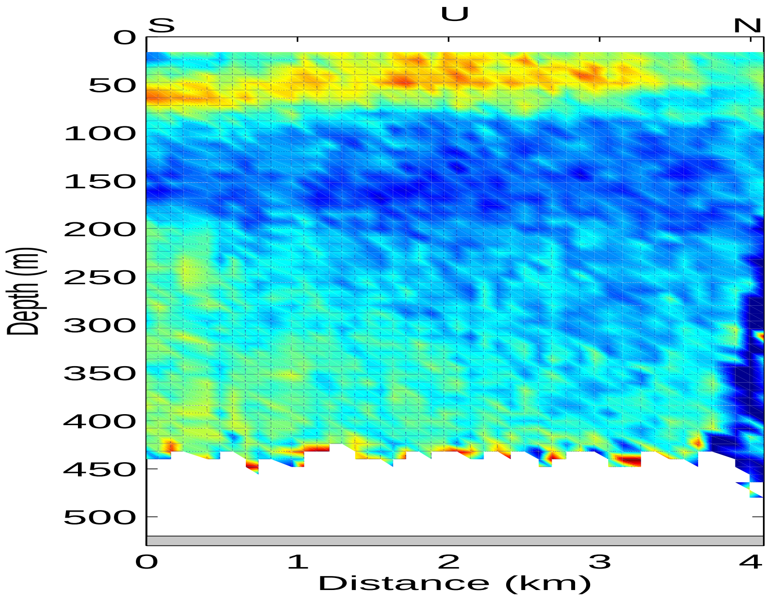
Master's Thesis in Physical Oceanography

Stratification and circulation in Sognefjorden



Sturla Winger Svendsen
Geophysical Institute, University of Bergen
May, 2006

UNIVERSITY OF BERGEN
GEOPHYSICAL INSTITUTE

Acknowledgements

Many, many times I've been asked what I'm doing in life. Well, maybe it wasn't that many times, but quite a few times, at least 20 or 15. Or maybe more like 5 times. Anyway, I tell that I'm studying oceanography. In most cases the person asking goes *oceanowhat?* For a while I tried to explain it by saying that I'm studying the ocean, which would in most often generates this response *Oh, so you're studying fishes and stuff like that?* I've have also tried to say that I'm studying climate, but then I'm usually asked about when the new ice age will come, or how many times I have seen The Day After Tomorrow. Sometimes I have even told people that I study mathematics, but then I just get these strange looks and the question *Isn't that boring?* At one occasion I decided to try something new. *Q: What are you studying? A:Oceanography. Q:Then what will you do when you have finished your studies? A: I'll be an oceanographer. Q:Yeah, but what does an oceanowhatever do? A: An oceanographer makes oceanographics, off course.* However, this seemed to offend the person asking the questions, and the conversation ended.

There have been one occasion when this 'so, what are you doing'-conversation baffled me a little. I met an old acquaintance from way back in the days and the same old conversation starts up. How are you and all those things, followed by the question 'So, what are you doing these days?'. And I, being sick of trying to explain what oceanography is, reply that I'm writing my master thesis about Sognefjorden. I'm expecting some of the same old answers, but instead he asks me if I'm studying oceanography. I was stunned, until he told me that he worked at the IMR. The conclusion must be that oceanography is a brilliant conversation killer, unless you're amongst your own kind. I bet that if I for some reason end up working with something completely different, and no longer call myself an oceanographer, I will come up with this superb way of making people understand what oceanography is all about. To be honest, I'm quite tired by this whole university business. You know, I never wanted to be an student. I always wanted to be... a lumberjack.

Thanks to supervisor Tor Gammelsrød for supervising, to Harald Svendsen and Lars Asplin for all input regarding fjords, to all people at UNIS for an unforgettable year, to the old folks(mum and Arthur, dad and AK, in randomly generated order) for all the free dinners, additional thanks to the old man for comments and discussions. Last, but not least, thanks to Hanna for listening to my endless whining and for keeping my spirits up.

To anyone who feel they should have been included in this acknowledgment, but has been left out, I can assure that this has probably most certainly been done on some kind of purpose, for some reason I at the moment can't quite recall.

Abstract

The winter time stratification and circulation above sill depth in Sognefjorden is studied from CTD and ADCP data from February 2002-2004. The year to year variability in distribution of temperature and salinity has been related to variations in Sognesjøen and offshore wind field, although the exact relationship is unknown. The circulation in the fjord is correlated with the vertical distribution of temperature and salinity. The variability in flow structure follows the variability in the vertical distributions. In 2004 there is a four layered circulation, while in 2002 there is a three layered circulation.

Both circulation and stratification show cross fjord variations, which most likely is due to rotational effects. The fjord is found to be wider than the baroclinic Rossby radius. From the cross fjord variations of the stratification, geostrophic flow has been calculated. The geostrophic flow is divided in similar layers of inflow and outflow as the flow measured by ADCP, although the magnitudes are different.

Sognefjorden is statically stable, but velocity shear may induce turbulence where the stratification is weak.

Contents

Chapter 1

Introduction

The nature of fjords have made them attracting since the early days of oceanography. Water mass exchange only occur at mouth of the fjord, and the sources of fresh water are typically rivers at the head of the fjord. The fjord mouth and the rivers are fairly easy to monitor. With knowledge of input and output to fjord, it is relatively easy to study the different the processes inside a fjord compared to the open ocean. When the variability at the boundaries are known, the effect of these variabilities on the fjord can be studied as well.

The Scandinavian fjords were the subjects of the earliest fjord investigations, and the focuse was on the brakish outflow in the surface and the deeper compensation flow. Ekman(1875) and Helland-Hansen(1906) were some of those who first turned their attention to the fjords. Later efforts were made to make theoretical descriptions of fjord circulation(e.g. Stommel and Farmer, 1952).

Another approach to the fjords was initiated by Tully(1949), who started to investigate the influence of human activity in estuaries. Gade(1970) used this approach in his survey of Oslofjorden. Svendsen(1977) investigated a Norwegian fjord system to study the consequences of river regulation for hydro power purposes.

In the seventies the first models of fjord circulation appeared(Long, 1975, Gade and Svendsen, 1977). These models focused on the estuarine circulation, and computed the thickness and salinity of the brackish along the fjord axis. Since then numerical ocean models have been widely used in fjord research(e.g. Eliassen et al, 2001).

In the eigthies there were several reviews of the current knowledge of fjord processes, one of the most important work from this decade was done by Farmer and Freeland(1982)[1].

In more recent time, the Arctic fjords of Svalbard have been subject for many investigations(e.g. Svendsen, 2002). The interest in these fjords are trig-

---

[1] Some of the historical references are obtained from Farmer and Freeland(1982)

gered by the concern of global warming.

The biological production in fjords has also been investigated. Aure and Stigebrandt(1989) studied the impact of fish farming on fjords, while Asplin(2004) has been studying the spreading of salmon lice in fjords. There has also been studies on how to increase the biological production in fjords by artificial upwelling(e.g. Aure et al, 2000 and Berntsen et al, 2002).

Despite all the efforts put into investigations of fjords, there are few publications describing Sognefjorden. The master degree thesis of Hermansen(1974) and a technical report(Gade, 1971) seems to be the highlights. Although the main features and driving forces in fjords are well known, it is far from trivial to make an accurate description of physical oceanography of fjords. Increased understanding of processes in semi-closed environments such as fjords could contribute to a better understanding of processes outside fjords as well, and ultimately be of use for new parameterizations for modeling purposes.

This paper is based upon three sets of data from Sognefjorden. The data sets origins from field courses for students at the Geophysical Institute, University of Bergen. The purpose of these field courses is typically to give the students an introduction to oceanographic field work, and the data sets is the result of rather random investigations. Thus the data has been gathered without any clear purpose, other than to get a general overview of Sognefjorden.

This paper attempts to describe the the stratification and circulation above sill depth in Sognefjorden. The data available was gathered in February 2002-2004, and it is thus the winter time conditions which are discussed. The most important data gathered are temperature and salinity from CTD, and current profiles from ADCP. The first objective is to compare the stratification and the current profiles to see if these are related. Next objective is to find any mechanisms causing any year-to-year variability in both stratification and circulation. This is done by studying offshore wind fields, flow at the bottom of the sill and variations in the coastal waters. As meteorological data from Sognefjorden is sparse, one fjord arm where there is a meteorological station located in the inner parts is studied to look for impact of atmospheric forcing. The effect of atmospheric forcing is also studied by looking at the short time variation in the fjord.

Various calculations are also important. Both static stability and shear stability is computed for some locations in the fjord for all three years, and in 2003 geostrophic flow will be studied.

In Chapter 2 there is a general description of Sognefjorden and descriptions of circulation and stratification of fjords in general. Chapter 3 is a description of data and the methods used for obtaining them. In Chapter 4 the various results are presented, and the discussions are found in Chapter 5.

Chapter 2

Sognefjorden

2.1 Geography

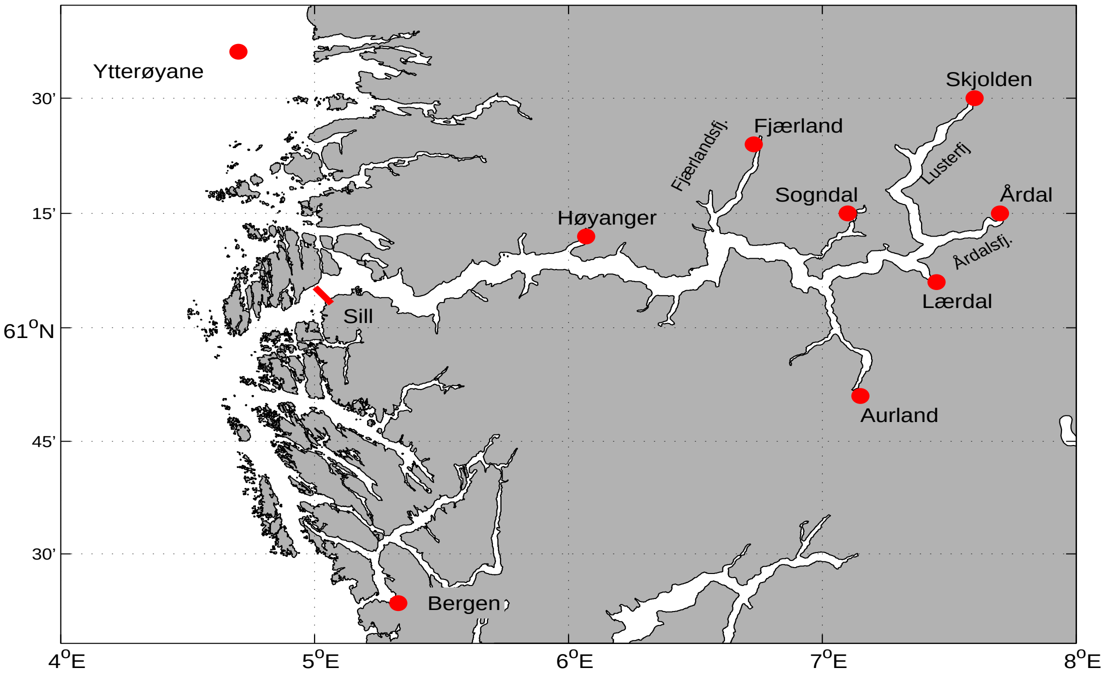


Figure 2.1: Overview map of Sognefjorden

Sognefjorden is the longest and deepest fjord in Norway, and is located on the west coast, see Fig.2.1. The greatest depth, 1308 meters, is found in main fjord just west of Høyanger. The distance from the sill to Skjolden, which is usually considered to be the head of the fjord, is about 175 km. In this paper the head of the fjord is chosen to be Årdal. Usually Årdalsfjorden is regarded as fjord arm, but choice is made because the data coverage of Lusterfjorden is insufficient for a study of the year to year variability.

The only sill in Sognefjorden is at the mouth of the fjord, and the sill depth is 165 meters. The details of the topography of the sill are not well known. The sill prevents free circulation for water masses below sill depth.

West of the sill is an area called Sognesjøen, which is sheltered by islands both in north and south. Sognesjøen is not sheltered by any sill and is in direct communication the open ocean.

Several of the rivers which ends up in Sognefjorden are regulated due to production of hydro electricity. The effect of the regulation is that the fresh water discharge is spread more even throughout the year. If the rivers were not regulated, the fresh water discharge would exhibit a very seasonal variability, with 92% of the discharge from May to October (Gade, 1971). The rivers typically enters a fjord at the head. However, in Sognefjorden rivers may also enter the heads of the many fjord arms.

Most of Sognefjorden is flanked by steep mountains, especially in the inner parts. Due to the steep mountains, the wind direction is typically upfjord or downfjord.

The outer part of the fjord experiences a mild coastal climate, while the innermost part is dominated by inland climate. In the innermost parts of the fjord ice covers might be present for weeks in cold winters(Den norske los, 2001).

2.2 Fjord features

Water masses Fjords with some sort of sill at the mouth are usually assumed to contain three different water masses; brakish/estuarine water, intermediate water and basin water. The brackish water is a mixture of fresh water from river discharge and the intermediate water. The salinity of the brackish is low, but the variability through the year is large(Hermansen, 1974). This is due to the seasonality in the the runoff. In wintertime the runoff is relatively low, and salinity of the brakish water is quite high. In this paper water with salinity less than 32.5 psu is assumed to be brackish water.

The intermediate water is found between the brackish water and sill depth. The intermediate water is coastal water. Because the intermediate water is found above sill depth, there is no obstacles for the circulation in this layer and it is generally well ventilated.

The basin water is found below sill depth. Basin water is the densest water in the fjord, and in order for this water to be replaced, water with greater density must cross the sill. In general replacement of basin water does not happen very often, and the basin water may become stagnant. Due to vertical mixing, the basin water gradually becomes less dense, increasing the possibility for replacement. In Sognefjorden replacement of the basin water occurs

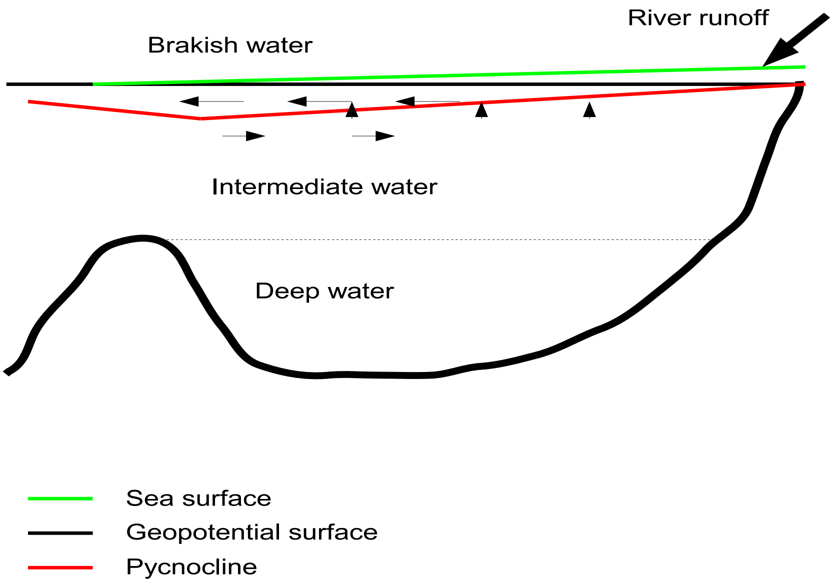


Figure 2.2: Schematic view of the estuarine circulation

approximately every 8^{th} year(Hermansen, 1974).

Estuarine circulation The brackish water is part of what is known as the estuarine circulation. The brackish water is a result of the mixing fresh water and the intermediate water near river mouths. Due to the input of water to the fjords from rivers, the surface is raised from the geopotential level. This gives a barotropic pressure gradient, driving the brackish water downfjord. The slope of the surface elevation due to the river discharge is typically 1 cm per 10 km (Farmer and Freeland, 1983). Due to the low salinity of the brackish water, there is a strong density gradient between the brackish water and the intermediate water. This density gradient is known as the pycnocline. If mixing due to wind and tides are small, there will be limited mixing across the pycnocline (Ellison and Turner, 1959). Still, there will be a small amount of mixing due to entrainment. Entrainment is a one way process which transports mass from a less turbulent medium into a more turbulent one (Kundu, 2004). Due to the entrainment the salinity of the brackish water increases towards the mouth of the fjord. The amount brackish water increases as well, and the downfjord transport in the brackish layer can be between 5 to 10 times as large as the freshwater input to the fjord (AMAP,1998). Thus there is a considerable amount of fjord water which is transported out the fjord. This water has to be replaced, and there exists an upfjord flow just beneath the brackish layer. This is the idealized situation, shown in Fig.2.2.

Wind driven circulation Both local and offshore wind field influences the fjord circulation. Svendsen(1981) found that the mean surface flow in the fjord is mainly wind driven. The offshore wind field generates upwelling and downwelling events along the coast. The upwelling and downwelling are caused by Ekman transports due to winds along the coast. Wind towards south gives upwelling while wind towards north gives downwelling. Sætre et al(1987) found that upwelling on the west coast of Norway occurs within 2-5 days after the onset of winds towards south. They further report that such an upwelling causes strong downfjord flow in the upper layer in the larger fjords. The offshore wind field causes fluctuations in the offshore ocean pressure field(Aure, 1996). Changes in the pressure field will alter the cirulation in a fjord.

