The spatial and temporal behaviour of stratification in the Fehmarnbelt strait

An analysis on when and where bi-directional plume spread due to stratification can occur during dredging activities in the Fehmarnbelt

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Picture on cover page: Femern A/S (2021b)

Abstract

The amount of suspended sediment spill released during dredging activities in the Fehmarnbelt strait is monitored along the excavated trench to prevent negative effects on local ecology. Stratification due to the interaction of saline water from the North Sea and fresh water from the Baltic Sea forces bi-directional flow of the layer above and below the density gradient, causing bi-directional spread of the dredging plume perpendicular to the trench as well. During such an event, monitoring on both sides of the trench is required. By mapping out the spatial and temporal behaviour of stratification, a prediction can be given on where and when measuring on both sides of the trench will be needed to include the baroclinic effect. Figures created with monitoring data show that the density profile is influenced by the salinity, rather than the temperature. Therefore, stratification predominantly depends on the in and outflow of water with respect to the Baltic Sea. The figures also show a larger density gradient during out than inflow. It can also be observed that where the water depth is restricted to 10 meters, wind and bottom friction mix the entire water column. Therefore, stratification occurs predominantly during outflow in sections deeper than 10 meters, indicating the need for monitoring the bi-directional plume spread during such circumstances. Whether stratification occurs during inflow in sections deeper than 10 meters likely depends on the duration and strength of the wind forcing and the initial strength of the density gradient prior to the inflow event. Further analysis should be done to confirm this. Signs of Ekman transport, return flows and the deflection of the currents towards deeper water can also be observed in the measurement figures. Since these processes affect the plume spread direction, additional research can be done on the behaviour of the current direction in the Fehmarnbelt.

Executive Summary

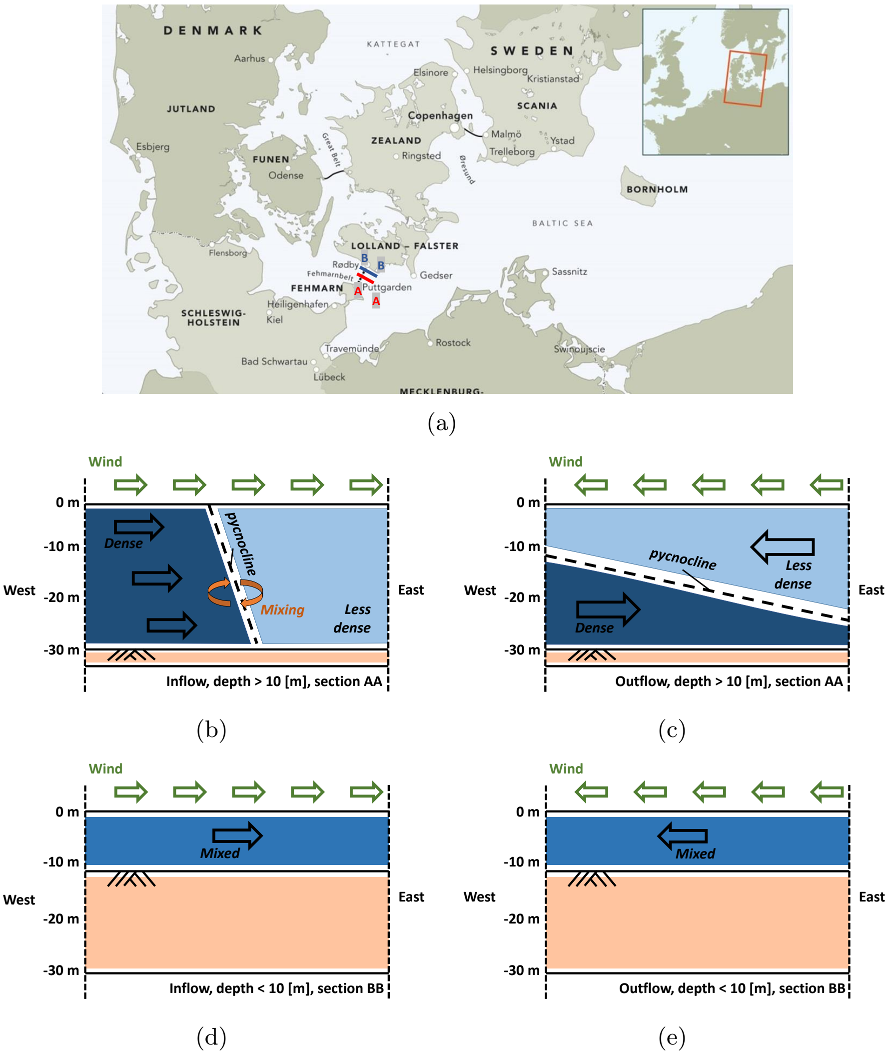
To improve the traffic connection between Germany and Denmark, an immersed tunnel will be built in the Fehmarnbelt strait. Fehmarn Belt Contractors (FBC), a joint venture between Van Oord and Boskalis, is responsible for dredging the tunnel trench. During dredging activities, suspended sediment spill enters the water column and flows with the currents before it settles down again. Local ecology could be negatively affected if the concentration of suspended sediment is too large. To ensure environmental restrictions are met, a strict spill limit is set. Monitoring of the dredging plume along the trench is implemented to show requirements are met.

Being part of the Danish Straits, the Fehmarnbelt is one of the connections between the Kattegat and the Baltic Sea. Gravity driven flow causes dense saline water from the North Sea to drift beneath fresh river run-off originated Baltic Sea water, resulting in a stratified belt containing a density gradient (pycnocline). If the pycnocline is strong enough to prevent the water column from being mixed by wind and bottom friction, a difference in flow direction between the layer above and below the gradient can occur. The layer above the pycnocline flows in the direction forced by the wind, whereas the layer beneath moves the opposite way. This bi-directional flow effect causes the top and bottom of the dredging plume to spread in opposite directions as well. In this case, measurements on both sides of the construction works are needed instead of only downstream. By mapping out the behaviour of stratification, a prediction can be given on where and when measuring of the baroclinic effect will be needed. The main objective of this research is to gain insight into the processes that increase and reduce stratification. This knowledge can be used while monitoring activities are planned. The bi-directional flow referred to in this study is directed perpendicular to the tunnel trench.

Based on the literature research it can be concluded that the stratification in the Fehmarnbelt is governed by two large scale processes: in and outflow with respect to the Baltic Sea and solar radiation intensity. In and outflow governs the supply of saline and fresh water to the area and high solar radiation intensity increases stratification through heating of the surface layer. A stratified system is stable when the dense is beneath the less dense layer. Since fresh water originates from the east, stratification is potentially more stable during outflow. Locally, wind forcing and bottom friction can mix the water column.

Three different monitoring data sets are used to visualize the current direction, wind direction and density profile of one measurement around the same time and location. The current direction and magnitude are measured using an ADCP, the density profiles are obtained from CTD measurements and the information about the wind and current direction at mid-depth is withdrawn from the open source website AEGIR [Femern A/S (2021c)]. By analyzing the measurement figures, it can be concluded that the shape of the density profile follows that of the salinity rather than the temperature profile. Therefore, stratification is less dependent on the seasonal behaviour of solar radiation intensity than on the occurrence of in or outflow with respect to the Baltic Sea. Since the fresh water from the Baltic Sea flows over the dense North Sea water during outflow, the belt is stably stratified in this case. During inflow, the surface layer is more saline. As dense North Sea water flows over the fresh, the belt is unstably stratified and internal mixing occurs. Therefore, the density gradient increases during outflow and decreases during inflow.

Stratification occurs during outflow, but whether it arises during inflow most likely depends on the strength and duration of the wind forcing the surface layer. When the density differences between the surface and bottom layer are large at the start of an inflow event, the water column is less easily mixed. The strength of the density gradient is presumably seasonally dependent due to an increase in fresh river run-off during spring and stronger winds in winter. As these are all theoretical findings from literature, further research is necessary to verify whether stratification during inflow depends on the initial strength of the density gradient, the magnitude and duration of wind forcing. Additionally, it can be concluded from the measurement figures that stratification does not occur in sections shallower than 10 meters. Wind and bottom friction mix the entire water column in this case.



(a)

(b) (c)

(d) (e)

The influence of in and outflow and bathymetry on stratification in the Fehmarnbelt, shown as two situations in two different sections as shown in sub-figure (a) [Femern A/S (2021a)]. Inflow (b) and outflow (c) in a region deeper than 10 meters. Inflow (d) and outflow (e) in a region shallower than 10 meters. The Coriolis effect is neglected in this figure.

The conclusions of this study are summarized in the figure above. Stratification and therefore bi-directional plume spread occurs during outflow in sections deeper than 10 meters. Whether stratification occurs during inflow in sections deeper than 10 meters presumably depends on the initial strength of the density gradient prior to the inflow event, the magnitude and duration of wind forcing. The water column is mixed in sections shallower than 10 meters.

Signs of Ekman transport, return flows and the deflection of the currents towards deeper water can also be observed in the measurement figures. Since the behaviour of the current direction has no direct influence on stratification, it falls beyond the scope of this study. As these processes do affect the plume spread direction, additional research can be done on the behaviour of the current direction in the Fehmarnbelt.

Contents

1 Introduction

1.1 Background

To improve the German and Danish traffic connection, an immersed tunnel is being built in the Fehmarnbelt strait. Becoming almost 18 kilometres long, the fixed link will decrease the travelling time between the two countries significantly. The duration of a train ride from Copenhagen to Hamburg can reduce from four and a half to two and a half hours [A Bjørnshave et al. (2019)]. Next to one single rail track in each direction, two road traffic lanes will be constructed. The project should enhance the trade relation between Scandinavia and Western-Europe, since the link is expected to close a gap in the transport network [Femern A/S (2021a)]. The construction area is situated between the Fehmarn island on the German side and the Danish Rødbyhavn on Lolland. The considered strait lies within the Southwestern Baltic Sea. Since local brackish water interacts with more saline in-flowing water from the North Sea through the Kattegat, the area is of great interest to oceanographers [Leppäranta and Myrberg (2009)].

Figure 1.1: Detail project site of the Fehmarnbelt fixed link [Femern A/S (2021b)].

The building process will contain multiple phases, in the end resulting in an emerged tunnel beneath the sea bed. Before the tunnel itself can be constructed, a trench needs to be dredged in the bed of the strait. The 15 million cubic metres of material that is to be removed will be used for land reclamation at both sides of the project, mostly on Lolland. At this location, the new land will become a nature reserve area. After the dredging activities are completed, 89 reinforced concrete modules will be immersed. The components are created in a local factory on Lolland. Stones and sand are placed on top of the structure to resemble the sea bed as it was before the construction of the tunnel [Femern A/S (2021a)]. Dredging works by Fehmarn Belt Contractors, a joint venture between Van Oord and Boskalis, started in November 2020 [FBC (2021b)]. The Fehmarnbelt tunnel itself is expected to open to public in 2029 [Femern A/S (2021a)].

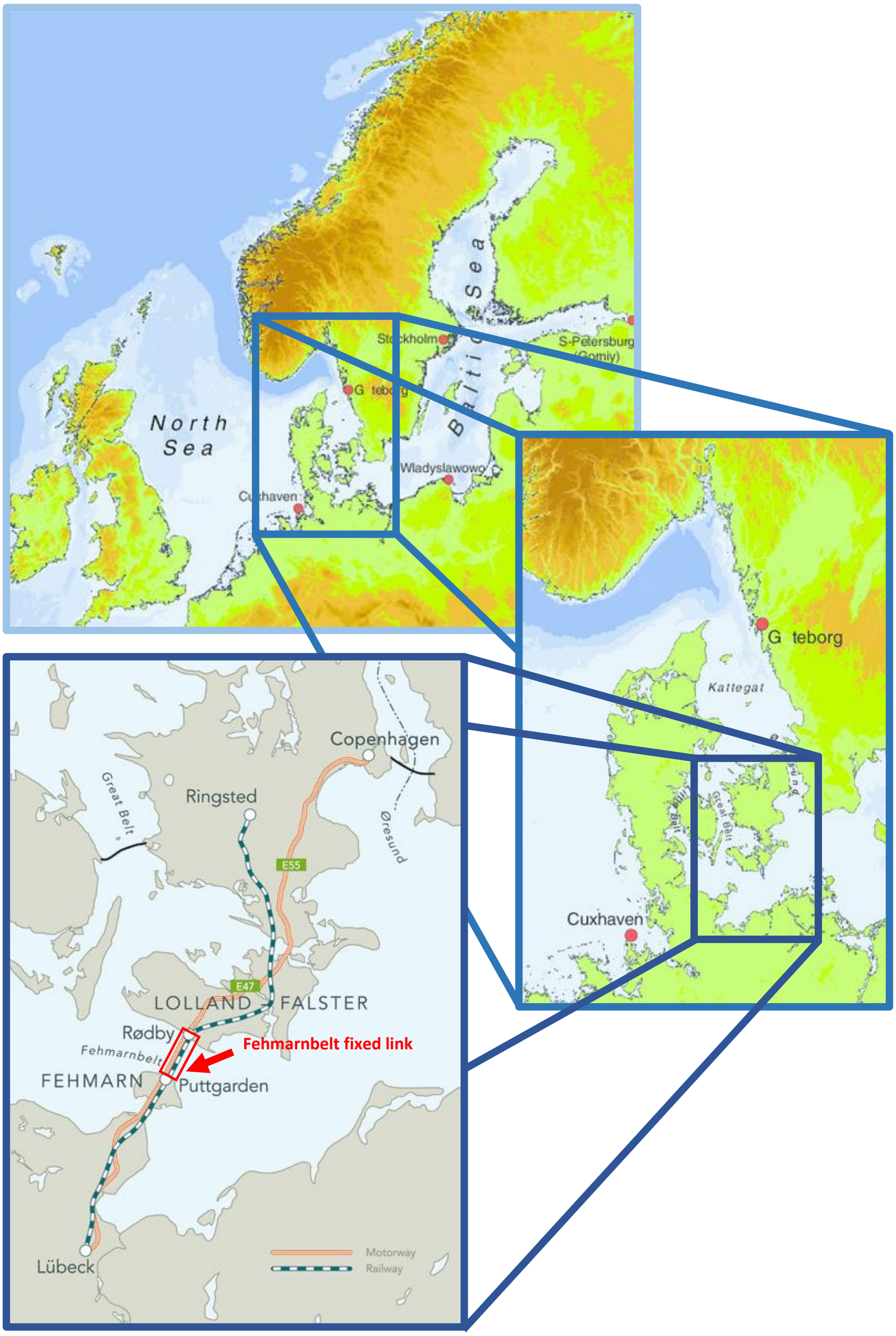
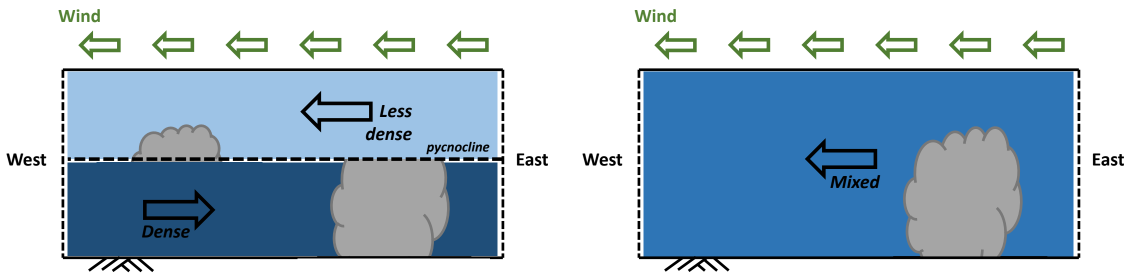


Figure 1.2: Location of the Fehmarnbelt fixed link. The figure is created with figures from Kulikov et al. (2015) and Femern A/S News Release (2013).

Environmental awareness is of great importance for large twenty-first century construction projects and therefore it is also relevant for the Fehmarnbelt fixed link. Various Environmental Impact Assessments were prepared to indicate potential negative effects of the activities on the water quality, hydrography and ecology and how to reduce or avoid them. According to the assessments, the influence of sediment spill created during dredging and disposal on water quality of the area could be adverse [Femern A/S (2021d)]. Spill can occur when, for example, the head of a grab dredger travels through the water column. Since the top is open, water can interact with the soil and particles leave the head, creating a so called plume [FBC (2021a)]. As this is only one example, sediment spill can occur in many ways. A sufficiently large increase in suspended sediment concentration leads to a reduction of light penetrating the water column [Fehmarnbelt Fixed Link EIA (2013c)]. The main consequences would be related to the visual attractiveness of beaches and hindered growth of marine life, although it must be noted that both effects would be temporal [Fehmarnbelt Fixed Link EIA (2013b)]. A limit has been determined by project owner Femern A/S to minimize the impact. So called 'Permanent Works Boundaries (PWB)' are introduced. The definition of sediment spill can then be made explicit, referring to sediment suspended due to dredging and reclamation activities leaving the Permanent Works Boundaries. This report will only focus on directly released dredging plumes, and therefore not on the effects of re-suspension or reclamation. Additionally, Femern A/S divided the project site into eight different zones. Varying seasonal limits are addressed to the zones, depending on local ecology [FBC (2021c)]. To ensure the requirements are full filled, monitoring of the dredging plume is required.



(a) Stratified water column

(b) Mixed water column

Figure 1.3: The interaction between a dredging plume and stratification.

The Fehmarnbelt is part of a dynamic transition area between the central Baltic Sea and the Kattegat. Dense flow from the North Sea interacts with fresh river run-off originated water, resulting in a stratified system. Gravity driven flow causes the denser water to travel beneath the fresh, resulting in a density gradient (pycnocline) in the water column [Pietrzak (2020)]. If the system is forced by wind and the density difference is large enough to prevent mixing of the water column, the layer above the gradient will flow opposite to the one below. This effect will be referred to as bi-directional flow. The bi-directional flow focused on during this study is directed perpendicular to the tunnel trench. When bi-directional flow occurs, the top and bottom of the dredging plume will spread in opposite directions as well. In this case, measurements on both sides of the construction works are needed instead of only at the downstream side of the plume.

1.2 Objective

The main objective of this research is to gain insight into the processes in the Fehmarnbelt that increase and reduce the density gradient in the water column. The obtained knowledge can be used to predict when and where bi-directional plume spread due to stratification can be expected and should be monitored. Describing the previously mentioned, the research question to be answered is:

What is the spatial and temporal behaviour of stratification in the Fehmarnbelt strait?

The corresponding sub-questions are:

- What are the physical oceanographic processes in the Fehmarnbelt influencing stratification?
- Is the shape of the density profile governed by temperature or salinity?
- In which sections is the water column mixed by wind and bed friction?

1.3 Research approach

To answer the main research question, the sub-questions need to be addressed first. By writing a literature study about the oceanography of the Fehmarnbelt, the processes influencing stratification are determined. The first sub-question can be answered using the obtained knowledge. To answer the second and third sub-question, a CTD measurement from a monitoring campaign is visualized together with an ADCP measurement around the same time. Corresponding information about the wind and current direction at mid-depth is used from Femern A/S' open source portal AEGIR [Femern A/S (2021c)]. The three different data sets are combined to visualize a monitoring campaign measurement. This process is applied to multiple campaigns, resulting in the 20 figures in Appendix D. To simplify the analysis, a frame of reference is derived containing axes along (v) and perpendicular to (u) the trench. All the directions referred to in this study are with respect to this reference frame. The figures are used to answer sub-question two and three.

1.4 Outline

Chapter 2 describes the oceanography of the Fehmarnbelt. The methodology of the analysis is given in Chapter 3, whereas the actual analysis is performed in section 4 and 5. Limitations and recommendations are given in the discussion, which can we found in Chapter 6. The conclusion is written in Chapter 7.

2 Oceanography of the Fehmarnbelt

The aim of the literature study on the oceanography of the Fehmarnbelt is to gain insight into processes that influence the stratification in the area. The topography is discussed in subsection 2.1, where important aspects of the bathymetry are mentioned in subsection 2.2. Furthermore, the meteorological effects are investigated in subsection 2.3. Subsection 2.4 gives a summary of the effects that govern stratification.

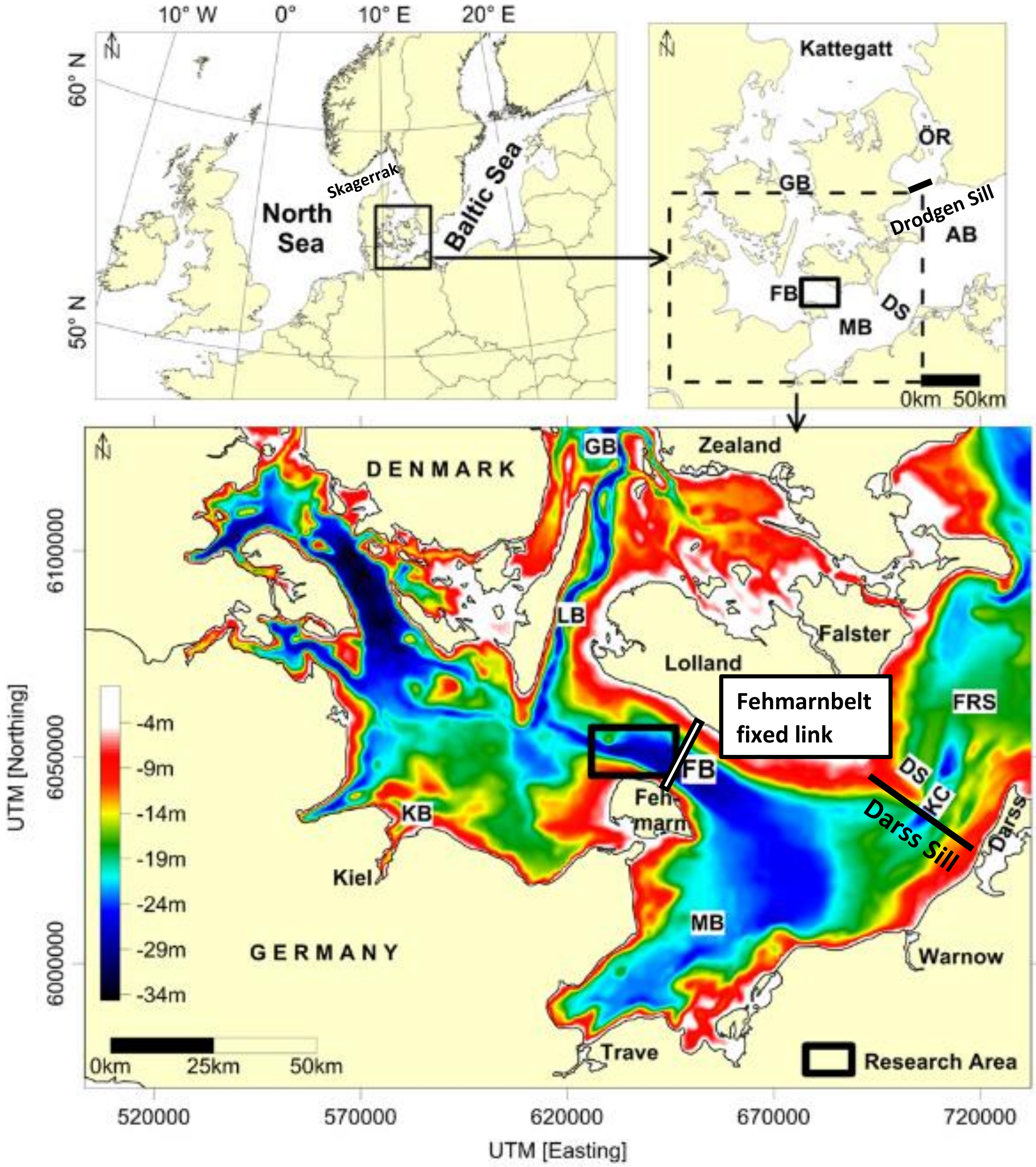


Figure 2.1: Topography and bathymetry of the area of interest. GB: Great Belt, FB: Fehmarn Belt, MB: Mecklenburg Bay, DS: Darss Sill, ÖR: Öresund, KB: KielBay, LB: Langeland Belt, KC: Kadet Channel, FRS: Falster–R̈ugen sand plain and AB: Arkona Basin. Figure adjusted from Feldens and Schwarzer (2012).

