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Study of the stratification on the Gullmar fjord through CTD casts acquired during a two-days field campaign in December 2018.

Abstract: *The stratification of the ocean is a key element to understand the biological and physical processes that occur on it. The fresh Baltic Sea water and the salty Atlantic Ocean water meet in the Skagerrak strait, between the Danish, the Norwegian and the Swedish coasts. These two water masses are found on the Gullmar fjord, on the Swedish west coast. The interaction between these two water masses has been studied. More than 50 CTD casts have been acquired during two consecutive days, in the fjord except for few of them, allowing a comparison of the offshore conditions. The Turner angle, that represents how much the temperature and the salinity control the stratification, and layers interfaces depths has been implemented and computed along the transects. It has been showed that the stratification is mainly leaded by the salinity, due to the high differences between the Skagerrak and the Kattegat water types, leading the water column almost insensitive to the seasonal variations of the upper layers temperature.*

Keywords: *CTD, Field work, stratification, Skagerrak, Kattegat*

Contents

1 Introduction

The stratification of the ocean comes from the density increase with depth. The density is driven by the temperature and the salinity at a fixed pressure. Temperature and salinity can act together in the same way, can have opposite effects on density and sometime compensate. The stratification plays an important role in blocking or promoting the transport of quantities (e.g. nutrients, oxygen, heat) between the different water masses. The mixing can be enhanced by some properties of the water, like the cabbeling, referring to the densification during mixing (*Klocker and McDougall*, 2010). The stratification and its variations play a main role on the temporal evolution of the temperature and salinity profiles. This study focuses on the Gullmar fjord, in Sweden, and on the presence of different water masses on this area.

The Baltic sea connects to the Atlantic through the Skagerrak, a strait situated between Norway, Denmark and Sweden. In-between Sweden and Denmark lies the Kattegat sea area, linked to the Baltic water. The Skagerrak is an area of multiple currents with both spatial and temporal salinity variations. These water heterogeneity 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)).

Two typical water masses are present along the western coast of Sweden. One water mass is composed by fresh water coming from the Baltic 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 salinity of 28 is a good separation between the two water masses (*Arneborg*, 2004). The position of the Skagerrak and the Kattegat water masses depends on the meteorological and oceanographical conditions. At the surface, a sharp front between these two masses is present but its position evolves from days to days (*Gustafsson and Stigebrandt*, 1996).

The Gullmar fjord is a threshold fjord situated on the west coast of Sweden. The depth of the sill is 45 m and its maximum depth of 125 m is reached is the middle of the fjord. The water in the Gullmar fjord is mainly composed of the Kattegat and Skagerrak waters (*Arneborg*, 2004). Two consecutive days of CTD casts have been conducted in December 2018 in the Gullmar fjord. The main wind came from north-northeast, one can expect upwelling conditions through the Ekman pumping (*Danielssen et al.*, 1997).

Temperature and salinity casts will be used to study the stability of the profiles, as well as the origin of there shape. The next section presents the measured data, the processing that have been conducting and the derived metrics, as the Turner angle and a multi-linear fitting of the temperature profile to extract interfaces information. The results are then described, discussed and concluded.

2 Materials and methods

2.1 Presentation of the field work and data acquisition

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. Due to a bad weather on the 10th, the plan has evolves from a study of the Skagerrak / Kattegat front to a study of the Gullmar fjord. 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.