Chapter 3

Data and methods

Data presented in this paper was gathered during surveys in Sognefjorden. In 2002 the survey was performed in the beginning of February(2^{nd} - 8^{th}), in 2003 in the beginning of February as well(5^{th} -11^{th}), while in 2004 in the end of February(22^{nd} - 27^{th}). The surveys were conducted by students during the field course taught at the Geophysical Institute at the University of Bergen. The results from the each year has been described and discussed in reports by the participants of the field course (Field course report, 2002, Field course report, 2003, Field course report, 2004). These reports are available from the Geophysical Institute in Bergen. For details on the instruments in use and calibration of these instruments, the reader is referred to these reports.

Naming conventions The following convention is used to describe the fjord. The fjord mouth is the intersection between the fjord and coastal waters. The sill is found at or close to the mouth. The head of the fjord is the innermost part of the fjord, furthest away from the open ocean. If wind or flow is said to be in downfjord direction, the direction of motion is toward the mouth of the fjord. If motion is upfjord, the direction of motion is toward the head of the fjord.

The shores of the fjord will be referred to as the northern and the southern side. When looking downfjord, the left hand side will be the southern side and the right hand side will be the northern side.

CTD CTD profiles were obtained with a Seabird Electronic Inc. SBE911plus sonde. The CTD were equipped with conductivity, temperature and pressure sensors. The measurements were processed by various versions of the SEASOFT data package by Seabird Electronic, which provided filters, averaging of the data and calculation of the salinity.

Water samples were obtained for calibration of the conductivity sensor. The water samples were analyzed with a Guideline Portasal Salinometer. In 2003 and 2004 the conductivity sensors were calibrated a few months prior to the surveys, and no adjustment of the salinity values proved necessary. There are some confusion about the calibration from the 2002 survey. The cruise report from 2002 only states that water samples has been obtained for calibration purposes, but no values are mentioned. The files containing the conductivity and salinity from the water samples exists, but the files do not tell at which station the water samples were obtained. All files relating the water sample bottles to CTD stations are missing, and it is thus not possible to calculate any correction factor. However, small variations in salinity distributions are not an important issue in this report, and the data from 2002 will be assumed to have a sufficient accuracy for the purpose of this report.

ADCP An ADCP(Acoustic Doppler Current Profiler) was used to measure the flow at different depths. The ADCP in use was a vessel-mounted narrowband ADCP(RD Instruments) on board R/V Håkon Mosby.

The recordings are averaged over depth and time. The vertical axis has been divided into 8 meters thick cells and the center of the uppermost cell is at 16 meters. Flow above 12 meters depth is not resolved. The temporal averaging time is about 1 minute.

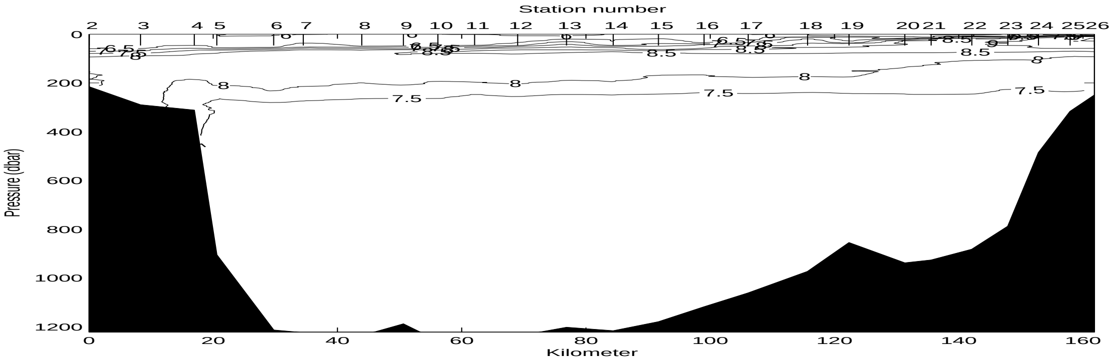
A vessel-mounted ADCP measures flow relative to the ship. On R/V Håkon Mosby the ADCP is connected with the navigational system of the ship. When the movement of the ship is known, the absolute flow can be obtained.

RCM A recording current meter from Aanderaa Instruments, a RCM7, was deployed at the sill in February 2004 and retrieved in May. The deployment depth was approximately 150 meters. The pressure sensor was not functioning, nor was the conductivity sensor. The RCM7 measures flow speed with a rotor, and direction with a vane. For speeds lower than 5 cm/s, the measurements of flow direction are not reliable (pers.com. Lars Asplin).

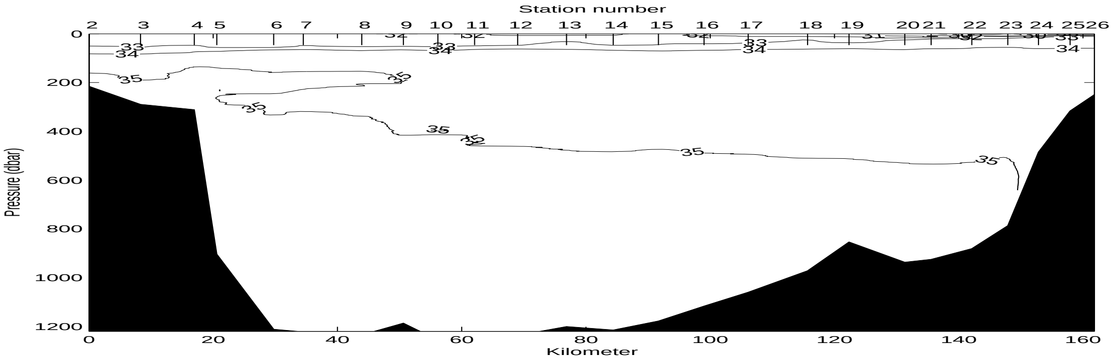
Chapter 4

Results

4.1 General results



(a) Temperature(°C)



(b) Salinity (psu)

Figure 4.1: Temperature and salinity distribution in Sognefjorden, February 2002

Fig.4.1 show the temperature and salinity distribution in Sognefjorden in

February 2002 in the entire fjord. The density is mainly controlled by the salinity, and will not be discussed. Positions of all stations are shown in Fig.4.2a. The two outermost stations, st. 2 and st. 3, are located outside the sill.

Close to the sill, at st. 4, the thermocline is found between 50 and 100 meters depth. Towards the head of the fjord the depth of the thermocline decreases, and the upper 30 meters becomes more stratified. The coldest water is found near the head of the fjord. Below the thermocline there is a layer of warm water. In the outer parts of the fjord, the temperature in this layer is around 8.2°C, while in the inner parts the temperature is around 9.1°C. Towards the head of the fjord the depth of the warm layer decreases. Below the warm layer the temperature decreases. The decrease is quite sharp from 8.0°C to 7.6°C. Below the 7.5 isotherm the temperature decreases to about 7.1°C at 500 meters depth. Below this the temperature is almost constant. Unlike the 8°C isotherm, the 7.5°C isotherm mostly horizontal.

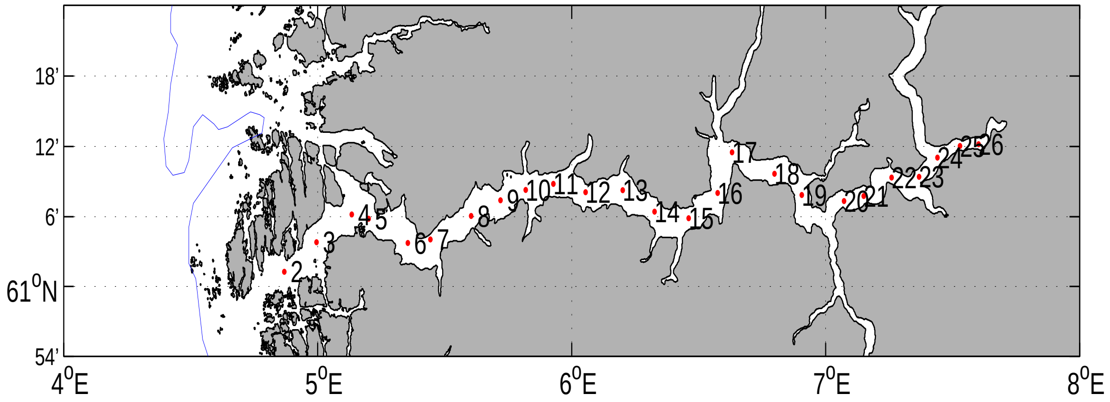
The halocline is located at about the same depth as the thermocline. Above the halocline the salinity is almost constant. The layer above the halocline becomes more stratified towards the head of the fjord. The 33 psu isohaline is inclined. Below the halocline the salinity is increasing slowly with depth. Close to the head the lowest salinity values are found. The salinity gradients are also strongest at the head. The 33.0 psu isohaline is inclined, but the 34.0 psu isohaline is horizontal. The depth of the 35.0 psu isohaline increases towards the head of the fjord. There is also a thin layer with salinity greater than 35.0 psu at around 200 meters depth in the outer part of the fjord.

4.2 Stratification above sill depth

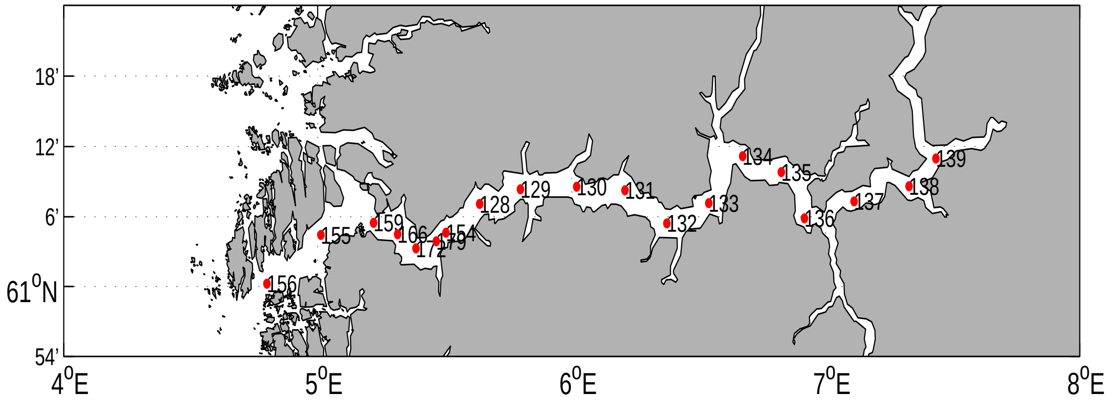
Maps of the CTD surveys are presented in Fig.4.2. The best spatial resolution was obtained in 2002. In 2003 the innermost stations is in the intersection between Årdalsfjorden and Lusterfjorden, while the other years the innermost stations are found inside Årdalsfjorden.

Fig.4.3 and Fig.4.4 show the temperature and salinity distribution in the upper 160 meters, respectively.

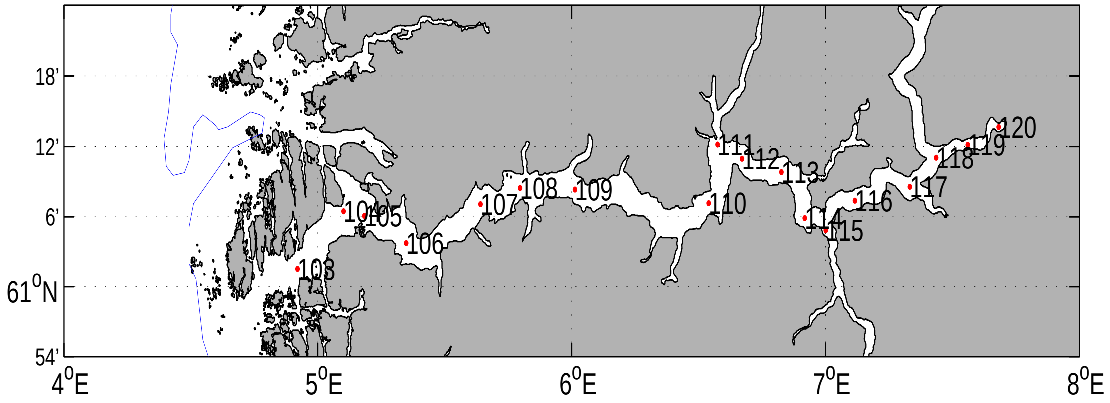
In all three years there are strong gradients in the surface close to the head. These gradients are the boundary between the brackish and the intermediate water. Due to the low salinities of the brackish layer, the density is low, and the brackish water will stay in the surface. In 2002 the depth of the thermocline and halocline increases rapidly downfjord, and the isolines are inclined. In 2003 the thermocline and the halocline are horizontal in the inner half of the fjord, and the stratification does not change much. In the upper 50 meters in the outer part of the fjord the isolines are inclined and the stability decreases. In 2004 the uppermost isolines are at constant depth along the whole length of the fjord. Some of the deeper isotherms are inclined, while the isohalines are



(a) Locations of CTD stations in February 2002

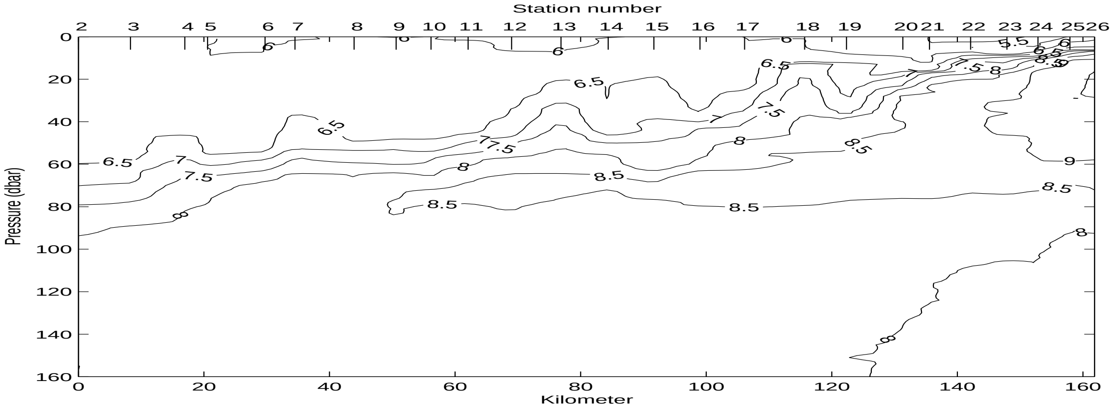


(b) Locations of CTD stations in February 2003

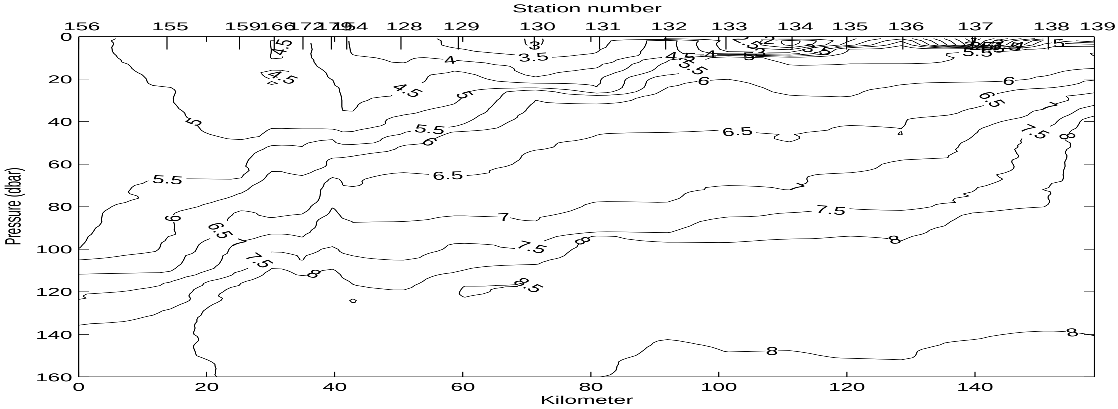


(c) Locations of CTD stations in February 2004

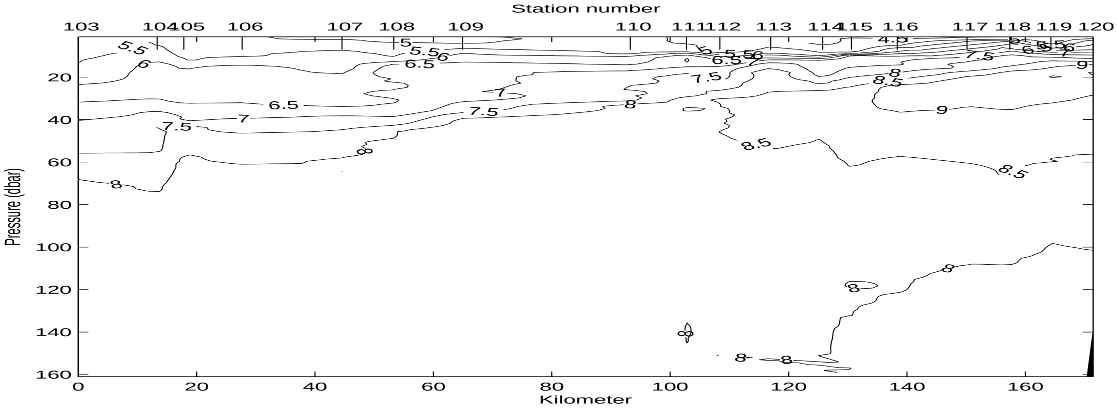
Figure 4.2: Maps of Sognefjorden and locations of CTD stations, 2002-2004



