring and summer.

Furthermore, pycnocline formations influence the chlorophyll-a concentrations and depth. Offshore locations generally show greater depths of maximum chlorophyll-a concentrations, whereas coastal locations show higher chlorophyll-a concentrations at shallower depths of pycnocline formations. The alignment between pycnocline depth and maximum chlorophyll-a depth indicates that stratification influences vertical phytoplankton distribution, although weak statistical relationships suggest additional factors also play a role.

Lastly, the current monitoring strategy does not fully capture the complex dynamics, within time (temporal) and space (spatial), of pycnocline occurrence and phytoplankton biomass. Low confidence in ecological dynamics asks for a different approach. The strong seasonal patterns for pycnocline occurrence, specifically present during spring and summer, indicate the need for higher resolution monitoring in time to better resolve ecological dynamics.

To conclude, the study demonstrates that pycnocline dynamics play an important role in shaping vertical phytoplankton distributions with differences between coastal and offshore locations. However, pycnocline dynamics do not fully explain the observed vertical phytoplankton distribution. Therefore, improved monitoring strategies are required to capture interacting physical and biological processes more effectively.

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Appendix 1- Data collection

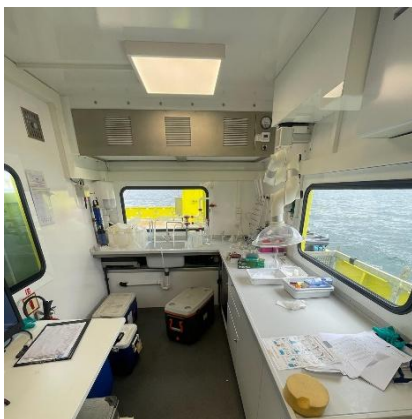
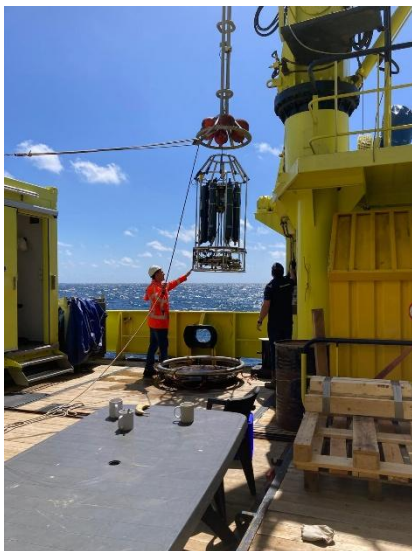


Figure 24: From top to bottom: Rosette sampler with sensors and Niskin bottles; deployment of the rosette sampler at sea; onboard laboratory for filling bottles and conducting additional analyses. Photos by Silke Brakkee.

Appendix 2 - Measurement Frequency Tables

year	GR2	GR6	NW10	NW20	NW2	NW70	SW10	TS100	TS10	TS135	TS175	TS235	TS50	WC20	WC2	WC70
1995			13	5	5	7	3	11	9	10	11	8	7	6	4	1
1996			28	9	16	9	2	12	6	12	12	10	3	3	3	2
1997			33	13	17	16		12	6	14	12	11	2	3	6	3
1998		3	22	8	9	9		9	4	12	9	8	2	2	4	1
1999																
2000																
2001																
2002																
2003		12	21	9	11	6	5	7	7	10	8	6	5	5	7	2
2004		5	18	9	12	9	3	9	3	11	10	10	1	2	4	5
2005		3	15	6	8	7	3	9	6	9	7	8	3	2	3	3
2006		5	11	7	8	3	3	10	4	10	9	7	2	2	3	1
2007																
2008	3	3	13	9	6	9	3	11	3	13	12	9	4	2	3	2
2009			3			1		7	1	11	7	8				
2010			2	1	1			3	1	4	2	2	1			
2011			1					5		5	3	3	1			1
2012								4		4	3	3				
2013	1	1	5	5	4	4	3	3	3	4	1	1	5		1	1
2014	1	2	7	11	7	3	5	9	7	7	2	2	9	2	1	4
2015	1	1	8	10	5	7	1	7	3	6	4	1	5	1	1	2
2016	4	3	12	10	8	7	6	5	6	2	1		8		3	3
2017			1				1	1	1				1			
2018	1	1	1	1	1											
2019	1		10	12	12	4	3	2	6	5	2	2	6	1	1	2
2020	7	6	5	7	7	1	6	5	3	2		1	5		4	1
2021	8	8	10	11	13	5	5	2	4	4	1	1	6		5	4
2022	3	4	11	10	9	4	3	4	4	4			4		3	2
2023	2	2	7	7	6	1	3	3	2	4		1	4		3	1
2024	5	4	6	4	5	5	3	1	2	2	1		5	1	2	2

Figure 25: Measurement frequency (number of available vertical profiles) of salinity profiles at each monitoring location per year.