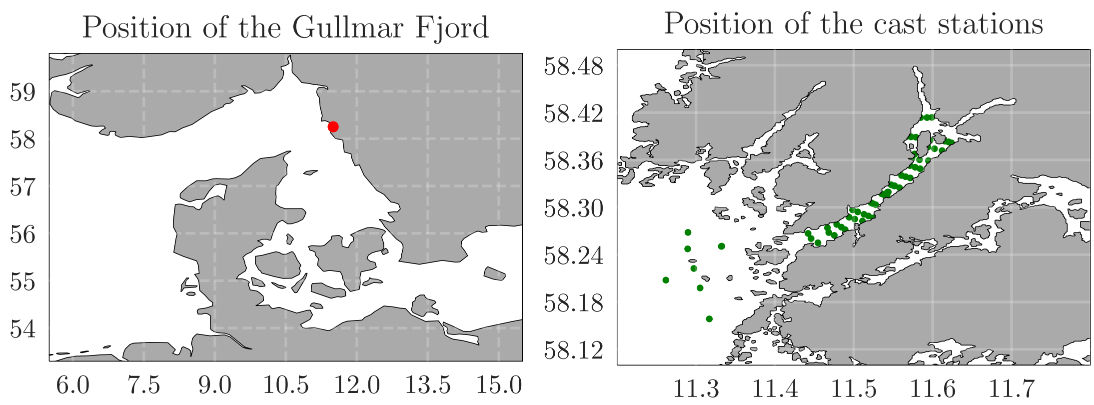


Figure 1: Situation of the Gullmar Fjord (red dot) and position of the CTD casts (green dots).

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 Gullmar Fjord, on the western coast of Sweden, as well as the position of the CTD casts.

Almost no work has been conducted during this study about sub-mesoscale heat fluxes equivalent or about geostrophy, mainly due to a lack of time. The change of the