(a) Temperature (°C), 2002

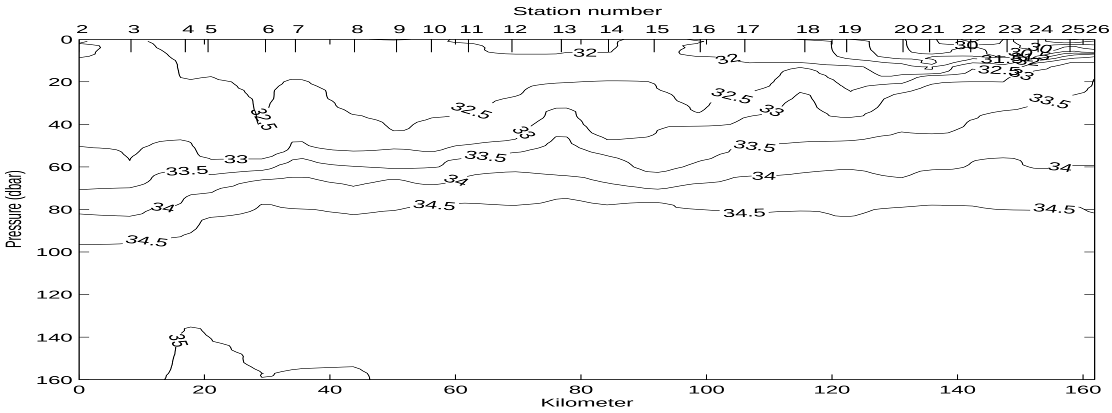


(b) Temperature (°C), 2003

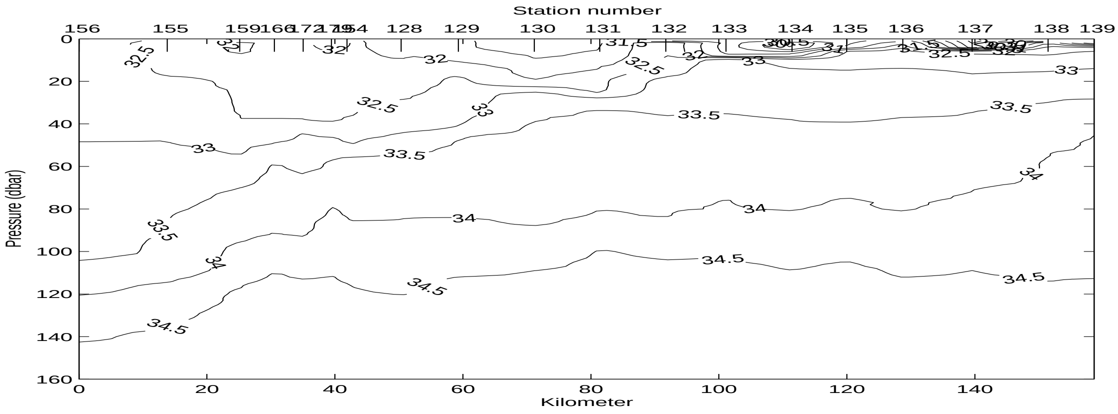


(c) Temperature (°C), 2004

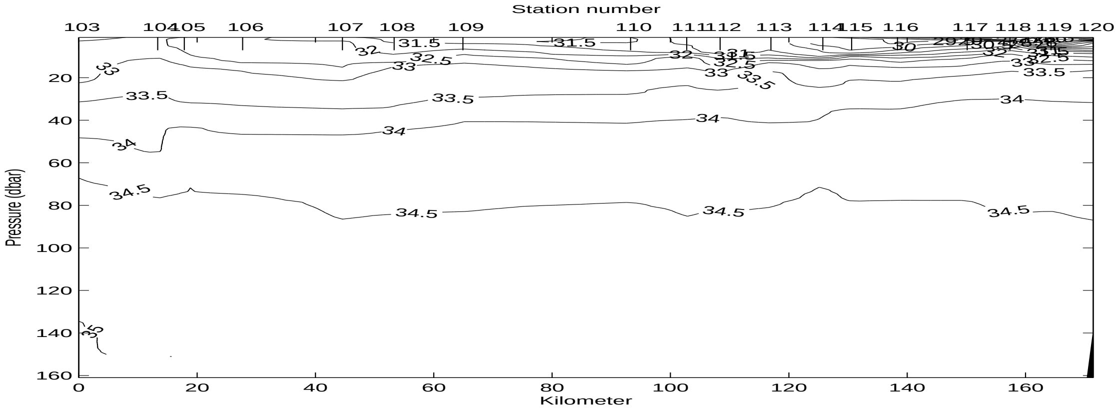
Figure 4.3: Temperature (°C) distributions in the upper 160 meters along Sognefjorden, 2002-2004.



(a) Salinity (psu), 2002



(b) Salinity (psu), 2003



(c) Salinity (psu), 2004

Figure 4.4: Salinity distributions in the upper 160 meters along the fjord, 2002-2004.

horizontal.

4.3 Individual profiles

Fig.4.5 and Fig.4.6 show some temperature and salinity profiled from individual CTD stations. There are stations from the outer, the middle and the inner part of the fjord, with one station from each year. The temperature profiles are organized such that Fig.4.5 a, b and c are from the outer part of the fjord from 2002-2004. Fig.4.5 d, e and f is from the middle of the fjord while Fig.4.5 g., .h and .i is from the inner part. The salinity profiles are in the same order.

In the outer part of the fjord in 2002 the upper 50 meters are homogeneous in both temperature and salinity. In 2003 and 2004 the upper 50 meters are stratified. In 2002 and 2004 there is a layer with fairly constant temperature, 8.2°C to 8.4°C, from 70 meters down to about 200 meters. In 2003 the layer with these temperatures are much thinner than in the two other years. The surface is coldest in 2003 and the upper 160 meters are less saline.

In the middle part of the fjord, the upper 50 meters has become more stratified in 2002. The warmest water is found at shallower depths than in the outer part of the fjord.

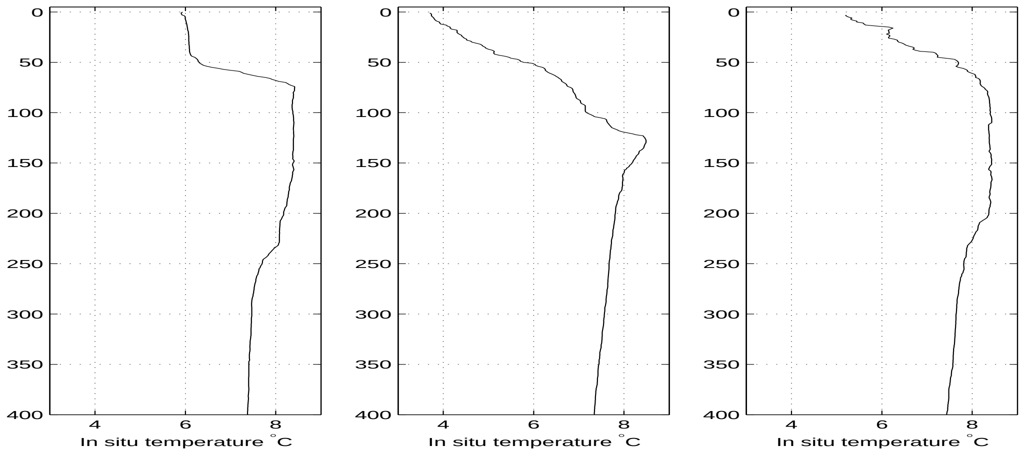
In the inner part of the fjord the warmest water is much closer to the surface for all three years, but 2003 is still coldest, and the warm layer is found at greater depths. In 2002 and 2003 the warm water is contained in almost homogeneous layers, but this is not the case in 2004, where there is a temperature maximum at 20 meters depth. There is more warm water in 2002 than in 2004. At 50 meters depth the salinity was 33.85 psu in 2002, 34.03 psu in 2003 and 34.2 psu in 2004.

4.4 ADCP sections

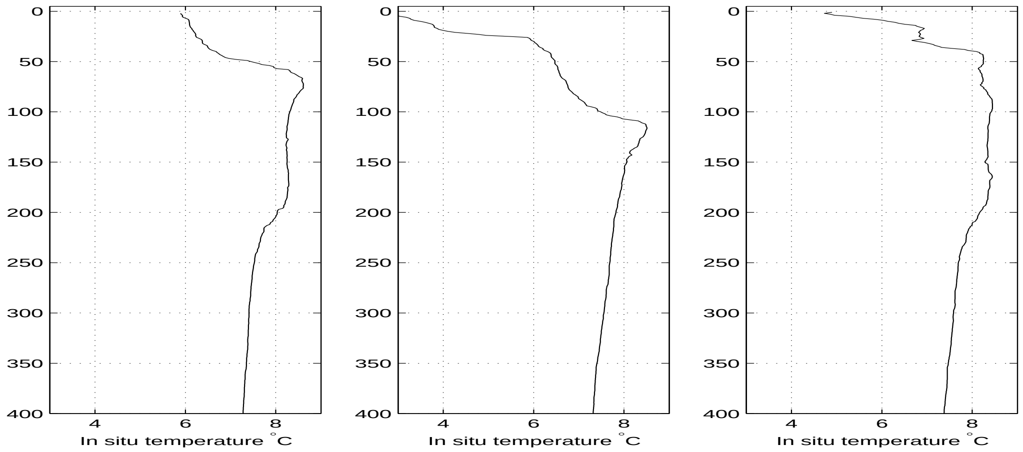
The position of the ADCP sections are shown in Fig.4.7. The ADCP sections from 2002-2004 is shown in Fig.4.8, Fig.4.9 and Fig.4.10, respectively. The sections are organized such that the outermost section is at the top and the innermost at the bottom.

The ADCP surveys shows distinct layers with flow in different directions, either upfjord or downfjord.

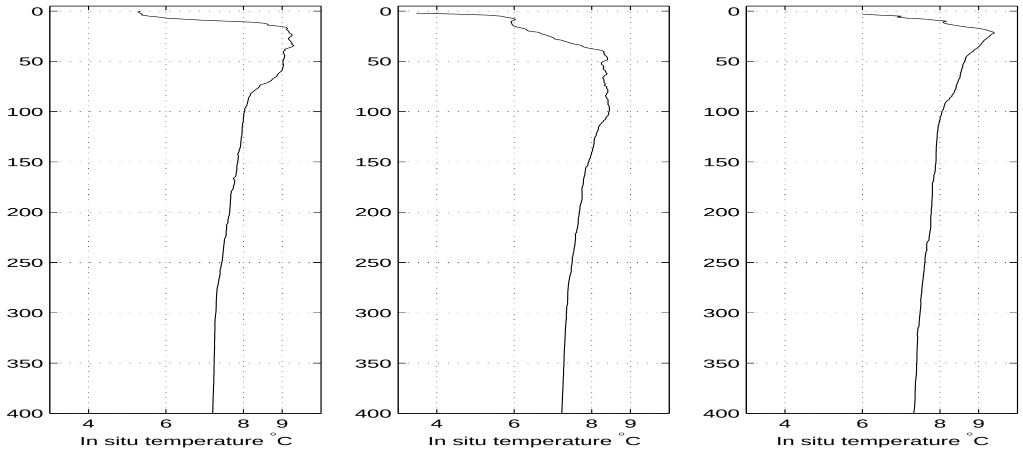
In 2002, Fig.4.8, there is upfjord flow in the uppermost layer. In the second layer from the top there is outflow. Comparing the depths of flow layers to the salinity profiles, the uppermost layer covers depths corresponding to the lower parts of the homogeneous layer and the halocline. The second layer is found at similar depths as the warm layer. The strength and depth of the flow decreases upfjord. The depth of the halocline decreases towards the head of



(a) St. 6, 4/2/2002 (b) St. 128, 6/2/2003 (c) St. 106, 22/2/2004

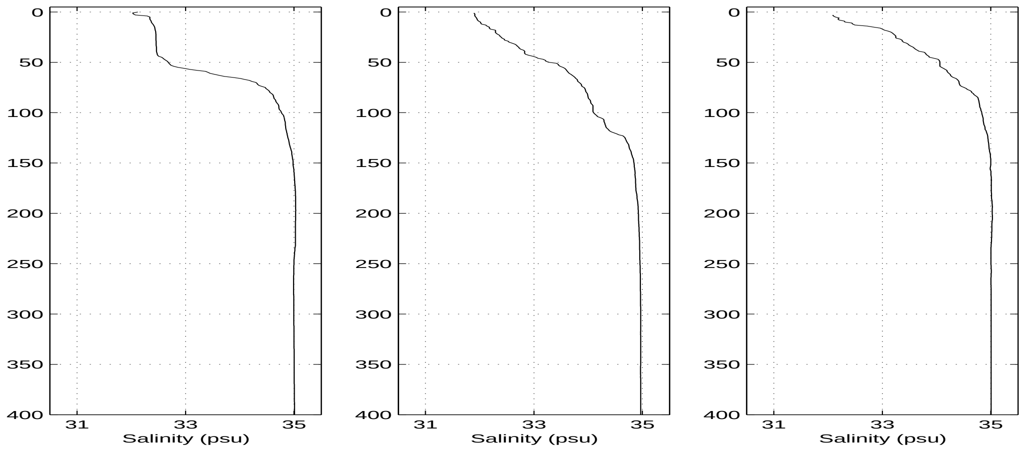


(d) St. 12, 4/2/2002 (e) St. 130, 6/2/2003 (f) St. 109, 22/2/2004

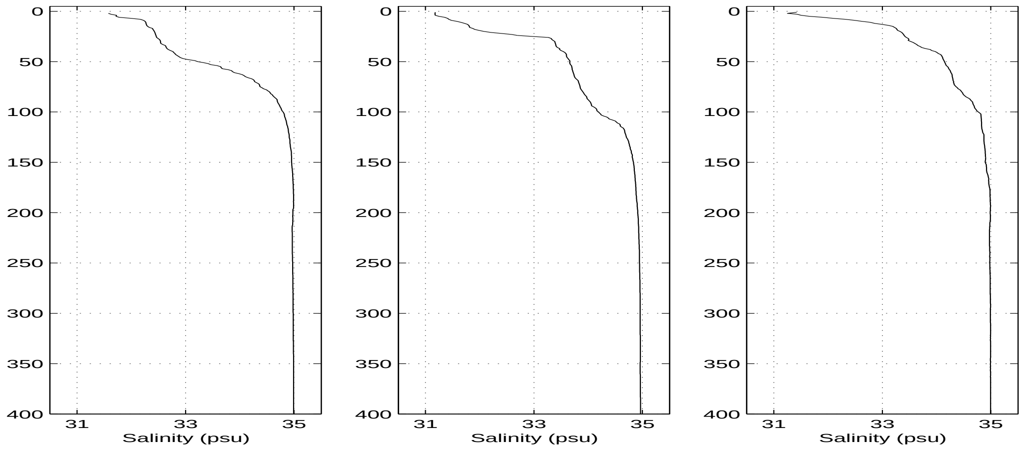


(g) St. 24, 5/2/2002 (h) St. 139, 6/2/2003 (i) St. 118, 23/2/2004

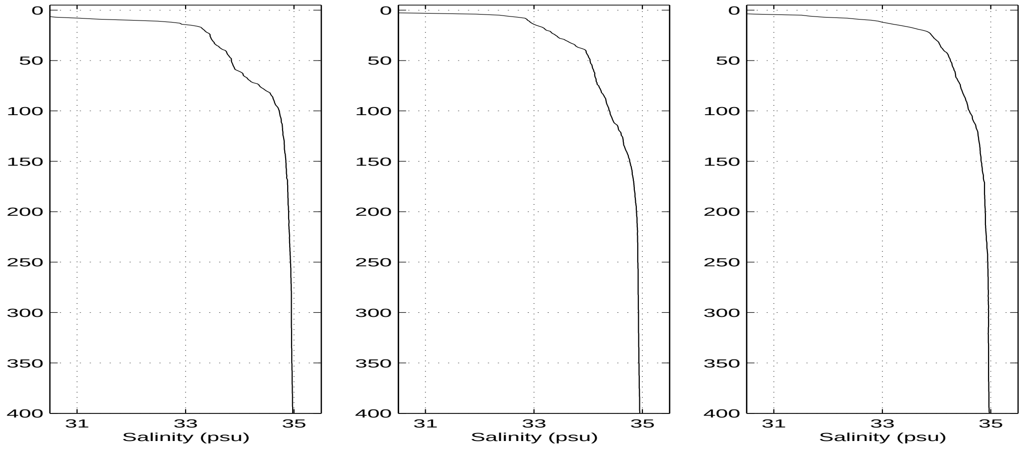
Figure 4.5: Temperature profiles from the outer part of Sognefjorden(a, b and c), the middle part(d, e and f) and the inner part(g, h and i)



