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Find a title.

Abstract: *TODO*

Keywords: *CTD, Field work, TODO*

Contents

1 Introduction

main question TODO

How Skagerrak and Kattegat water masses influence the Gullman fjord water?
What can we say about the stratification?

context The Baltic sea connects to the Atlantic through the Skagerrak, a strait situated between Norway, Denmark and Sweden. Inbetween Sweden and Denmark lies the Kattegat sea area, linked to the Baltic water. The Skagerrak is an area of multiple currents and bith spatial and temporal salinity variations. These water heterogeneousity has a main impact on the primary production, that is influenced by the nutrient supply, the oxygen concentration, or the wind main direction (e.g. *Lindahl et al.* (1998); *Dahl and Danielssen* (1992); *Andersson and Rydberg* (1993)). The reason is that water coming from the Baltic sea is fresh and lies over the salty Atlantic water. The position of the different masses depends a lot on the meteorological and oeanographical conditions, especially at the surface, where a sharp front between fresh and salty water has a variable position (*Gustafsson and Stigebrandt*, 1996).

Two typical water masses are present along the western coast of Sweden. One water masse is composed by fresh water coming from the Batic sea through the Kattegat. Its salinity is situated between 15/20 and 25. The second one comes from Atlantic water and is largely present in the Skagerrak and has a salinity of about 33 at the surface and 35 at 100 meters depth.

The water in the Gullman fjord is mainly composed of these Kattegat and Skagerrak waters (*Arneborg*, 2004), limit of salinity 28 between them.

Synoptic conditions: uppwelling

Plan

2 Materials and methods

2.1 Presentation of the field work and data acquisition

TODO bad weather: from high sea to fjord

This report focuses on a field work that has been conducted on December 2018, the 10th and 11th, as part of the course OC4920 of the University of Gothenburg. Two days have been spent on two ships, the Skagerrak and the Trygve. Both ships had fully equipped CTD, with temperature, salinity, and oxygen concentration sensors. Some other variables have been recorded but not discussed on this report. Niskins bottle have been used for the oxygen calibration on board of the Skagerrak.

We got more than 50 casts, covering the fjord with a very good spatial coverage. We also made 3 mooring measurements, setting the CTD at a certain depth for 30 minutes, recording the temporal variations instead of the spatial variations. Figure 1 presents the position of the Gullman Fjord, on the western coast of Sweden, as well as the position of the CTD casts.

2.2 Data processing

For a better readability, we will refer to potential temperature as temperature and to absolute salinity as salinity. If needed, we will explicitly use the term *in situ* to refer to measured temperature and salinity.

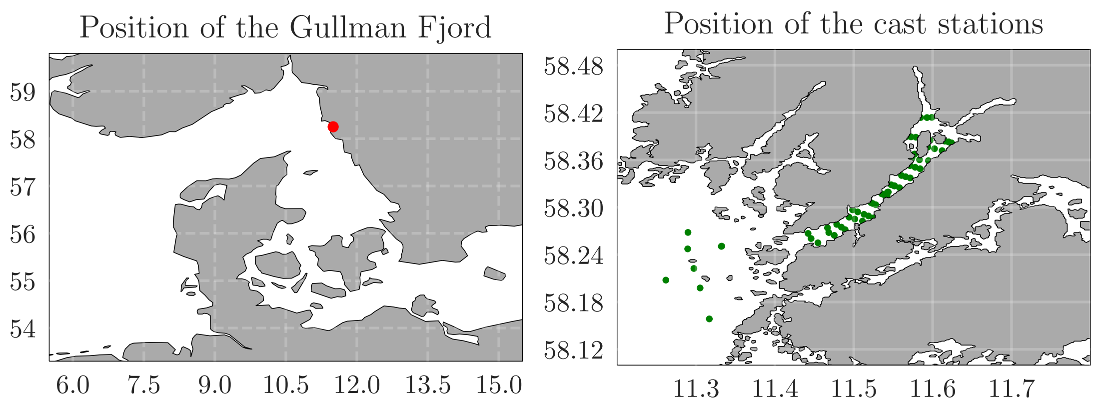

Figure 1: Situation of the Gullman Fjord (red dot) and position of the CTD casts (green dots).