field work because of the weather made me focus on other physical processes.

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.

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.

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 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) presents 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

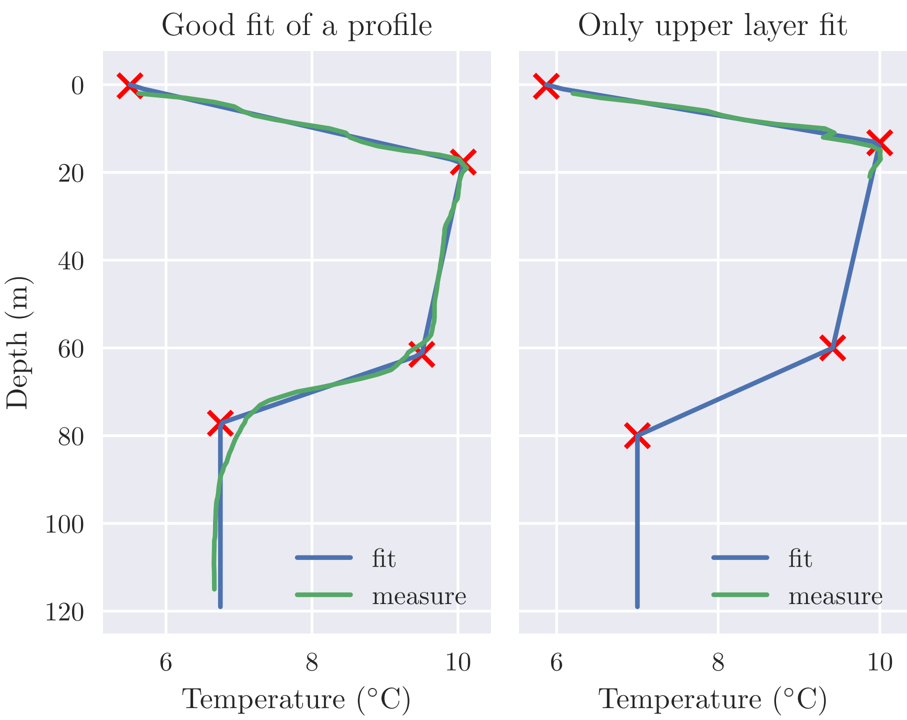
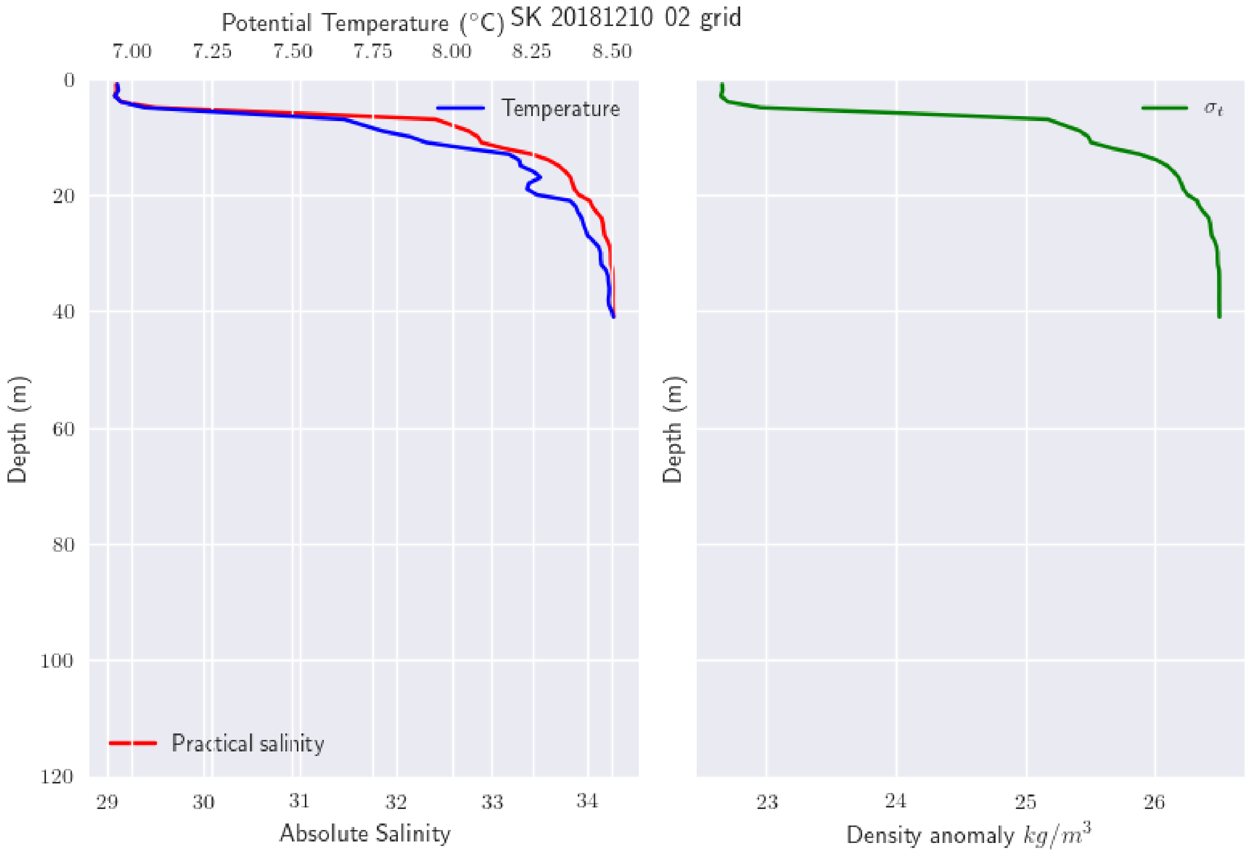