year	GR2	GR6	NW10	NW20	NW2	NW70	SW10	TS100	TS10	TS135	TS175	TS235	TS50	WC20	WC2	WC70
1995			13	5	5	7	3	8	9	7	8	8	4	6	5	1
1996			28	9	16	9	2	11	6	11	10	9	3	3	3	2
1997			33	13	17	16		12	6	14	12	11	2	3	6	3
1998		2	22	7	9	8		9	4	12	9	8	2	1	3	
1999																
2000																
2001																
2002																
2003		11	20	8	10	6	5	7	7	10	8	5	5	5	7	2
2004		5	18	9	12	9	3	9	3	11	10	10	1	2	4	5
2005		3	15	6	8	7	3	9	6	9	7	8	3	2	3	3
2006		5	11	7	8	3	3	10	4	10	9	7	2	2	3	1
2007																
2008	3	3	13	9	6	9	3	11	3	13	12	9	4	2	3	2
2009			1					3	1	5	3	4				
2010																
2011			1		1			4		4	3	3	1			1
2012								4		4	3	3				
2013	1	1	6	6	4	4	3	3	4	4	1	1	5		1	2
2014	1	2	7	11	7	5	5	9	8	7	2	2	9	2	1	4
2015	1	1	9	12	5	7	2	7	4	6	4	1	4	1	1	2
2016	4	3	12	10	8	7	6	5	7	3	1		8		3	3
2017			2	1			2	1	1				1		1	
2018	1	1	3	4	3	1	1	1		1	1		1			
2019			15	16	16	5	5	5	8	7	1	3	8	2	1	5
2020	1	2	2	2	3		2	1	2	1		1	1			
2021																
2022																
2023	2	2	6	6	5	1	3	3	2	4		1	4		3	1
2024	5	4	6	5	6	6	3	1	3	2	1		5	1	2	2

Figure 26: Measurement frequency (number of available vertical profiles) of chlorophyll-a fluorescence profiles at each monitoring location per year.

Appendix 3 – Removed profiles

Table 4: Number of observations and vertical profiles per monitoring location before and after data filtering. “Rows” refers to individual CTD values, while “profiles” refers to aggregated values into vertical profiles.

Location	Rows_original	Rows_filtered	Profiles_original	Profiles_filtered
GR2	73422	56796	40	27
GR6	74860	49433	64	38
NW10	567174	520479	278	258
NW2	321049	282640	185	165
NW20	581301	535685	178	165
NW70	469649	436831	125	116
SW10	186662	168821	69	61
TS10	303411	289942	99	91
TS100	915438	881950	156	149
TS135	904696	867536	169	164
TS175	511854	491951	119	115
TS235	325307	302655	106	102
TS50	545304	511526	94	86
WC2	88644	69599	66	50
WC20	58942	55208	33	31
WC70	279736	255967	47	42

Appendix 4 – Density Calculations

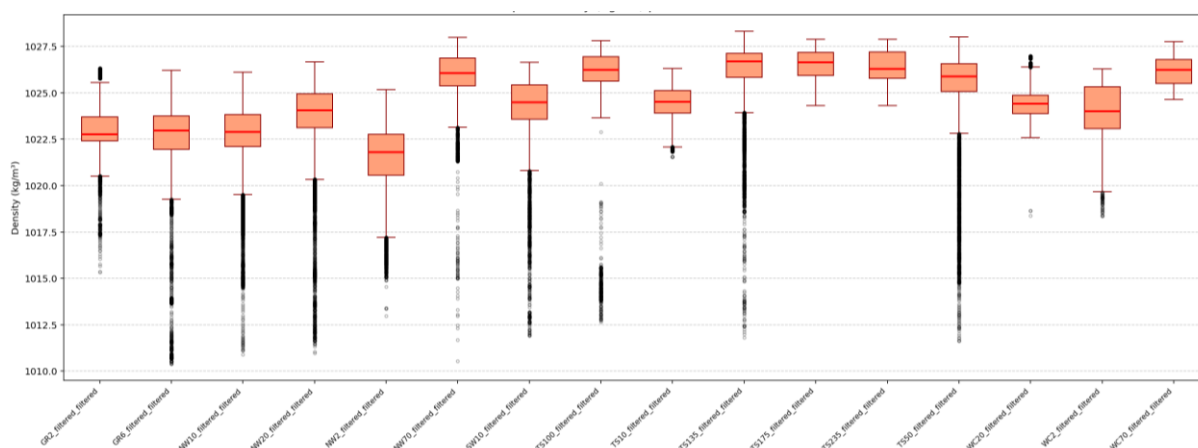


Figure 27: Distribution of calculated density values (in kg/m³) across monitoring locations.

Table 5: Overview of data completeness for temperature and salinity measurements at each monitoring location. The table presents the total number of observations (rows), the number of complete observations containing both temperature (T) and salinity (S) measurements, the percentage of missing values, and the number of missing temperature and salinity values. Only station TS135 contains missing salinity values. Therefore, all profiles containing missing salinity measurements were excluded from further analyses.