2.1 Topography

The Baltic Sea is situated between Scandinavia and Eastern-Europe, which form the land borders. The western water boundary is most often defined behind the passages Great Belt, Little Belt and "Oresund leading to the Kattegat. The Fehmarnbelt is located between the Arkona Basin and the Danish Straits, containing the Little and Great Belt. River run-off from the mainland causes an outflow of fresh low-density surface water from the Baltic Sea, through the Kattegat and Skagerrak, to the North Sea. Since the North Sea is more saline, dense marine water flows the opposite way along the bed. Mass conservation results in advection, causing entertainment. The bottom layer mixes with the mass above, after which it leaves the Baltic Sea again by the previously mentioned freshwater outflow at the surface. This phenomenon is also referred to as estuarine circulation [Pietrzak (2020)] or the 'Baltic Sea haline conveyor belt' [Leppäranta and Myrberg (2009)].

2.2 Bathymetry

2.2.1 Longshore

The Baltic Sea consists of 14 sub-basins, varying greatly in depth [Leppäranta and Myrberg (2009)]. Water exchange between the sub-basins is governed by the presence of sills. The Kattegat, northern part of the "Oresund, the Great Belt, the Little Belt and the Fehmarnbelt together form the Belt Sea. This transition area between the Central Baltic Sea and the North Sea is relatively shallow. Two sills create a natural border between the Belt Sea and the Central Baltic Sea, namely: the Darss and Drogden sill. The Darss sill, located around 75 km east of the Fehmarnbelt with a depth of about 18 m, limits deep water inflow from the belt through the Mecklenburg Bay basin to the Arkona Basin [She et al. (2007)]. Therefore, the Belt Sea is generally more saline than the Central Baltic Sea and a density gradient (pycnocline) occurs. The depth of the shallow area differs significantly from the mean (54 m) and maximum (460 m) depth of the Baltic Sea [Gustafsson and Andersson (2001)]. Since the pycnocline of the Baltic Sea is located around 60-80 m, which is deeper than the sill depth, dense water bodies beneath remain rather stagnant during regular in and outflow conditions. Only during large inflow events, forced by water level differences, a significant saline volume enters the basins by being pushed over the boundary [Gustafsson (1997)].

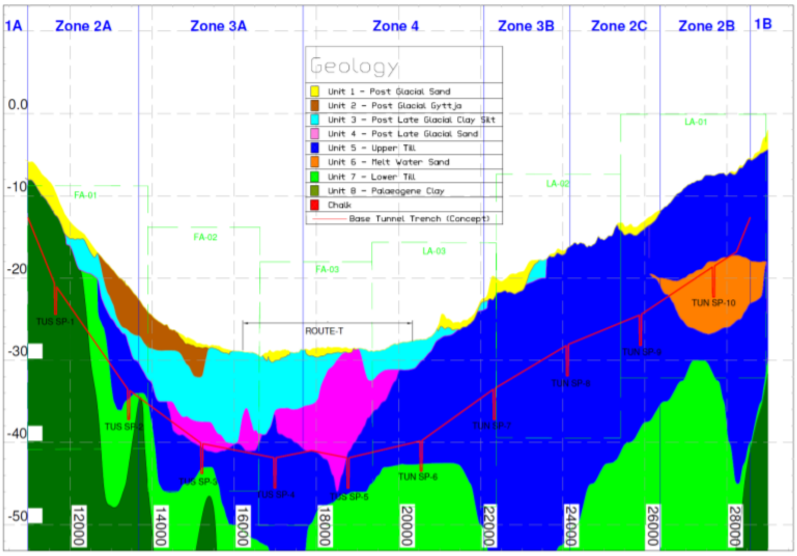


Figure 2.2: Cross section of the Fehmarnbelt as indicated by the box in figure 2.1 orientated to the East, including soil types and the base of the tunnel trench indicated with the red line [FBC (2021a)]. Fehmarn is to the South and Lolland to the North.

2.2.2 Cross shore

The cross section of the belt is asymmetric, the slope on the German side of the project being steeper than near Lolland. A variation in depth is visible for the different sections of the site, with a maximum depth of 30 meters orientated near the Fehmarn island. The shape of the bathymetry can generate a difference in density gradient magnitude between the sections, since the influence of the bed may be more pronounced in shallow area's. Turbulence due to wind and bottom friction can mix the whole water column, where in deep water only the lower and upper part would be stirred.

2.3 Meteorology

2.3.1 Coriolis

The effect of the earth's rotation on the deflection of flow direction is called the Coriolis force. Fluids turn to the right in the Northern and to the left in the Southern Hemisphere. The Rossby Radius of deformation gives an estimate of the length scale at which Coriolis influences the flow pattern [Pietrzak (2020)] and is not repressed by the influence of friction. For stratified flows the Internal Rossby Radius of deformation is used, in combination with the reduced gravity:

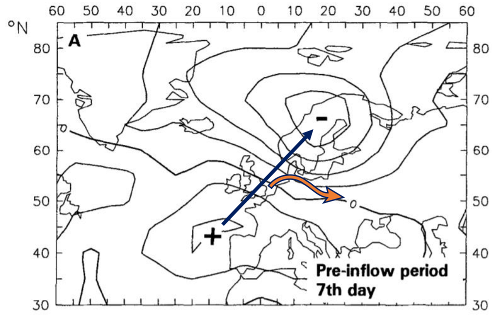
$$R_I = \frac{\sqrt{Hg'}}{f} \tag{2.1}$$

$$g' = \frac{\rho_1 - \rho_2}{\rho_0} g \tag{2.2}$$

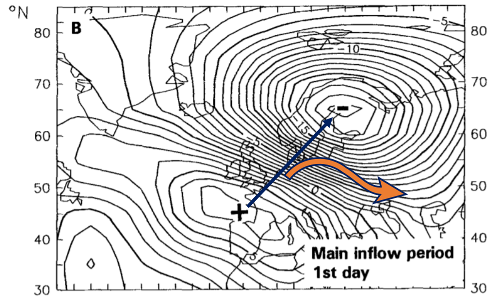
The Internal Rossby Radius of the Fehmarnbelt is estimated using values from the Fehmarnbelt Fixed Link EIA (2013a) Hydrography report. Monitoring measurements at station MS02 (figure 3.1) between May 2009 and December 2010 showed that the maximum density difference during summer was about 15 [kg/m^3]. The water depth at station MS02 is approximately 25 [m]. Typical values of ρ_0 = 1000 [kg/m^3], f = 10^{-4} [s^{-1}] and g = 9,81 [m/s^2] are used. One finds an Internal Rossby Radius magnitude of 19 [km]. This is in the order of magnitude of the cross section, being about 18 [km]. The Coriolis effect can therefore influence the flow.

2.3.2 Large scale wind

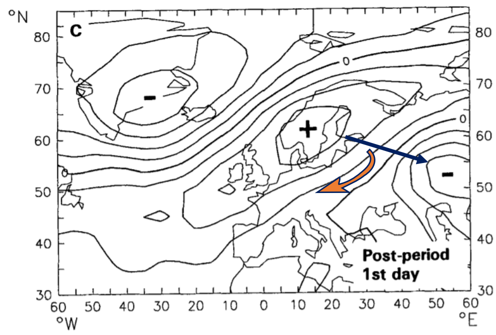
The cyclonic movement of air over the earth's surface does not only affect climate and weather, it also influences surface elevation [Girjatowicz et al. (2016)]. High and low pressure fields pass Scandinavia on a weekly basis [Fehmarnbelt Fixed Link EIA (2013a)]. Theoretically, air flows from a high to a low pressure field. This movement gives rise to a pressure gradient. Since the flow is in geostrophic balance [Gustafsson (1997)], the pressure gradient equals the Coriolis force. The resulting wind component is deflected to the right in the Northern Hemisphere [de Roode (2021)], forcing set-up or set-down of water levels. When a low pressure field is situated above Scandinavia, the wind is blowing from the west. The water is pushed against the Eastern coastlines, creating local set-up. The surface elevation of the Baltic Sea and the Kattegat are therefore higher on average, whereas the water level in the Belt is relatively low. Inflow from the Kattegat is forced through the Fehmarnbelt. Using the same reasoning, outflow is initiated when a high pressure field occurs above Scandinavia [Fehmarnbelt Fixed Link EIA (2013a)]. Winds from the east create local set-down at the Eastern coastlines of the Kattegat and the Baltic Sea. During outflow, fresh water from the Baltic Sea floats over the dense North Sea water resulting in a stably stratified system [Pietrzak (2020)] and an enhance pycnocline. During inflow, the dense saline water is forced over the fresh. Gravity forces the dense particles below the less dense, causing mixing of the water column an a reduced pycnocline. Using the knowledge above it can be concluded that, on a large scale, water flows in the direction forced by the wind. The direction of the wind depends on the existence of a high or a low pressure field above Scandinavia. On a local scale, the current direction might be altered as described in section 2.3.3.



(a) Before strong inflow



(b) During strong inflow



(c) Outflow after strong inflow

Figure 2.3: Schematic overview of the difference in strength of pressure fields over Scandinavia during in and outflow. Dark blue arrows represent the pressure gradient and orange arrows show the resulting wind vector. The contour interval is 1 hPa. The closer the contours, the stronger the resulting wind vector. Picture used is an example in the paper of Matthäus and Schinke (1994) of a strong inflow event sequence.

The North Atlantic Oscillation (NAO) index gives an average monthly measure of the zonal wind strength, with zonal wind referring to components at the same latitude . A positive NAO indicates a relatively stronger pressure gradient over mid-latitudes and therefore stronger westerlies [Lehmann et al. (2002)]. A negative NAO shows the opposite. As earlier mentioned, water level differences can force a large inflow event. Since the probability of occurrence is highly dependent on a specific sequence of events, as the state of the NAO, large inflow is observed on a decadal timescale. First, outflow should occur to enhance the pycnocline in the Belt Sea. Furthermore, it should be followed by multiple weeks of strong zonal westerly winds [Schinke and Matthäus (1998)]. During such an event the dense bottom layer in the Baltic Sea is renewed, refreshing the oxygen content. The ecological state of the area is highly dependent on this form of deep water ventilation [Omstedt et al. (2012)].

2.3.3 Local wind

Wind forcing can affect the Fehmarnbelt in two ways on a local scale. Where earlier mentioned density differences tend to restore stratification, wind causes shear stress over the surface layer resulting in mixing of (a part of) the water column. Turbulent flow entrains particles from the lower in the upper layer [Pietrzak (2020)]. If the pycnocline is strong, turbulence can be retained and the wind will only mix the water body above the density gradient. Furthermore, the wind causes transport of water. A well mixed system is observed at first, to describe the theoretical framework of the relevant advection processes. Whether the currents follow the direction initiated by the wind forcing directly depends on the influence of friction and Coriolis. If friction is dominant, the currents follow the wind forcing directly. If Coriolis is dominant, the currents are deflected.

To describe the influence of local wind, four theoretical options are given. In reality, a combination of these cases will occur. Long- and cross shore wind forcing are distinguished. Furthermore the system is assumed to be dominated by friction or Coriolis. When the currents directly follow the wind forcing in a friction dominated system, inflow (outflow) will occur during longshore wind from the west (east). Set-up and set-down at the coastlines occurs as a result of cross shore wind. When the wind is directed to the north (south), the advection will also be to the north (south). Water piles up against the northern (southern) boundary, resulting in a lower water level at the southern (northern) boundary. Due to mass conservation, a circular flow pattern arises in the cross-section of the belt. Up-welling (down-welling) will occur at the southern (northern) boundary, causing the colder and more saline bottom layer to reach the surface. Down-welling (up-welling) will be observed at the northern (southern) boundary [Leppäranta and Myrberg (2009)]. The difference in water level can also create jet flows at both closed borders with scales of the internal Rossby radius [Fennel (1986)]. Since the belt is about the width of this parameter, this phenomenon is not taken into account.

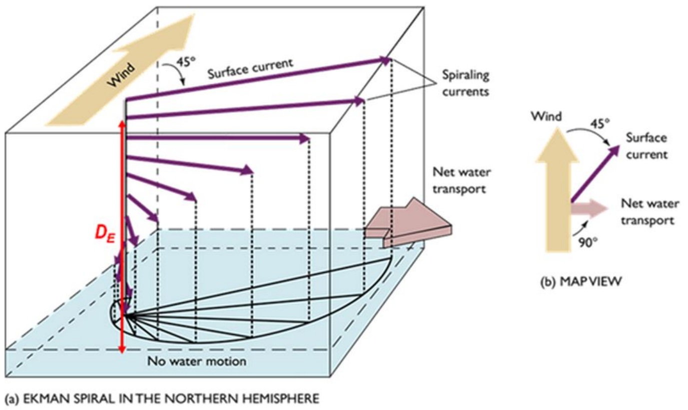


Figure 2.4: Schematic overview of an Ekman spiral [offshoreengineering.com (2021)] and transport.

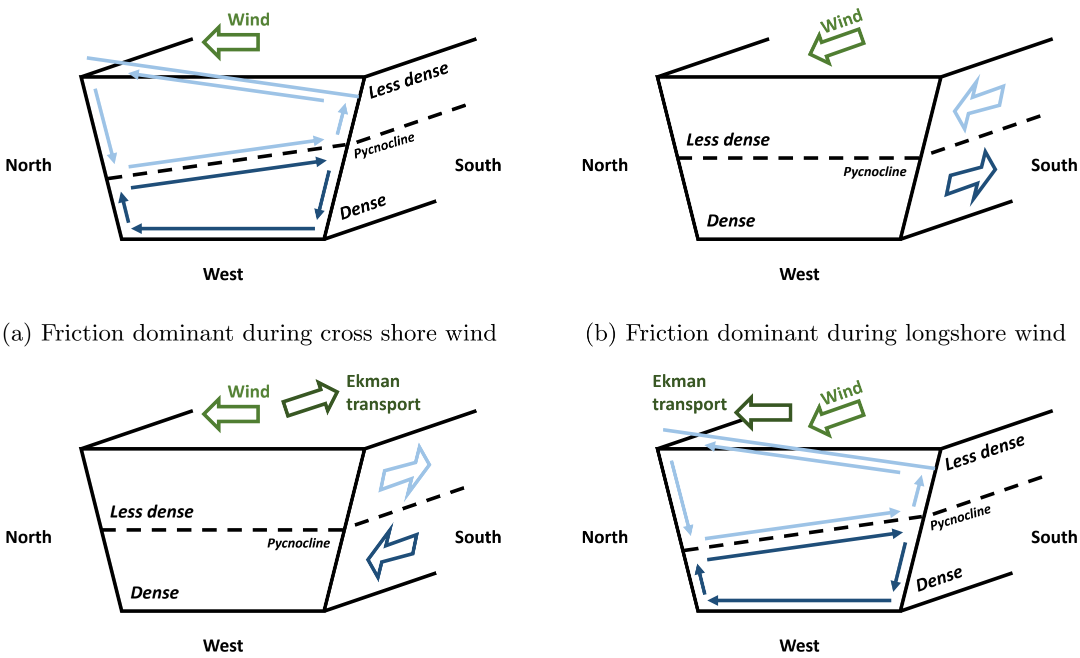
If the current direction is dominated by Coriolis, the resulting surface current is °45 to the right of the wind. The movement of this upper layer acts on the one below, where the flow is deflecting even more to the right and the magnitude decreases due to frictional loss between the layers. This process will repeat itself down to a certain depth D_E where the current is opposite to the surface direction, resulting in an Ekman spiral [Pietrzak (2019)]:

$$D_E = \pi \sqrt{\frac{2v_t}{f}} \tag{2.3}$$

Parameter f represents the Coriolis force [s^{-1}] and v_t the turbulent viscosity [m^2/s]. Since the deepest point in the belt is about 30 meters, the area can be considered shallow and a fully developed surface spiral is not likely to occur. When the velocity components of an fully developed Ekman spiral are integrated over its depth, an average mass flow expression is derived. This is called Ekman transport. When the wind component flows alongshore, Ekman transport occurs to the right in the Northern

Hemisphere. If cross shore wind is directed to the east (west), the transport will be to the south (north). The earlier mentioned set-up, up-welling and return current mechanism occurs. When the wind blows longshore, Ekman transport along the coastline occurs. If the wind is directed to the north (south), inflow (outflow) will take place.

Because stratification is relevant in the Fehmarnbelt, the phenomenon should be added to the four theoretical wind forcing frameworks. This results in an additional flow beneath the pycnocline opposite to the one above [Leppäranta and Myrberg (2009)]. When the return flow is cross shore, the closed boundaries cause the flow to be a return-current and the pycnocline gets tilted [Pietrzak (2020)]. Since this study focuses on the behaviour of stratification, it is assumed that the current direction directly follows the wind forcing. In reality a combination of both friction and Coriolis related transport is expected in deep water in the Fehmarnbelt.



(a) Friction dominant during cross shore wind

(b) Friction dominant during longshore wind

(c) Coriolis dominant during cross shore wind

(d) Coriolis dominant during longshore wind

Figure 2.5: Theoretical framework describing the influence of friction and Coriolis in combination with stratification on the current velocity direction. Mixing is neglected.

2.3.4 Seasonality

During summer, the surface layer of the belt is warmed by strong solar radiation. In combination with a larger river run-off and therefore lower salinity in the upper layer of the Baltic proper during spring, the pycnocline is strong throughout summertime. Local wind forcing is stronger in autumn and winter, whereas solar radiation decreases. The water column is therefore more easily mixed during this period [Leppäranta and Myrberg (2009)].

2.3.5 Tide

Due to the shallow bathymetry, the tidal amplitude originating from the North Sea decreases through the Danish straits and the total influence is limited [Fehmarnbelt Fixed Link EIA (2013a)]. Tides have little influence on the magnitude of the water level in the belt. The amount of water flowing through the area can also have a small dependence on this effect, but not enough to cause a major inflow event. Therefore, the influence of tides is neglected in this study.

2.4 Relation to stratification

Temperature and salinity influence the density of water, where a colder and more saline content will lead to a higher value [Pietrzak (2020)]. Larger density differences enhance the stratification of the area. On a large scale, stratification is influenced by solar radiation intensity and the in and outflow through the belt. The solar radiation intensity governs the heating of the upper layer, being higher in summer than in winter. The presence of high and low pressure fields above Scandinavia largely influence the sea level difference between the Kattegat and the Baltic proper, forcing in - or outflow and therefore the supply of saline and fresh water to the area. On a local scale, the stratification in the Fehmarnbelt is reduced by wind and bottom friction.

3 Methodology

Monitoring campaigns are performed by FBC to control the sediment spill. A part of the data obtained during these campaigns can be used to quantify and control the behaviour of stratification. First the availability of the relevant data is discussed 3.1. To simplify and clarify the analysis, a frame of reference is obtained in subsection 3.2. The way the data is processed and visualized is mentioned in subsection 3.3. Subsection 3.4 shows the criteria used to select data sets suitable for the analysis in this report.

More instruments are used than the ones discussed in this section during monitoring campaigns. The devices mentioned also gather more information than the measurements used in this study. A detailed explanation about the monitoring campaigns can be found in FBC (2021c).

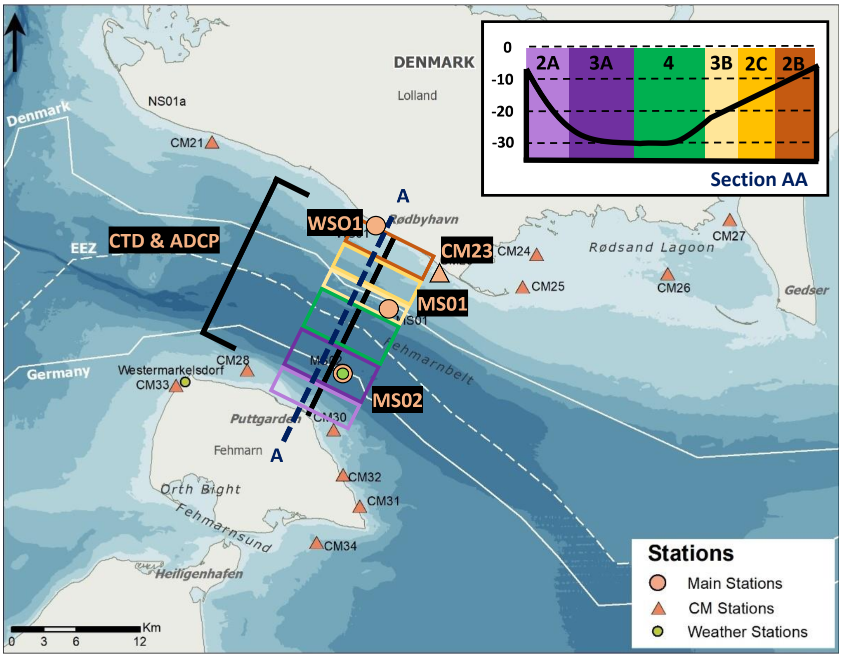


Figure 3.1: Locations where measurements are taken and AEGIR stations with CM (Coastal Monitoring Stations, MS (Main Stations) and Weather Stations (WS).