(a) St. 6, 4/2/2002 (b) St. 128, 6/2/2003 (c) St. 106, 22/2/2004

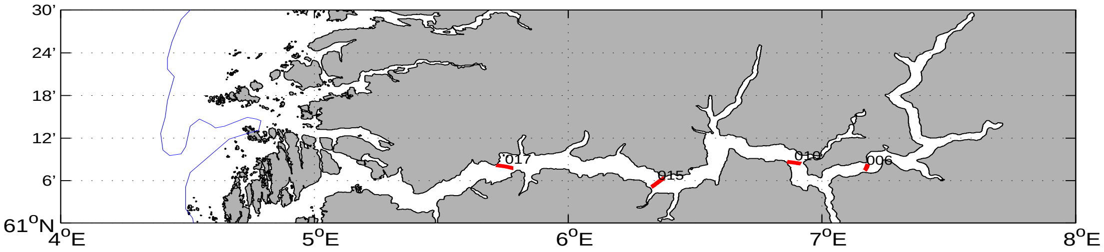


(d) St. 12, 4/2/2002 (e) St. 130, 6/2/2003 (f) St. 109, 22/2/2004

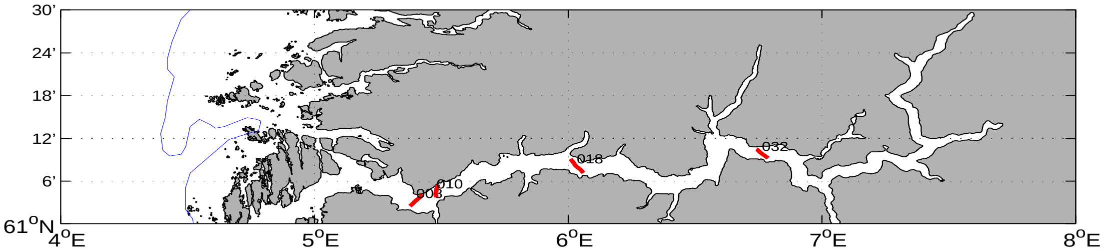


(g) St. 24, 5/2/2002 (h) St. 139, 6/2/2003 (i) St. 118, 23/2/2004

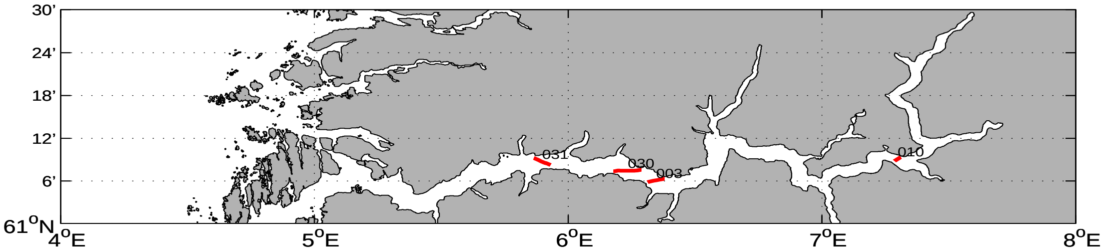
Figure 4.6: Salinity profiles from the outer part of Sognefjorden(a, b and c), the middle part(d, e and f) and the inner part(g, h and i)



(a) Location of the ADCP sections in 2002



(b) Location of the ADCP sections in 2003



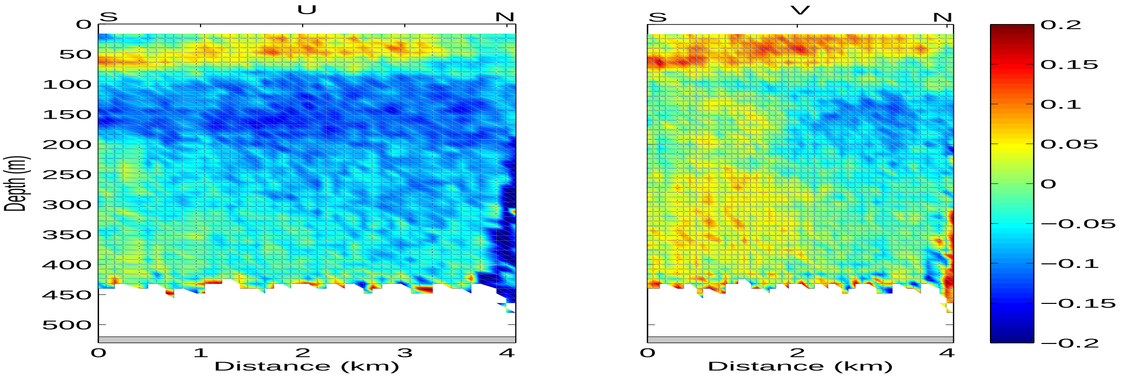
(c) Location of the ADCP sections in 2004

Figure 4.7: Location of ADCP sections, 2002-2004.

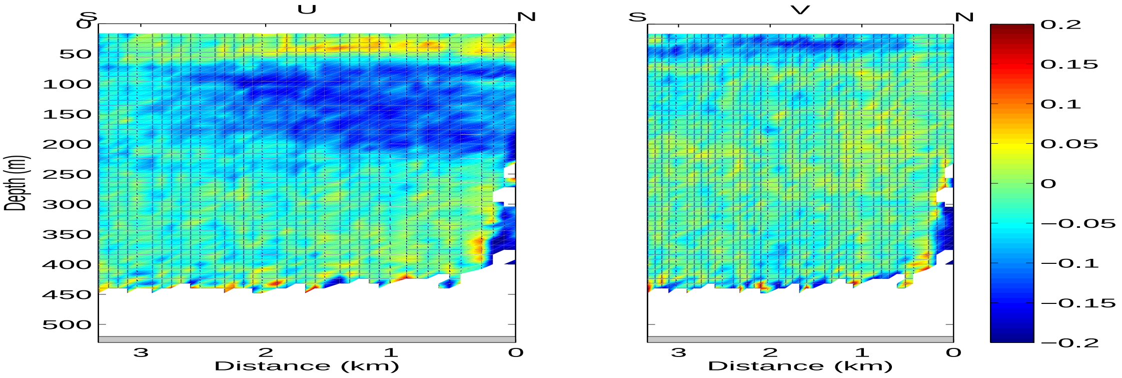
the fjord as well. The warm layer behaves similar, the depth and thickness decreases towards the head of the fjord.

In the two outermost section in 2003, Fig.4.9a and b, the uppermost layer shows downfjord flow. In the second layer from the top the flow is upfjord. The second layer is found at depths corresponding to the halocline, which in the outer part of the fjord is strongest at around 50 meters depth. In the third layer the flow is weaker than the flow at corresponding depth in 2002. There are large differences between the warm layer in 2002 and 2003. In the two innermost sections there is no clear structure below the uppermost layer, but the inflow in the uppermost layer is strong. The strong inflow corresponds to the depths above the maximum temperature.

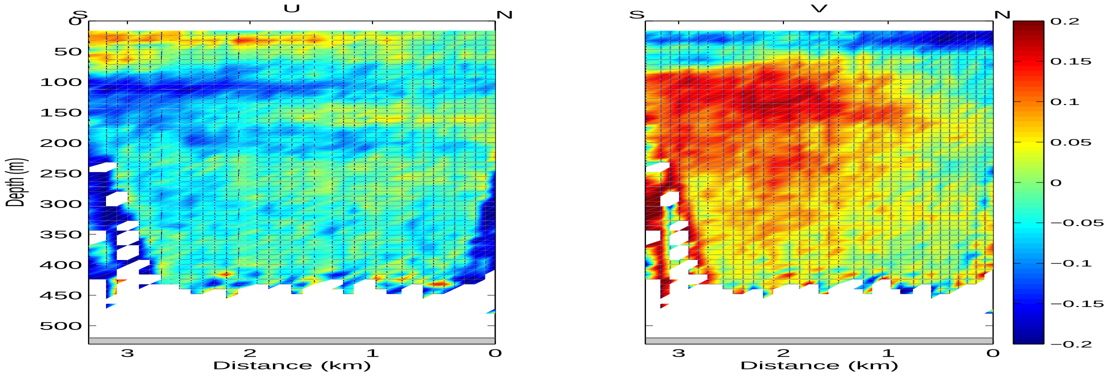
In the two outermost sections in 2004, Fig.4.10a and b, a three layer structure is seen. In the uppermost layer there is upfjord flow, in the second layer there is downfjord flow and in the third layer from the top there is upfjord



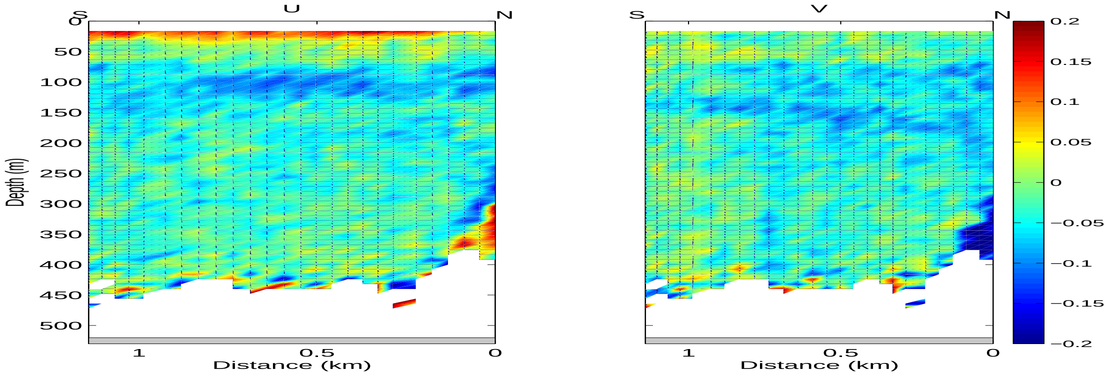
(a) U and V component(m/s), ADCP section 17, 2002



(b) U and V component(m/s), ADCP section 15, 2002

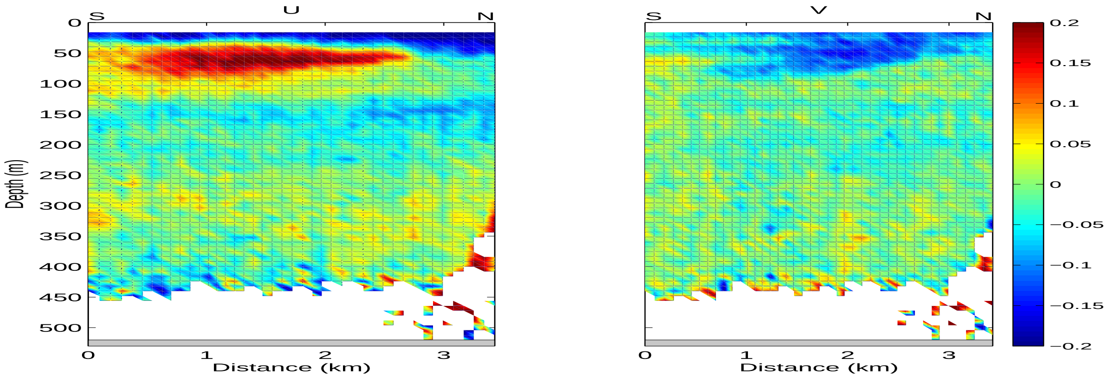


(c) U and V component(m/s), ADCP section 10, 2002

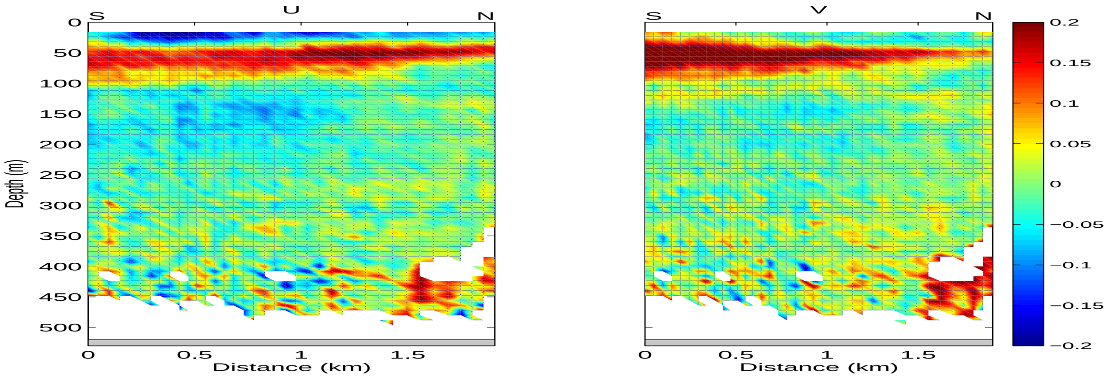


(d) U and V component(m/s), ADCP section 6, 2002

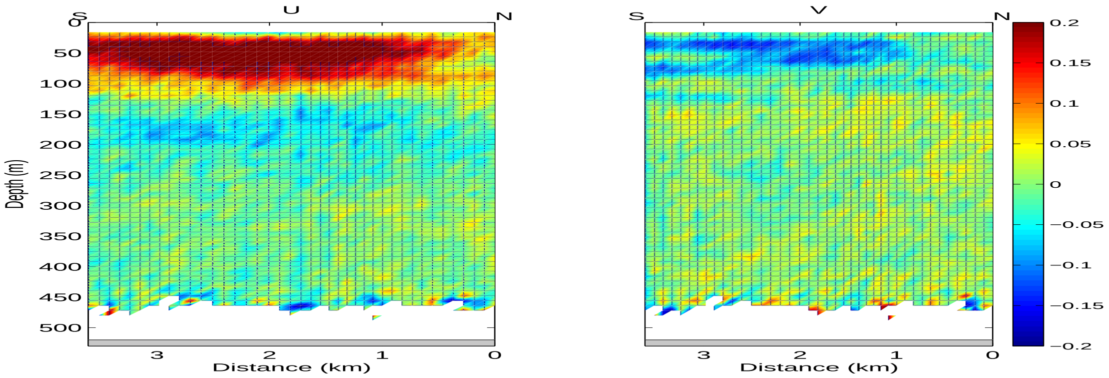
Figure 4.8: ADCP sections, 2002



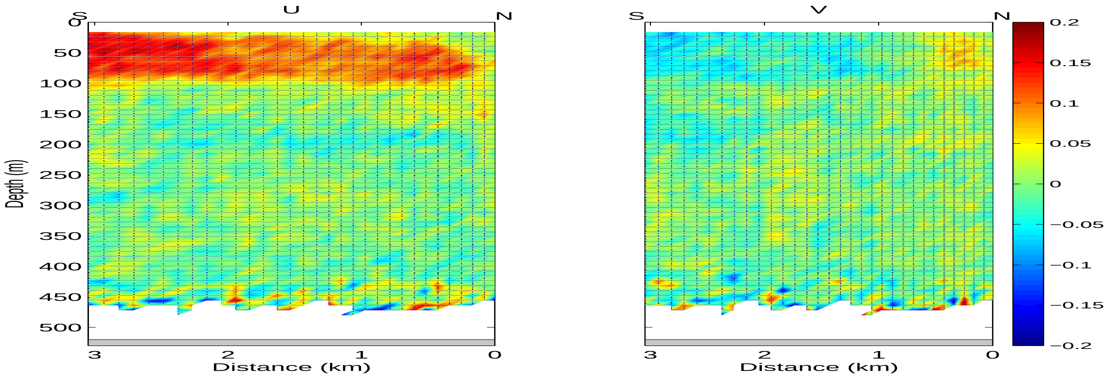
(a) U and V component(m/s), ADCP section 8, 2003



(b) U and V component(m/s), ADCP section 10, 2003

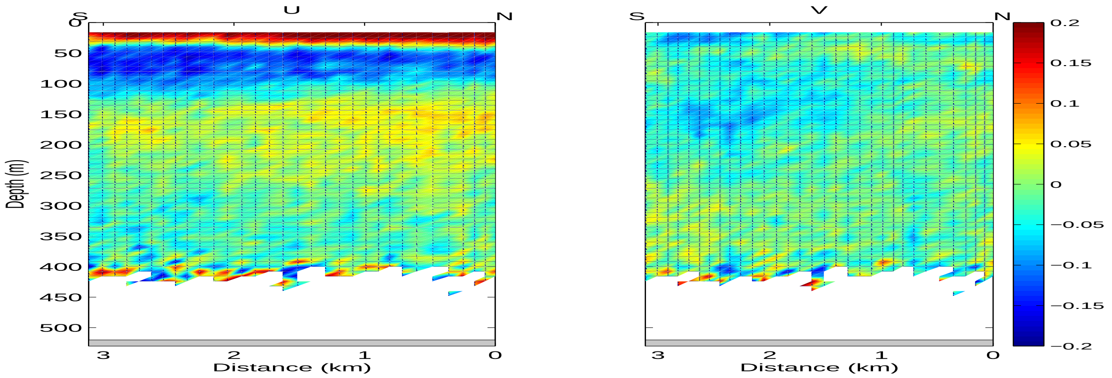


(c) U and V component(m/s), ADCP section 18, 2003

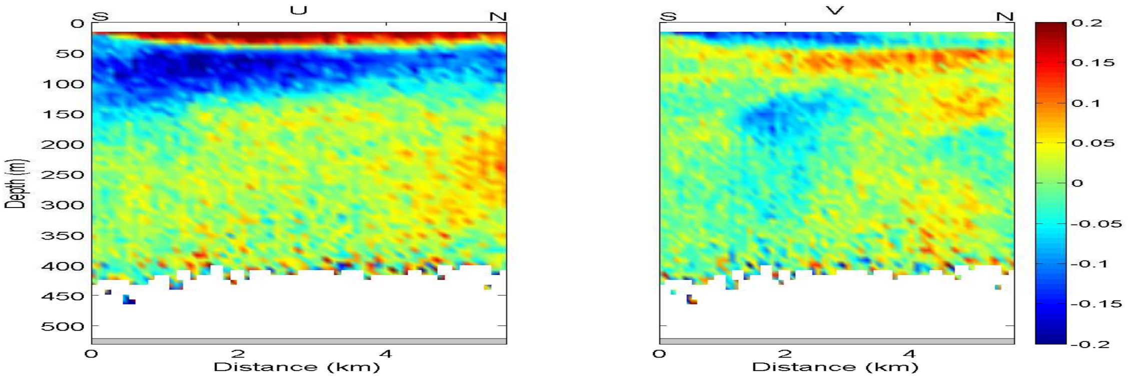


(d) U and V component(m/s), ADCP section 32, 2003

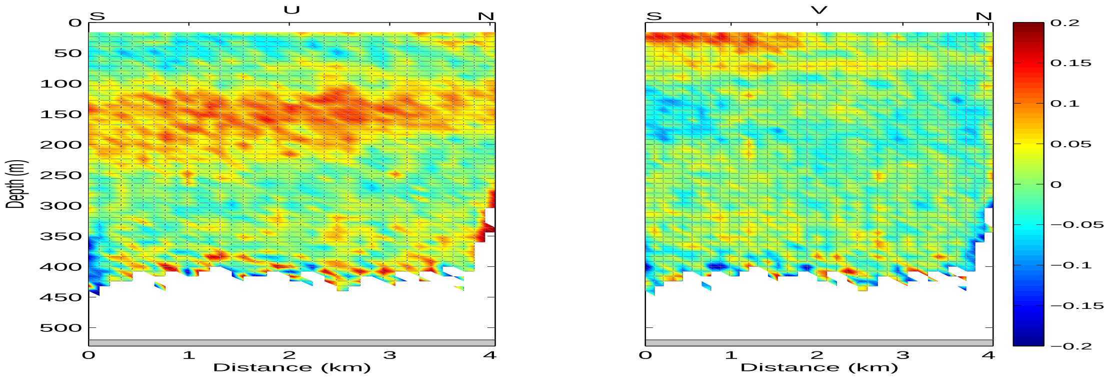
Figure 4.9: ADCP sections 2003



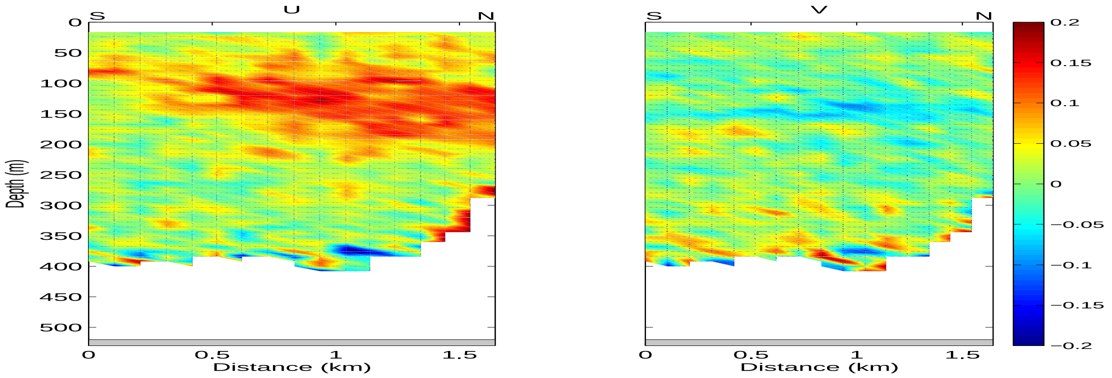
(a) U and V component(m/s), ADCP section 31, 2004