Figure 2: Profile fitting with a multi-linear function. The measured profiles are plotted in green, the fitted functions in blue, and the red crosses represent depth and temperature at the interfaces between the different layers. On the right plot, the fit corresponds to the *a priori* model for the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

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.

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 stratification is mainly controlled by the salinity and the the fjord would be classified as a Beta ocean (*Carmack*, 2007), but here this is the result of a strong halocline which is a very



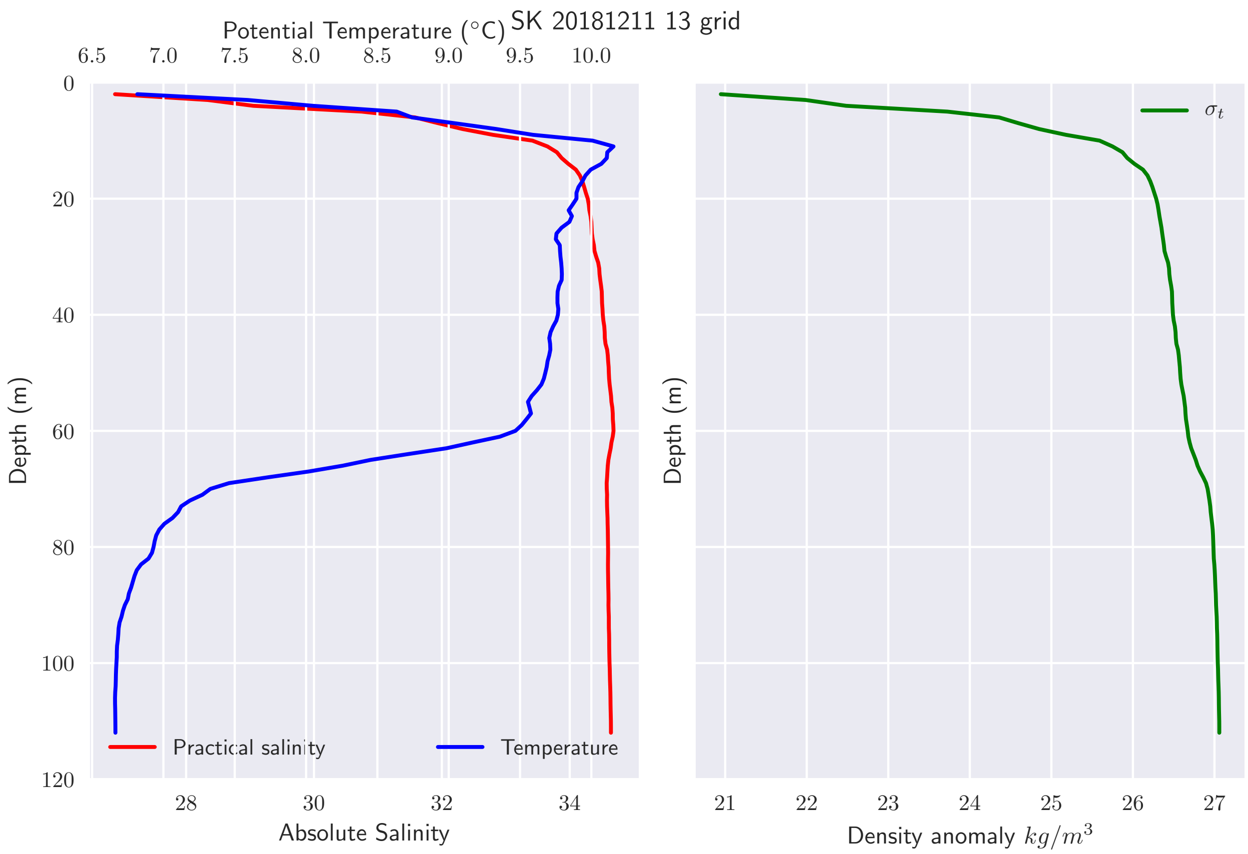


Figure 3: Example of two profiles, offshore on the top and in the Gullmar fjord on the bottom. These profiles are very representative of all the measured profiles. The emperature is in blue, the salinity is in red and the density anomaly is in green.