3.1 ADCP, CTD and AEGIR data availability

3.1.1 ADCP

During the daily monitoring campaigns, from the summer of 2020, FBC sails daily ADCP transects of 10 minutes each [FBC (2021c)]. Every second a measurement is obtained, returning information about every 0.5 meters of the water column. The data sets obtained with the ADCP, called 'raw transect files', contain among others the absolute current velocity magnitude and direction of multiple points in the water column measured every second. Nearshore ADCP 'raw transect files' are available from the summer of 2020 till October 2021. The measurements till January 2021 are very shallow (depth smaller than 6) and mostly from reclamation works. From February till June 2021 information is available between 6 and 10 meters. Deep water measurements (depth larger than 10 meters, section 3A, 4, 3B and 2C) start from July 2021. Dredging and reclamation activities started at the Danish side (section 2B, 2C, 3B, 4 and 3A), so no information is available of section 2A near Germany. The very shallow measurements are not used for this study.

3.1.2 CTD

One CTD profile is measured during a daily monitoring campaign. The device measures depth, temperature and conductivity with a time interval of one second. The conductivity is used to determine the salinity. The CTD data sets vary in total time and sometimes consist of multiple surface layer measurements. The device started operating during the summer of 2020 but did not work in April, May and June 2021. The availability of nearshore and deep water measurements is furthermore comparable with the ADCP 'raw transect files'.

3.1.3 AEGIR stations

Environmental data is collected with sensors connected to buoys in the Fehmarnbelt (figure A1). Results are uploaded to Femern A/S' open source portal AEGIR Femern A/S (2021c). Two devices are situated above the cross section where the fixed link will be built; MS01 and MS02. Several other stations are placed near the coast of Lolland and Fehmarn. The hourly measurements go back to January 2020 and will be taken at least until the construction phase is finished. The values for the current direction at mid-depth, wind direction and wind magnitude are taken from the stations during a monitoring campaign and stored in so called 'calibrated transect files'. During monitoring campaigns in section 2A and 2B, the wind information is used from WS01 and the current information from CM23. In the other sections, the MS02 gives the wind information. Whether station MS01 or MS02 is used for the current direction depends on which one is closest. The measurements are stored in so called 'calibrated transect files'. If the stations are not operating during a monitoring campaign, earlier measurements that go back until three hours before are used instead. Otherwise the 'calibrated transect files' store no information from AEGIR.

3.2 Frame of reference

To simplify the analysis, a frame of reference is chosen with axes along (v) and perpendicular to (u) the trench. The directions used in this study are with respect to this frame of reference. The derivation of the frame of reference and the transformation of the current and wind direction are given in Appendix B.

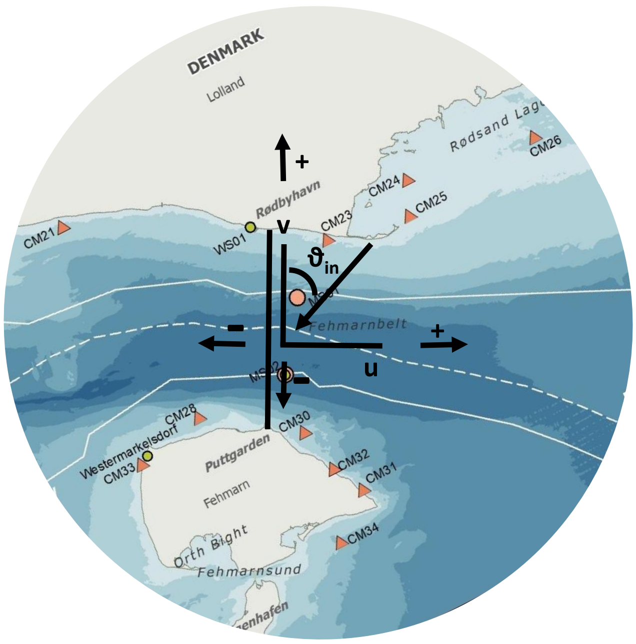


Figure 3.2: Frame of reference

3.3 Data processing and visualization

3.3.1 Measurement visualization

To investigate the behaviour of stratification in the Fehmarnbelt, measurements of the current magnitude, current direction, wind direction, wind magnitude and shape of the density profile around the same time and location are visualized in one figure with the python script from Appendix F. Three different files are used: an ADCP 'raw transect file', a 'CTD file' and a 'calibrated transect file' containing AEGIR data. The files are matched based on the time of measurement, which is stored in the file name. The following subsections focus on the ways the subplots are obtained.

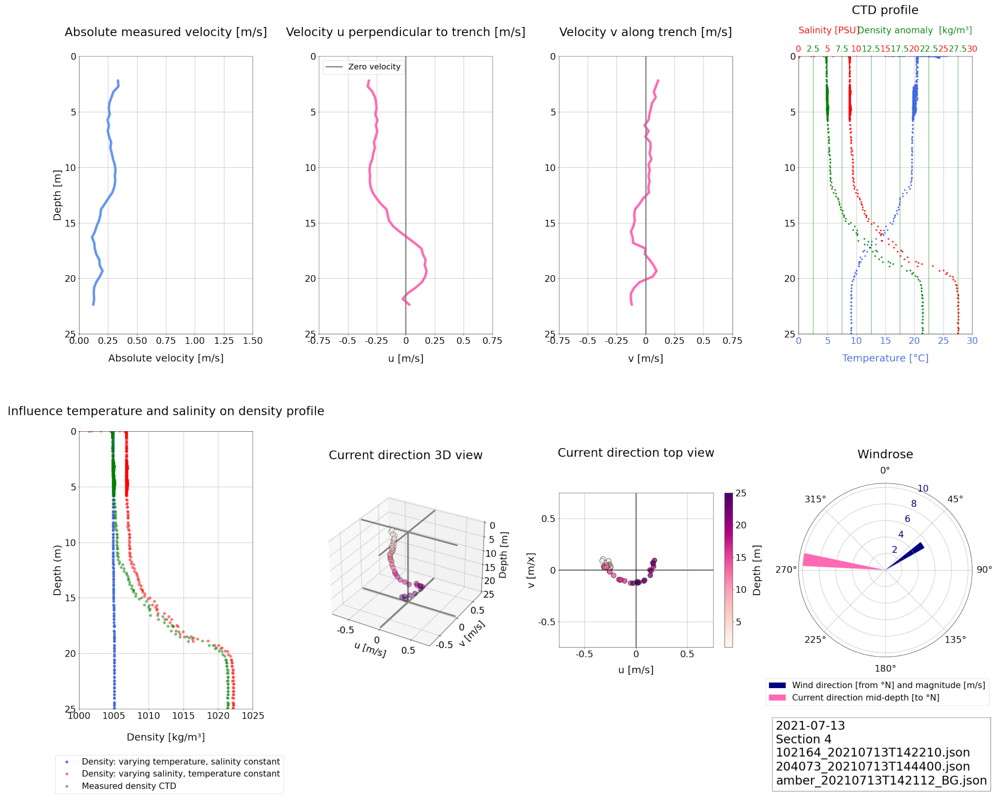


Figure 3.3: Example of one of the twenty measurement figures. Measurements 13-07-2021 in zone 4 giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth. A larger version can be found in Appendix D figure D14.

3.3.2 Current velocity profiles

The current velocity profiles are visualized with the ADCP 'raw transect files' as described in 3.1.1. The measured current direction and absolute velocity are averaged over time. The first subplot of figure 3.3 gives the mean velocity profile in time against depth using the averaged absolute velocity. As described in Appendix B.3, the mean absolute velocity of each point in the water column is factorized using the mean current direction to create the current velocity component perpendicular to and along the trench. These components are shown in subplot 2 and 3 of figure 3.3. The same data points are used together to visualize the evolution of the current direction against depth in subplot 5 and 6 of figure 3.3.

3.3.3 CTD profiles

All the temperature, salinity, and density data points from one CTD measurement are plotted against the depth at which they are obtained in subplot 4 of figure 3.3. Subplot 5 is created with the calculation shown in 4.2.

3.3.4 Windrose

The information shown in the windrose (subplot 8, figure 3.3) is taken from a 'calibrated transect file' which stores the values for the current direction at mid-depth, the wind direction and magnitude from one of the earlier mentioned AEGIR stations. Note that the wind and current directions are shown as bars. The wind is coming from and the current is going to the given direction.

3.3.5 Information box

The information box in the lower right corner of the figure shows the names of the three data files used. It also gives the date from the 'calibrated transect file'. The section where the measurements were taken are determined by using the mean latitude from the 'raw transect data', as shown in detail in Appendix C.

3.4 Data selection

Since there is only one CTD profile available for each monitoring campaign, the starting point of the data file selection is to search for 'calibrated transect files' and 'raw transect files' that were obtained around the same time as the CTD profile. The maximum difference between files is limited to 30 minutes. Fehmarn Belt Contractors quality checks FBC (2021c) all the 'raw transect files' to filter out files with noise from for example propeller wash. The list with selected 'raw transect files' is compared with a list of approved ones. The files that do not occur in the latter are discarded. The resulting sets containing three different files (a calibrated transect file, a raw transect file and a CTD measurement) are visualized using the approach described in subsection 3.3.1.

During monitoring campaigns, the CTD profile is often more shallow than the ADCP measured velocity profile. This way, it is ensured that the CTD measurement device is not damaged. Therefore, the figures with a shallow CTD profile but deep velocity profile can be used for the analysis. If however the CTD profile is more than 5 meters deeper than the velocity profiles measured by the ADCP, the figure is discarded. The measurements are likely from different sections in the belt. If the current direction at mid-depth shown in the windrose is not in accordance with the current direction at mid-depth shown in the current direction profiles, the figure is also discarded. After the data selection, the 20 figures shown in Appendix D remain.

4 Shape of the density profile

During the first part of the analysis, the shape of the density profile is further examined. This study will be used to give a recommendation on when bi-directional plume spread perpendicular to the trench occurs. Therefore, a comparison is made between the u and density profile (4.1) to ensure the first follows the latter. Subsection 4.2 gives the equation used to calculate a temperature and salinity dependent density profile. These profiles will be used in subsection 4.3 to conclude which of the two parameters governs the shape of the density profile. This conclusion will then be related to the temporal behaviour of stratification in the Fehmarnbelt (4.4).

4.1 Relation density and current velocity profiles

From the twenty measurement figures in the Appendix, one can conclude that the evolution of the current velocity profile perpendicular to the trench (u) follows the density profile. Where the pycnocline starts the current velocity turns. An example is clearly visible in figure D20 and a detail in figure 4.1. Where the pycnocline starts at a depth of about 12 meters, the current velocity in v and u direction both turn. In area's with a depth between 20 and 25 meters, the current velocity along the trench (v) follows the density profile but seems to be influenced by other processes as well. Additional turning of the current velocity is visible in the lower part of the profile, as can be seen in figure D19. Since this study focuses on the bi-directional plume spread perpendicular to the trench, these effects are not taken into account.

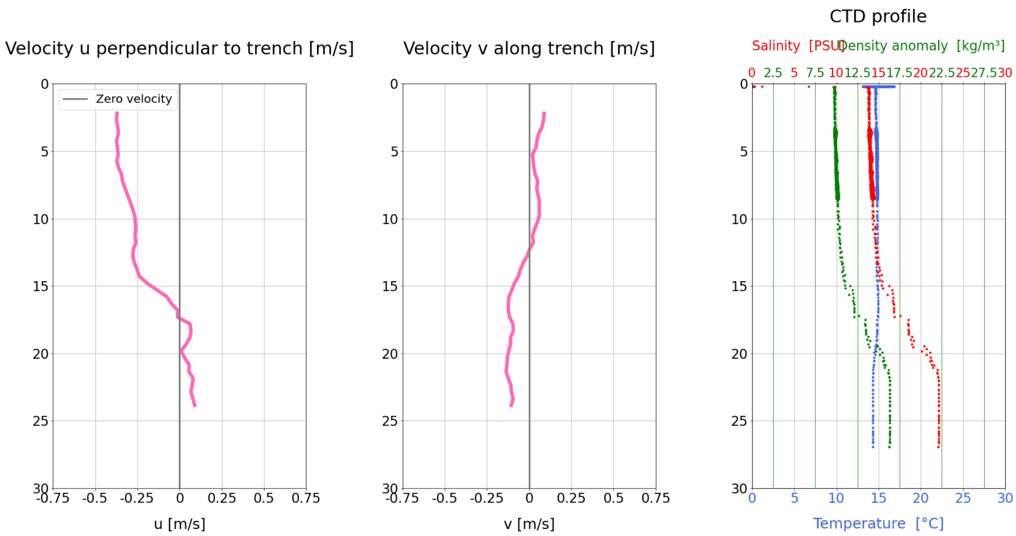


Figure 4.1: Detail from figure D20 in Appendix D.

4.2 Equation of state

To investigate whether the shape of the density profile is influenced by the salinity or temperature parameter, two density profiles are determined. Both shapes are compared with the measured density profile. For each point in the water column that is measured with the CTD, two new density values are calculated. One calculation contains the mean salinity and varying temperature measured by the CTD. The other uses a mean temperature and varying salinity values. The density in a single point of the water column is calculated using a simplified form of the 1980 Equation of State by Gill and Adrian (1982), as given in Stratified Flows [Pietrzak (2020)] lectures:

$$\rho = \rho_0 + 0.805S - 0.0166(\theta - 4 + 0.212S)^{1.69} \tag{4.1}$$

With fresh water density $\rho_0 = 1000$ [kg/m^3] and S being the salinity [PSU]. Because the maximum depth is 30 meters, the Fehmarnbelt is considered to be shallow enough to equalize the potential temperature ϑ to temperature T [°C]. With the obtained values for the density in the different points in the water column, two new profiles can be plotted. The red dots shows the density determined using the varying salinity values and the blue dots contain the varying temperature. The calculation is performed for each of the twenty measurements.

4.3 Influence temperature and salinity parameters on density

By comparing the calculated profiles with the measured shape, one can conclude that the salinity governs the shape of the density profile. In regions without a density gradient the shapes of the three different profiles are comparable, but as soon as a pycnocline is visible the temperature dependent plot differs from the other two. An example is given in figure 4.2, but the effect can be observed in all the deep water measurement figures in Appendix D. The temperature of the surface layer depends on heating by solar radiation. The largest difference in temperature between the surface and bottom layer should be visible during summer months, when solar radiation intensity is largest. Since it can be observed that the density profiles in July are also governed by salinity, it can be assumed that the effect of temperature is small. Stratification depends on the in and outflow with respect to the Baltic Sea.

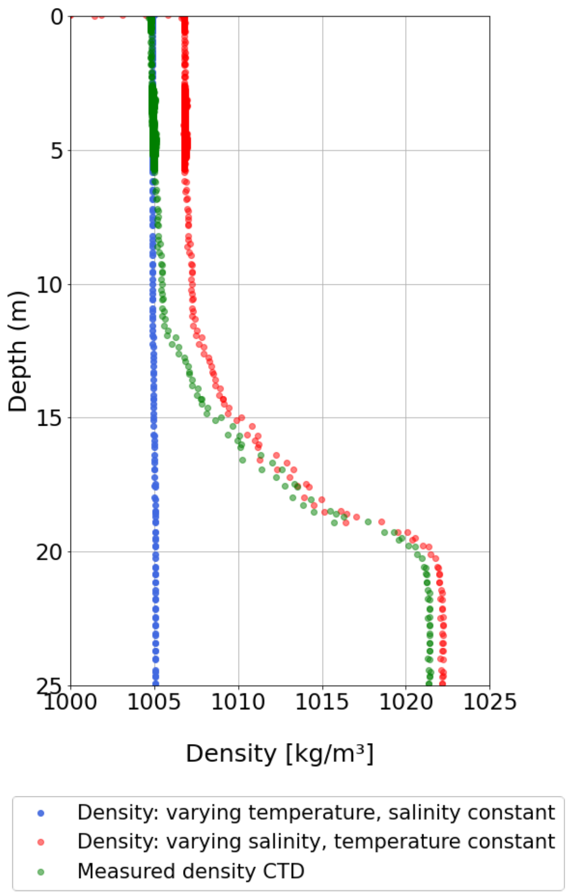
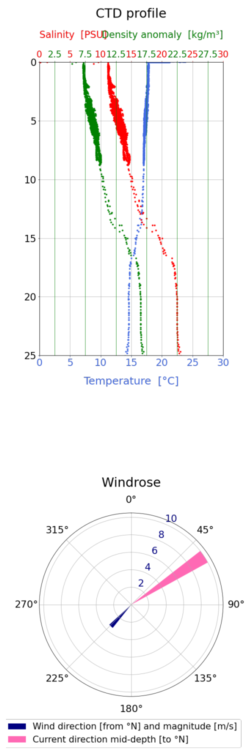


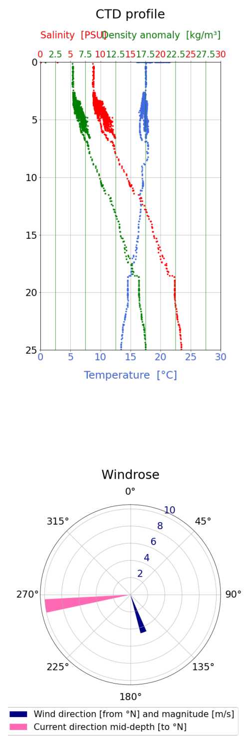
Figure 4.2: Detail from figure D14 in Appendix D.

4.4 In and outflow

In the measurement figures, one can observe higher salinity and density values in the surface layer during inflow when compared to outflow with respect to the Baltic Sea. An example is shown in figure 4.3. Since the bottom values are comparable for both cases, the density gradient is smaller during inflow. During this analysis the current direction is assumed to follow the wind forcing and inflow (outflow) is therefore related to wind forcing from the west (east) and current directions in the surface layer to the east (west). The observation can be explained by the earlier mentioned concept of stable and unstable stratification. During inflow, part of the dense saline water is pushed over the fresh water. The dense particles are heavier, causing mixing and the reduction of the density gradient. During outflow the fresh water is pushed over the dense water, resulting in a stable stratified system and an increase in the density gradient. It can be assumed that stratification occurs during outflow.



(a) CTD profile, current direction at mid-depth and wind direction during inflow



(b) CTD profile, current direction at mid-depth and wind direction during outflow

Figure 4.3: Detail from figure D18 (a) and D19 (b) in Appendix D.

Whether stratification occurs during inflow plausibly depends on the duration and strength of the wind forcing in combination with the magnitude of the density gradient when the inflow event starts. When the wind forcing inflow blows long and strong enough, stratification will be unstable and the water column mixes. When the duration is short or the wind is weak, the density gradient is reduced but the water column will not completely mix. If the density gradient at the start of an inflow event is large due to for example a long and strong outflow event before, it is less easily mixed by in-flowing saline water. Furthermore, the magnitude of the density gradient is plausibly seasonal, since fresh river run-off originated water increases during spring and wind forcing is stronger during winter. Further analysis is needed to investigate when stratification during inflow occurs.

5 Stratification restricted by depth

The second part of the analysis focuses on determining whether stratification is restricted by depth (5.1). If so, a threshold value for stratification to occur is assessed. This threshold value will then be related to the spatial behaviour of stratification in the Fehmarnbelt (5.2).

5.1 Size of the mixed layer

Wind and bottom friction can both mix the water column. The CTD profiles deeper than 15 meters in Appendix D show a mixed surface layer by wind forcing of at least 5, but often more towards 10 meters. Furthermore the mixed bottom layer appears to be around 5 meters, but conclusions are difficult to make since CTD measurements often do not reach all down. When these two processes together cover the entire water column, the whole density profile is mixed. By observing the CTD and current velocity profiles from Appendix D, it is assumed that the water column is well mixed when the depth is less than 10 meters. When a density gradient can be observed above 10 meters, it is not large enough to cause bi-directional flow above this threshold. The only exception where a density gradient results in bi-directional flow above 10 meters during one out of 20 measurements is: 01-03-2021 in figure D5 of Appendix D. Since the wind blows from the south west during this example, a possible explanation could be that up-welling of dense water occurred at the Northern coastline where the measurement is taken due to Ekman transport to the south. Although this measurement differs, it can be assumed that the average threshold value for stratification to occur is 10 meters.

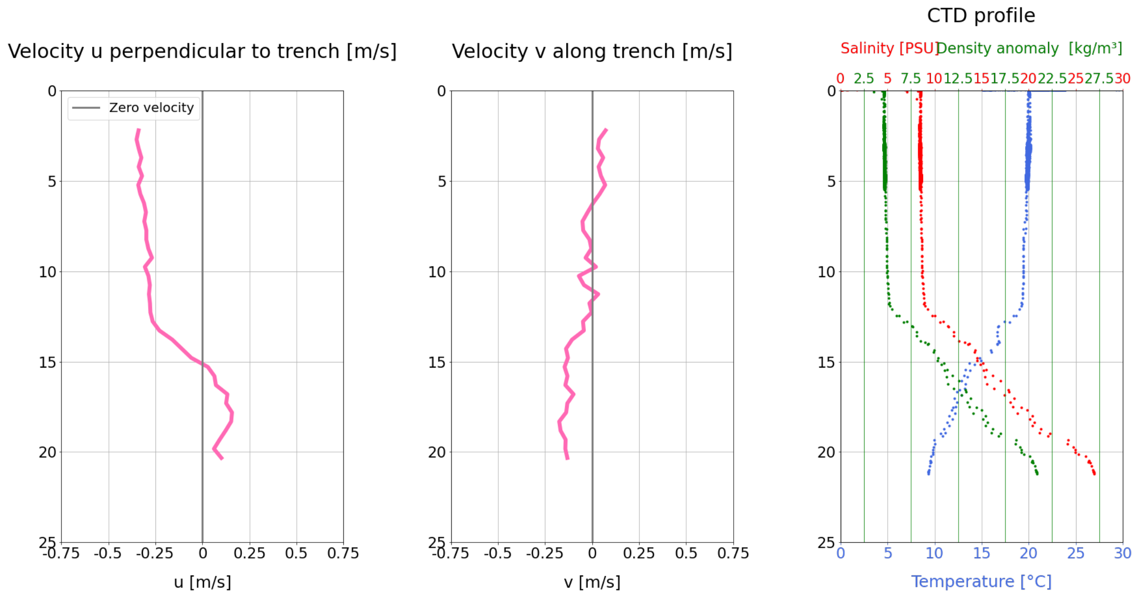


Figure 5.1: Detail from figure D15 in Appendix D.