(b) U and V component(m/s), ADCP section 30, 2004



(c) U and V component(m/s), ADCP section 3, 2004



(d) U and V component(m/s), ADCP section 10, 2004

Figure 4.10: ADCP sections 2004

flow. The flow in the third layer is weaker than in the two uppermost layers. Section 3 and section 30 are located quite close to each other, but they show very different structures. The sections were obtained 2 days apart. In the innermost section there are no clear structures, but there is mainly upfjord flow in the depths resolved by the ADCP.

Chapter 5

Discussion

5.1 Stability

Fig.5.1 show profiles of Richardson number, flow, density and buoyancy frequency. The buoyancy frequency, N, is calculated from

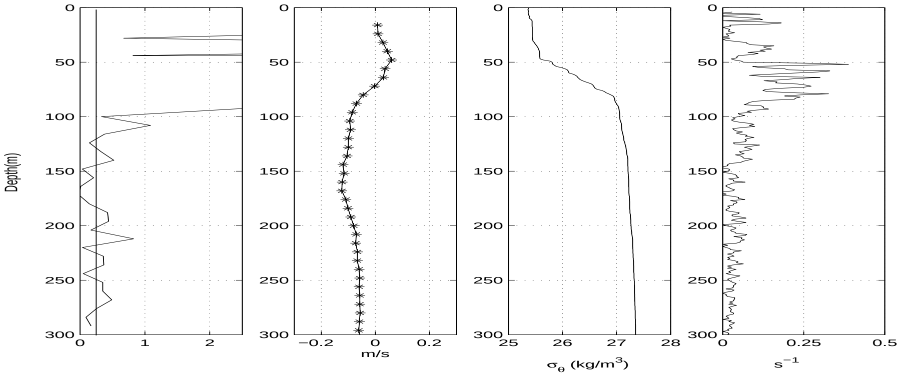
$$N^2 = \frac{-g}{\rho_{ref}} \frac{d\rho}{dz}$$

and is a measure of the static stability. The static stability depends upon the density distribution. At depths where strong density gradients are found, the stability is high. However, at depths where strong velocity shears are found, the stratification might not be strong enough to prevent turbulence. The dimensionless Richardson number,

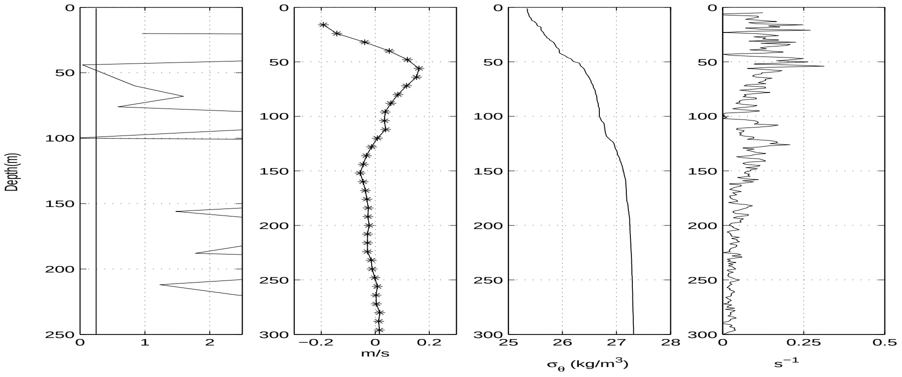
$$Ri = \frac{N^2}{(\frac{du}{dz})^2}$$

relates the strength of stratification and any velocity shear present. According to Benoit-Cushman(1994) $Ri > \frac{1}{4}$ is a sufficient condition for stable stratified flow, and that the converse is a necessary condition for unstable flow. In general $Ri < \frac{1}{4}$ is a reliable predictor of instability. However, there is evidence of the existence of decaying turbulence for $Ri > \frac{1}{4}$, and that $Ri > 1$ is a necessary and sufficient criterion for stability(Skogseth et al, 2005). Thus when $Ri < 1$ the velocity shear can be expected to generate turbulence.

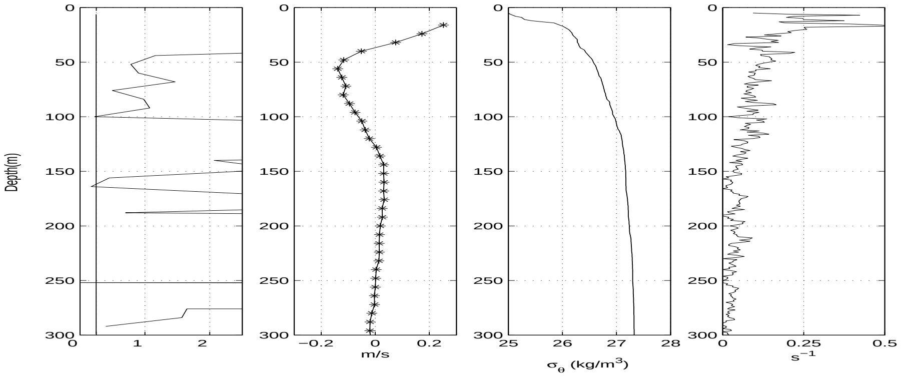
In the profiles of N, the strongest static stability is found in the upper 100 meters where the density gradients are strongest, as expected. Looking at the flow profile from 2002, the flow changes sign within the pycnocline. At these depths the Richardson number is high, thus the the strong stratification prevents turbulence. Below 100 meters the conditions favor turbulence, as the Richardson number is small. The velocity shears at these depths are small, but stratification is almost neutral.



(a) 2002



(b) 2003



(c) 2004

Figure 5.1: Richardson number(Ri), flow profile, density distribution and buoyancy frequency(N). The flow profiles are cross-fjord averages of the U-component from the ADCP measurements. The buoyancy frequencies are calculated from the density distribution. The Richardson number is calculated from the buoyancy frequencies and the flow profiles. The full vertical line in the Richardson number profiles is drawn at $Ri = 0.25$. All data from the outer part of the fjord.

In 2003 and 2004 there are some depths where the Richardson number is less than 1, but there are also depths where Ri takes on large values. The low Richardson numbers indicate presence of turbulence.

The flow profiles are obtained from a cross-fjord averages of the outermost ADCP sections from each year. The density profile is obtained from the CTD station closest to the ADCP section. It is thus assumed that the CTD profile and the flow profile represents the same water masses, which is not true, and the calculated values of N and Ri are not exact.

In the inner parts of the fjord, Fig.5.2 the strength of the flows decreases. Except for the upper 20 meters the static stability is low, but it is not possible to determine if turbulence is more likely to occur in the inner part of the fjord than in the outer part of the fjord.

The available data does not provide any information about the temporal development of the Richardson number.

5.2 Temperature and salinity variability

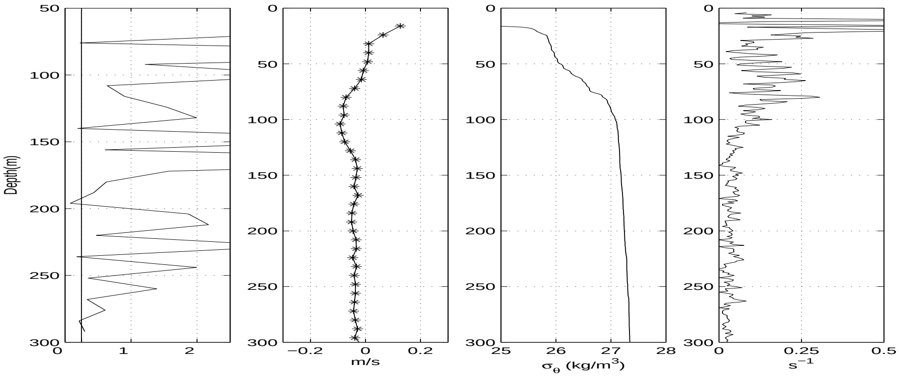
The variations in the stratification in the upper 50 meters, the brackish layer, are caused by variation in freshwater discharge, precipitation/evaporation, atmospheric heating/cooling and mixing by tides and wind. Below the brackish layer the variability in stratification is due variations in pressure field at the sill and in the fjord.

The are not many meteorological stations in Sognefjorden, and there is limited amount of data available on air temperature, local wind field and precipitation. Evaporation is not expected to have any strong impact on the stratification in the winter. Although the local wind field inside the fjord is unknown, the offshore wind field is known. Variations in the offshore wind field is compared to variations in the stratification in the fjord. Measurements from Ytterøyane Lighthouse is assumed to be representative for the offshore wind field.

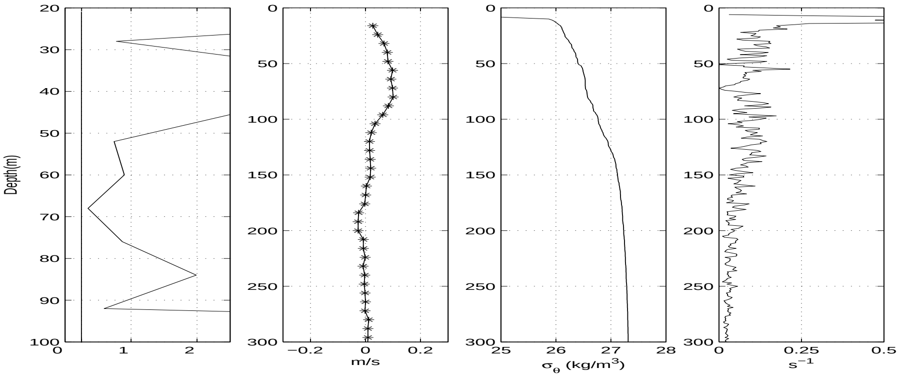
In Fjærlandsfjorden, which is one of the larger fjord arms of Sognefjorden, wind and temperature observations are available from the head of the fjord. The effect of wind and temperature on the stratification in Fjærlandsfjorden will be discussed in a separate section.

5.2.1 River runoff

To discuss the effect of river runoff, the flow of water in two rivers has been obtained. This is not sufficient to make quantitative calculations, but allows a comparison of the variations of flow of water in the rivers to the variations in the fjord stratification. The flow of water is obtained from two of the Norwegian Water Resources and Energy Directory(NVE) stations in Lærdalselvi

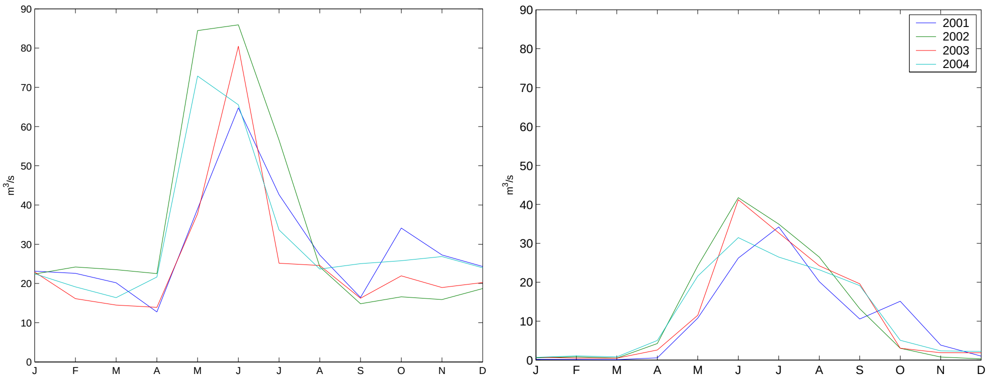


(a) 2002, inner part of the fjord



(b) 2004, inner part of the fjord

Figure 5.2: Richardson number(Ri), flow profile, density distribution and buoyancy frequency(N). The flow profiles are cross-fjord averages of the U-component from the ADCP measurements. The buoyancy frequencies are calculated from the density distribution. The Richardson number is calculated from the buoyancy frequencies and the flow profiles. The full vertical line in the Richardson number profiles is drawn at $Ri = 0.25$. All data from the inner part of the fjord.



(a) Stuvane, Lærdalselvi (regulated) (b) Gilja, Mørkrisdalselvi (not regulated)

Figure 5.3: Monthly average of the flow of water per second at Stuvane in Lærdalselvi and Gilja in Mørkrisdalselvi(m^3/s). Both Lærdalselvi and Mørkrisdalselvi are regulated, but Gilja is located in an unregulated part of Mørkrisdalselvi.

and Mørkrisdalselvi. Stuvane is located in a regulated part of Lærdalselvi, while Gilja is found in an unregulated part of Mørkrisdalselvi. The mouths of Lærdalselvi and Mørkrisdalselvi are found in Lærdal and Skjolden, respectively. See Fig.2.1. The monthly average of the flow of water per second is shown in Fig.5.3.

The lowest amount of runoff in October-December is found in 2002 in both rivers, although the differences between 2002 and 2003 are small. The highest amount of runoff was in the autumn of 2001. The runoff in the autumn possibly influences the following winter. Thus autumn 2001 is related to the variations in February 2002. Equivalent for the other two years.

In the unregulated river there is almost no runoff at all in January-March. In the regulated river the January the runoff is about the same for all three years, but in February the least amount of runoff is found in 2003. The difference between 2003 and 2004 are quite small small.

From Fig.4.3 and Fig.4.4, the most developed estuarine circulation is seen in 2003 and 2004. In 2004 the halocline is horizontal throughout most of the fjord, while in 2003 the halocline is horizontal in the inner half of the fjord. In 2002 the surface gradients are only maintained close tho the head. According to Gade (1971) the thickness of the brackish layer during the runoff season, May to October, is between 5 to 15 meters thick. In February the brackish layer would be expected to be thinner. The brackish layer is often assumed to be homogeneous (Stigebrandt,1980), which is caused by the strong halocline between the brackish water and the intermediate water. Strong stratification prevents vertical turbulence, and most of the energy from wind stress is used for acceleration and homogenization of the brackish layer.

If the upper 50 meters of the fjord were dominated by the river discharge, stratification should be stronger in 2002 than in 2003 and 2004, since the river discharge is greatest this year. But the situation is opposite, the stratification seems to be better maintained in 2003 and 2004. The difference is seen by studying inclination of the 32.5 psu isohaline in Fig.4.4. In 2004 it is horizontal through most of the fjord, in 2003 it is horizontal in the inner half of the fjord, while in 2002 it is only horizontal very close to the head. If the 32.5 psu isohaline is horizontal, the estuarine circulation is intact, but if it is inclined like in 2002, the stability has not prevented mixing between the brackish layer and the intermediate water. This indicates that either the stability for some reason was weaker in 2002, or that there has been stronger winds in 2002 than in the previous years.

In Lærdalselven and Møkrisdalselvi the largest flow of water was found in 2002, but it is possible that the the two rivers are not representative for the river discharge to the fjord, or that there has been precipitation altering the stratification. Møkrisdalselvi provides very little fresh water to the fjord in January and February, and this is most likely the same for all unregulated rivers entering Sognefjorden or any fjord arms. The discharge from the regulated river, Lærdalselvi, might not be representative for other regulated rivers, as the production at various power stations may vary. If the rivers are not representative for the total fresh water input to the fjord in the winter months, this could reason for the weaker surface stratification in 2002.

Some of the properties of the warm layers might be due to the strength of the stability in the brackish layer. The main feature of the warm layer is that it is located closer to the surface near the head of the fjord, and the temperatures are higher in the inner parts of the fjord. The strongest stabilities are found in the inner part of the fjord. Thus the isolation from the surface forcing by the brackish layer has maintained the temperature in the warm layer, and due to small amounts of mixing the warm layer resides close to the surface. Downfjord the salinity in the brackish layer increases and the stability decreases. This allows more vertical mixing, which can explain why the temperature in the warm layer is lower in the outer part of the fjord. The increased mixing would also contribute to the increased thickness of the warm layer towards the mouth. The depth of the warm layer was also commented by Hermansen(1974), who concluded that the stability of the surface layer allowed the warm water to reside close to the surface at the head of the fjord.