Location	Total_Rows	Complete_Rows (T+S)	Missing_%	Missing_T	Missing_S
GR2	8824	8824	0	0	0
GR6	7683	7683	0	0	0
NW10	81381	81381	0	0	0
NW20	82450	82450	0	0	0
NW2	43790	43790	0	0	0
NW70	69203	69203	0	0	0
SW10	25570	25570	0	0	0
TS100	137150	137150	0	0	0
TS10	43725	43725	0	0	0
TS135	135747	135685	0.05	0	62
TS175	77058	77058	0	0	0
TS235	47263	47263	0	0	0
TS50	79702	79702	0	0	0
WC20	8611	8611	0	0	0
WC2	11130	11130	0	0	0
WC70	40201	40201	0	0	0

Appendix 5 – Threshold determination

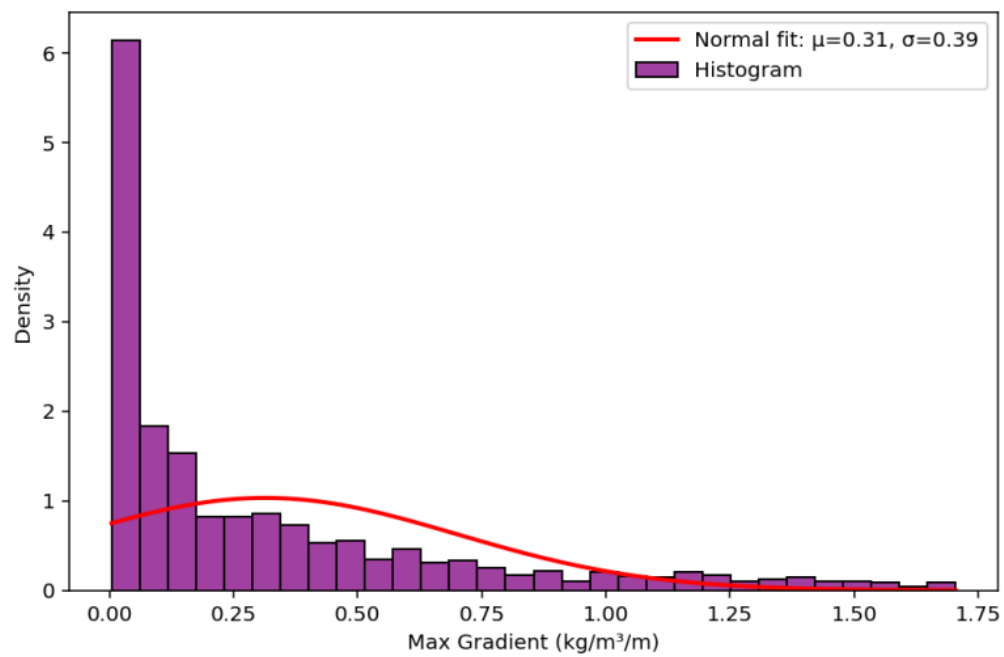


Figure 28: Example of the normal distribution of maximum density gradients calculated using the Savitzky–Golay filter, after removing outliers. The distribution has a mean of 0.31 and a standard deviation of 0.39.

Appendix 6 – Boxplots

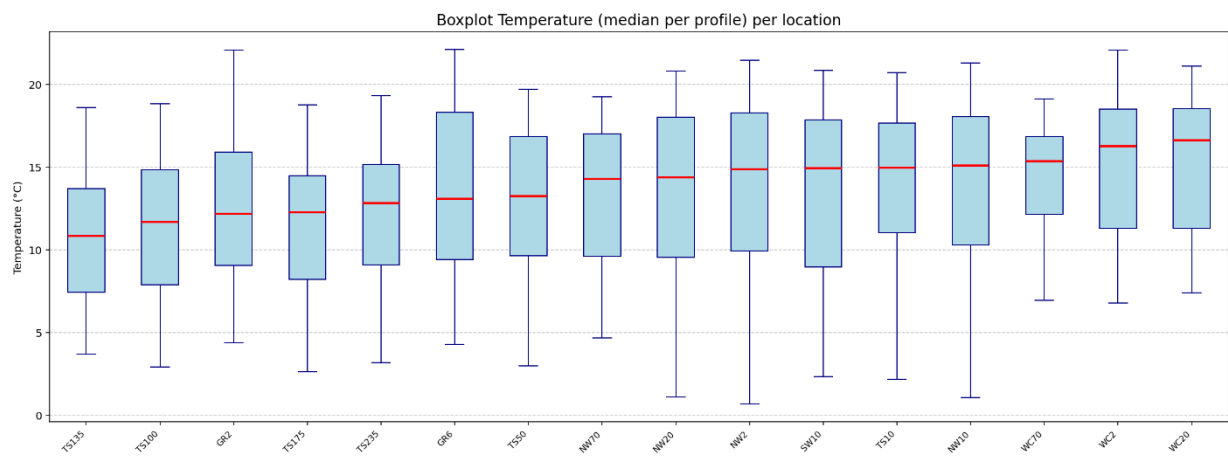


Figure 29: Distribution of median temperature values per vertical profile across monitoring locations. Boxplots show the median (red line), interquartile range (box), whiskers, and outliers of temperature measurements (°C) for each location. Monitoring locations are ordered according to increasing median temperature.