5.2 Stratification in project sections

The construction area is divided into eight different project sections, with six zones (2A, 2B, 2C, 3A, 3B, 3C, 4) situated in the water and two on the mainland (1A, 1B). An overview of the sections and their depth is given in figure 5.2. As the bathymetry near Germany is steeper than the slope near Denmark, only region 2B is shallower than 10 meters. Stratification is likely to occur in all sections located in the water, except for 2B.

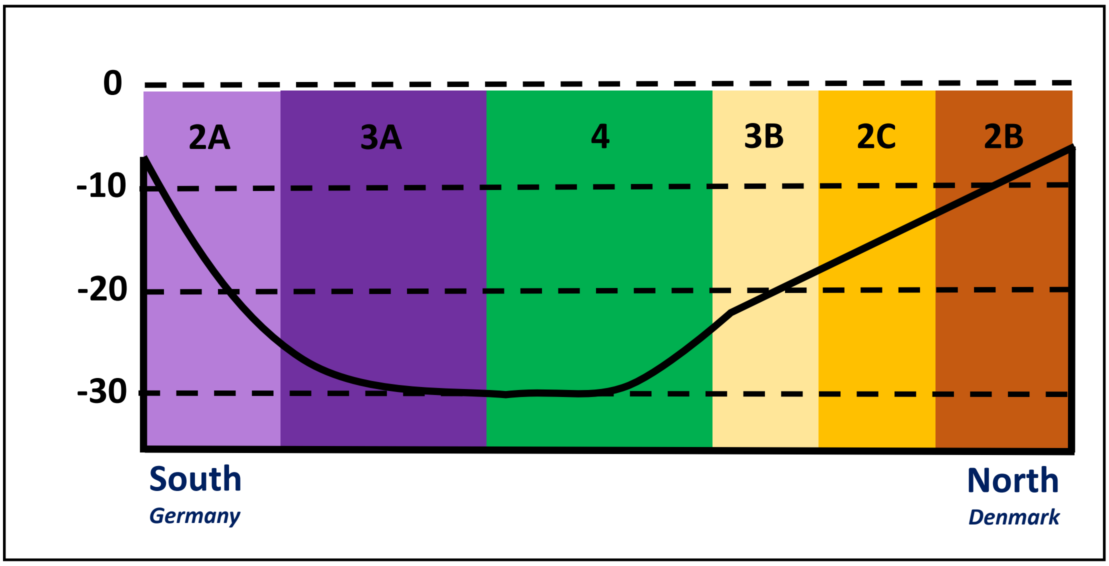


Figure 5.2: Detail from figure 3.1, showing a cross section of the belt and the bathymetry.

6 Discussion

The assumptions and simplifications made during this study and the resulting limitations are discussed below (6.1). Furthermore, recommendations about future studies are given (6.2).

6.1 Limitations

The assumption is made that the magnitude and duration of the wind forcing, in combination with the strength of the pycnocline during the start of an inflow event, presumably affects the occurrence of stratification during inflow in the Fehmarnbelt. Further research is necessary to verify this expectation.

The measurements used for this analysis are obtained in the same year during five months: February, March, July, September and October. Furthermore, measurements of water columns deeper than 10 meters are only available for the last three months. A density profile in deep water during winter cannot be visualized. Yearly effects can also not be distinguished.

Since a lot of ADCP 'raw transect files' corresponding to the CTD profiles did not pass the quality checking mentioned in subsection 3.4, the amount of figures obtained is limited. Only two examples of inflow in deep water are visualized, which is little since the difference in density of the surface layer between in and outflow is an important conclusion from this study.

Three separate data sets are matched on the basis of the time labels in the titles of the files to obtain the figures used in the analysis. The maximum difference allowed during this study is 30 minutes. Furthermore, there are only three AEGIR stations from where the current direction at mid-depth is taken. This value is not measured at the same location as the CTD and ADCP data sets. If a weather or current station did not work during a monitoring campaign, measurements can be used of an earlier point in time. The maximum difference allowed is three hours. The differences in time and space between the three data sets can lead to inaccuracies.

The theory derived in this study does not take into account the occurrence of large storms or the effect of up- and down-welling. The water column can for example be mixed during outflow if a large storm passes the area. Furthermore, figure D5 shows signs of up-welling resulting in stratification and bi-directional flow in regions shallower than 10 meters.

The equation used in subsection 4.2 to calculate density profiles is a simplified form of the EOS-80 algorithm, which can be found in Gill and Adrian (1982). The resulting error is assumed to be limited, since the goal of the calculation was to qualitatively compare the shapes of the obtained density profiles.

To formulate a clear conclusion, it is assumed stratification will occur in all the project sections except for 2B. It must be noted that the near-shore regions of zone 2A and 2C, being both about 1/3 of the section, can also be considered shallow enough for stratification not to take place. The regions are close to or shallower than 10 meters.

The effect of Coriolis on the current direction is neglected, since it is assumed the current direction follows the wind forcing. Since the current direction at mid-depth observed in the figures in Appendix D shows a large angle with respect to the wind direction, Coriolis does affect the area of interest. The currents will not directly flow in the direction forced by the wind. As discussed in Appendix E, the measurement figures also show signs of return flows and the deflection of the currents to deep area's. Since the plume spreading direction is affected by the currents, further research can be done on the occurrence of these phenomena.

6.2 Recommendations

Recommendations for future studies are:

- To analyze the effect of wind strength and duration on stratification during out but mostly during inflow.
- To analyze the effect of the initial slope of the pycnocline on stratification during inflow.
- To create measurement figures like in this study using data sets that will become available later this year from winter months (December, January, February) in sections deeper than 10 meters.
- To analyze whether there is a relation between stratification and the daily NAO index.
- To analyze the occurrence and effect of Ekman transport, return currents and deflection of the flow to deeper regions on the current and therefore plume spreading direction. A study could focus on visualizing a possible tilted interface in the cross-section of the belt and comparing it with wind direction and current velocity profiles.

7 Conclusion

This study aims to answer the following research question:

What is the spatial and temporal behaviour of stratification in the Fehmarnbelt strait?

From literature it is known that stratification in the Fehmarnbelt, on a large scale, is governed by in and outflow with respect to the Baltic Sea supplying the area with saline and fresh water and the intensity of solar radiation heating the surface layer. Mixing by wind and bottom friction can reduce or remove stratification on a local scale.

Figures created with monitoring data from the Fehmarnbelt and a simplified version of the 1980 Equation of State show that the shape of the density profile follows the salinity rather than the temperature profile, indicating that in and outflow with respect to the Baltic Sea is the dominant large scale mechanism. During outflow, when the wind blows from east to west, the surface layer originating from the Baltic Sea is fresh. Since the dense water is situated below the fresh, the Fehmarnbelt is in this case stably stratified. During inflow, when the wind blows from west to east, the surface layer is more saline. Dense North Sea water flows over the fresh, resulting in a unstably stratified system that gives rise to internal mixing. The density gradient therefore increases during outflow and decreases during inflow with respect to the Baltic Sea. Stratification occurs during outflow, but whether it arises during inflow presumably depends on the strength and duration of the wind forcing the movement of the water surface layer. Additionally, it will depend on the slope of the pycnocline prior to the start of the inflow event. A strong pycnocline is less easily mixed. This initial strength of the pycnocline also depends on a larger fresh river run-off in spring and stronger winds during winter. Further research is necessary to verify whether stratification during inflow depends on the initial strength of the pycnocline, the magnitude and duration of wind forcing. It can also be observed from the monitoring data figures that wind and bottom friction result in a well-mixed water column when the water depth is less than 10 meters. Since only section 2B is shallower than 10 meters, stratification likely occurs in all other sections located in the water.

Using the knowledge above, a prediction can be made on where and when bi-directional plume spread due to stratification can be anticipated. The water column will be mixed when the water depth is less than 10 meters. Therefore, bi-directional plume spread can be expected in section 2A, 2C, 3A, 3B, 3C and 4 as shown in figure 3.1. Section 2B is too shallow. Stratification will occur in sections deeper than 10 meters during outflow. Whether stratification and therefore bi-directional plume spread will occur in sections deeper than 10 meters during inflow likely depends on the initial strength of the pycnocline, the magnitude and duration of wind forcing but further research is necessary to confirm these assumptions.

Signs of other processes than stratification influencing the current direction can also be observed from the figures: return currents, Ekman transport and the deflection of currents to deeper water. Additional research can be done on the behaviour of the current direction in the Fehmarbelt, since these processes can also influence the plume spread direction.

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Appendix

A AEGIR stations

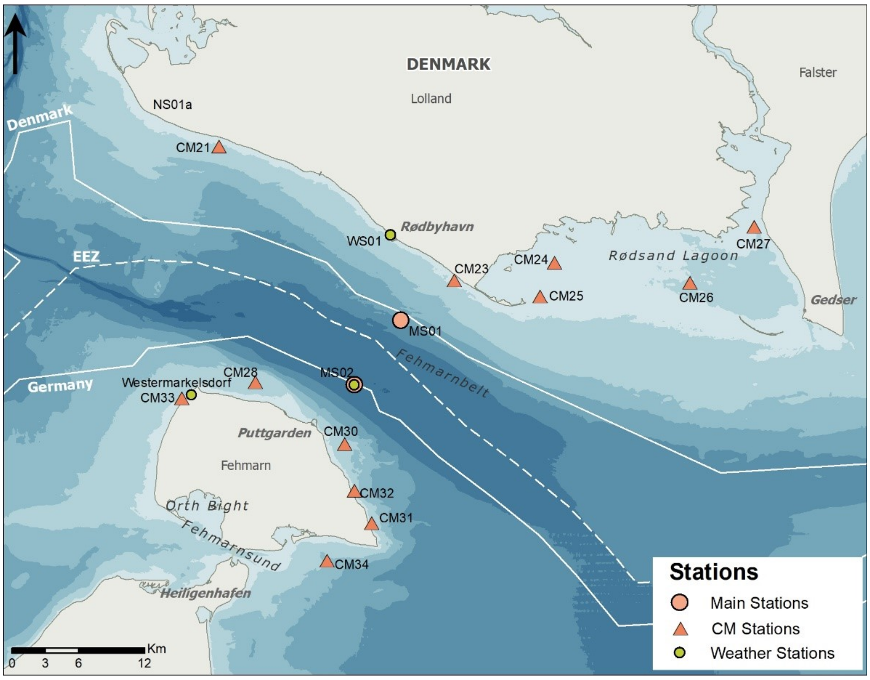

Figure A1: Measurement stations from Femern A/S (2021c)

B Details frame of reference

B.1 Derivation angle of rotation

The frame of reference is obtained by turning the orientation of the system. The distances are approximated with the measurement function of Google Maps, as shown in figure B1. The angle at which the system should be turned is calculated using the measured distances:

$$\theta_{rotation} = tan^{-1}(7470/16907) = 23.84^{\circ} \tag{b.1}$$

B.2 Adjustment current and wind direction

Since the frame of reference is rotated, the incoming wave and outgoing current directions should also be adjusted. The following two expressions are implemented in the python notebook in Appendix F:

When the angle measured is larger than 23.84 °:

$$\theta_{new} = \theta_{incoming} - 23.84^{\circ} \tag{b.2}$$

When the angle measured is smaller than 23.84 °:

$$\theta_{new} = (\theta_{incoming} - 23.84^{\circ}) + 360^{\circ} \tag{b.3}$$

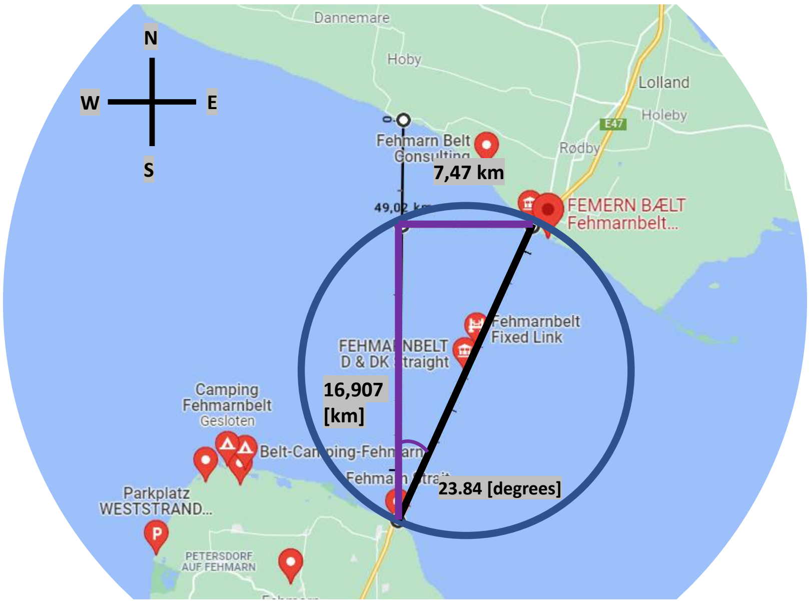

Figure B1: Measured distances used to calculate the angle at which the belt is tilted. The fixed link is shown in black.

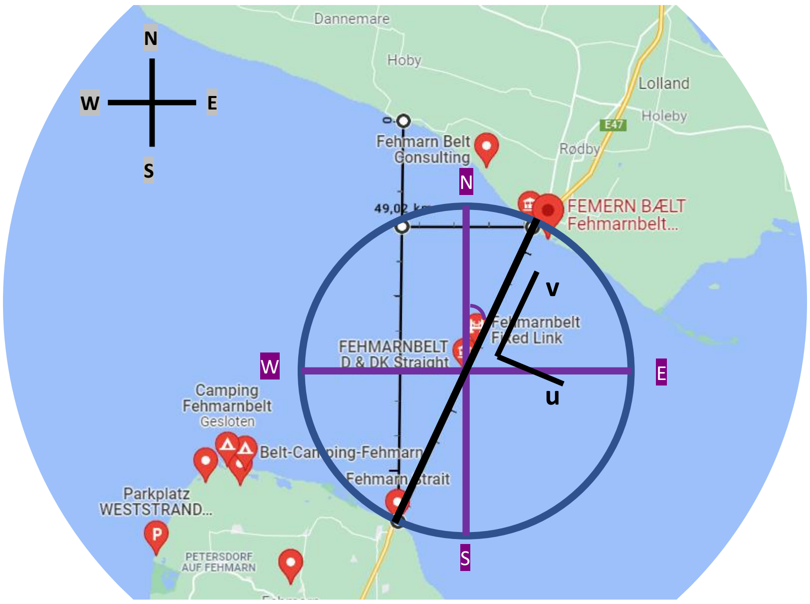

Figure B2: The new frame of reference (black) against the old (purple).

B.3 Derivation v and u components

The absolute measured velocity is factorized by using the angle measured in subsection B.2:

$$v = u_{abs}cos(\theta_{new}) \tag{b.4}$$

$$u = u_{abs}sin(\theta_{new}) \tag{b.5}$$

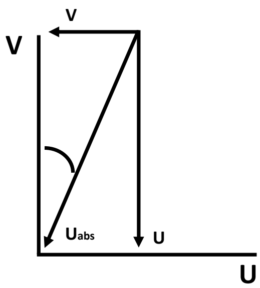

Figure B3: Derivation of the v and u current velocity components.

C Determination section measurement figure

The location printed in the text box of a measurement figure is determined by taking the mean latitude in a 'raw transect file'. Latitude ranges are defined in the python notebook in Appendix F. This determination used the original frame of references. Since measurements are obtained within two kilometers of the trench the error this approach will give is negligible. The latitudes shown in figure C1 are estimated using the measurement function of Google Maps.

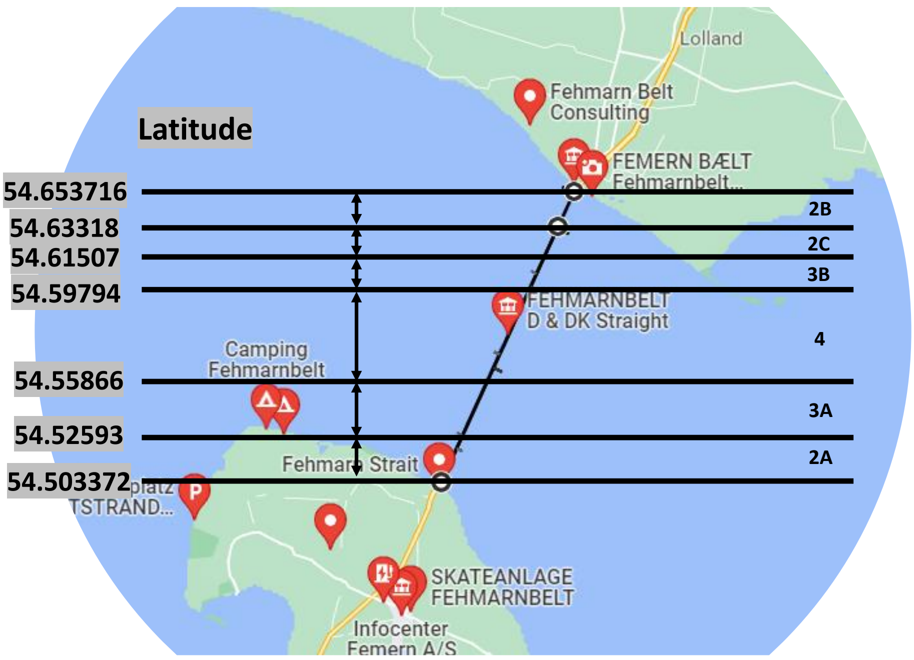

Figure C1: The section returned in the information box in the measurement figures depends on the mean latitude.

D Measurement figures

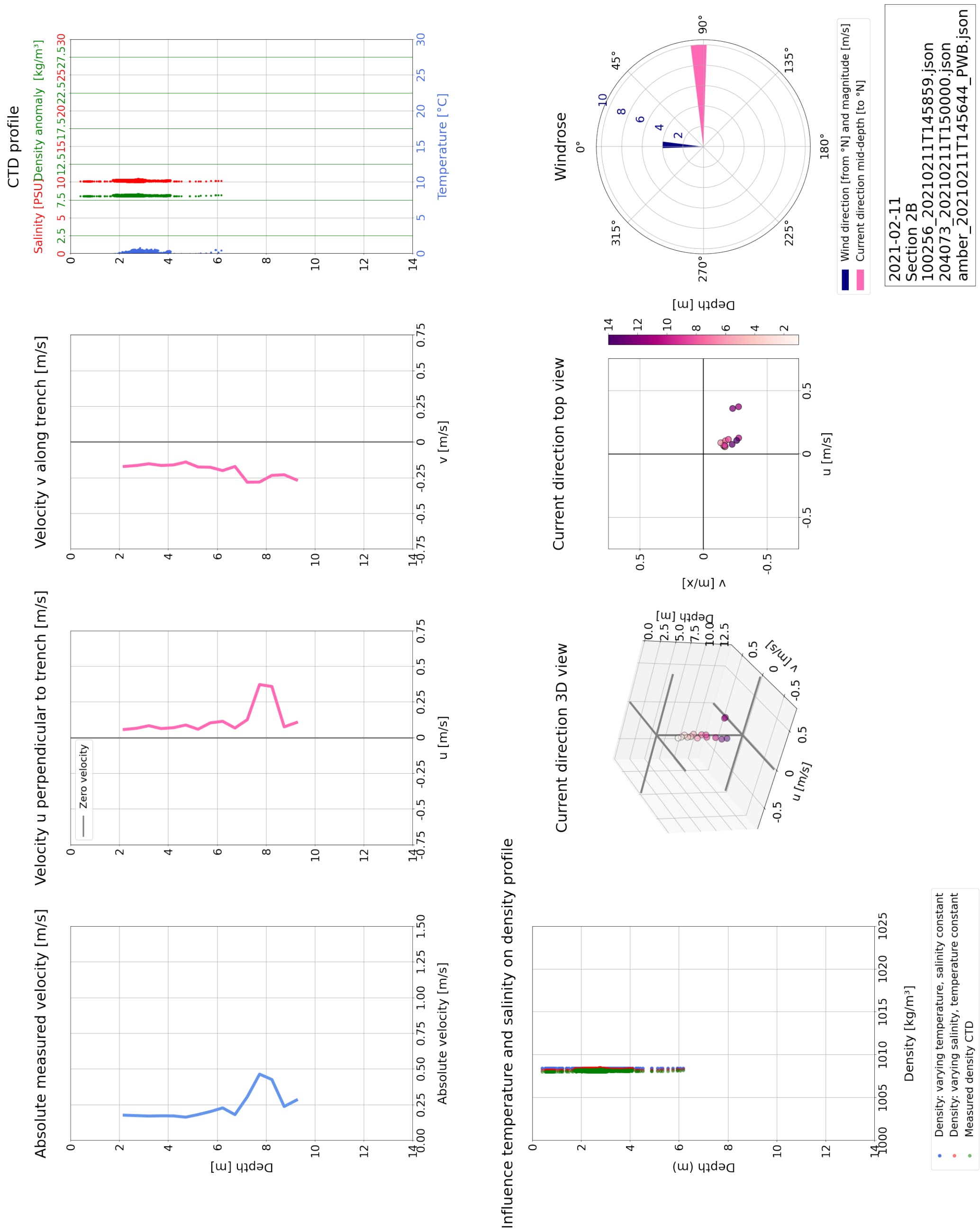

Figure D1: Measurements 11-02-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