However this argument does not explain why the warm layer is colder and located deeper in 2003 than in 2002, even though the surface stability seems to be stronger in 2003 than in 2002. The inner most station in 2003, station 139, is located in the mouth of Årdalsfjorden, while in 2002 and 2004 the innermost station is located inside the fjord. The stations from 2002 and 2004 which corresponds to station 139 is station 24 and station 118, respectively. From Fig.4.3 it is seen that the warm layer is colder and found at greater depth in 2003 compared to 2002 and 2004 in this area.

It is possible that there has been some short time variations in the surface layer which could have had some influenced the stratification. Some short time variations from 2004 will be discussed later. It is also possible that the there are other mechanisms than the strength of the stability which causes the variations in the warm layer.

5.2.2 Sea ice

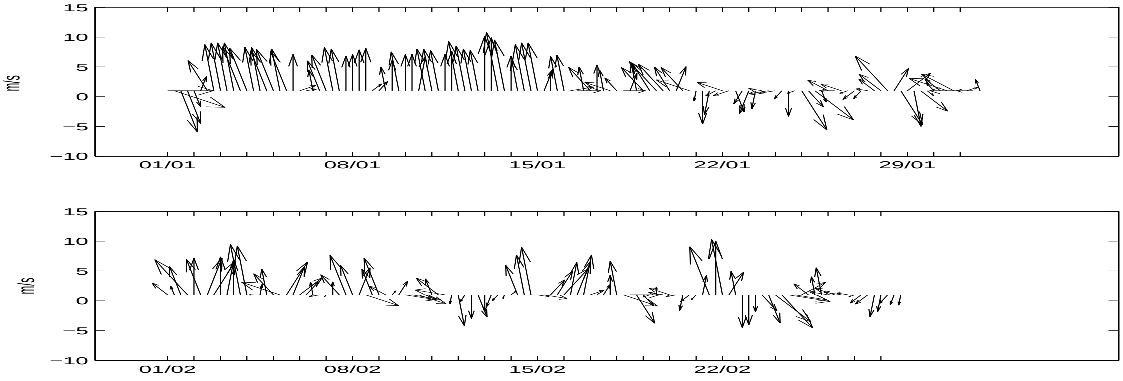
Sea ice might be an important factor for the variability in distributions in Sognefjorden. When parts of the fjord is covered with ice, the stratification is protected from both atmospheric cooling and wind stress. In 2003 and 2004 there was ice in the inner parts of the fjord(authors personal log). The extent of the ice cover is not known, neither is the ice conditions in 2002. If there were significant amounts of ice in 2003 and 2004, but not in 2002, this could explain why the surface gradients are maintained in 2003 and 2004 with less river runoff than in 2002. In 2002 the CTD survey covered all of the fjord arms in Sognefjorden, while in 2003 and 2004 this was not possible due ice in some part of the fjord. This indicates that there was less ice 2002.

The presence of an ice cover allows an alternative explanation for the reason of why the warm water is located close to the surface near the head of the fjord. Svendsen and Utne (1979) observed a large horizontal temperature gradient in a fjord. An ice cover was moved downfjord by downfjord winds, raising warm and saline water almost to the surface. However, without rotational effects to balance the inclined isohalines caused by such an upwelling, the isohalines would return to an equilibrium state after the wind ceased. Since the isohalines are inclined in all three datasets, it seems like the warm layer is in equilibrium state. So unless strong and steady downfjord winds are very common, the inclination is not caused by upwelling.

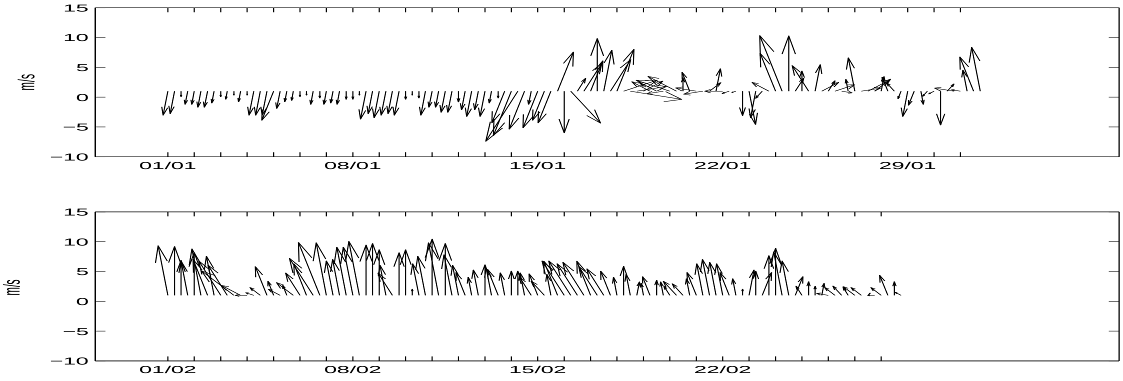
5.2.3 Offshore windfield

There are some pronounced differences from year to year in the the offshore wind field. The wind field is shown in Fig.5.4. In January 2002 and 2004, there are long periods where the wind is towards north, while in January 2003, there is a long period with wind towards south. In February 2002 and 2004 the wind direction is variable, while in February 2003 the wind is towards north the whole month. The stratification in 2002 and 2004 is similar and the offshore wind field is similar, while in 2003 both wind field and stratification differs from the other years.

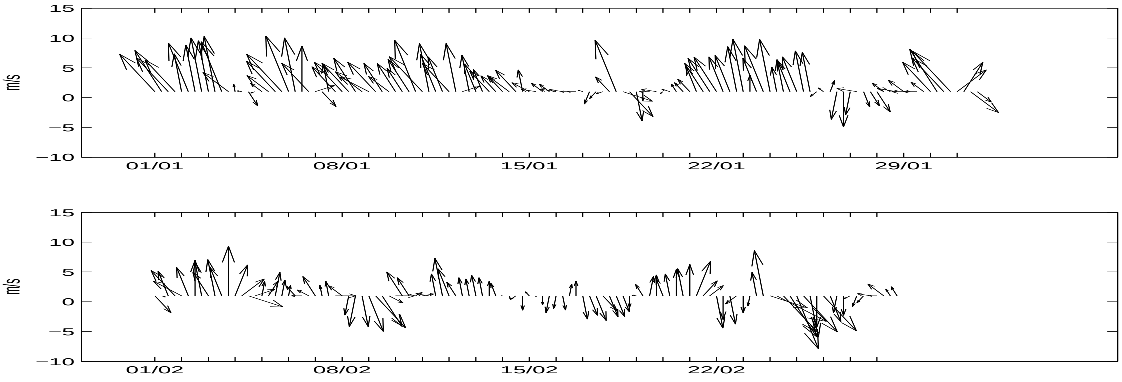
The long period of wind towards south in January 2003 would create an upwelling event at the coast, transporting surface water out from the coast.



(a) 2002



(b) 2003



(c) 2004

Figure 5.4: Wind observations at Ytterøyane Lighthouse from January and February, 2002-2004. Data is provided by the Climate division at the Norwegian Met Office(eklima.met.no)

This has possibly drained the almost all brackish water out of Sognefjorden, leaving only a very thin insulating brackish layer in 2003, allowing cooling and mixing. In February, when the wind direction is more variable, a new brackish layer may have developed in the inner half of the fjord.

5.2.4 Variability in Sognesjøen

Most of the the water entering and leaving Sognefjorden must pass through Sognefjorden. The water in Sognesjøen is made up of water from Sognefjorden and water transported northwards by the Norwegian Coastal Current(NCC). The variability in Sognesjøen will thus be influenced by the variability in the NCC and by which type of water that leaves Sognefjorden.

The Institute of Marine Research(IMR) has a coastal monitoring CTD station in Sognesjøen. Around three times per month CTD measurements are performed at a fixed location and at fixed depths. The data from these measurements are shown in Fig.5.5. Notice that the measurements are not evenly spread through the year, and due to the bad temporal resolution the figures might not be representative. In 2003 most of the salinity data has not been calibrated. Yet, the figures will be discussed as if they were representative for the temporal variation in Sognesjøen.

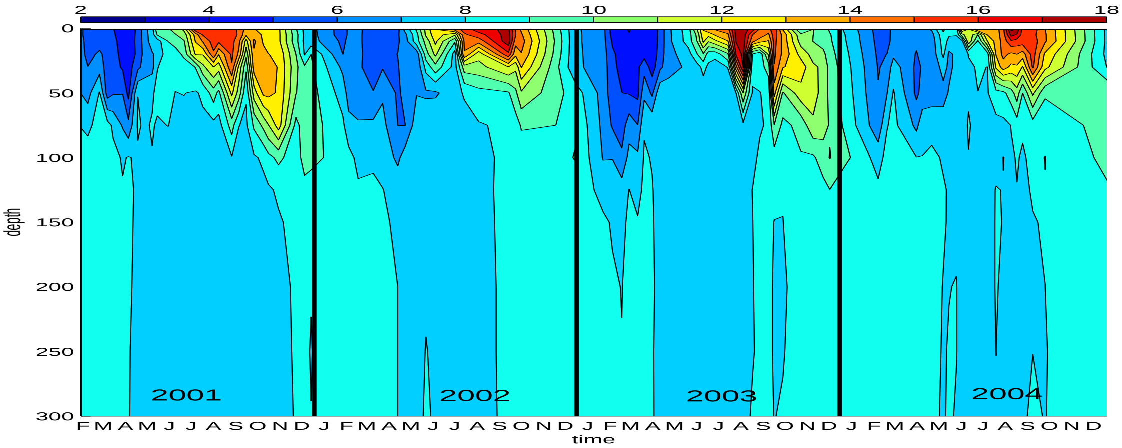
The summer of 2002 was less saline in the upper 50 meters than the summers of 2001 and 2003. In the autumn of 2002 there is less warm water, and there was less warm water available for inflow to Sognfjorden, which is coldest in 2003. In February 2003 cold water extends deeper down than in the other years. It is unclear if this is because the fjord had less warm water in 2003, or if this cold water contributed to cold conditions in Sognefjorden this year.

5.3 Circulation

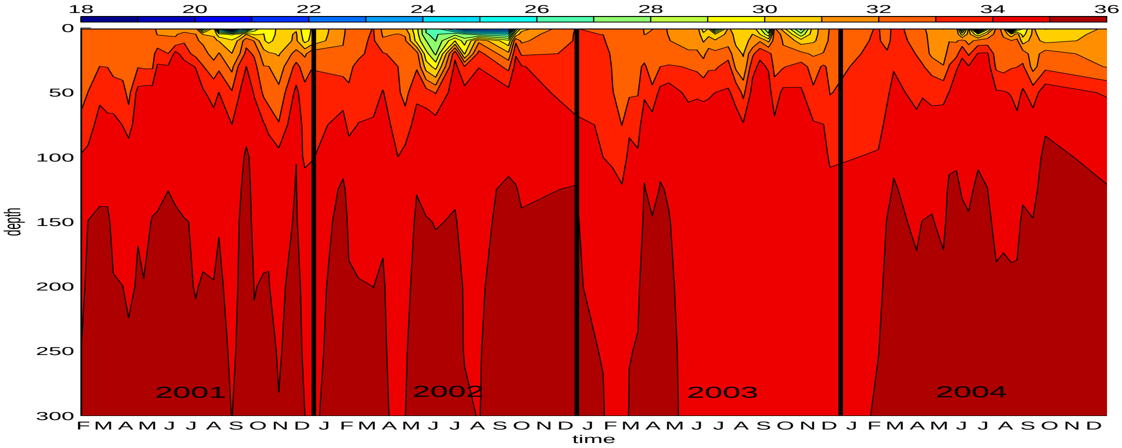
The ADCP surveys will be used for the discussion of the variability in the fjord circulation. The year to year variability of the measured flow is compared to the variability in the stratification.

5.3.1 Flow structure related to stratification

The ADCP surveys shows distinct layers with flow in different directions, either upfjord or downfjord. The different layers can be related to the stratification and the assumed structure of fjords with the brakish and the intermediate layers. A crude comparison of the flow versus the stratification is shown in Fig.5.6. Due to the limitations of the ADCP, the upper part of the brakish layer is not resolved in most sections.

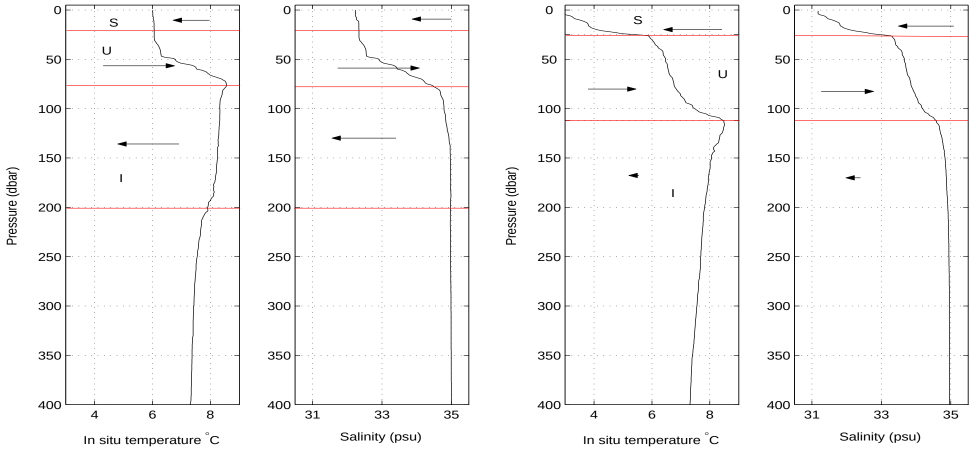


(a) Temperature (°C)



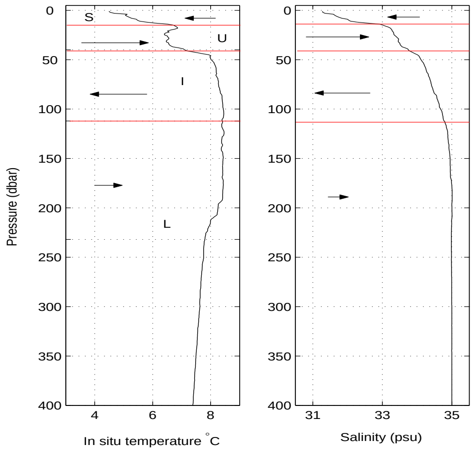
(b) Salinity (psu)

Figure 5.5: Temperature(a) and salinity(b) at the Institute of Marine Research's CTD station in Sognesjøen. Measurements from 2001 to 2004. A colorbar is shown on top of each figure



(a) Profiles and flow layers, 2002

(b) Profiles and flow layers, 2003



(c) Profiles and flow layers, 2004

Figure 5.6: Temperature and salinity profiles from stations in the vicinity of the outermost of the ADCP sections for each year. The red lines are the depths where the flow changes direction, and the arrows show the direction of flow in each layer. Arrows pointing left right means downfjord flow. The arrows are not representing the true proportion of the speed of the flow in each layer. The letter refers to the name of the layer; S - surface layer, U - upper layer, I - intermediate layer, L - lower layer. The surface layers are not visible in the ADCP sections in 2002 and 2004, but the surface layers are assumed to be there with downfjord flow.

In the three outermost sections in 2002, Fig.4.8a, b and c, the uppermost layer corresponds to the lower part of the homogeneous layer and the halocline. From the knowledge of the estuarine circulation, there should be downfjord flow in surface. Thus the brakish layer should be considered as two layers, in this paper referred to as the surface layer and the upper layer. The surface layer is where the freshest water is transported downfjord, and in the upper layer the compensation flow is found. In 2002 the surface layer is not resolved, while the upper layer extends down to where the temperature maximum is found.

In the outermost sections in 2003, Fig.4.9a and b, the uppermost flow layer is believed to be the surface layer. Compared to the profile, this downfjord flow is found where the strongest gradients are found. The upfjord flow in the upper layer is found at depths where gradients are weaker. This inflow extends much deeper than in 2002, but the maximum temperature is found at greater depths in 2003 than in 2002.

In the outermost sections from 2004, Fig.4.10a and b, there is an inflow layer at about the same depths as the surface layer outflow in 2003. Thus it is possible that the entire flow structure has been reversed. However, the inflow layer extends almost down to the temperature maximum, like the the upper layer inflow from 2002 and 2003 do. And as seen in Fig.5.6c the inflow is found where the there is a thin layer of constant temperature, with a strong temperature gradient above. This strong gradient corresponds to the strong gradients where the surface layer outflow was found in 2003. This suggest that there is a thin, unresolved surface layer with outflow in 2004, and that the flow structure is the same as in the previous years.

Assuming that the inflow found in the upper layer is entirely due to the compensation current of the estuarine circulation, the strength of the flow in the surface layer can be calculated, since the transport through the two layers is about the same, but in opposite directions. It is assumed that the motion in the surface layer only is due to the barotropic pressure gradient. Using section 17 from 2002, Fig.4.8a, as a reference, the thickness of the compensation flow,H_c is about 50 meters. The average speed of the compensation flow,U_c across the section is taken to be 0.15 m/s. Further it is assumed that the thickness of the surface layer outflow,H_s is 10 meters, and that the width of the fjord is the same at all depths. This gives the surface layer speed as

$$U_s = \frac{H_c U_c}{H_s} = 0.75 m/s$$

Flow speed of 0.75 m/s seems too be to fast for the surface layer outflow, since the maximum speed in the part of the surface layer which is resolved is 0.35 m/s. Thus upper layer inflow can not just be the compensation flow of the estuarine circulation in 2002.