To ensure coherence in the whole dataset and between the two ships, all the data have been regridded on a 1 meter grid, from 0 to 119 meters depth. Depths without any measurement points have been filled with NaN.

Conversion following TEOS-10 Using the library provided by TEOS-10 (*McDougall and Barker*, 2011), *in situ* temperatures and practical salinities have been converted to potential temperature and absolute salinity. Potential density anomaly has also been derived.

Calibration One cast has been conducted at the same position with the two ships each day, so that all the measured variables can be calibrated between the two datasets. The Skagerrak data have been chosen as reference data, because of a more recent recalibration of the CTD sensors than the Trygve sensors. After a linear regression between Trygve and Skagerrak calibration profiles under the thermocline, the coefficients have been used to recalibrate Trygve profiles for each day. See Table 2 for the used coefficients.

2.3 Turner angle

One way to estimate the role of the salinity and the temperature on the stratification is to use the Turner angle Tu (*Ruddick*, 1983; *Johnson et al.*, 2012):

$$Tu = atan2(\alpha\partial_z T + \beta\partial_z S, \alpha\partial_z T - \beta\partial_z S),$$

with α the thermal expansion, β the haline contraction, $\partial_z T$ the vertical gradient of the temperature, $\partial_z S$ the vertical gradient of the salinity, and $atan2$ the four-quadrants inverse tangent. If $Tu = 45°$ the temperature controls totaly the density changes, if $Tu = -45°$ the salinity controls totaly the density changes, at $0°$ the temperature and the salinity control both equally the density changes. If $|Tu| > 45°$ the temperature and the salinity are working one against the other, with total compensation if $|Tu| = 90$. If $|Tu| > 90$, the stratification is unstable, which is not the case in our study.

The Turner angle has been computed at every depth for each profile, using values of α and β given by the TEOS-10 library.

2.4 Profile fitting and layers

Temperature profiles in the fjord all look very similar, with 1. an upper thermocline; 2. a warm water mass; 3. a lower thermocline; 4. the lowest layer where temperature is approximately constant. It is not easy to compute the depth of these layer by using a threshold (on the value or on the gradient) due to the irregularities of the temperature. Inspired by the work of *Pauthenet et al.* (2017), we decided to approximate the profiles with a function and then extract the layers information from the functions properties. As the studied profiles have all the same shapes, we used a mutli-linear fit, fitting the 4 layers. The parameters of the fitted function are the depths and the temperatures of the interface between each layers. We considered that for the lowest layer, the fitted temperature will be a constant. An *a priori* model was set for these 8 parameters, with values set by eye to be a good candidate. Table 1 in Appendix presents the parameters. The least squares approximation has been used to find the best parameters. For the profiles that are not deep enough, only the part where data are present has been used for the least squares method. The *a priori* model has been set for the lower part, with a confidence flag set to 0. Figure 2 presents two examples of profiles: one where the 4 layers are present and one where the fjord was not deep enough, so only the upper layer is fitted.