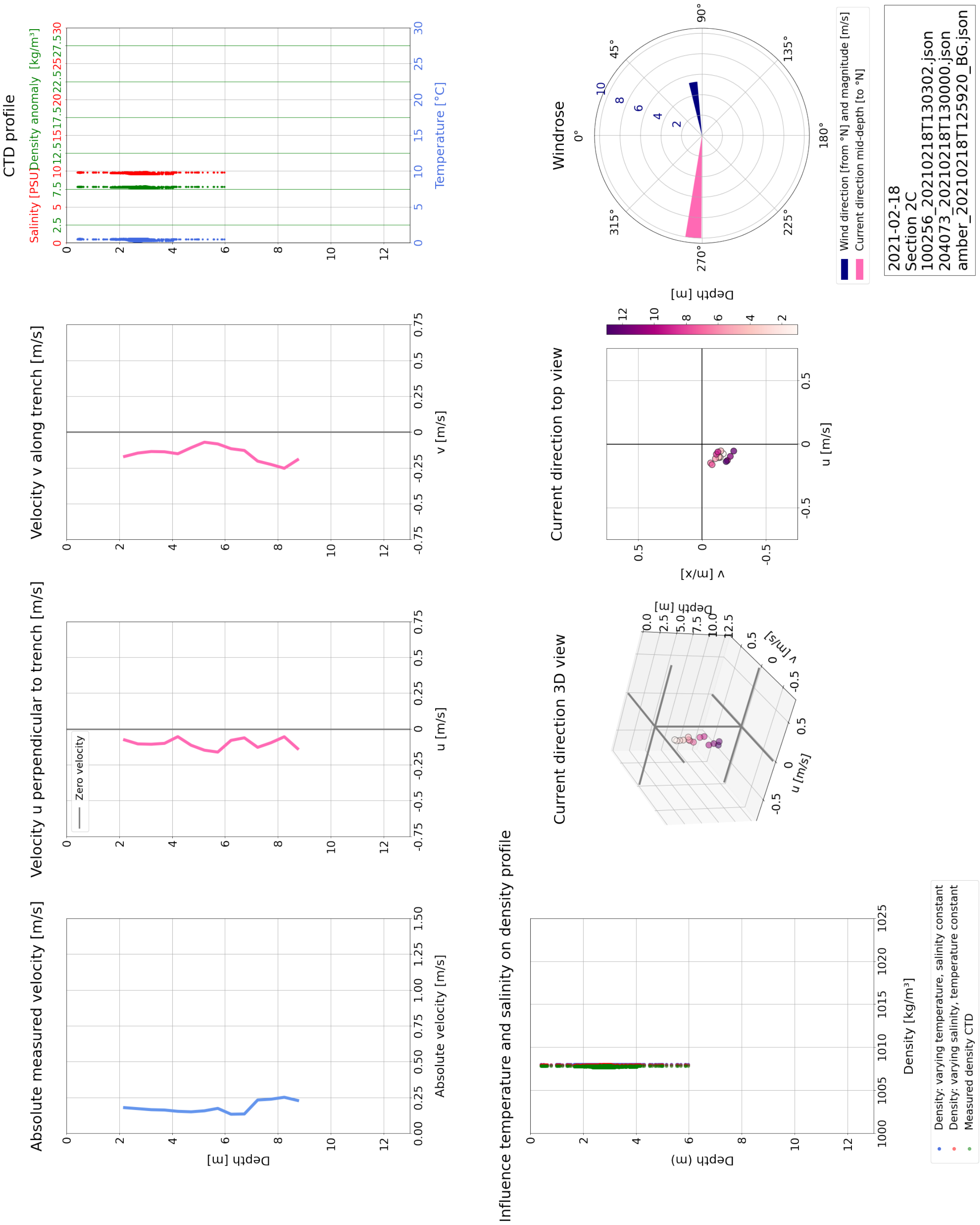

Figure D2: Measurements 18-02-2021 in zone 2C giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

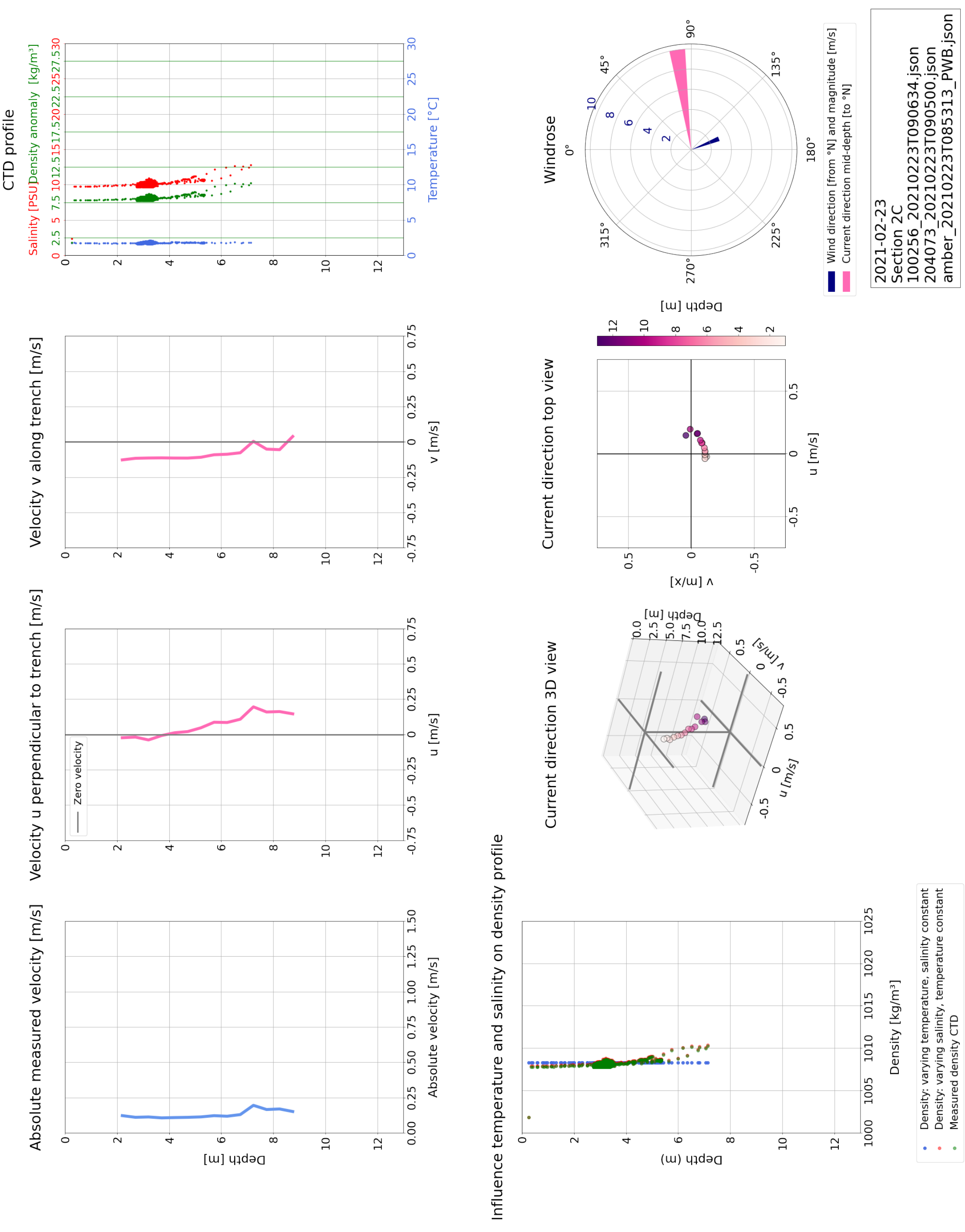

Figure D3: Measurements 23-02-2021 in zone 2C giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

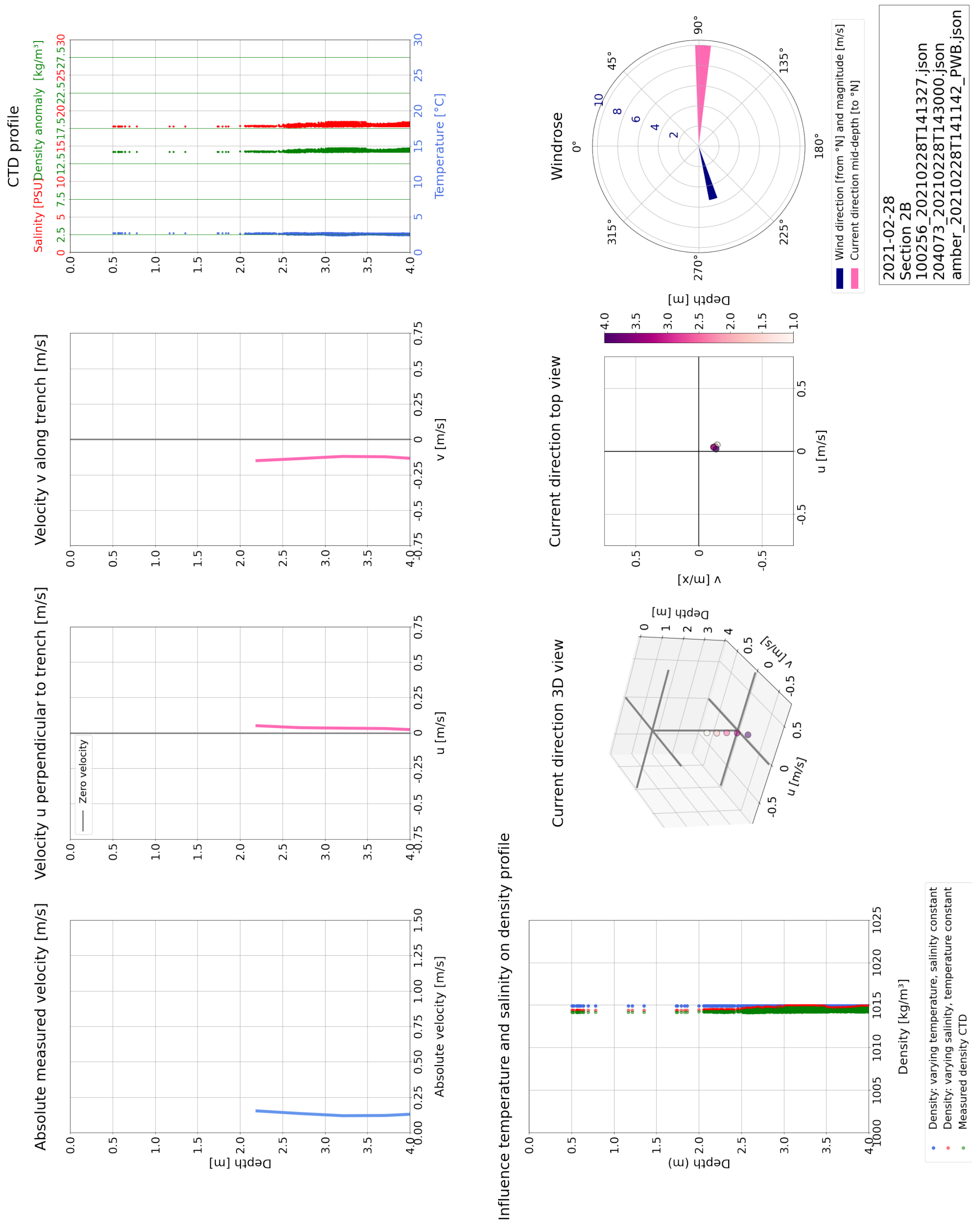

Figure D4: Measurements 28-02-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

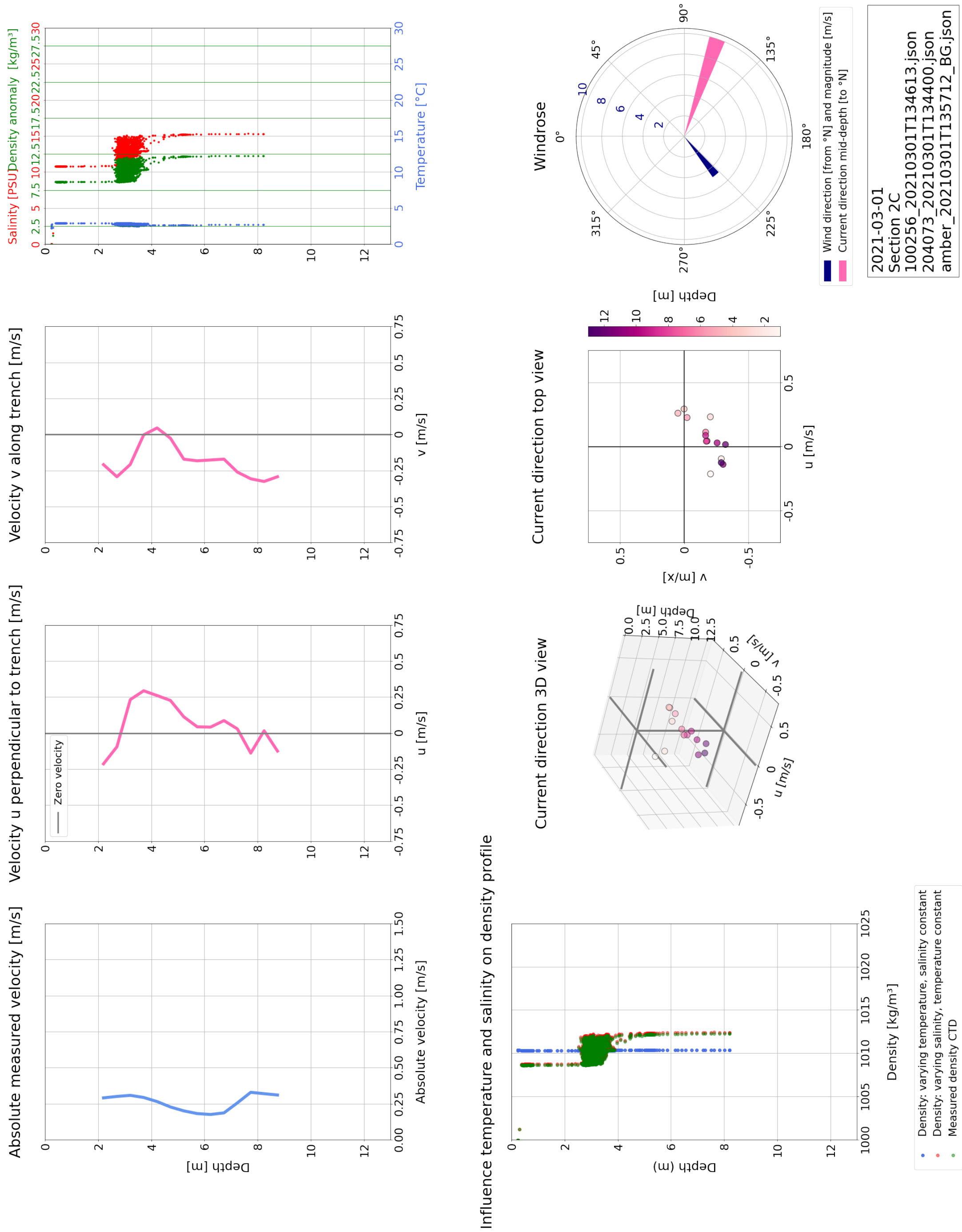

Figure D5: Measurements 01-03-2021 in zone 2C giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

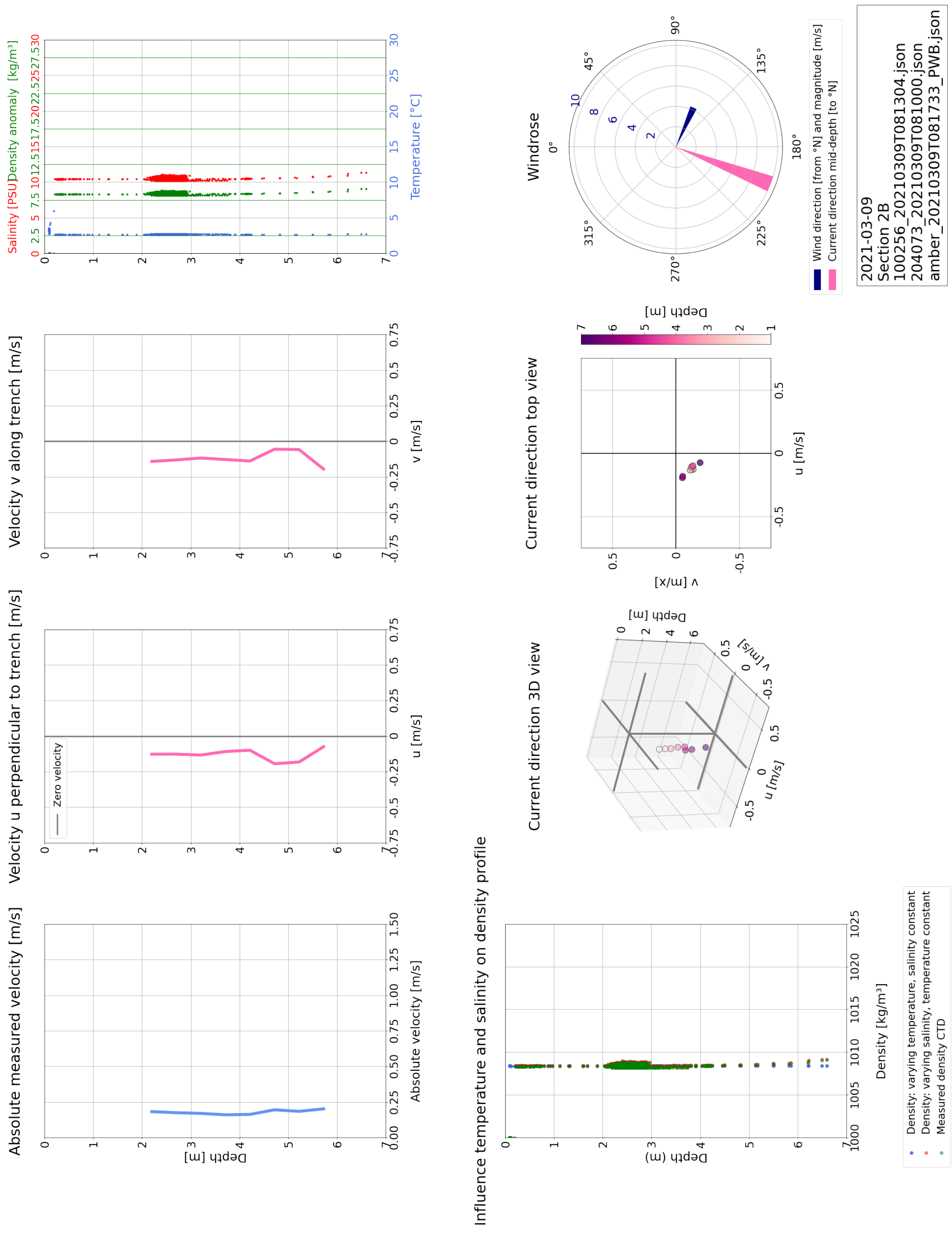

Figure D6: Measurements 09-03-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

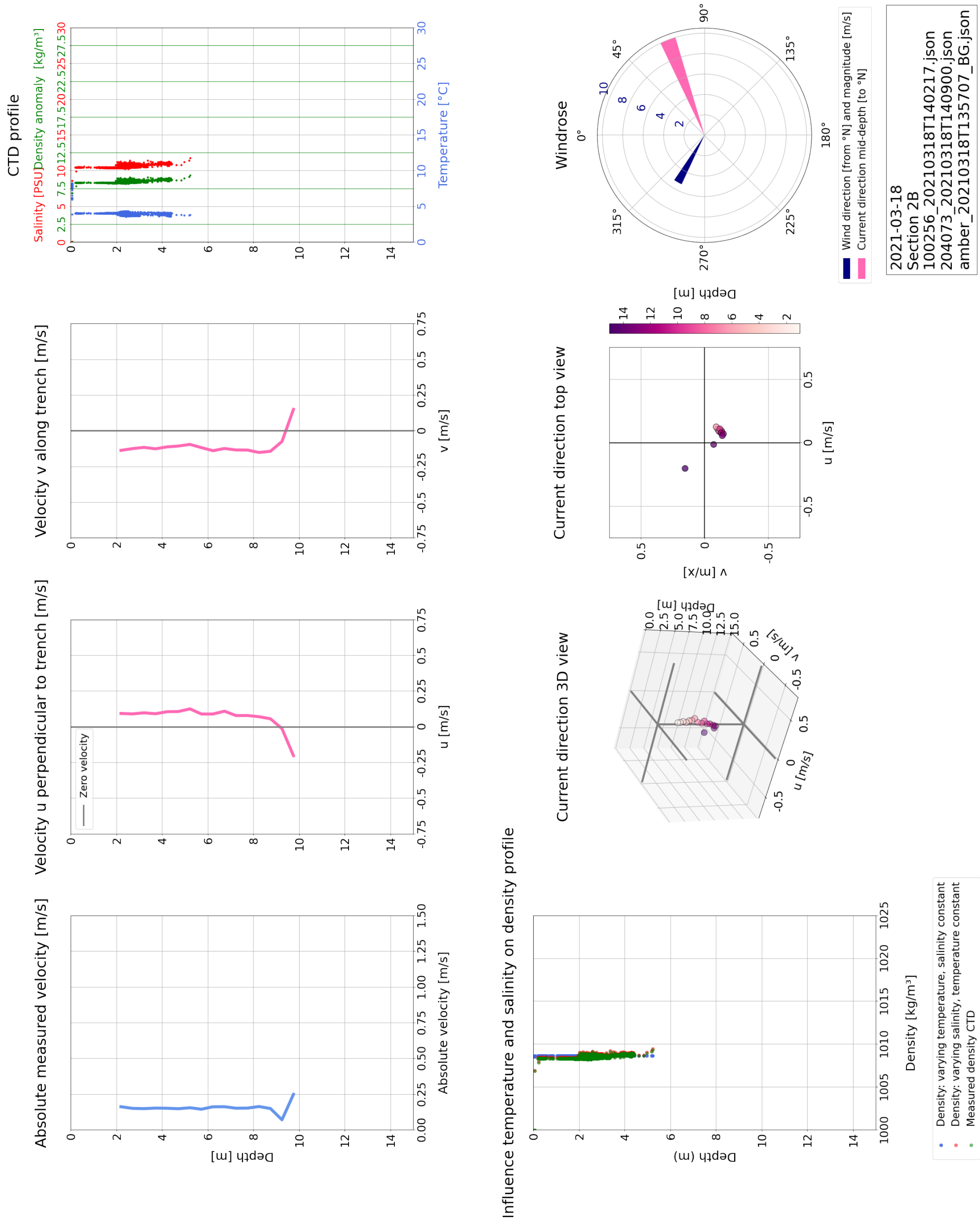

Figure D7: Measurements 18-03-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