Appendix 7 – Scatterplots and boxplots

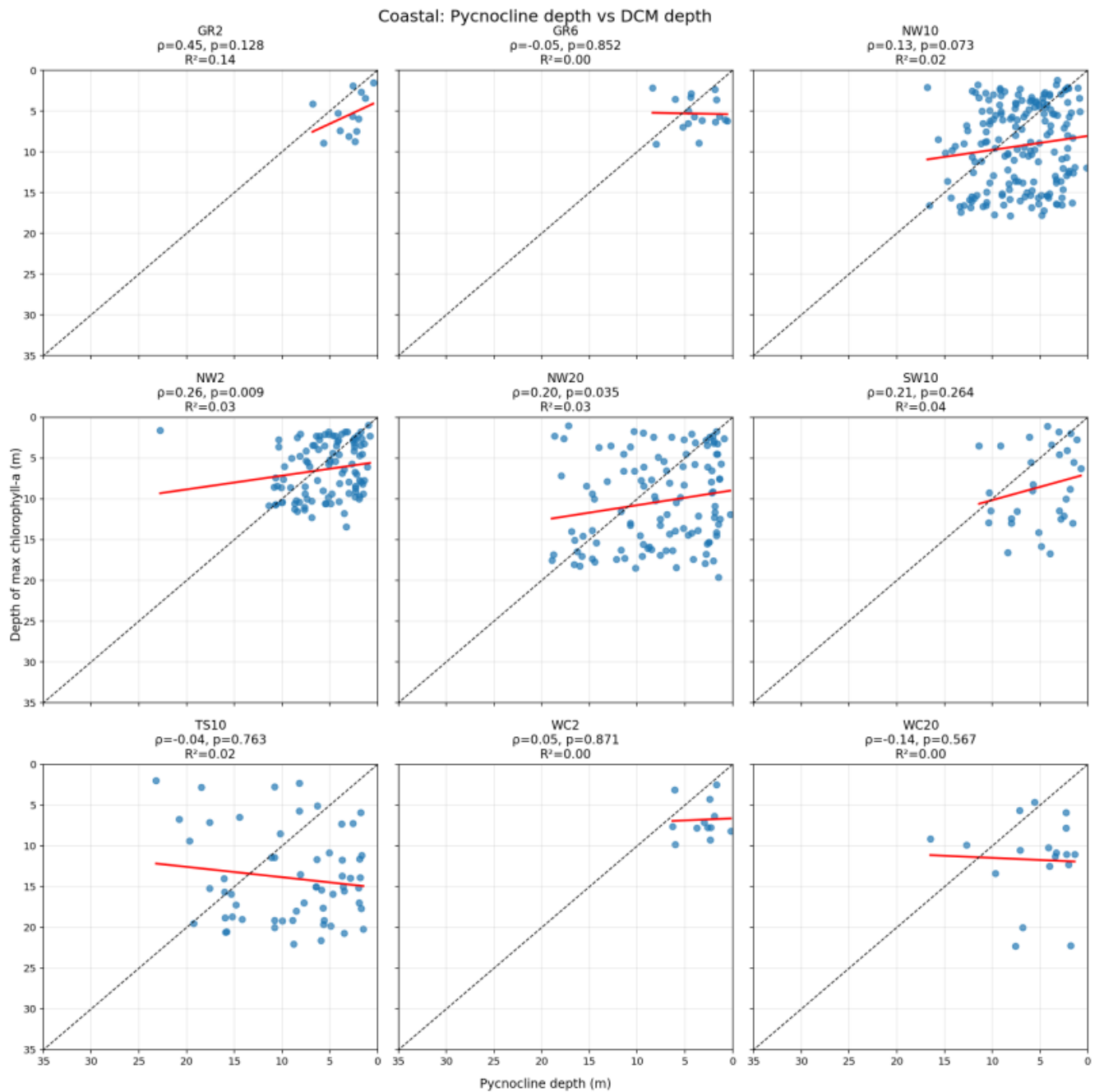


Figure 30: Scatter plots showing the relationship between pycnocline depth and the depth of the maximum chlorophyll-*a* concentration at coastal monitoring locations. Each panel represents a monitoring location. Blue dots indicate individual observations/vertical profiles, the red line shows the linear regression fit, and the dashed line represents the 1:1 relationship. Spearman correlation coefficients (ρ), *p*-values, and R^2 values are displayed for each location. Depth is expressed in metres below the water surface.