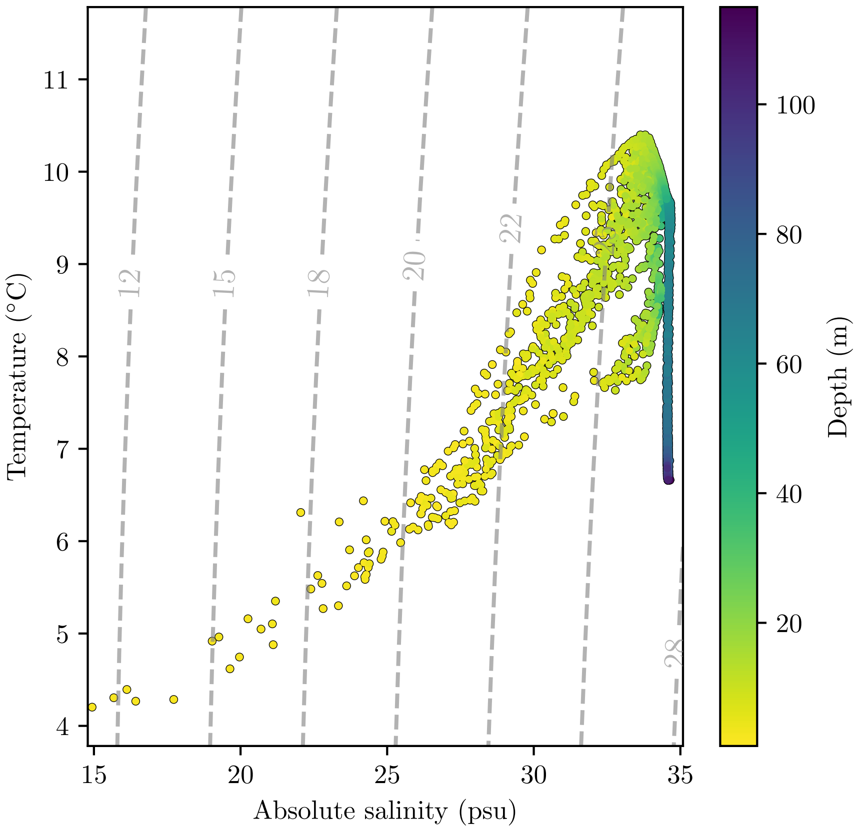


Figure 4: T-S diagram regroupping all profiles. The color of points represents the depth. The dashed lines are the lines of constant density anomalies in kg/m^3.

different cause than the small sensibility of the density to temperature at low temperature.

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

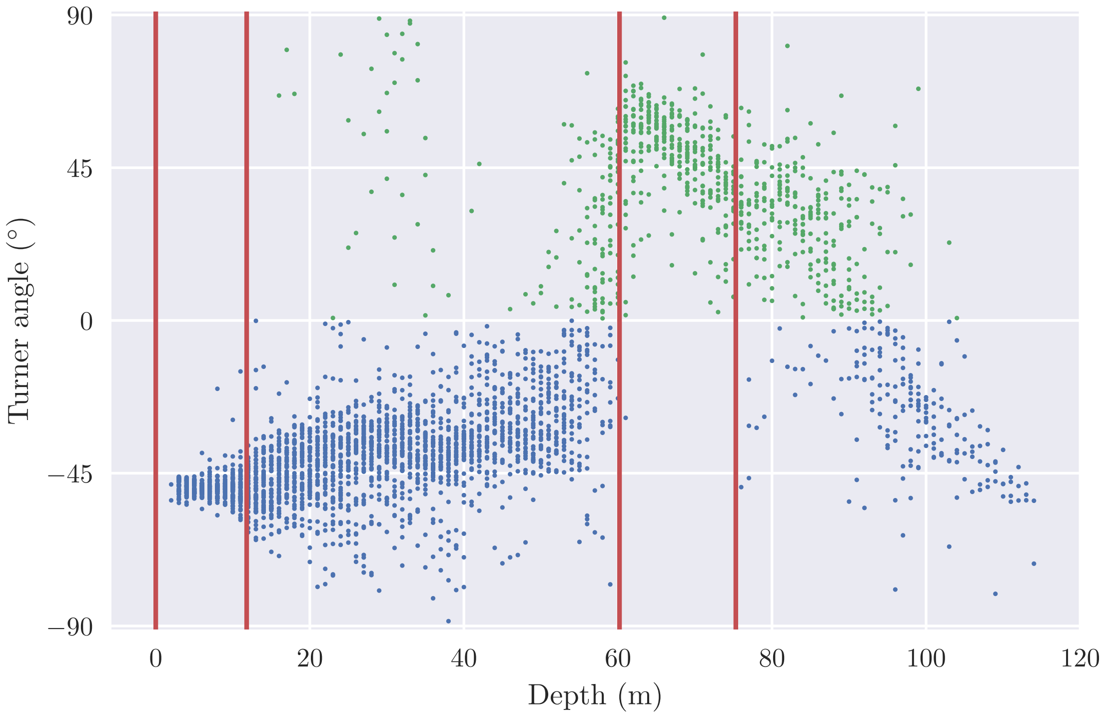


Figure 5: Turner angle as a function of depth. Colors have been used to delimit the area where the temperature is the principal actor ($0 < Tu < 90$, green) and the area where the salinity controls the density changes ($-90 < Tu < 0$, blue). The red lines represent the mean position of the interfaces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