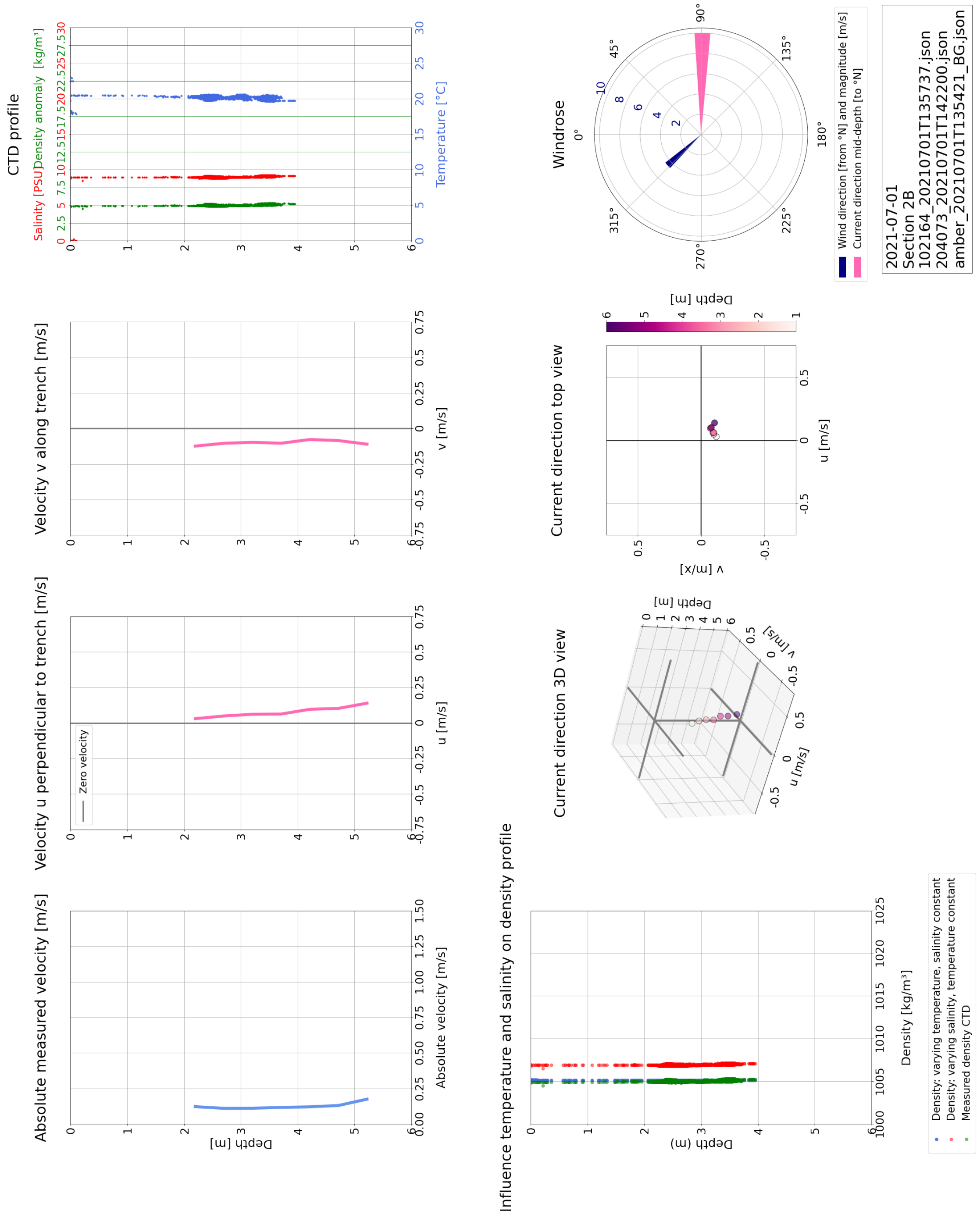

Figure D8: Measurements 01-07-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

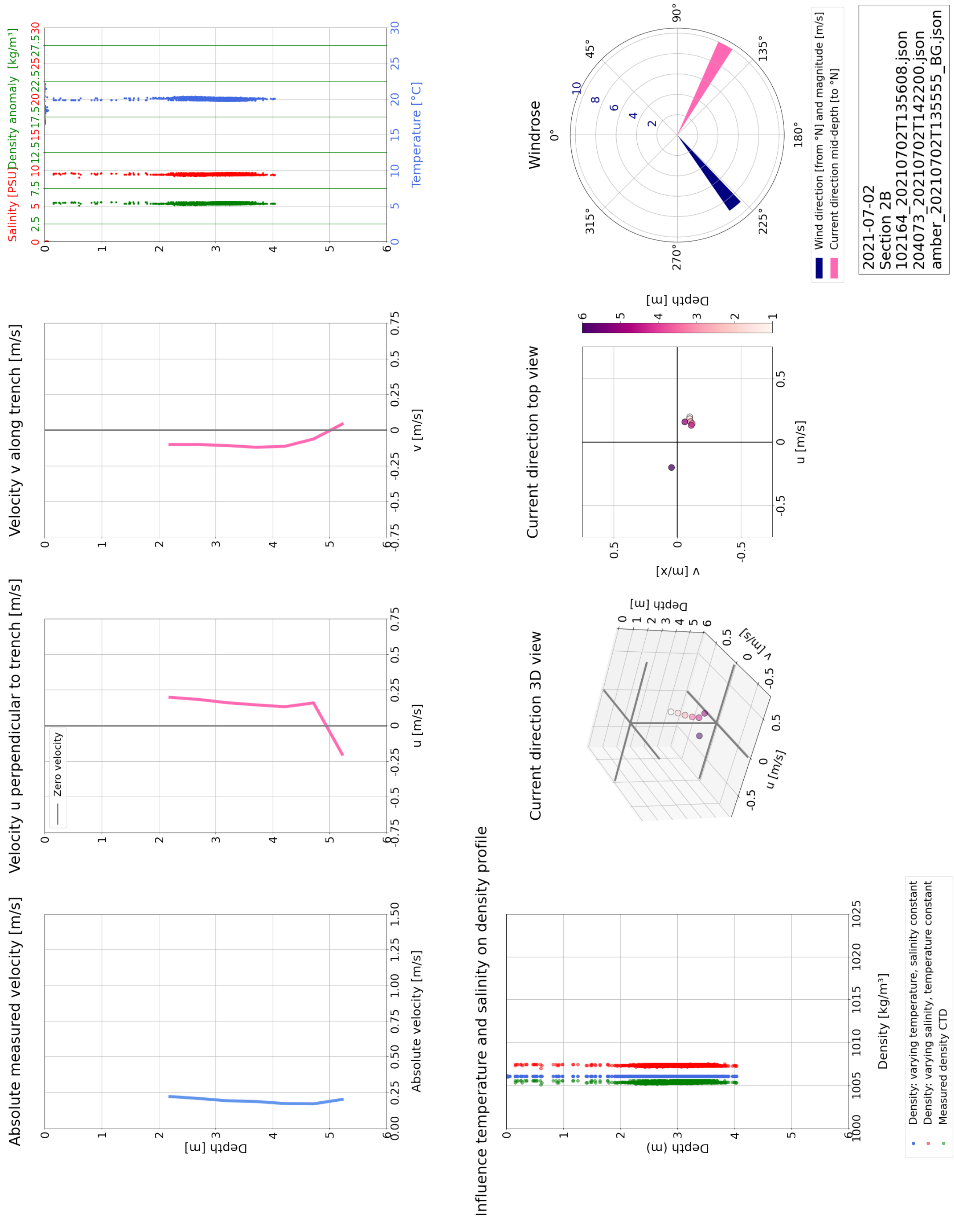

Figure D9: Measurements 02-07-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

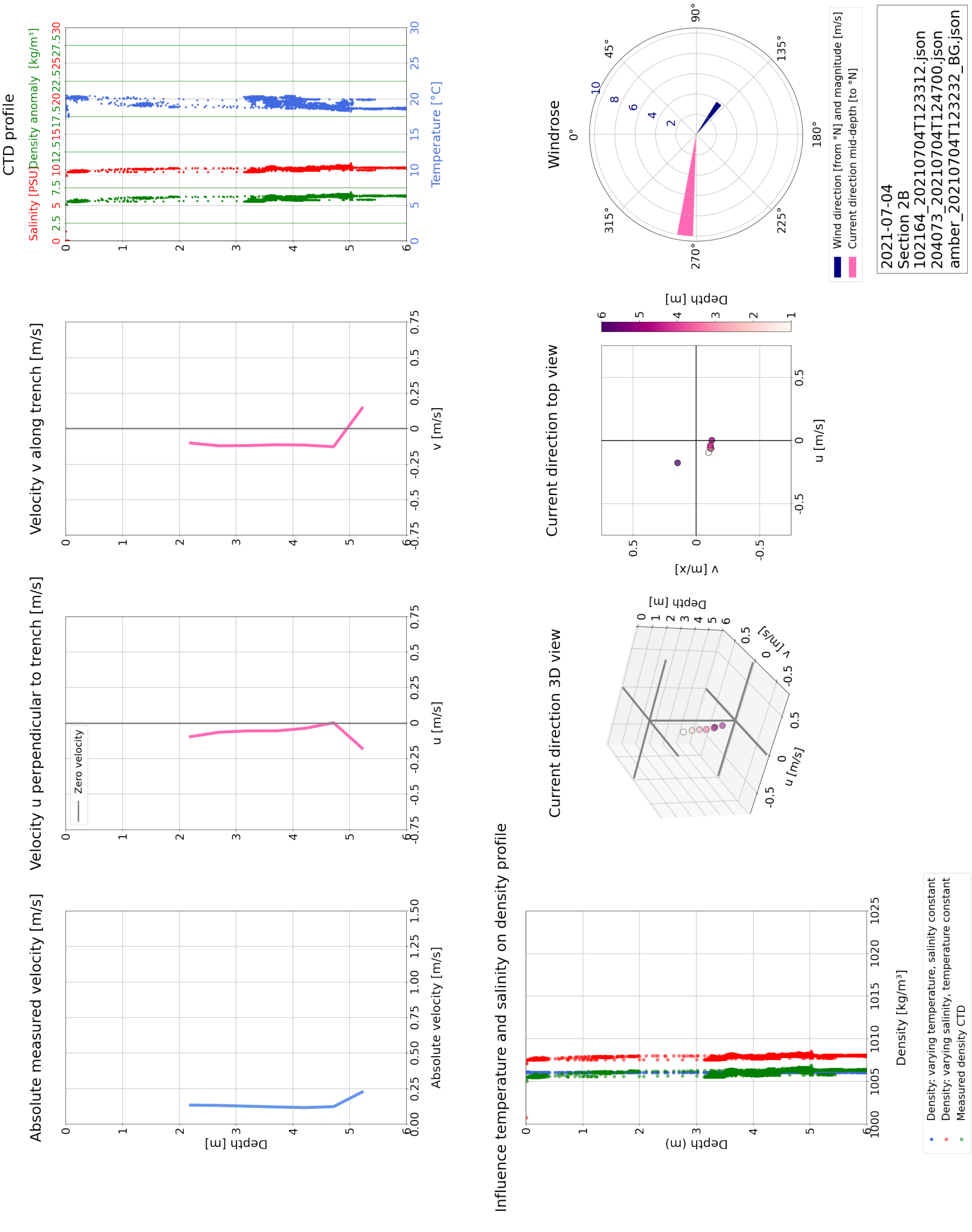

Figure D10: Measurements 04-07-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

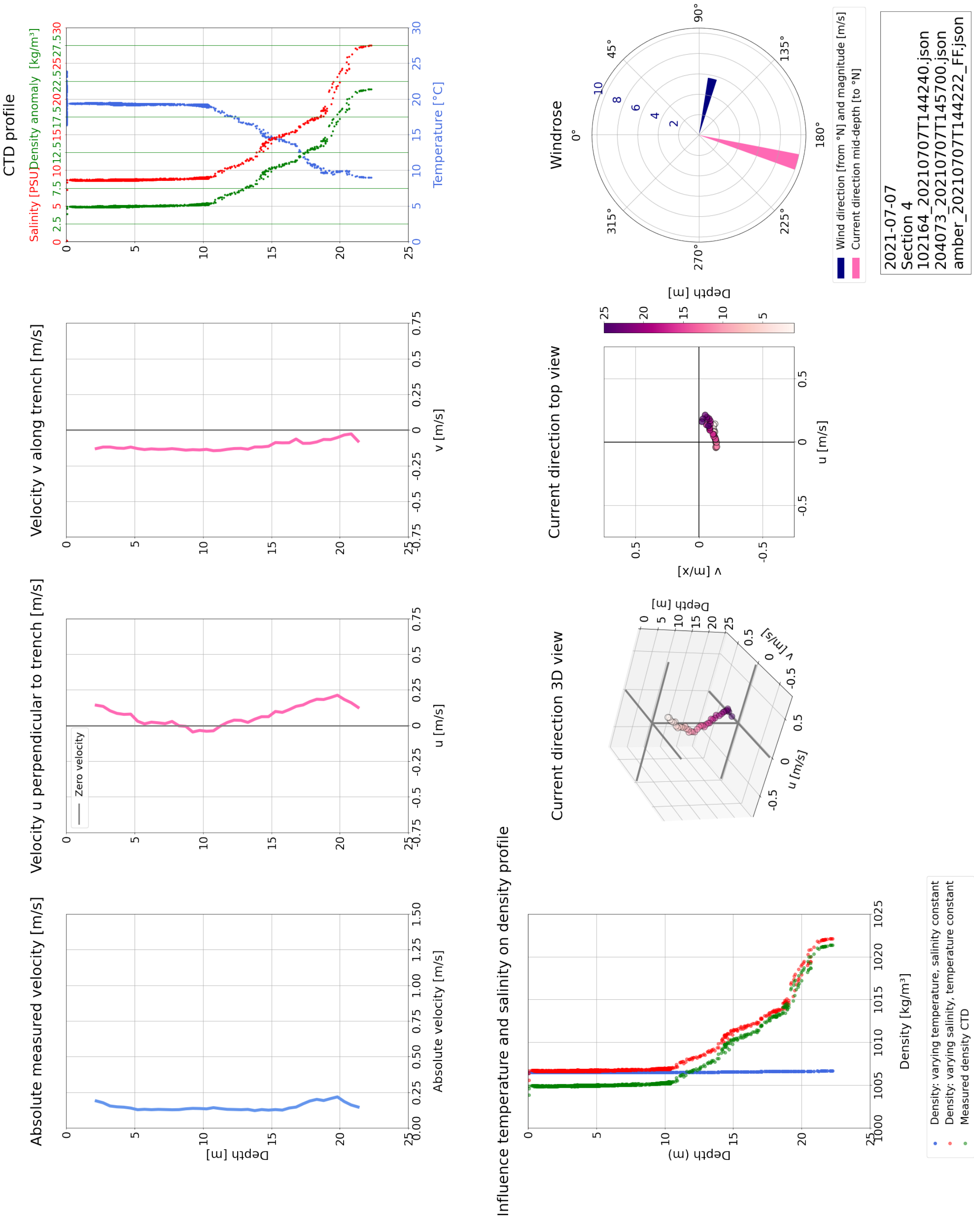

Figure D11: Measurements 07-07-2021 in zone 4 giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

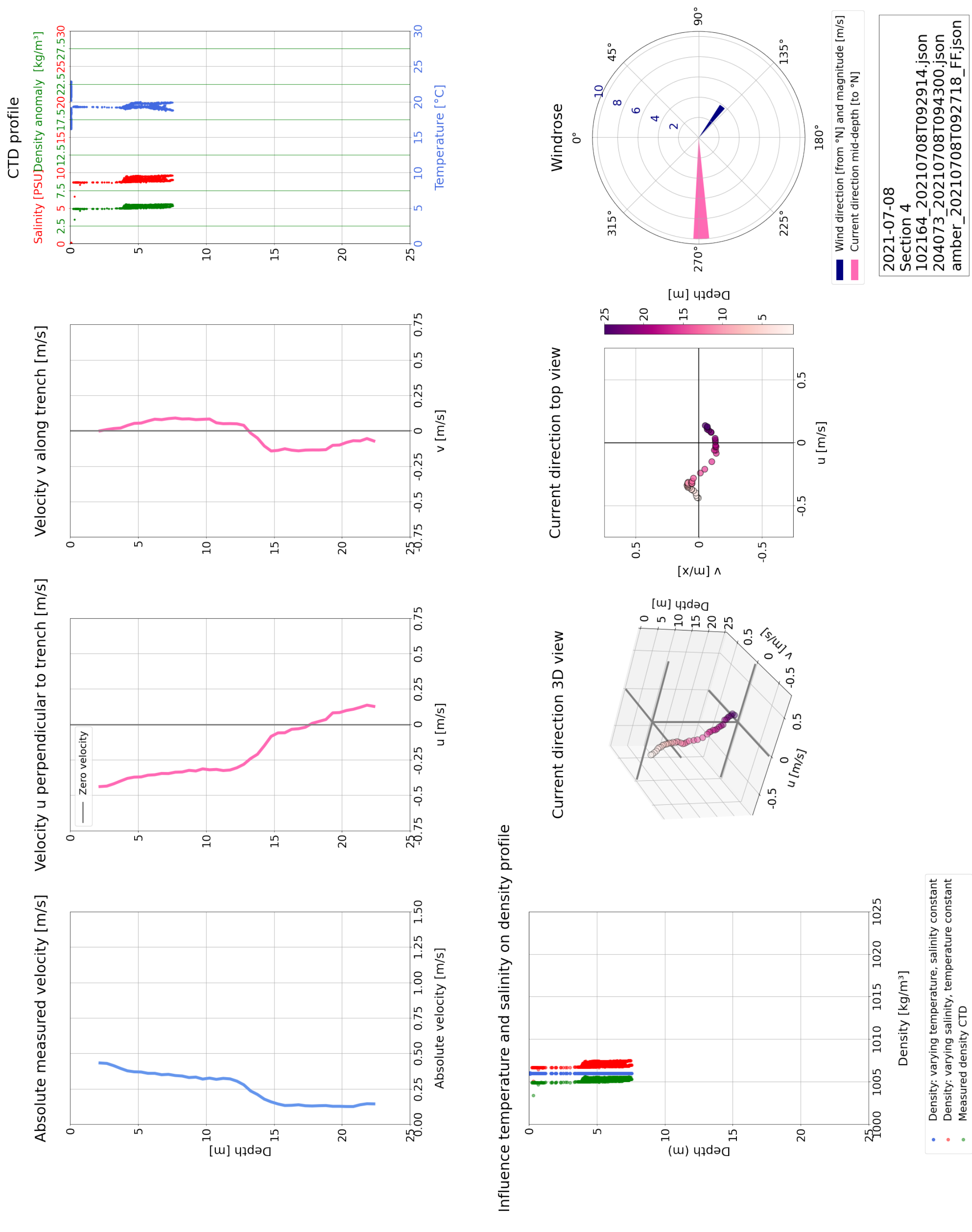

Figure D12: Measurements 08-07-2021 in zone 4 giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

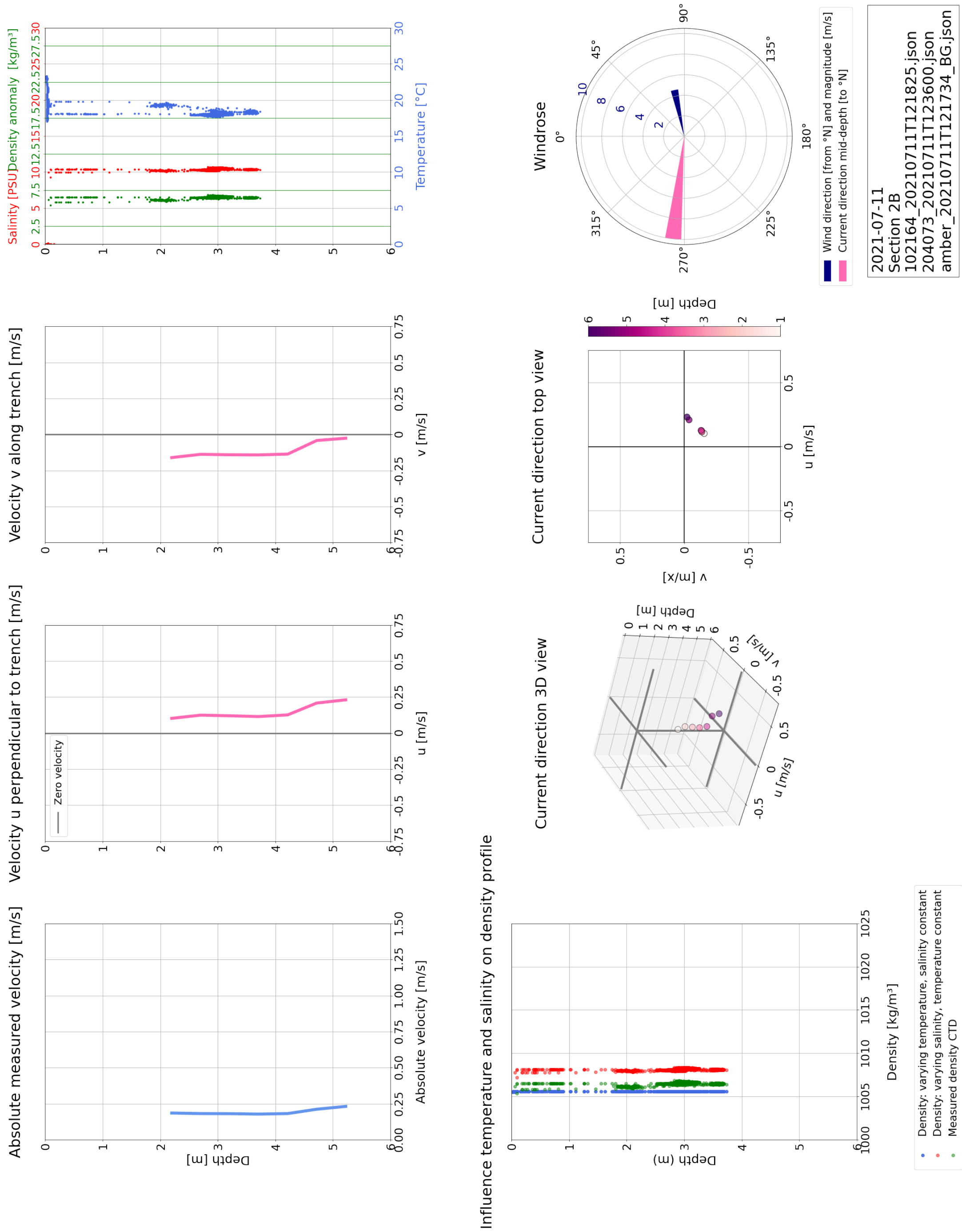

Figure D13: Measurements 11-07-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