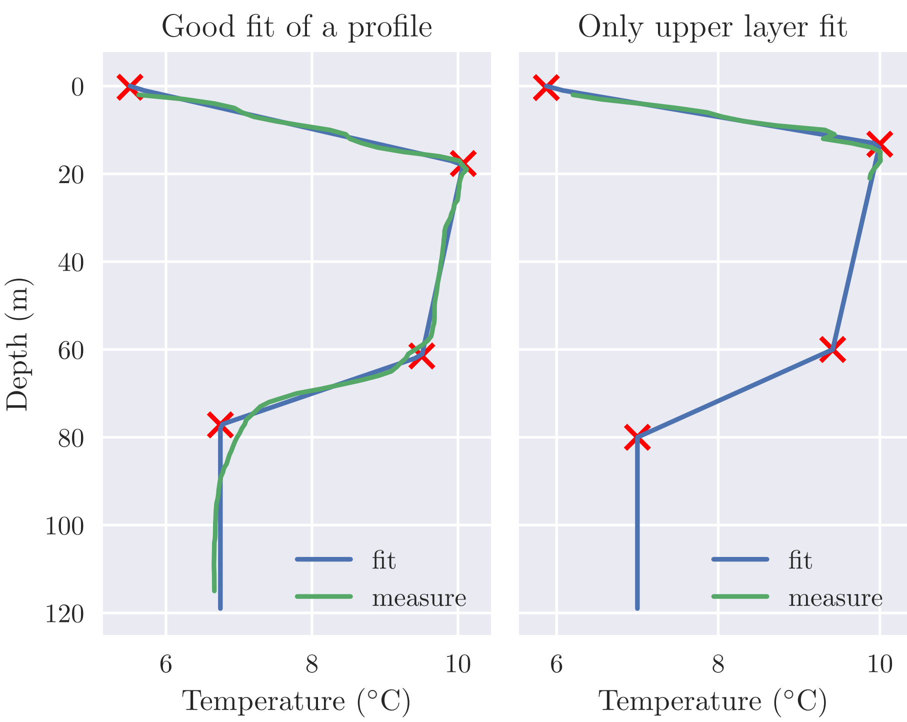

Figure 2: Profile fitting with a multi-linear function. The measured profiles are plotted in green, the fitted functions in blue, and the red crosses represent depth and temperature at the interfaces between the different layers. On the right plot, the fit corresponds to the *a priori* model for the two lowest interfaces.

3 Results

The offshore transect and the casts inside the fjord have different shapes (Figure 3). A mixed layer of few meters is present offshore. The salinity is around 29 at the surface of the offshore