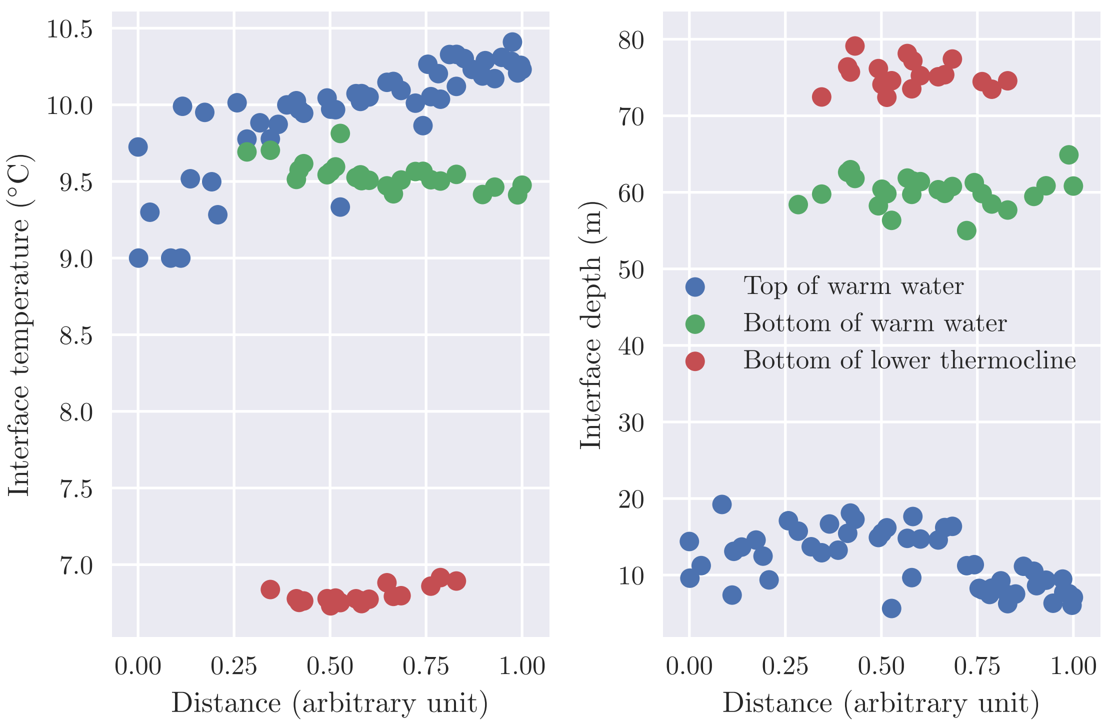


Figure 6: Temperature and depth of the fitted interfaces between the water layer. The distance is expressed using an arbitrary unit, 0 meaning near Kristineberg and 1 near the end of the fjord.

4 Discussion and conclusions

Upwelling event are common in december (*Björk and Nordberg*, 2003), which agrees with the wind direction present during the field work. The top of the upper halocline is near to the surface, signature of an upwelling and an inflow of Skagerrak warm water in the fjord. Despite this, the shape of the warm water would let imagine an outflow of the warm water: the thickness is not coherent with an inflow from the mouth of the fjord. This would need more attention, particularly in term of internal waves and precise current velocities to confirm or refute this remark.

The strong differences between the Skagerrak and the Kattegat water salinities is at the origin of the salinity controlled density at the interface between these two water types. The surface water (at least up to more than 30 m) temperature is following a seasonal cycle, from more than 15 °C at 5 m during the summer to few degrees in the winter (*Björk and Nordberg*, 2003). The strong thermocline is not sufficient to inverse the stratification and then lead to a mixing of the two water masses. The Turner angle only becomes positive under about 60 m, where the water is not subject anymore to the seasonal temperature cycle in a non mixing environment. The low salinity of the Baltic sea leads to a stratification controlled by the temperature only at some depth where the temporal variations of the temperature and the salinity are low. This conduct to a three stable layered fjord: the Kattegat water lying over Skagerrak water, and a stagnant mass is present at the bottom. During the summer, the upper part of the water column is heated, leading to a decreasing of the density of the surface layer, strengthening the stratification.