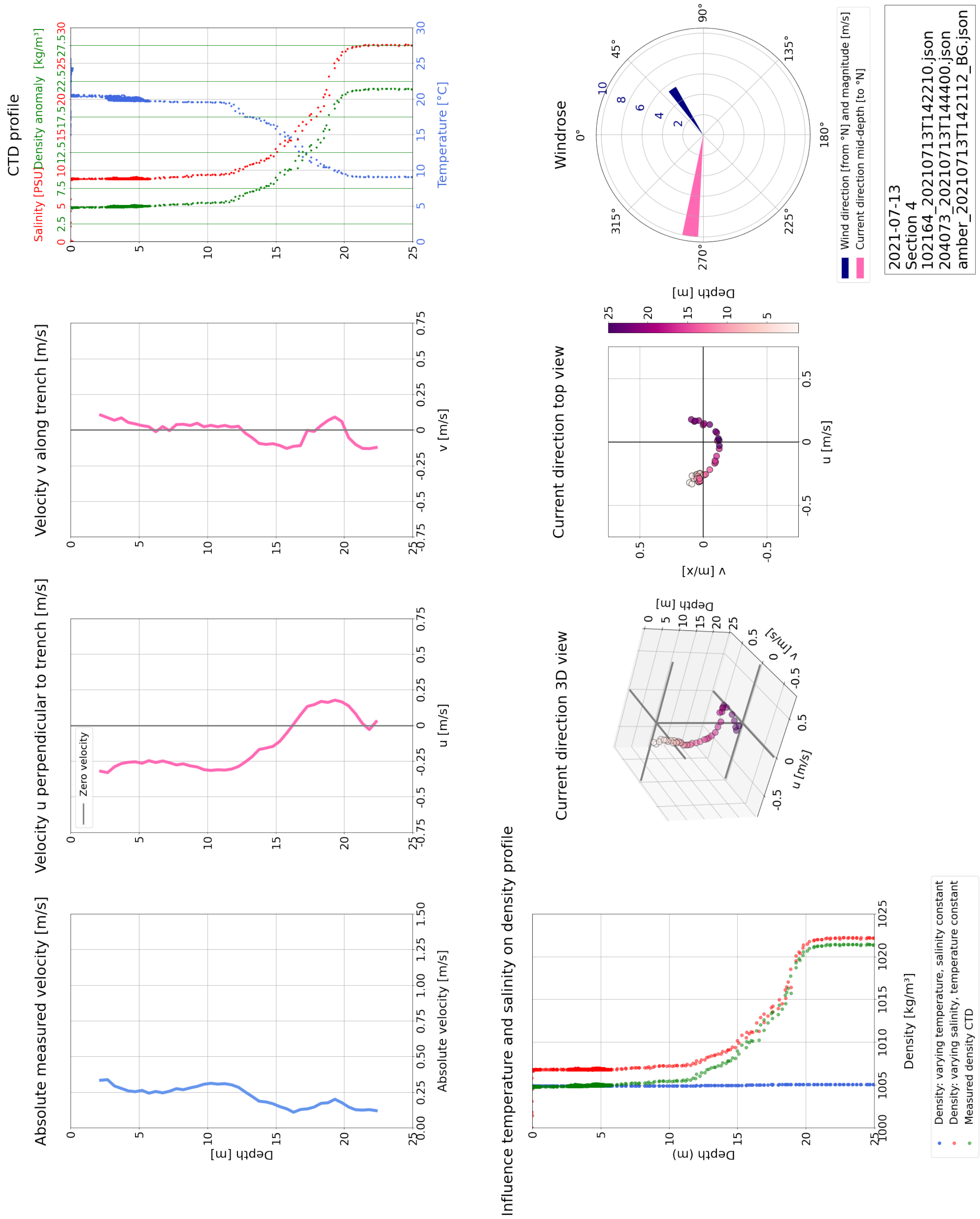

Figure D14: Measurements 13-07-2021 in zone 4 giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

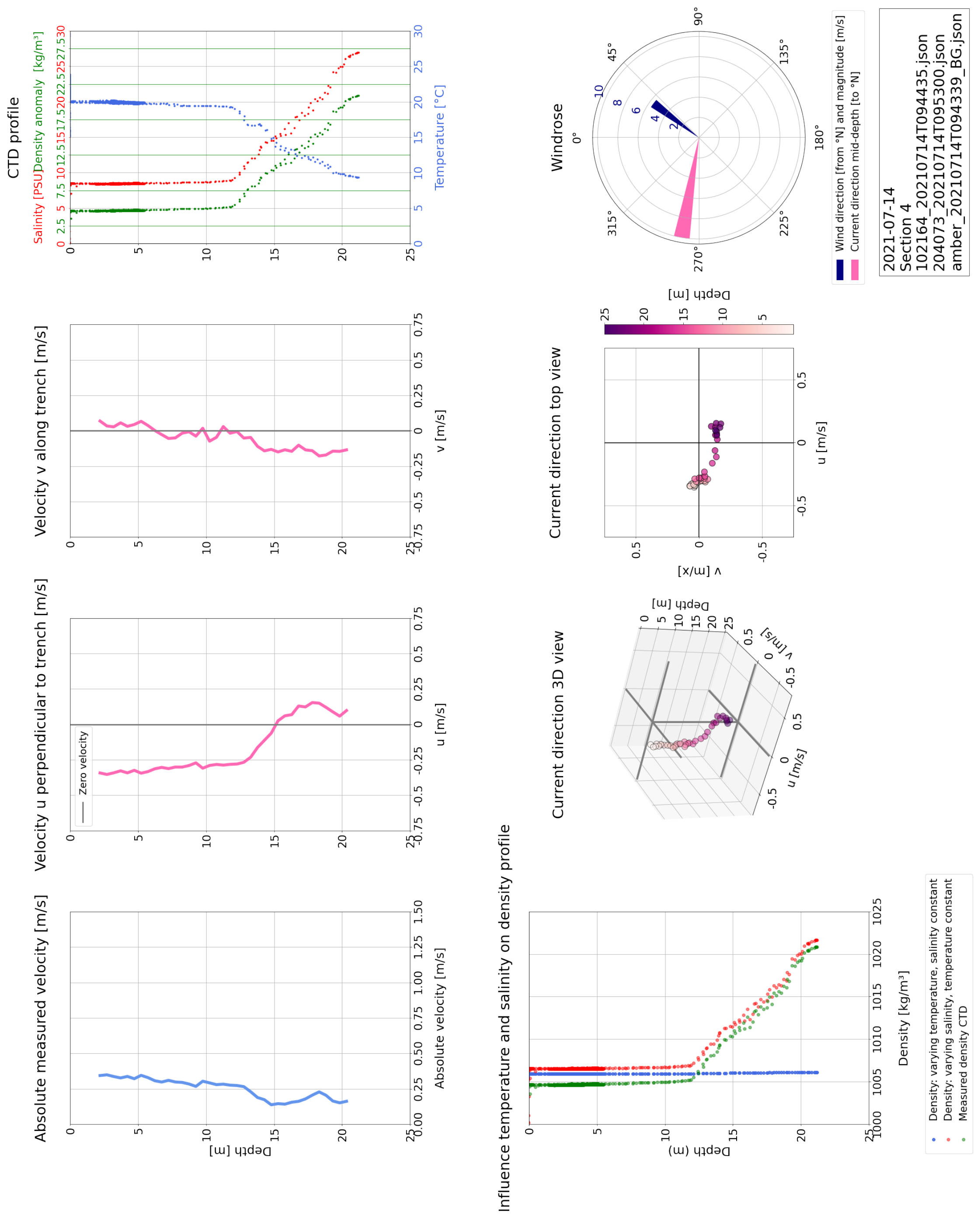

Figure D15: Measurements 14-07-2021 in zone 4 giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

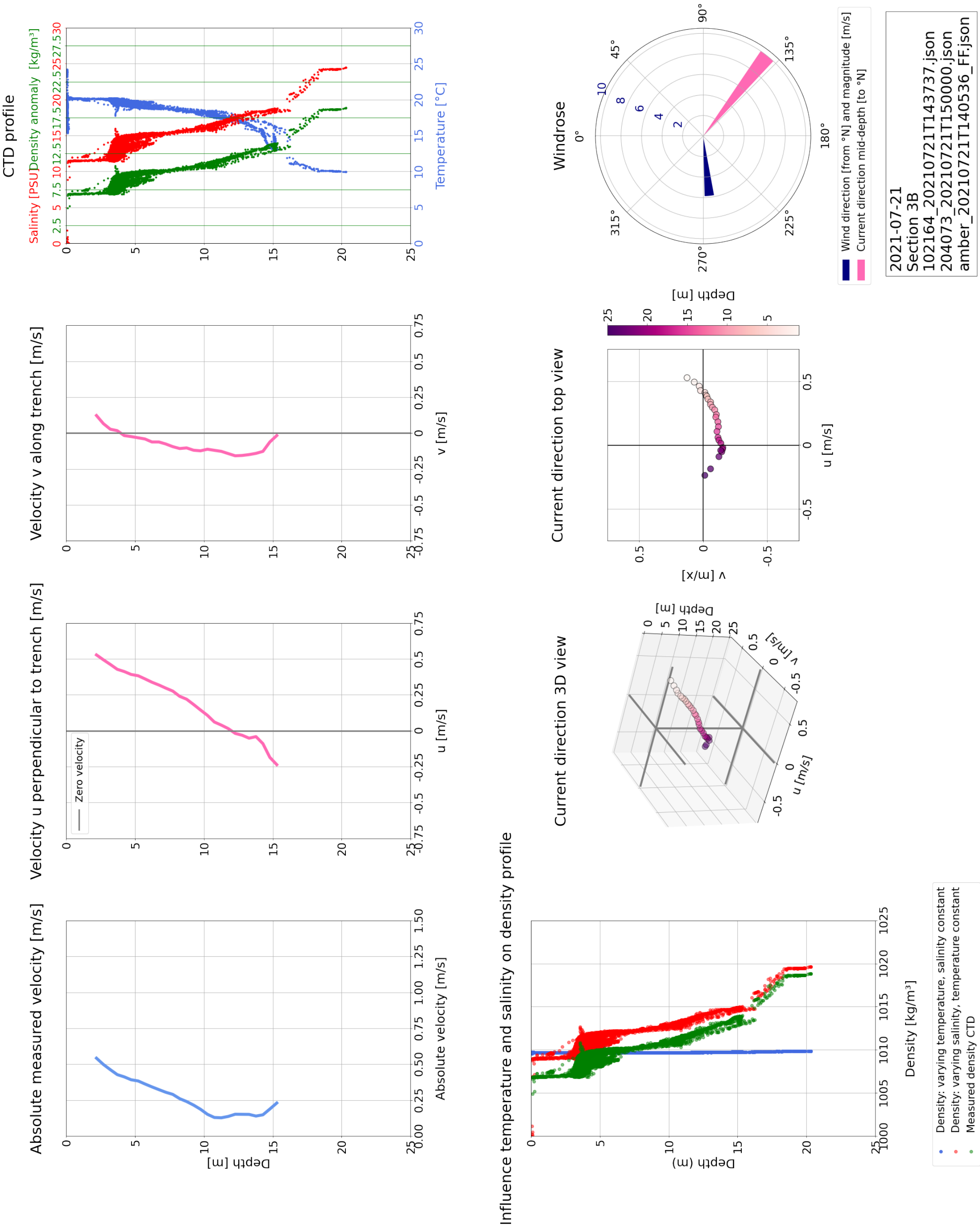

Figure D16: Measurements 14-07-2021 in zone 4 giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

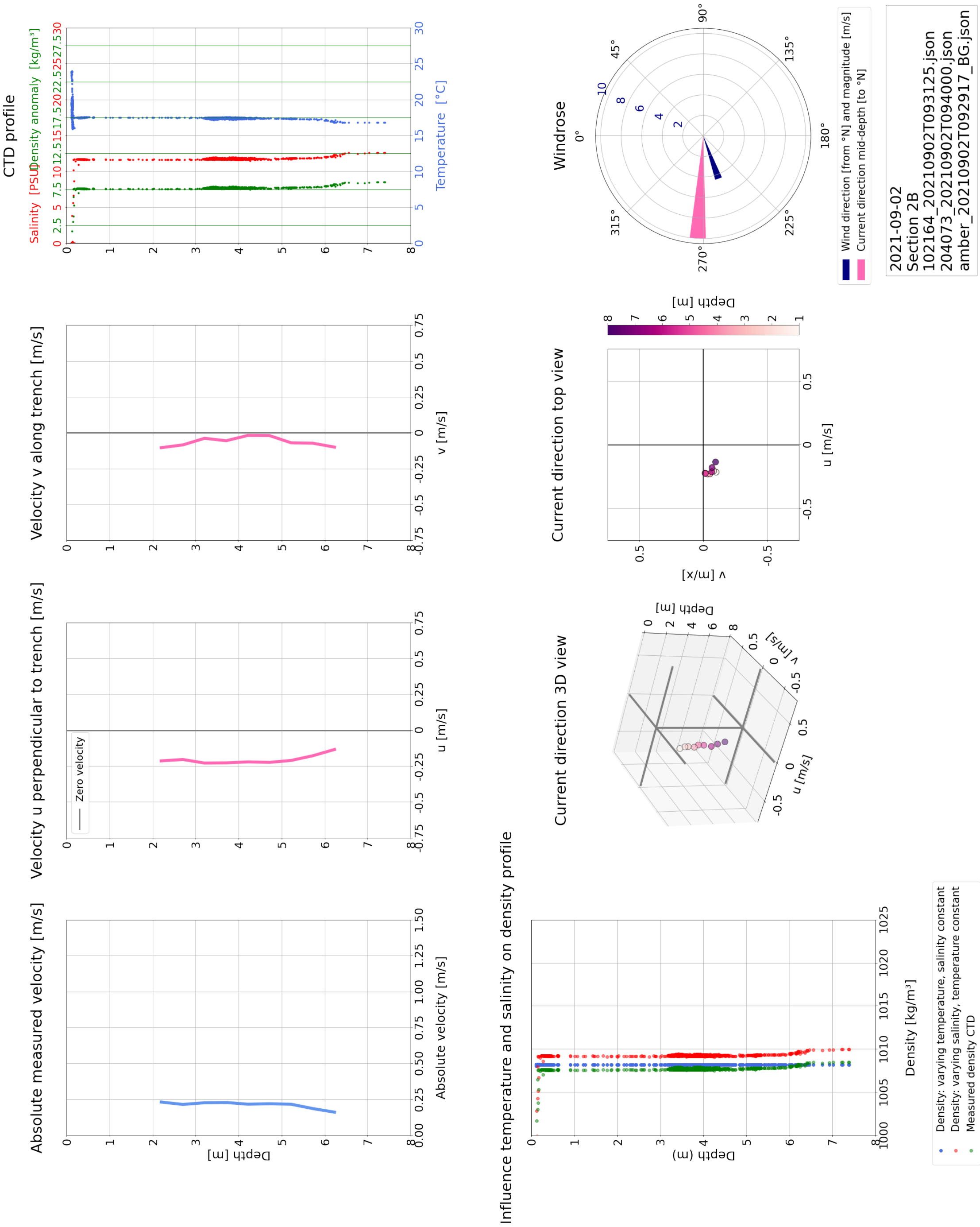

Figure D17: Measurements 02-09-2021 in zone 2B giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

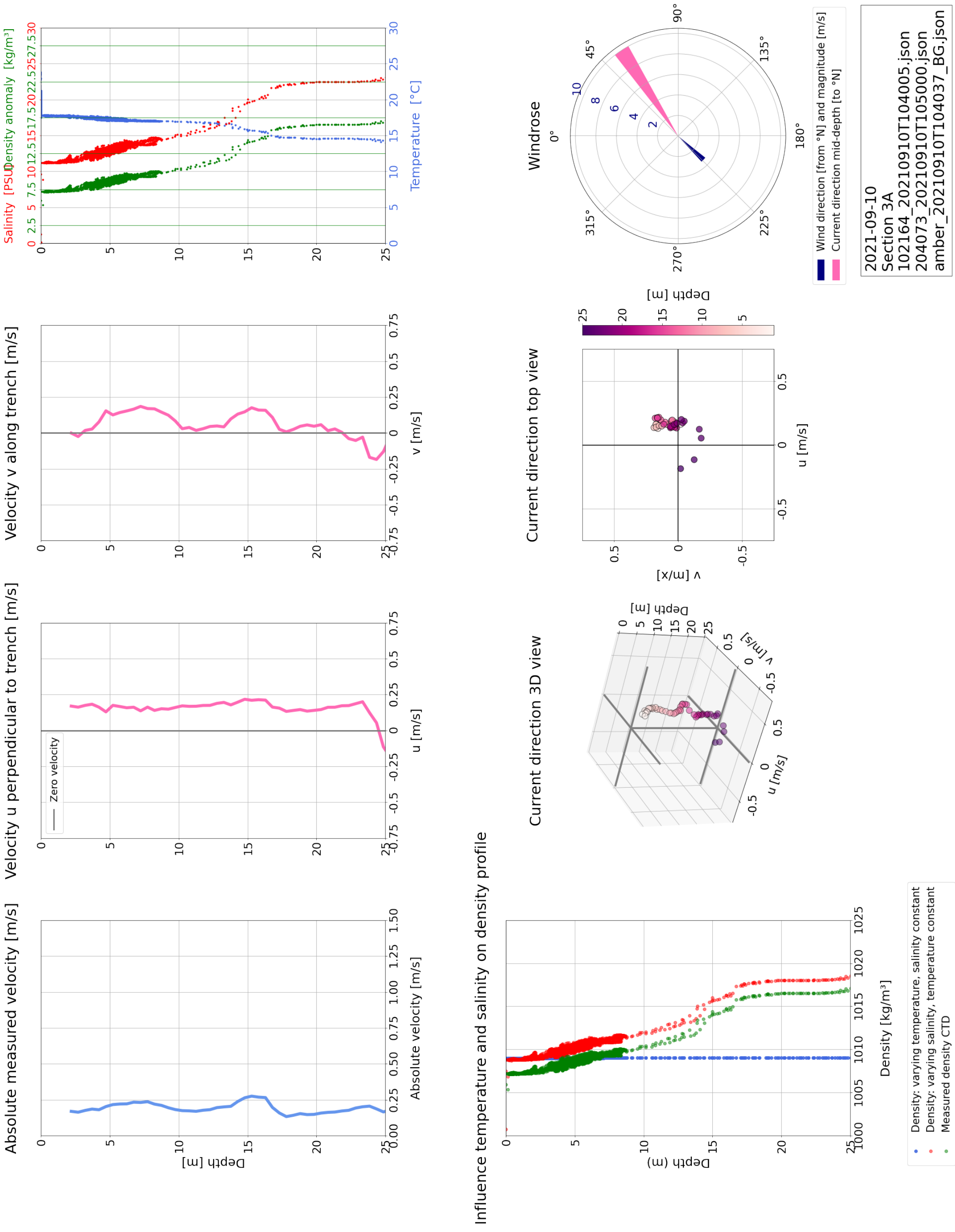

Figure D18: Measurements 10-09-2021 in zone 3A giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

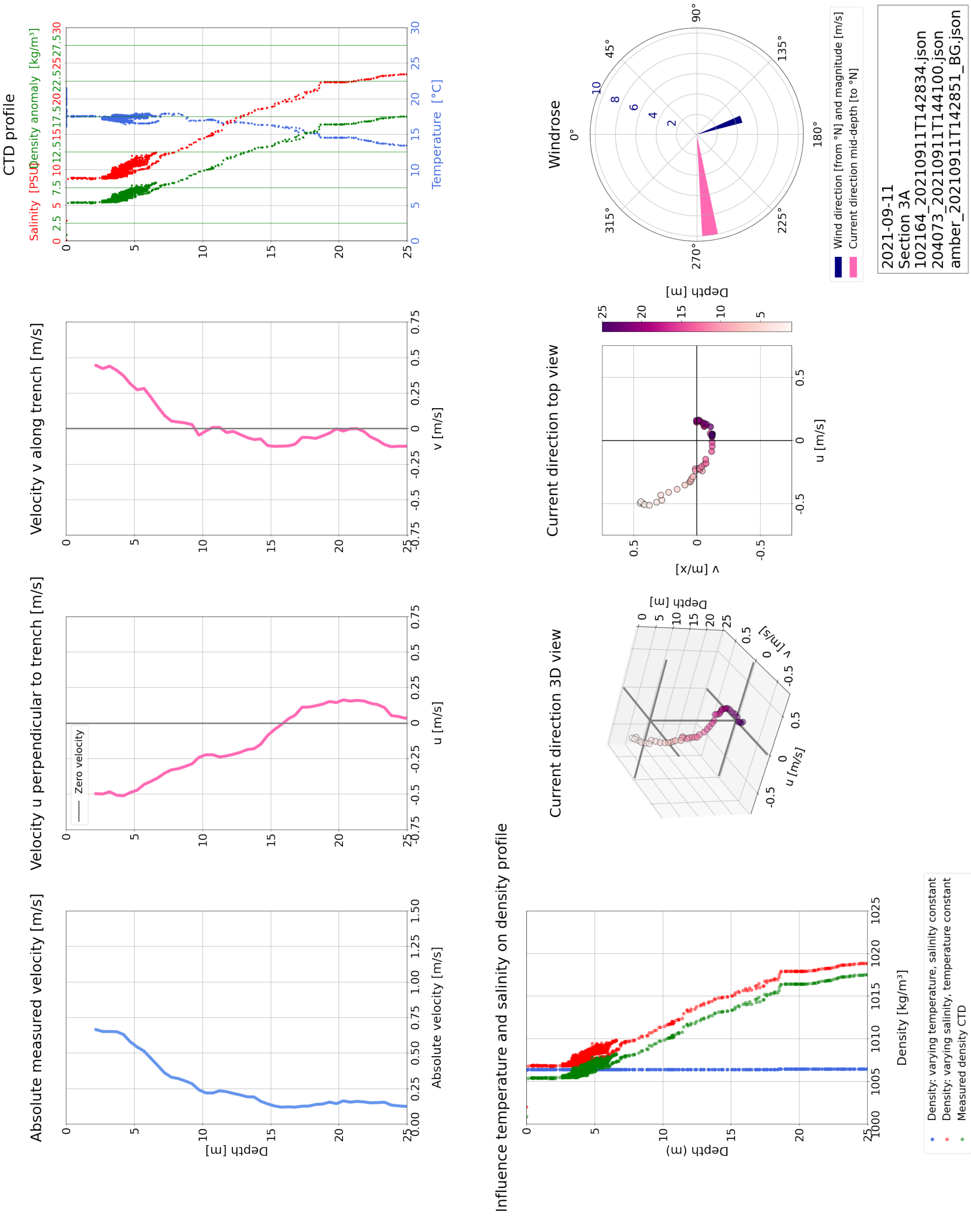

Figure D19: Measurements 11-09-2021 in zone 3A giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

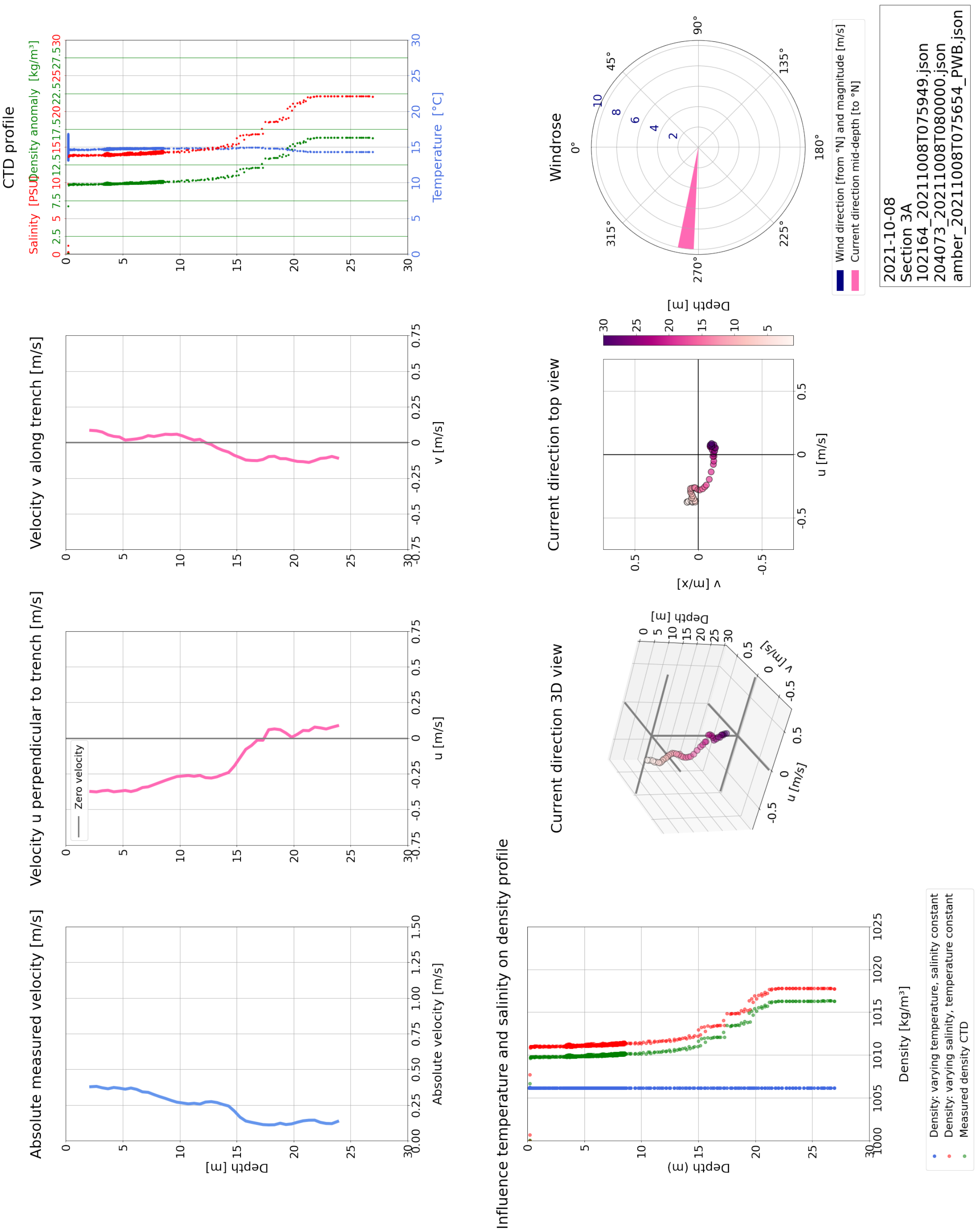

Figure D20: Measurements 10-08-2021 in zone 3A giving the current direction, magnitude, CTD profiles, calculated density profiles, wind direction and current direction at mid-depth.