In 2002 there is downfjord flow below the halocline, in the intermediate layer, and the flow in the upper layer is probably a compensation of this downfjord flow. The situation in 2004 is different, since within the warm layer there is both inflow and outflow. The flow structure below the halocline is then separated into the intermediate layer and the lower layer. Then the upper layer inflow only compensates for the assumed surface layer outflow, since the intermediate layer and the lower layer compensates each other. This would explain why the upper layer is found at shallow depths in 2004 compared to 2002.

In 2003 the surface layer is thicker than the other years, and more water must replaced by the compensation flow. Still it seems like there is more water moving upfjord than downfjord in 2003, because the flow below the halocline is so small.

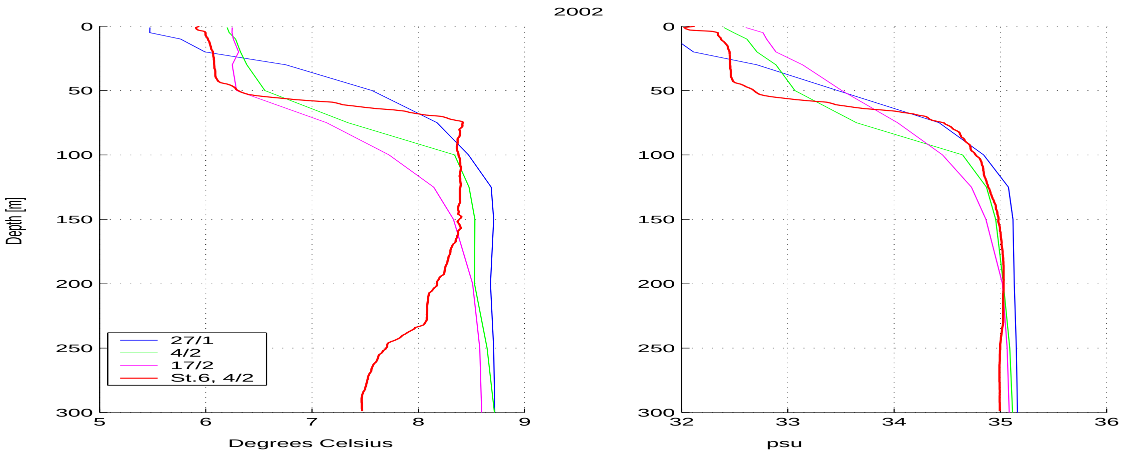
As these ADCP measurements have not been averaged over more than 1 minute, it is not possible determine how much of flow is due tidal effects, which is a possible explanation of the changes between section 30 and section 3 in 2004, Fig.4.10b and c. For all three years the structures weakens and disappears in the inner part of the fjord. The general feature in the stratification is that the the depth of the halocline decreases towards the head of the fjord. Thus one explanation for the changing flow structure is changes in the pressure field. The compensation flow of the estuarine circulation is expected to be weaker towards the head of the fjord, since less water has been entrained into the brakish layer.

5.3.2 Vertical distributions in Sognesjøen

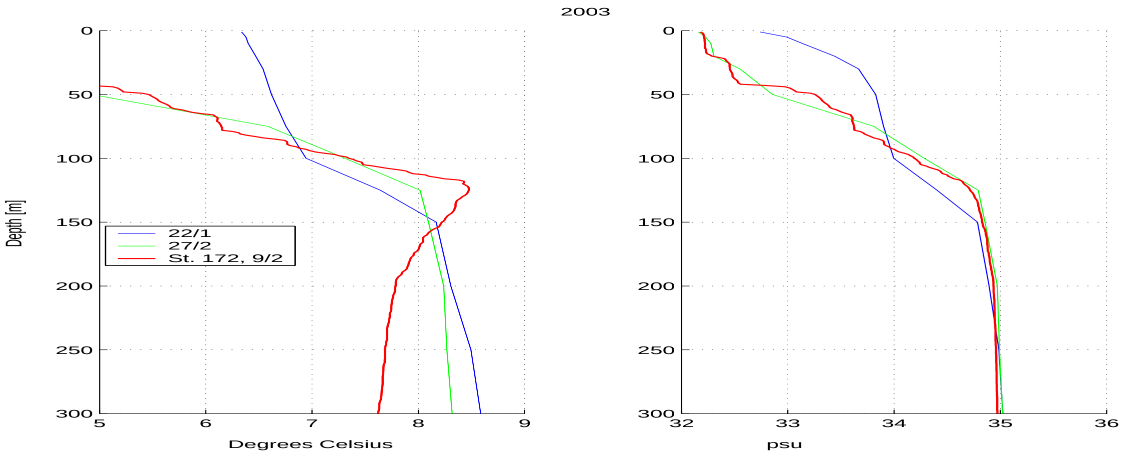
Differences inside and outside the sill Fig.5.7 shows the temperature and salinity profiles from Sognesjøen in January and February 2002-2004. Profiles from CTD stations inside the fjord, close to the sill, has been added for comparison.

In 2002 there are measurements on both sides of the sill February 4^{th}. Above 60 meters depth Sognesjøen is most saline, while from 60 to 150 meters depth Sognefjorden is most saline. These differences in salinity coincides with the flow structure in 2002, Fig.4.8a. The upper layer inflow is found at depths where Sognesjøen is most saline, while the outflow is found where the fjord is most saline.

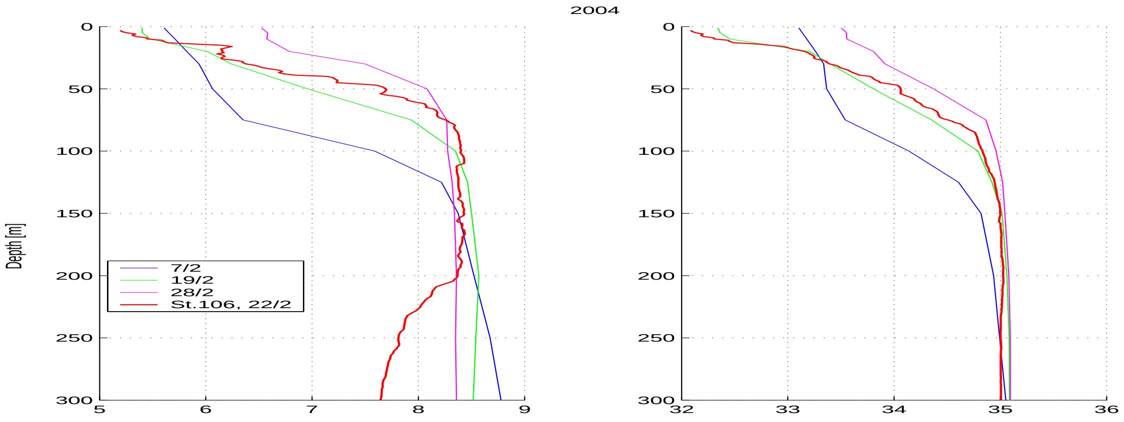
In 2003 the measurements inside and outside the sill differs in time, and the comparison is less direct. January 22^{nd} Sognesjøen is more saline than in the upper 100 meters than the fjord is at February 9^{th}. From 100 meters to 150 meters the fjord is most saline. The salinity difference between the coastal water and the fjord water could be used to explain the inflow in 2003, Fig.4.9b, but at the depths where the fjords are most saline there is no clear outflow. This could mean that the the pressure surfaces at this depth are horizontal.



(a) 2002, temperature and salinity profiles



(b) 2003, temperature and salinity profiles



(c) 2004, temperature and salinity profiles

Figure 5.7: Temperature and salinity profiles from IMR's station in Sognesjøen and from the fjord(red curves), January-February 2002-2004

In 2004 are measurements in Sognesjøen February 19th while the measurements in the fjord are from February 22nd. The differences above 100 meters depth are subtle, but at the depths where the fjord is most saline, the outflow is found. In the upper 15 meters Sognesjøen is most saline, and the upper layer inflow is upfjord. Looking at the temperature profile, Sognesjøen is colder than the fjord above 100 meters depth, but warmer below. In 2004 there is a four layer circulation, possibly is the lower layer inflow related to this temperature difference.

These interpretations are based on the assumption that the pressure field is determined by salinity gradients between Sognesjøen and Sognefjorden, without regard to any surface elevations. Thus it is not certain that it is possible to determine the flow structure from salinity differences, but they seem to be related. Since the measurements are not done at the same time, except in 2002, the gradients might appear larger than they really were at the time.

Differences below sill depth In 2002 and 2003 Sognefjorden is colder than Sognesjøen below 150 meters depth. In 2004 Sognefjorden is coldest below 200 meters depth. This is a typical feature for fjords with deep sills like Sognefjorden(Gade, 1980). The water below sill depth can only be renewed when water with greater density is available outside the sill. From Fig.5.5 it is seen that the coldest water in Sognesjøen appears in the late spring and early summer. The salinity does not inhibit the same seasonal pattern. As seen from Fig.5.7 the salinity below sill depth is almost the same inside and outside the sill. The temperature difference then determines which water mass is the densest. Thus the warm water outside the sill in January and February is not dense enough to replace any basin water in 2002 and 2003. But in 2004 where the the temperature is the same inside and outside the sill down to 200 meters depth, there must have been some replacement of basin water. The reason for this replacement is unclear. There must be some short events where coastal water flows into the fjord, replacing some of the upper basin water. An explanation for the inclination of the 35.0 psu isohaline in Fig.4.1b could then be that the partial replacement events are only able to influence the outer parts of the fjord, and there has not been time for adjusting the salinity gradient along the the fjord.

5.4 Cross fjord variations

The CTD surveys have mainly been focused on resolving the variations along the fjord, while the ADCP surveys have been used for resolving cross fjord variations. Direct comparison of CTD and ADCP is therefor not very accurate, but it still leaves indications of the properties of the water moving upfjord and downfjord.

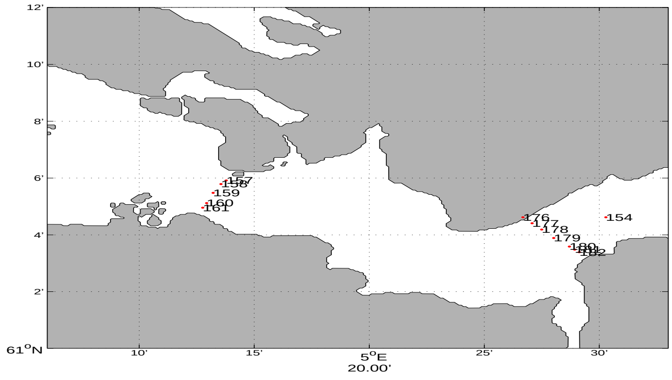


Figure 5.8: Location of the CTD stations in cross fjord CTD section 1 and 2. Station 154 is included as a reference point.

From 2003 there are some sections of CTD stations across the fjord. These sections allows a comparison of cross fjord variation in stratification and circulation. The CTD sections are located in the outer part of the fjord, 20 to 25 km inside the sill, see Fig.5.8. Section 1 is the outermost section, shown in Fig.5.9a and b, section 2 is in Fig.5.9a and b. The sections are shown with the north side of the fjord to the right in the figures. The sections will be compared to ADCP sections 8 and 10, Fig.4.9a and Fig.4.9b. Locations of the ADCP sections are shown in Fig.4.7b. The ADCP sections are located closer together than the CTD sections, and the direct comparison might not be completely justified.

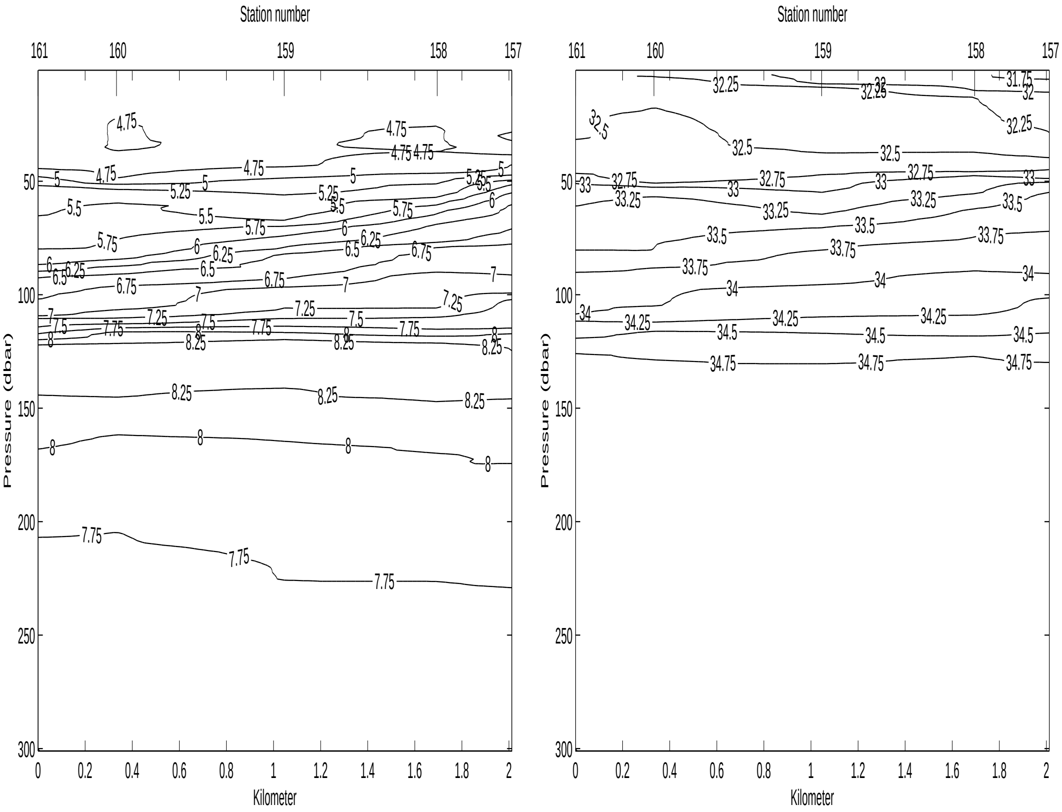
In general the ADCP surveys reveals asymmetrical flow across the fjord. It has been reported that due to the Coriolis force, flow in fjords will tend to follow the coast to the right of the flow(Svendsen,1981). Most of flow seen in the ADCP sections is indeed focused to the right hand side of the flow direction.

The internal radius of deformation, R_d, is a measure of the importance of the rotational effects. R_i depends upon stratification and depths of the different layers, and there are many possible choices of values. R_i is given by

$$R_d = \frac{\sqrt{g'H'}}{f}$$

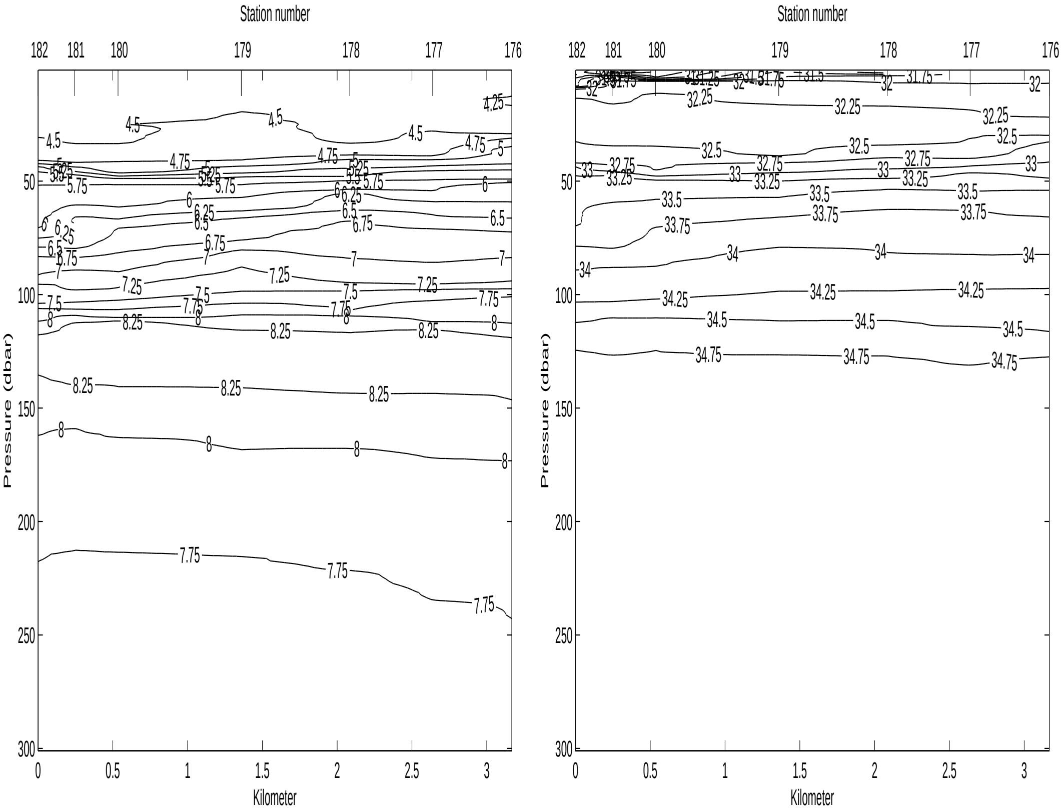
where $g^{'} = \frac{\rho_2 - \rho_1}{\rho_{ref}}$ and $H^{'} = \frac{H_1 * H_2}{H_1 + H_2}$.