The fitting of the profile with a mutli-linear funtion has been executed for reasons of simplicity and leaded to good enough efficiency. Using splines could give better fits, but the gain of accuracy could be to the detriment of physical sense and the interfaces postion ease. A mixed layer need to be added if present on the data, but here also a linear fit has a physical sense, because of homogeneity of the properties in the mixed layer. The Turner angle can also be used to separate the different layers, especially for the bottom of the warm water where the stratification becomes governed by the temperature changes. This would lead to better estimation of the thickness of the layers. Associating the profile fitting with mooring data could also be usefull to study internal waves.

The Gullmar fjord is situated in a coastal region where two main water types are present: the salty Skagerrak water and the fresh Kattegat one, that come from the Baltic sea. Skagerrak warm water comes inside the fjord, especially during upwelling events. The average turnover time of these warm water is 40 days (*Arneborg*, 2004). The study of the processes that lead to a strong stratification as well as the analyze of the layer properties has been conducted with data acquired durinf a two-days field campaign. The main result is that the stratification is very stable, mainly leaded by the salinity, not because a cold temperature but because of very high salinity variations. The temperature variations induced by the seasonal cycle are not strong enough to counterbalance the halocline. The shape of the profiles, coming from the intrinsic properties of the Baltic sea and the Atlantic ocean are not suspect to major changes, except for interfaces depth variations.

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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	0.07856246515108189499
2018-12-11	1.006636216123387273	-0.09514920786826941423

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.

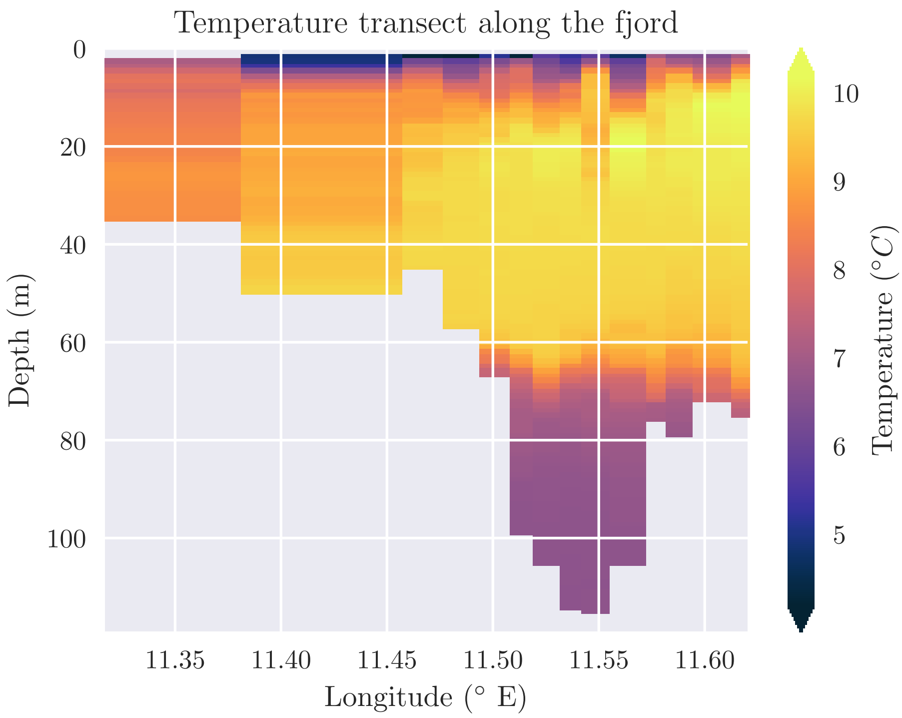

Figure 7: Transect of the temperature along the fjord. The top of the warm water is deeper at the beginning of the fjord than at the end. On the contrary, the bottom of the warm water is deeper at the end of the fjord, leading to a thinner warm layer at the beginning of the fjord.