E Additional effects observed influencing current direction

The existence of different phenomena influencing the current direction, next to wind forcing, is indicated by the large angle between the current direction at mid-depth and the wind. Since the processes do not directly affect stratification but can alternate the plume spread direction, observations made during the analysis of the measurement figures in Appendix D are mentioned in this section. A distinction is made between area's shallower (E.1) and deeper (E.2) than 10 meters. Further research should be done to verify the observations.

E.1 Shallow regions

The current direction in the shallow area's, with a depth smaller than 10 meters, seems to be restricted by the land boundary. An example can be observed in figure E1.

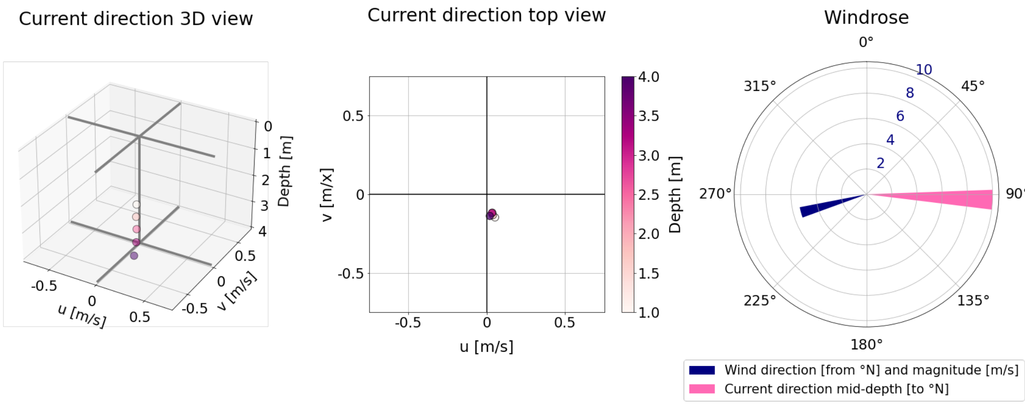

Figure E1: Detail from figure D4 in Appendix D.

E.2 Deep regions

In deep regions, the currents do not directly flow to the direction forced by the wind. All deep water measurement figures show a deflection to the south at mid-depth. A possible explanation might be that the deepest region in the belt is orientated to the south. Since less friction is exerted on the currents in deeper regions, the flow turns towards this part of the cross section. The current direction in the water column can also be turned by Ekman transport and return currents, as mentioned in subsection 2.3.3.

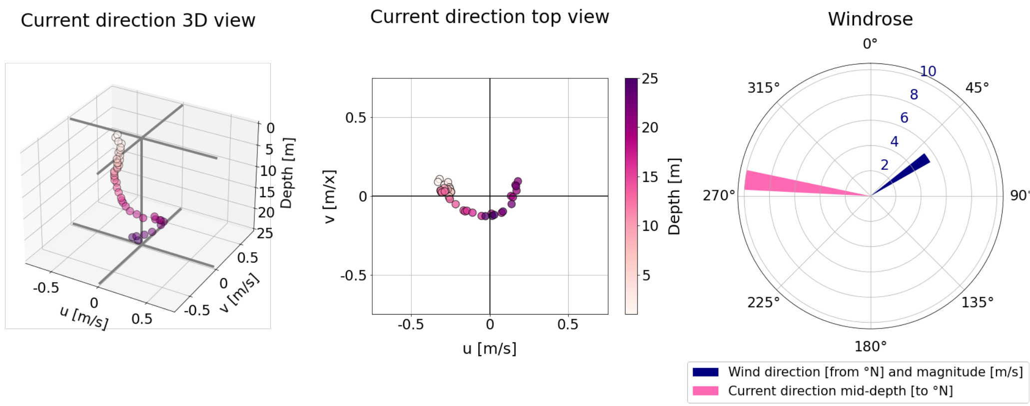

Figure E2: Detail from figure D14 in Appendix D.

F Python script

```
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
import json
from scipy.optimize import curve_fit
from mpl_toolkits import mplot3d
%matplotlib inline
import matplotlib.cm as cm
from collections import OrderedDict
from scipy.optimize import curve_fit
from mpl_toolkits.axes_grid1 import make_axes_locatable
import math

import os

path= r'C:ADCP'
path_ctd = r'C:CTD'
path_wind = r'C:AEGIR'

files = os.listdir(path)
ctdfiles = os.listdir(path_ctd)
windfiles = os.listdir(path_wind)

def velocityprof(i):

    adcp = pd.read_json(files[i],dtype=float)

    m = adcp.loc[:]['vMag']
    d = adcp.loc[:]['vDir']
    z = adcp.loc[:]['binDepth_v_m']
    section = []
    de = []

    m_df = pd.DataFrame(m.to_list(), index=m.index,
    columns=np.linspace(2.2,71.7,139))
    m_df = m_df.fillna(value=np.nan)
    d_df = pd.DataFrame(d.to_list(), index=m.index,
    columns=np.linspace(2.2,71.7,139))
    d_df = d_df.fillna(value=np.nan)

    mmean = m_df.mean(axis=0,skipna=True)
    dmean = d_df.mean(axis=0,skipna=True)
    vx = np.zeros(len(m[0]))
    vy = np.zeros(len(m[0]))
    mmeana = np.array(mmean)
    dmeana = np.array(dmean)
    dmeanan = np.zeros(len(dmeana))

    for ia in range(len(dmeana)):
        if dmeana[ia] >= 23.84:
            dmeanan[ia] = dmeana[ia] - 23.84
        if dmeana[ia] < 23.84:
```

```
        dmeanan[ia] = (dmeana[ia] - 23.84) + 360

for iz in range(len(m[0])):
    vx[iz] = mmeana[iz] * np.sin((np.pi/180)*dmeanan[iz])
    vy[iz] = mmeana[iz] * np.cos((np.pi/180)*dmeanan[iz])

if 54.63318 < np.mean(adcp.loc[:]['lat_deg']) < 54.653716:
    section = 'Section 2B'
if 54.61507 < np.mean(adcp.loc[:]['lat_deg']) < 54.63318:
    section = 'Section 2C'
if 54.59794 < np.mean(adcp.loc[:]['lat_deg']) < 54.61507:
    section = 'Section 3B'
if 54.55866 < np.mean(adcp.loc[:]['lat_deg']) < 54.59794:
    section = 'Section 4'
if 54.52593 < np.mean(adcp.loc[:]['lat_deg']) < 54.55866:
    section = 'Section 3A'
if 54.503372 < np.mean(adcp.loc[:]['lat_deg']) < 54.52593:
    section = 'Section 2A'

if pd.Series(mmeana).last_valid_index() <= 25:
    de = pd.Series(mmeana).last_valid_index()
if pd.Series(mmeana).last_valid_index() > 25:
    de = 25

fig, ax = plt.subplots(figsize=(40,30))

ax1 = plt.subplot(2,4,1)
ax1.set_ylim(0,de)
ax1.set_xlim(0,1.5)
ax1.plot(mmean,dmean.index,linewidth=6,
color='cornflowerblue')
ax1.set_title('Absolute measured velocity [m/s]',
fontsize=30,loc='center',pad=50)
ax1.set_xlabel('Absolute velocity [m/s]',
fontsize=25,labelpad=20,loc='center')
ax1.set_ylabel('Depth [m]',fontsize=25)
ax1.tick_params(axis='x',labelsize=23)
ax1.tick_params(axis='y',labelsize=23)
ax1.invert_yaxis()
ax1.grid()

ax2 = plt.subplot(2,4,2)
ax2.set_ylim(0,de)
ax2.set_xlim(-0.75,0.75)
ax2.plot(vx,dmean.index,linewidth=6,color='hotpink')
ax2.plot(np.zeros(100),np.linspace(0,de,100),
label='Zero velocity',linewidth=3,color='grey')
ax2.set_title('Velocity u perpendicular to trench [m/s]',
fontsize=30,loc='center',pad=50)
ax2.set_xlabel('u [m/s]',fontsize=25,labelpad=20,loc='center')
ax2.tick_params(axis='x',labelsize=23)
ax2.tick_params(axis='y',labelsize=23)
ax2.set_xticks([-0.75,-0.5,-0.25,0,0.25,0.5,0.75])
ax2.set_xticklabels([-0.75,-0.5,-0.25,0,0.25,0.5,0.75])
```

```
ax2.legend(fontsize=20,loc='upper left')
ax2.invert_yaxis()
ax2.grid()

ax3 = plt.subplot(2,4,3)
ax3.set_ylim(0,de)
ax3.set_xlim(-0.75,0.75)
ax3.plot(vy,dmean.index,linewidth=6,color='hotpink')
ax3.plot(np.zeros(100),np.linspace(0,de,100),
linewidth=3,color='grey')
ax3.set_title('Velocity v along trench [m/s]',
fontsize=30,loc='center',pad=50)
ax3.set_xlabel('v [m/s]',fontsize=25,labelpad=20,loc='center')
ax3.tick_params(axis='x',labelsize=23)
ax3.tick_params(axis='y',labelsize=23)
ax3.set_xticks([-0.75,-0.5,-0.25,0,0.25,0.5,0.75])
ax3.set_xticklabels([-0.75,-0.5,-0.25,0,0.25,0.5,0.75])
ax3.invert_yaxis()
ax3.grid()

#plot CTD

df = pd.read_json(ctdfiles[i])
zmax = df.index[df['Depth [m]'] == np.max(df['Depth [m]'])]
zmaxv = float(pd.read_json(ctdfiles[i])['Depth [m]'][zmax])

ax4 = plt.subplot(2,4,4)
ax4.plot(df['Temperature [°C]'],df['Depth [m]'],
'.',color='royalblue',label='Temperature [°C]')
ax4.set_xlabel('Temperature [°C]',fontsize=25,
labelpad=20,color='royalblue')
ax4.tick_params(axis='x', color='royalblue',
labelcolor='royalblue',labelsize=23)
ax4.tick_params(axis='y',labelsize=23)
ax4.set_xlim(0,30)
ax4.set_ylim(0,de)
ax4.set_title('CTD profile',fontsize=30,pad=30)
ax4.grid()

ax5=ax4.twiny()
ax5.plot(df['Salinity [PSU]'],df['Depth [m]'],'.',
color='red',label='Salinity [PSU]')
ax5.set_xlabel("Salinity [PSU]",fontsize=22.5,
labelpad=30,loc='left',color='red')
ax5.set_xlim(0,30)
ax5.set_xticks([0,5,10,15,20,25,30])
ax5.set_xticklabels([0,5,10,15,20,25,30])
ax5.tick_params(axis='x', color='red',
labelcolor='red',labelsize=21)

ax6=ax4.twiny()
ax6.plot(df['Density anomaly [kg/m³]'],df['Depth [m]'],'.',
color='green',label='Density anomaly  [kg/m³]')
ax6.set_xlabel("Density anomaly  [kg/m³]",
```

```
fontsize=22.5,labelpad=30,loc='right',color='green')
ax6.tick_params(axis='x', color='green',
labelcolor='green',labelsize=21)
ax6.xaxis.tick_top()
ax6.set_xticks([2.5,7.5,12.5,17.5,22.5,27.5])
ax6.set_xticklabels([2.5,7.5,12.5,17.5,22.5,27.5])
ax6.set_xlim(0,30)
ax6.grid(color='green')
ax6.invert_yaxis()

#check salinity or temperature driven

ax7 = plt.subplot(2,4,5)

r_c = np.array(df['Density anomaly [kg/m³]']) + 1000
s_c = np.array(df['Salinity [PSU]'])
d_c = np.array(df['Depth [m]'])
t_c = np.array(df['Temperature [°C]'])
smean_c = np.mean(s_c)*np.ones(len(r_c))
tmean_c = np.mean(t_c)*np.ones(len(r_c))

rt_c = np.zeros(len(r_c))
rs_c = np.zeros(len(r_c))

for ir in range(len(r_c)):
    rt_c[ir] = 1000 + 0.805*smean_c[ir] - 0.0166*((t_c[ir]
    - 0.212*(float(smean_c[ir]))**1.69))
    rs_c[ir] = 1000 + 0.805*s_c[ir]
    - 0.0166*(float(tmean_c[ir])-(0.212*((s_c[ir])))**1.69)

ax7.plot(rt_c,d_c,'o',label='Density: varying temperature,
salinity constant',color='royalblue',alpha=0.9)
ax7.plot(rs_c,d_c,'o',label='Density: varying salinity,
temperature constant',color='red',alpha=0.5)
ax7.plot(r_c,d_c,'o',label='Measured density CTD',
color='green',alpha=0.5)
ax7.set_title('Influence temperature and salinity on density profile',
fontsize=30,loc='center',pad=40)
ax7.legend(loc='upper right',fontsize=21,bbox_to_anchor=(1.2, -0.15))
ax7.set_xlabel('Density [kg/m³]',fontsize=25, labelpad=30,loc='center')
ax7.set_ylabel('Depth (m)',fontsize=25)
ax7.set_ylim(0,de)
ax7.set_xlim(1000,1025)
ax7.set_xticks([1000,1005,1010,1015,1020,1025])
ax7.set_xticklabels([1000,1005,1010,1015,1020,1025])
ax7.tick_params(axis='x',labelsize=23)
ax7.tick_params(axis='y',labelsize=23)
ax7.grid()
ax7.invert_yaxis()

#Current direction 3D

c = np.linspace(0,math.ceil(mmean.index[de]),len(vx))
ax8 = plt.subplot(2,4,6, projection='3d') #direction plot
```

```
ax8.scatter(vx,vy,dmean.index,c=c, cmap='RdPu',s=150,
alpha=0.5,edgecolor='black',zorder=100)
ax8.set_title('Current direction 3D view',fontsize=30,loc='center',pad=60)
ax8.set_xlabel('u [m/s]',fontsize=23,labelpad=15,loc='center')
ax8.set_ylabel('v [m/s]',fontsize=23,labelpad=15,loc='center')
ax8.set_zlabel('Depth [m]',fontsize=23,labelpad=12)
ax8.grid()
ax8.plot(np.zeros(100),np.linspace(-0.75,0.75,100),
np.zeros(100),color='grey',linewidth=4,zorder=1)
ax8.plot(np.linspace(-0.75,0.75,100),np.zeros(100),
np.zeros(100),color='grey',linewidth=4,zorder=1)
ax8.plot(np.zeros(100),np.zeros(100),np.linspace(0,de,100),
color='grey',linewidth=4,zorder=1)
ax8.plot(np.zeros(100),np.linspace(-0.75,0.75,100),
de*np.ones(100),color='grey',linewidth=4,zorder=1)
ax8.plot(np.linspace(-0.75,0.75,100),np.zeros(100),
de*np.ones(100),color='grey',linewidth=4,zorder=1)
ax8.set_xlim(-0.75,0.75)
ax8.set_ylim(-0.75,0.75)
ax8.set_zlim(0,de)
ax8.set_xticks([-0.5,0,0.5])
ax8.set_xticklabels([-0.5,0,0.5])
ax8.set_yticks([-0.5,0,0.5])
ax8.set_yticklabels([-0.5,0,0.5])
ax8.tick_params(axis='x',labelsize=23)
ax8.tick_params(axis='y',labelsize=23)
ax8.tick_params(axis='z',labelsize=23)
plt.gca().invert_zaxis()

#Top view current direction

ax9 = plt.subplot(2,4,7)
topview = ax9.scatter( vx, vy , c=c,
            cmap = 'RdPu', s=150, alpha=0.75, edgecolor='black')
divider = make_axes_locatable(ax9)
cax = divider.append_axes('right', size='5%', pad=0.4)
cax.tick_params(axis='y',labelsize=23)
bardata = np.arange(de, 0, -1).reshape(1, de)
im = ax.imshow(bardata, cmap='RdPu')
cbar = fig.colorbar(im, cax=cax, orientation='vertical')
cbar.set_label('Depth [m]',fontsize=25, labelpad=15)
ax9.set_title('Current direction top view',fontsize=30,loc='center',pad=90)
ax9.set_xlabel('u [m/s]',fontsize=25, labelpad=15,loc='center')
ax9.set_ylabel('v [m/x]',fontsize=25, labelpad=5,loc='center')
ns = np.linspace(-0.8,0.8,50)
nsyx = np.zeros(50)
ax9.set_xlim(-0.75,0.75)
ax9.set_ylim(-0.75,0.75)
ax9.set_xticks([-0.5,0,0.5])
ax9.set_xticklabels([-0.5,0,0.5])
ax9.set_yticks([-0.5,0,0.5])
ax9.set_yticklabels([-0.5,0,0.5])
ax9.plot(ns,nsyx,'black')
ax9.plot(nsyx,ns,'black')
```

```
ax9.set_aspect('equal', 'box')
ax9.tick_params(axis='x',labelsize=23)
ax9.tick_params(axis='y',labelsize=23)
ax9.grid()

#wind rose
wind = pd.read_json(windfiles[i],dtype=float)
w_m = []
if wind['transect_info']['wind_speed'] is not None:
    w_m = wind['transect_info']['wind_speed']
else: w_m = 0

w_d = []
if wind['transect_info']['wind_direction'] is not None:
    if wind['transect_info']['wind_direction'] >= 23.84:
        w_d = wind['transect_info']['wind_direction'] - 23.84
    if wind['transect_info']['wind_direction'] < 23.84:
        w_d = (wind['transect_info']['wind_direction'] - 23.84) + 360
else: w_d = 0

c_m = []
if wind['transect_info']['current_speed'] is not None:
    c_m = wind['transect_info']['current_speed']
else: c_m = 0

c_d = []
if wind['transect_info']['current_direction'] is not None:
    if wind['transect_info']['current_direction'] >= 23.84:
        c_d = wind['transect_info']['current_direction'] - 23.84
    if wind['transect_info']['current_direction'] < 23.84:
        c_d = (wind['transect_info']['current_direction'] - 23.84) + 360
else: c_d = 0

ax10 = plt.subplot(2,4,8, polar=True,theta_offset=np.pi/2, theta_direction=-1)
ax10.bar(x=((w_d*np.pi)/180), height=w_m, width=np.pi/20,
bottom=0,color='navy',label='Wind direction [from °N] and magnitude [m/s]')
ax10.bar(x=((c_d*np.pi)/180), height=10, width=np.pi/20,
bottom=0,color='hotpink',label='Current direction mid-depth [to °N]')
ax10.set_rmax(10.5)
ax10.tick_params(axis='y',labelsize=23,pad=20,labelcolor='navy')
ax10.tick_params(axis='x',labelsize=23,pad=20,labelcolor='black')
ax10.set_title('Windrose',fontsize=30,pad=20)
ax10.legend(loc='upper right',fontsize=21,bbox_to_anchor=(1.12, -0.1))

#Information box

day = wind['transect_info']['start'][0:10]
props = dict(boxstyle='square', facecolor='white', alpha=0.8)
textstr = '\n'.join((day,section,files[i],ctdfiles[i],windfiles[i]))
ax10.text(0.78, -.12, textstr, transform=ax.transAxes, fontsize=30,
verticalalignment='bottom',ha='left',bbox=props)

plt.subplots_adjust(left=None, bottom=None, right=None,
top=None, wspace=0.38, hspace=0.35)
```

```
    fig.savefig(str(i) + 'MonthYear_Version.png')

    plt.close(fig)

    return

for i in range(len(files)):
    velocityprof(i)
```