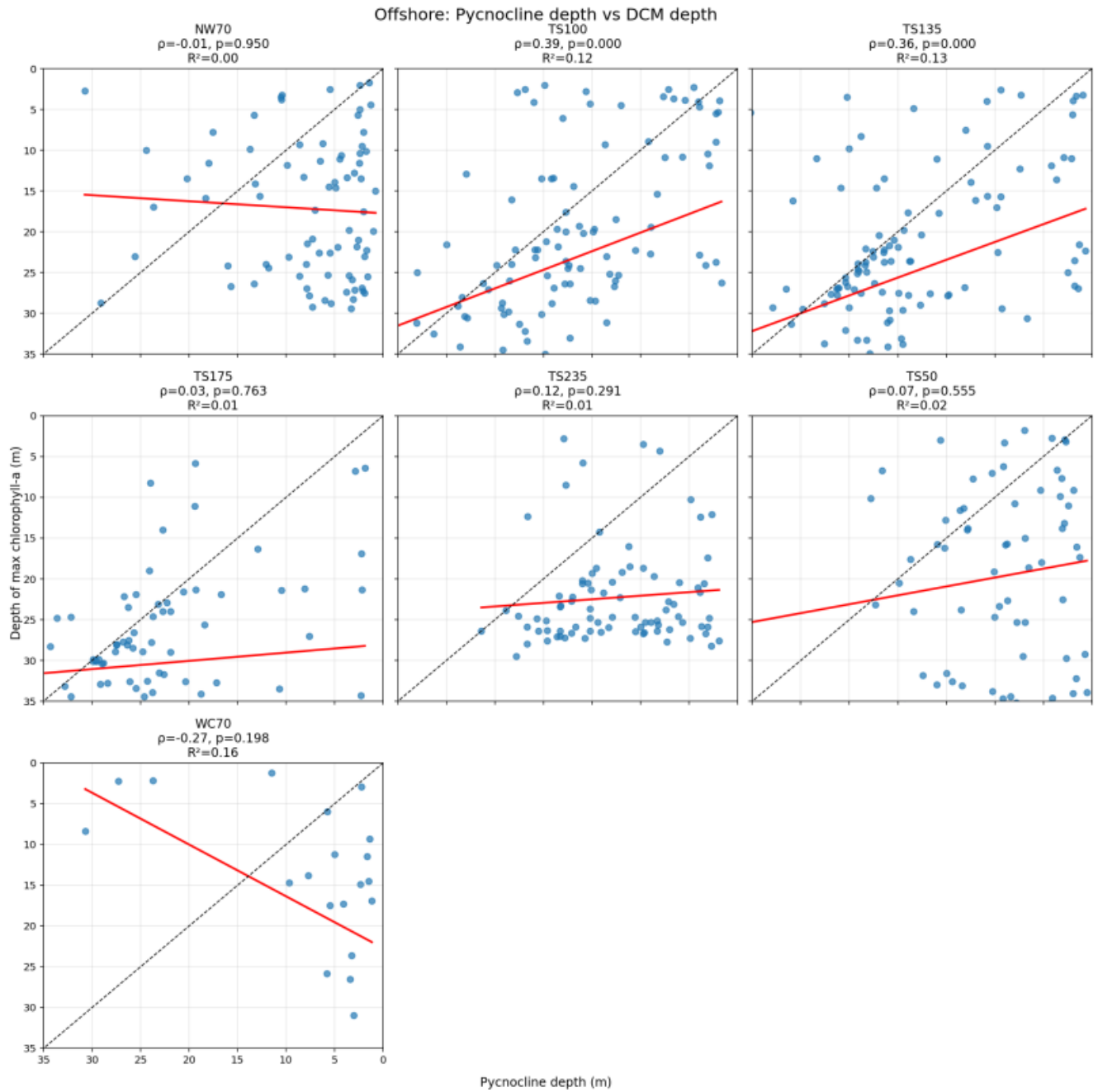


Figure 31: Scatter plots showing the relationship between pycnocline depth and the depth of the maximum chlorophyll-a concentration at offshore monitoring locations. Each panel represents a monitoring location. Blue dots indicate individual observations/vertical profiles, the red line shows the linear regression fit, and the dashed line represents the 1:1 relationship. Spearman correlation coefficients (ρ), p-values, and R^2 values are displayed for each location. Depth is expressed in metres below the water surface.