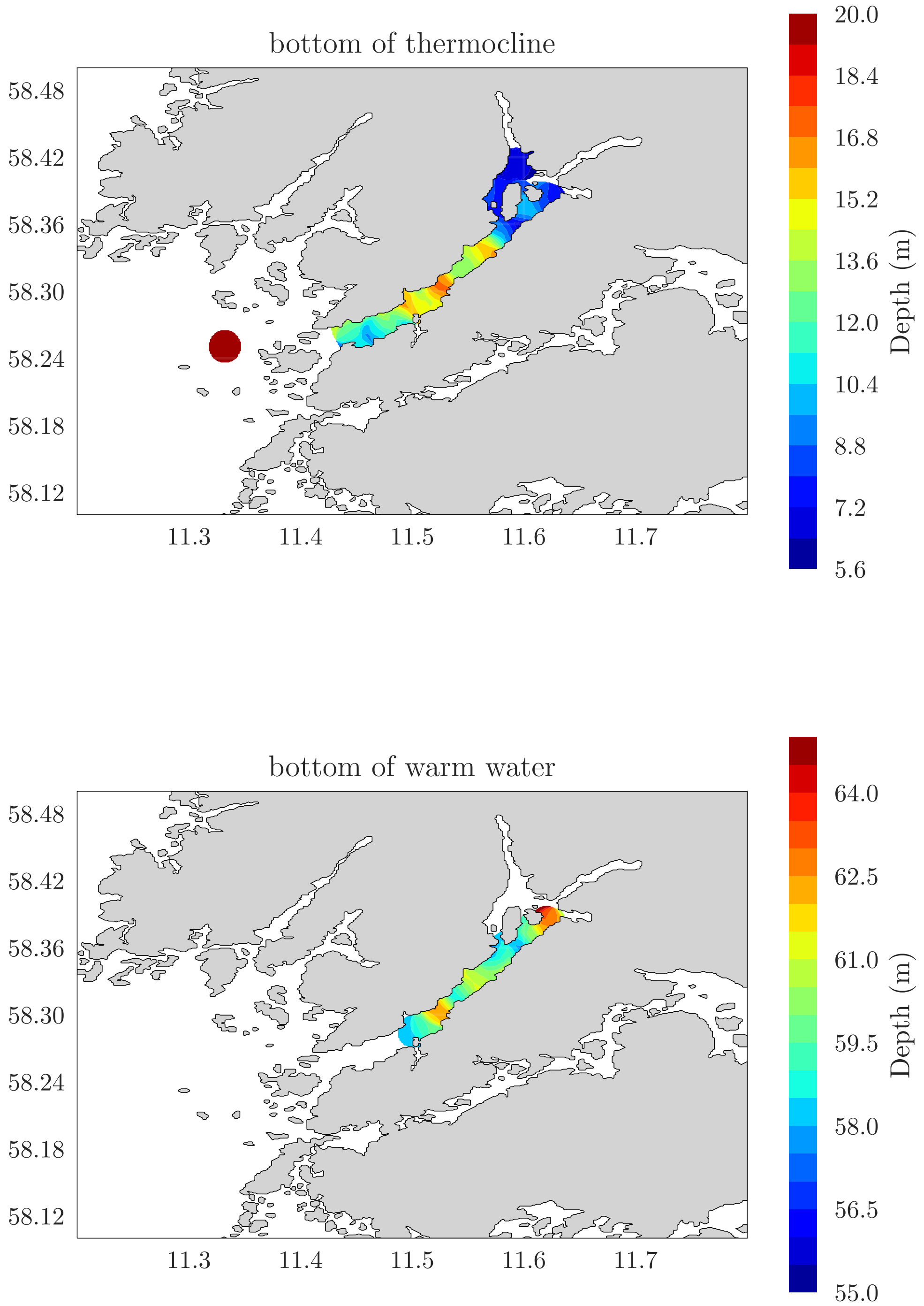

Figure 8: Map of the depth of the top and the bottom of the warm water.