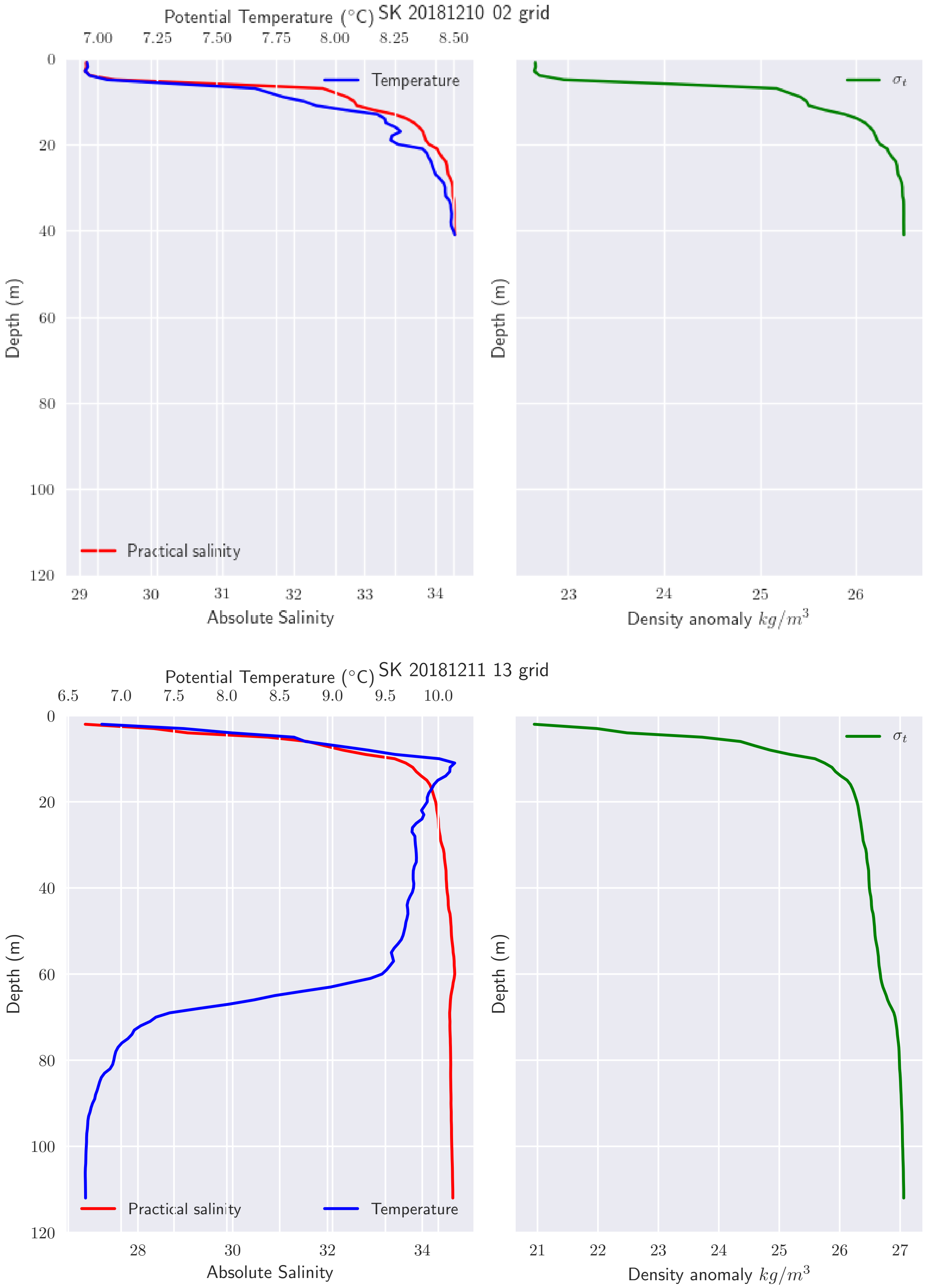

Figure 3: Example of two profiles, offshore on the top and in the Gullman fjord on the bottom. These profiles are very representative of all the measured profiles. The emperature is in blue, the salinity is in red and the density anomaly is in green.

profile, increasing along a sharp halocline to more than 34. The salinity is here representative of Skagerrak water. The temperature follows the same kind of shape: roughly constant in the mixed layer and then increasing. The density is increasing under the mixed layer, even if the temperature increases, it is not sufficient to compensate the large variation of the salinity, leading to a density controlled by the salinity here.

On the opposite, in the very calm conditions of the fjord, no mixed layer is visible. An upper layer of 10 to 20 meters controlled by a strong halocline lies over a warm water mass, where density seems to follow the shape of the salinity. The salinity changes a little bit in this warm water and in the lower layers, but keeps values over 34 when the temperature variates from 10 °C to 9.5 °C at the bottom of the warm water to reach a little more than 6.5 °C at the bottom. Despite a slight decrease of the salinity after 60 meters, the density seems to be controlled by the temperature variations of the lower thermocline.

The 28 salinity limit in the fjord profiles is in the middle of the upper cline. *Arneborg* (2004) present an upper layer (around 10 meter depth) of Kattegat water in the fjord during the summer, under which a halocline and the Skagerrak water are present. The depth of the halocline is strongly related to the inflow or outflow of water in the fjord. Even if the Kattegat water seems to be present at the surface (Figure 4), the main part of the water is Skagerrak water. The upper cline is visible on Figure 4, as the mixing between the Kattegat (yellow points) and the Skagerrak upper water (yellow/green points). The salinity and the temperature of the bottom stagnant layer have very little spatial variation.