Pycnocline depth - DCM depth per quarter and location

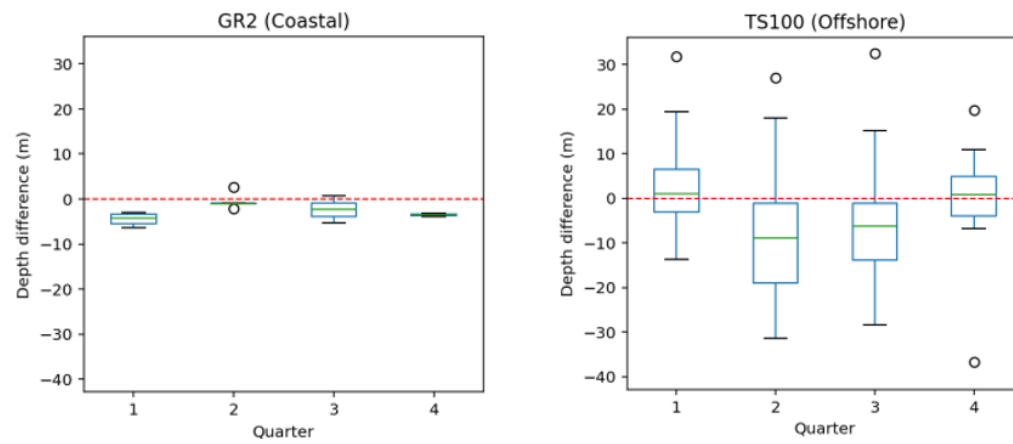


Figure 32: Pycnocline depth minus the depth of the maximum chlorophyll-a concentration (depth difference) in meters for coastal (GR2) and offshore (TS100) location per quarter over time.

Appendix 8 – Pairwise similarity matrices

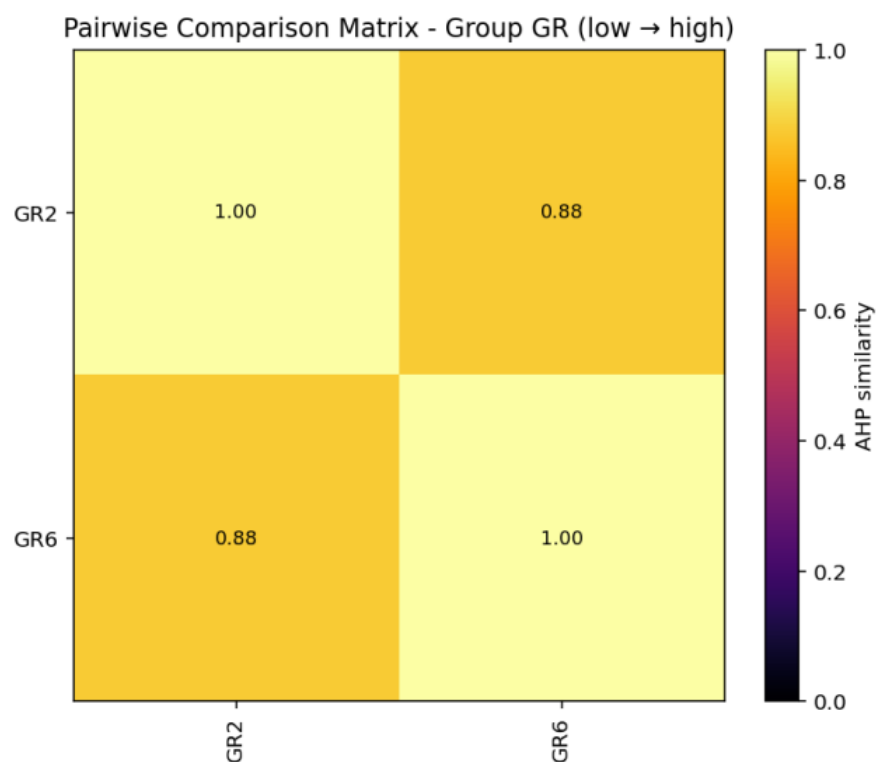


Figure 33: Pairwise similarity matrix for GR-monitoring locations.

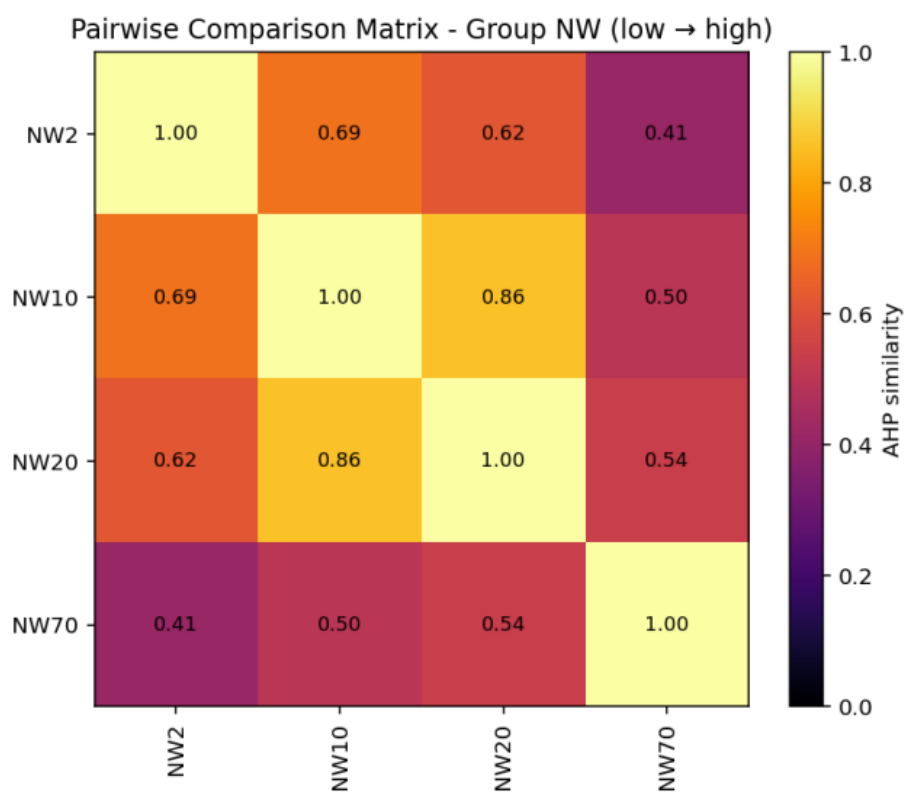


Figure 34: Pairwise similarity matrix for NW-monitoring locations.

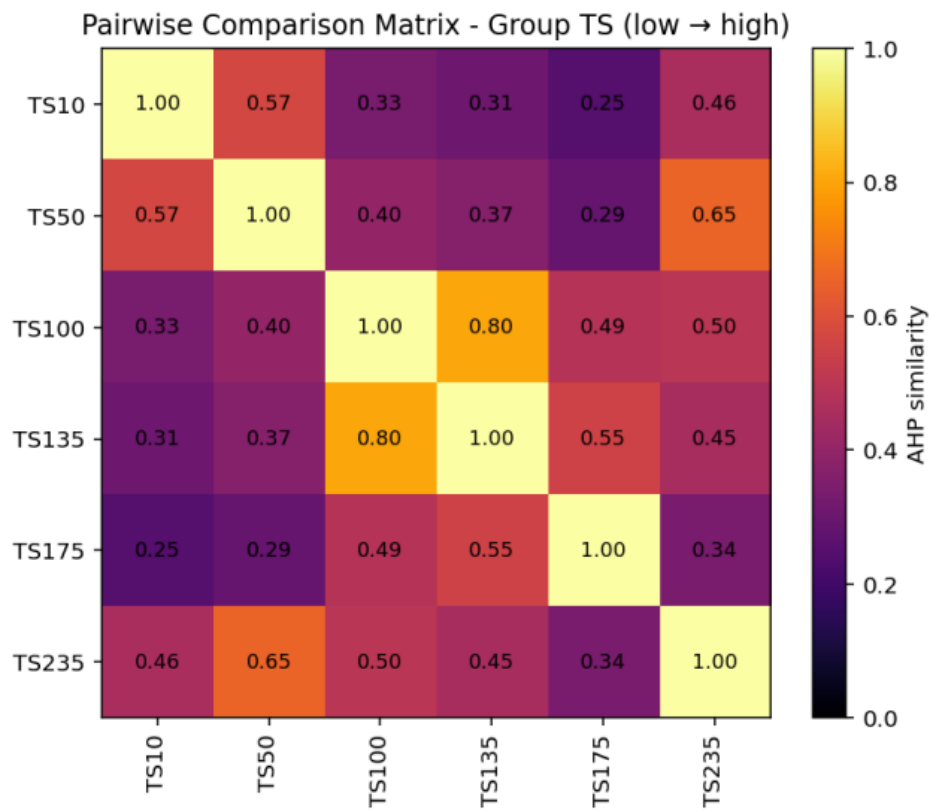


Figure 35: Pairwise similarity matrix for TS-monitoring locations.