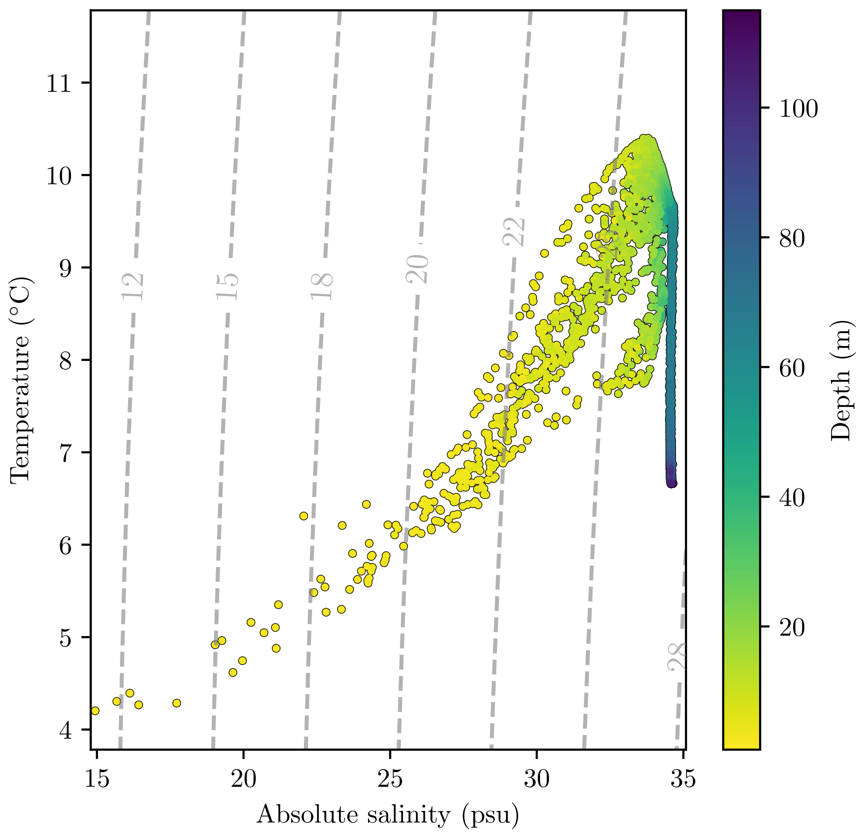

Figure 4: T-S diagram regroupping all profiles. The color of points represents the depth. The dashed lines are the lines of constant density anomalies in kg/m^3.

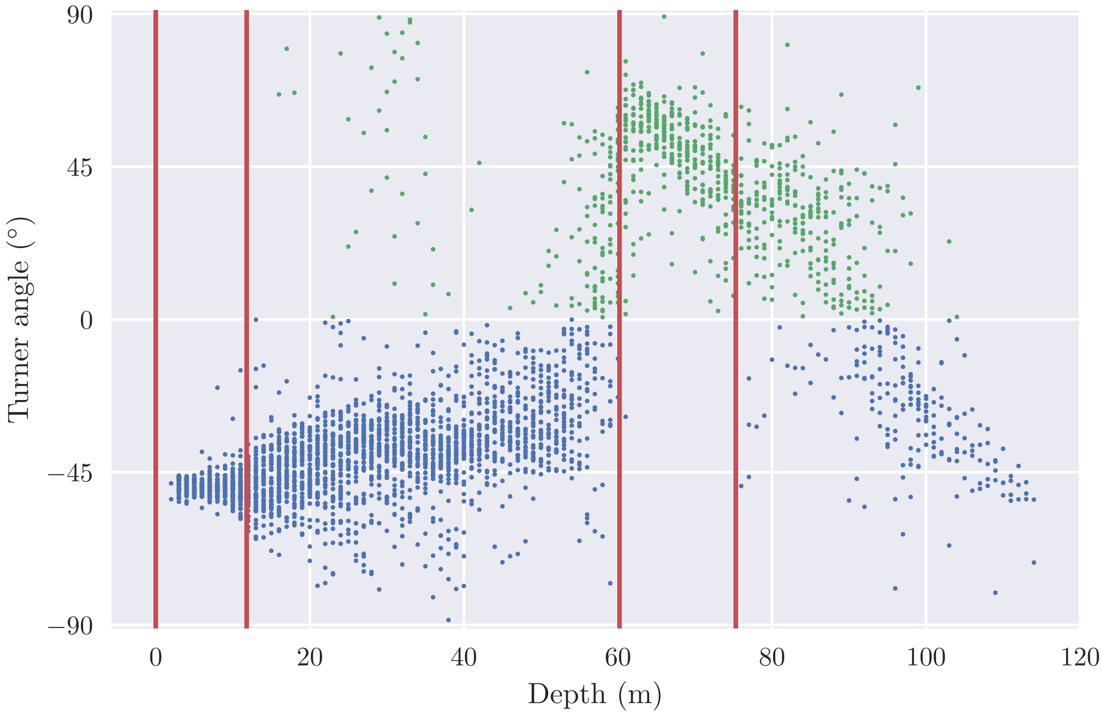

Figure 5: Turner angle as a function of depth. Colors have been used to delimit the area where the temperature is the principal actor ($0 < Tu < 90$, green) and the area where the salinity controls the density changes ($-90 < Tu < 0$, blue). The red lines represent the mean position of the interfaces between the different water layers.

By a visual analyze, it has been seen that both the temperature and the salinity can control the stratification, depending on the depth. This result is confirmed by the Turner angle. To help the analyze, mean depth for each fitted interface have been plotted in red in Figure 5. In the upper halocline, the Turner angle is indicating that the salinity is almost totaly controlling the stratification, with a little opposite effect of the temperature ($Tu_{mean} \simeq -48.5°$, $Tu_{std} \simeq 11.5°$). This is consistant with the strong halocline that acts to densify the water and the temperature augmentation that lightens the water.
On the second layer (warm water) the temperature decreases slightly, while the salinity continues to increase. Tu is mainly situated between $-45°$ and $0°$ ($Tu_{mean} \simeq -33.0°$, $Tu_{std} \simeq 25.7°$), meaning that the salinity and the temperature have the same effect on the stratification, but the salinity still has the main impact.
The warm layer has a completely different behaviour: $Tu_{mean} \simeq 48.4°$, $Tu_{std} \simeq 14.1°$. The temperature is now the main actor of the stratification.
From 60 to 110 m, the Turner angle decreases starting at an almost only temperature controlled stratification to an almost only salinity controlled stratification. This is due to the fact that the temperature decreases on the lower thermocline but does not variate a lot at the bottom of the stagnant water mass.

The interfaces between each water layers have been computed using the temperature variations as described previously. The temperature at the top of the warm water increases from the beginning to the end of the fjord (Figure 6) when the temperature at the bottomn of the warm water decreases slightly from the beginning to the end of the fjord. The thickness of the warm water is minimum at the beginning of the fjord (42.6 m), maximum at the end of the fjord (57,3 m), with a mean thickness of 47,6 m (standart deviation of 3.7 m). The spatial

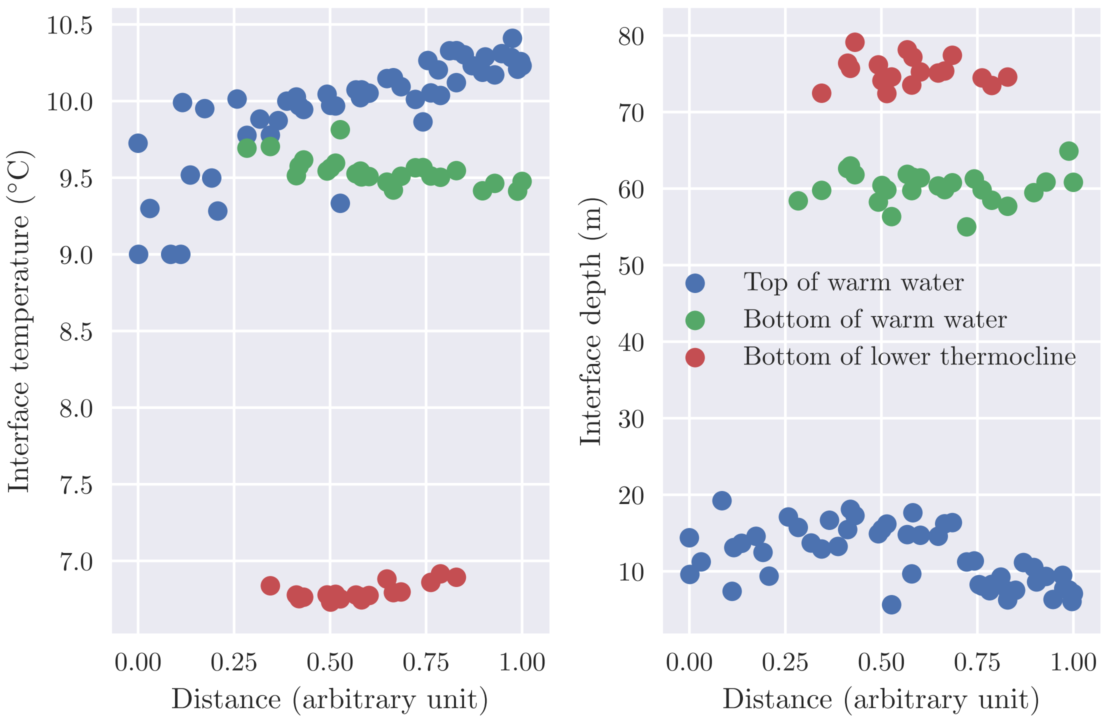

Figure 6: Temperature and depth of the fitted interfaces between the water layer. The distance is expressed using an arbitrary unit, 0 meaning near Kristineberg and 1 near the end of the fjord.

variations of the warm water boundaries depth can be well seen on Figure 7 and Figure 8, on the Appendix.