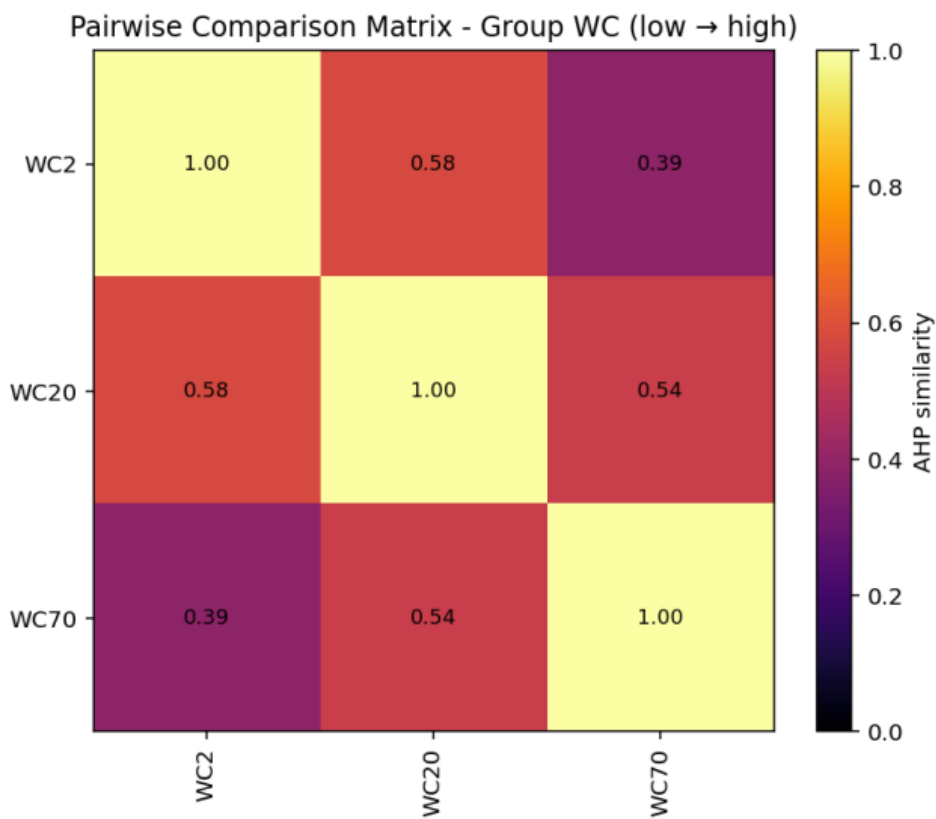


Figure 36: Pairwise similarity matrix for WC-monitoring locations.

Appendix 9 – Chlorophyll-a fluorescence peak versus max. chlorophyll-a fluorescence concentration

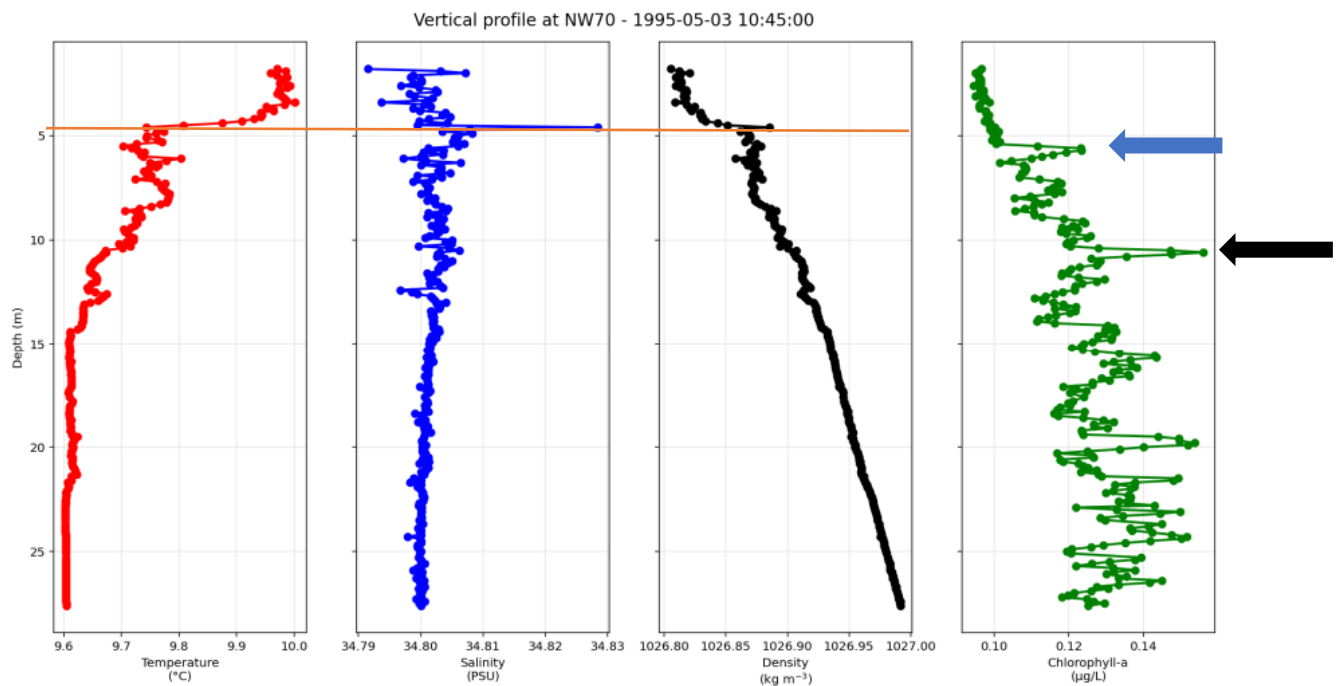


Figure 37: Example of a vertical CTD profile at station Noordwijk 70, displaying temperature (°C), salinity (PSU), density (kg/m³) and chlorophyll-a fluorescence (µg/L) against depth (m). The orange horizontal line represent the depth of the pycnocline. The chlorophyll-a vertical profile shows two metrics at different depths within the same profile: the chlorophyll-a fluorescence peak below the pycnocline, indicated by a blue arrow, and the maximum chlorophyll-a concentration, indicated by a black arrow.