4 Discussion and conclusions

Common uppwelling event in december (*Björk and Nordberg*, 2003), agree with wind direction. Top of the upper halocline near surface, upwelling (*Arneborg*, 2004).

Temperature is following a seasonal cycle ion the first tens of meters. Salinity controls strati up to about 60 m: Kattegat water always over Skagerrak water.

On the turner angle, visible that the constant T fit fopr the bottom layer is not correct.

fitting of the profile, using spline could be better. but here maybe not necessary. Using turner angle top separate the different layer can also be used for bottom of warm water

Opening work: sub-mesoscale heat fluxes because no mixed layer, geostrophy

See what is the context

What we did

What we showed/saw

What is the conclusion

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A Appendix

Depth (m)	Temperature (°C)	Comment
0	5	Surface
20	10	Bottom of the upper thermocline / top of the warm water
60	9	Bottom of the warm water / top of the lower thermocline
80	7	Bottom of the lower thermocline / top of the lowest layer

Table 1: Values of the *a priori* model for the multi-linear fit.

Temperature

Date	a_T	b_T
2018-12-10	0.9938598212928323461	0.0785624651510818949
2018-12-11	1.006636216123387273	-0.0951492078682694142

Salinity

Date	a_S	a_S
2018-12-10	0.8453445700814513630	5.276859099581269419
2018-12-11	0.8190729895351881451	6.231978296168669829

Table 2: Regression coefficients, the calibration has the following shape: $X_{Trygve} = a_X \cdot X_{Skagerrak} + b_X$, with X the temperature or the salinity.

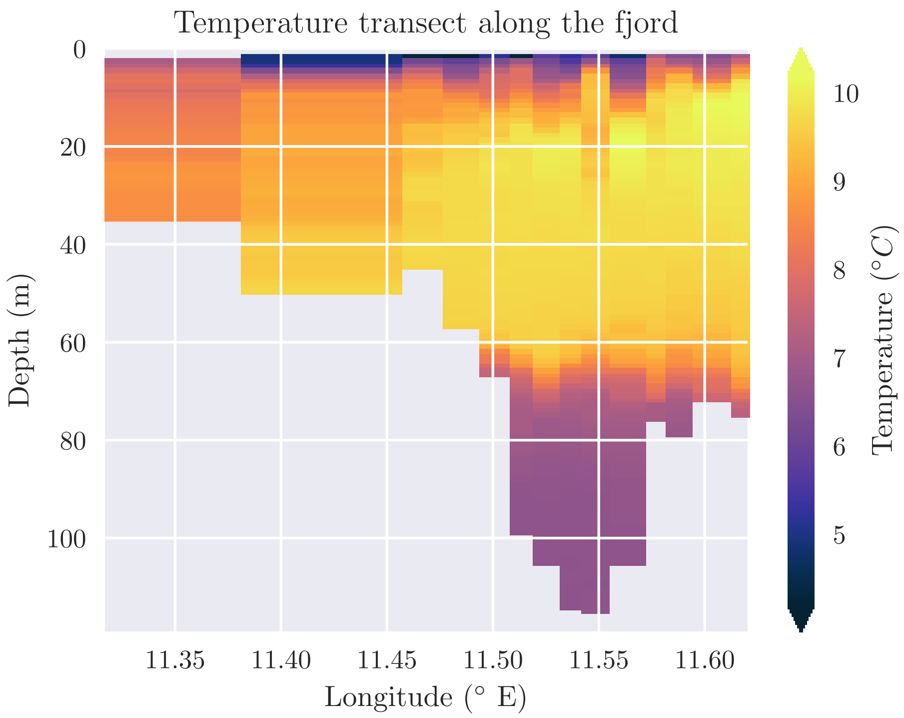

Figure 7: Transect of the temperature along the fjord. The top of the warm water is deeper at the beginning of the fjord than at the end. On the contrary, the bottom of the warm water is deeper at the end of the fjord, leading to a thinner warm layer at the beginning of the fjord.

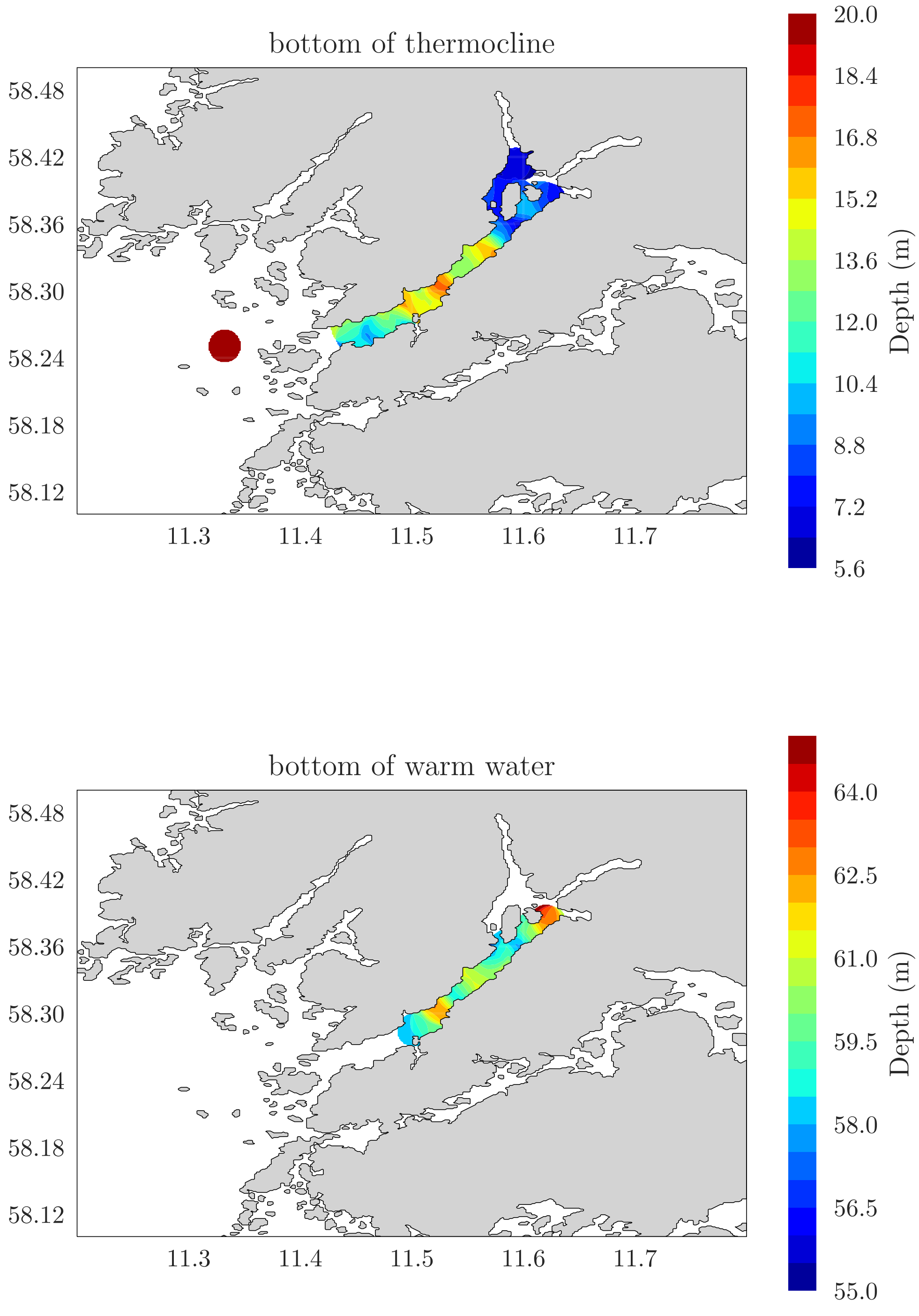

Figure 8: Map of the depth of the top and the bottom of the warm water.