$\rho_1(H_1)$ and $\rho_2(H_2)$ is the density(thickness) of the upper and lower layer, respectively. For a range of different density and thickness values, the baroclinic radius of deformation is found to be $R_i = 5km \pm 2km$. The width of Sognefjorden varies from 5 km in the outer part to around 2 km in the inner parts(Hermansen, 1974). Thus the Coriolis force must be included in equation of motion in Sognefjorden. This also means that geostrophic flow may exist inside the fjord, as long as the fjord is wide enough and the stratification is favorable. Flow set up by pressure gradients between the coastal water and the



(a) Section 1, Temperature(°C)

(b) Section 1, Salinity(psu)



(c) Section 2, Temperature(°C)

(d) Section 2, Salinity(psu)

Figure 5.9: CTD cross fjord sections, 2003. North is on the right hand side

fjord may exist far into the fjord, if the flow is in geostrophic balance. Thus the different stratifications from year to year might be a reason for different flow regimes, in addition to the differences in the pressure fields. It is also be an explanation for why the flow structures changes towards the head of the fjord, where the fjord width is less than R_i.

In both CTD sections there is a surface layer of constant temperature. This layer of constant temperature is thicker in section 1, which could be due to the topography. The salinity is not constant in the upper 50 meters. In section 1 the lowest salinities is found on the northern side of the fjord. The salinity on the northern side at section 2 is about the same as at section 1, but the salinities are lower on the southern side. This low salinity probably origins from the small fjord arm southwest of section 2. Brackish water formed in this fjord arm will not have much time to get mixed with fjord water, and therefor is quite fresh. At the mouth of the small fjord arm the brackish water turns towards east due to the Coriolis force.

The isolines located at around 120 meters depth are horizontal, but some of the shallower isolines are inclined. The inclination of the isolines are most pronounced at section 1.

A layer with downfjord flow is found in the shallowest depths resolved by the ADCP at section 8. The outflow reaches deepest at the northern side. This outflow is probably the cold and fresh water seen in CTD section 1, moving downfjord as part of the estuarine circulation. The upfjord flow is found at about the same depth as the 32.5 psu isohaline. Thus the inflow is found within the halocline, which means that the water moving upfjord has properties different from both the surface layer and the intermediate layer.

At ADCP section 10, the surface layer outflow is less resolved than at the previous section. The reason for this is unclear.

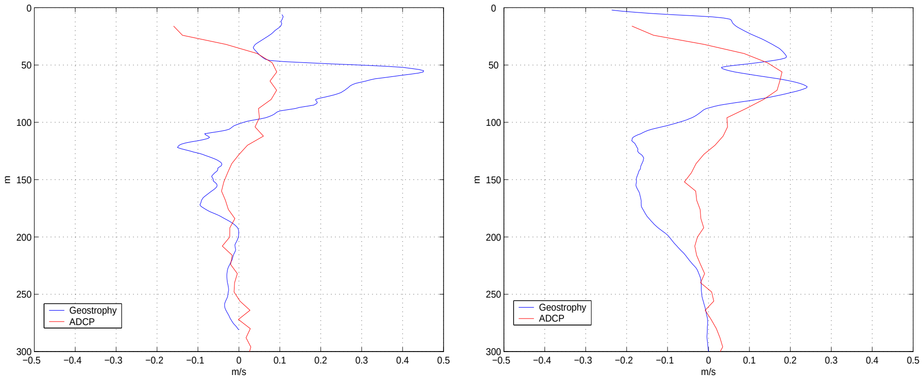
The asymmetrical flow and the inclined isolines must be due to rotational effects.

Geostrophic flow has been calculated from cross-fjord section 1, by using a method described by Pond and Pickard(1983). The flow has been calculated between each of the stations

$$V - V_0 = \frac{1}{Lf}(\Delta\Phi_b - \Delta\Phi_a)$$

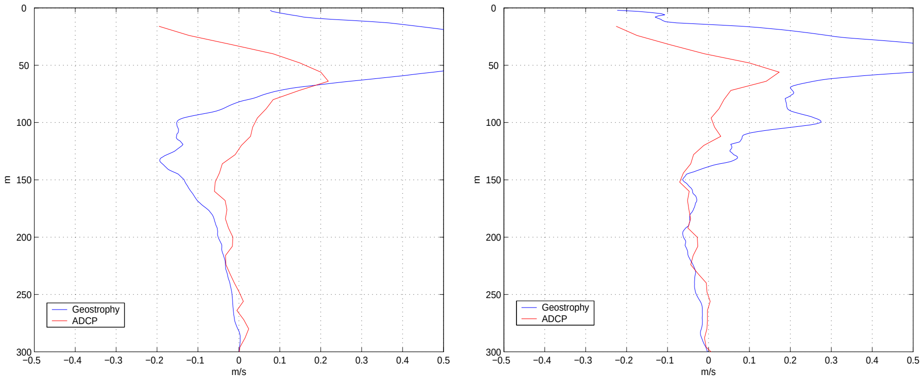
where L is the distance between the two stations and f is the coriolis constant. $\Delta\Phi_a$ and $\Delta\Phi_b$ is the geopotential anomalies at the two stations. V_0 is speed at 300 meters depth, which is the reference depth. It is assumed that 300 meters depth there is no motion and $V_0 = 0$. The geostrophic velocities are shown in Fig.5.10

In general the geostrophic flow is larger than the flow measured by the ADCP. The larges differences are found in the two northernmost profiles. Although the magnitude is to large, the geostrophic flow is divided in layers



(a) 161-160, the southernmost profiles

(b) 160-159



(c) 159-158

(d) 158-157, the northernmost profiles

Figure 5.10: Profiles of calculated geostrophic velocities between the CTD stations in the outermost cross-fjord section and flow profiles from the ADCP section 8. The flow profiles are averages from the ADCP section. The ADCP section was divided into four parts, and each flow profile is an average of one part. Positive values is upfjord flow, while negative values is downfjord flow. Blue line is geostrophic flow profile, red line is flow from ADCP.

with upfjord and downfjord motion. The layers are not exactly at the same depths as the layers measured by the ADCP. The differences between the calculated flow and the measured flow could be caused by the distance between the ADCP and the CTD section. It should also be noticed that both sections are snap shots of the conditions, and the influence of tides and wind is unknown. The assumption that there is no motion at 300 meters depth is not very accurate, in Fig.4.9a it is seen that there is some motion at this depth. Despite all the possible error sources, this is still an indication of the importance of rotational effects in fjords.

5.5 Sognesjøen

5.5.1 Short-time variability

The changes in the profiles in Sognesjøen, Fig.5.7, are compared to wind observations at Ytterøyane Lighthouse, shown in Fig.5.4.

The temperature and salinity distribution in Sognesjøen in January and February differs from year to year. In 2002 the upper 50 meters becomes more stratified, while in 2003 the upper 50 meters becomes fresher and colder. In 2004 the upper 50 meters becomes less homogeneous.

During the first 20 days of January 2002 the wind was towards north, but prior to the measurements January 27^{th} there was some wind towards south. In the beginning of February the wind is towards north. There are no long periods with constant wind direction prior to the measurements from February 17^{th}, but the two days before the wind was towards north. One possibility is then that the winds towards north prior to January 27^{th} drained brakish water from Sognesjøen and Sognefjorden, while wind towards north prior to the two next measurements caused stacking of the brakish water. It is possible that wind field is causing the difference below 50 meters as well, but from Fig.5.5 it is seen that water down to 100 meters depth typically becomes colder and less saline in February.

In 2003 the is wind towards south during the first half of January. The days prior to January 22^{nd} the wind is first towards west and towards east. In most of February there is quite strong winds towards north. It's unclear if the wind towards south is the reason for the saline and warm water in the surface in January. Possibly the constant southern winds have drained almost all brakish water out of the fjord in January, and the small amount of brakish water continuously leaving the fjord is mixed with coastal water in Sognesjøen.

In 2004 the depth of the thermocline and halocline are found to increase from February 7^{th} to 28^{th}. During this period the wind changes direction several times, and it is difficult to make any interpretation. The offshore wind field cannot on their own explain the changes in the temperature and salin-

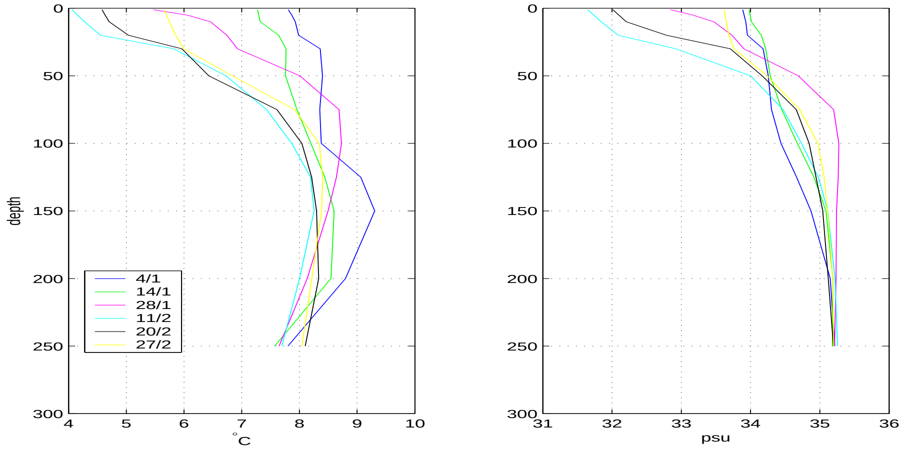


Figure 5.11: Vertical temperature and salinity distribution in January and February in 2004 at IMRs station at Utsira, located at N 59° 19′ E 4° 48′, approximately 180 km south of Sognesjøen.

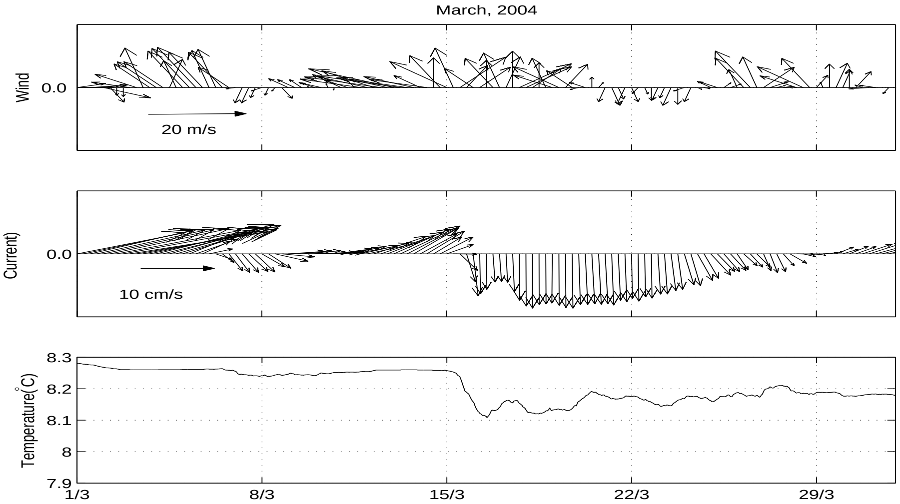
ity distribution in Sognesjøen. Fig.5.5.1 shows the vertical temperature and salinity distribution at Utsira in January and February 2004. Utsira is located on the south west coast of Norway, around 180 km south of Sognesjøen. At Utsira warmer and more saline water are found in the end of January. It is possible that this warm and saline water has been transported northwards by the Norwegian Coastal Current(NCC), and contributes to the increase in temperature and salinity in Sognefjorden. Assuming an average speed of 0.1 m/s of the NCC, it would take about 21 days for the warm water to be transported up to Sognesjøen.

Another possibility is that the downfjord transport of warm water in Fig.5.6 persists over some period long enough to increase both temperature and salinity in Sognesjøen.,

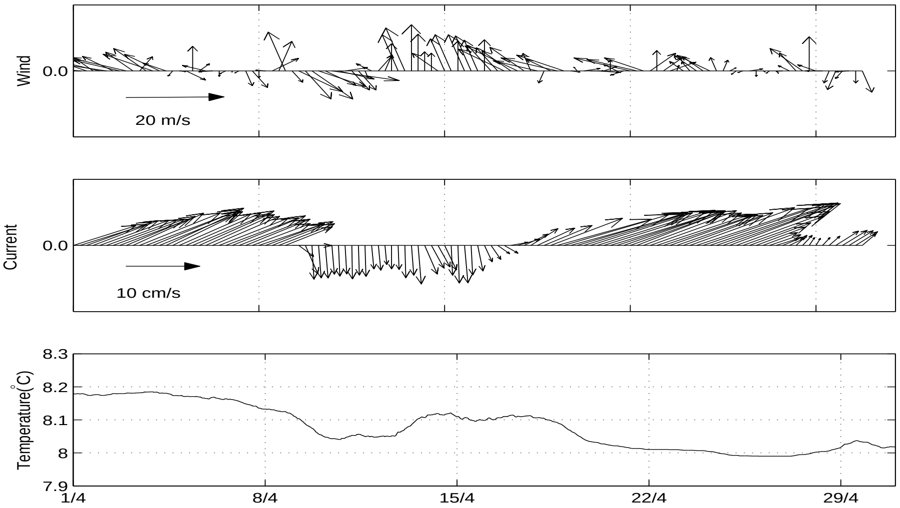
5.5.2 Sill flow

Fig.5.12a and Fig.5.12b shows recordings of velocity and temperature from a RCM and wind measured at Ytterøyane Lighthouse for March and April, respectively. The RCM was moored at the sill. The depth of the RCM was approximately 150 meters. The time series have been treated with a 24-hours running mean filter, to remove most of the contribution from the tides and any internal waves.

Due to the orientation of Sognesjøen, which is southwest-northeast, inflow should be towards northeast while outflow should be towards southwest. However, as the RCM records show, the dominant flow directions are towards northeast and towards south. The flow towards northeast is obviously inflow to the fjord, while the flow towards south must be outflow. The reason for the

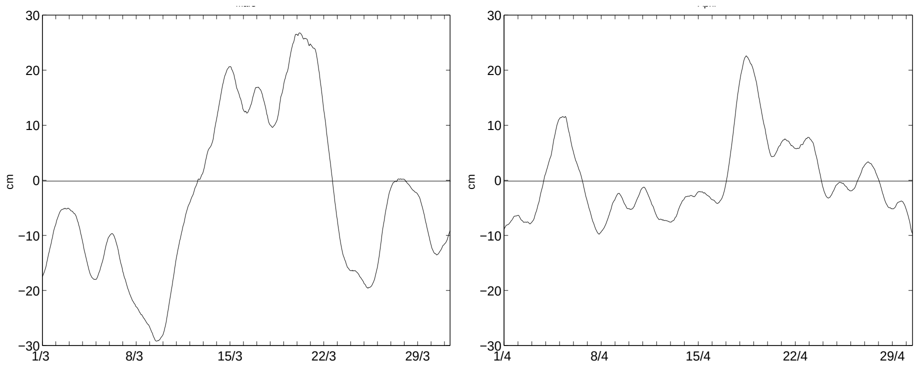


(a) Offshore wind field(m/s), sill bottom flow(cm/s) and sill bottom temperature(°C). March, 2004



(b) Offshore wind field(m/s), sill bottom flow(cm/s) and sill bottom temperature(°C). April, 2004

Figure 5.12: The offshore wind field is measured at Ytterøyane Lighthouse. The sill bottom flow and temperature are from an RCM deployed at the bottom of the sill



(a) March

(b) April

Figure 5.13: The difference between the observed water level and the predicted water level from the harmonic constants as measured at The Norwegian Hydrographic Service's tide gauge in Bergen. The data was obtained from statkart.no

outflow to be directed towards south rather than towards southwest is probably due to topographic effects.

During the first half of March the flow direction is mainly towards northeast, except for a short period were the flow is towards southeast and east. The flow turns towards southeast approximately at the same time as the winds towards north ceases. While the flow is towards southeast the temperature decreases slightly. Around March 9^{th} the wind is towards west-northwest, and the flow first changes towards east, then towards northeast. Around the 14^{th} the wind turns towards north and northeast, and at the same time there is strong outflow at the bottom of the sill. At the onset of this outflow event, the temperature drops by 0.15°C. The temperature increases a little when the strength of the outflow decreases.

In the beginning of April the wind is towards west-northwest, and there is strong inflow. During the next days the wind is variable, while the inflow is still strong. The inflow does not end until the wind is towards southwest for some days. During the following outflow event the wind changes towards north, which does not seem to change much in outflow. However, in the beginning of the outflow event the temperature drops, but when the wind changes towards north the temperature increases. At the onset of the last inflow event in April the temperature decreases.

When the wind changes towards northwest again, the outflow ends and and inflow event begins. The inflow persists long after the wind towards northwest has ceased.

There seems to be a stronger correlation between the flow direction and onshore/offshore component of the wind than between the flow direction and the along-shore component of the wind. But any correlation is not very clear.

It also seems like like inflow can persist long after any steady wind has ceased. One possibility is that if an upwelling occur, and the isohalines are raised, they may stay raised due to a geostrophic balance. As long as this geostrophic balance last, the pressure field outside the sill will be maintained.

The wind field causes variations in the both the barotropic and the baroclinic pressure field. Assuming that the flow at the sill is two-layered, the direction of flow in the upper layer is determined by the surface elevation, the barotropic pressure, while the lower layer flow is determined by the baroclinic pressure. This relationship between the offshore wind field and upwelling/downwelling has been documented by Sætre et all(1987). Fig.5.13 show the difference between observed sea surface level and predicted sea surface level, the sea level elevation, in Bergen. This difference is mainly due to athmospheric forcing. The measurements from Bergen are assumed to be representative for the sea level in Sognesjøen. By comparing the sea level difference, Fig.5.13, with the flow at the bottom of the sill, Fig.5.12, there seems to be no clear relationship between the surface elevation and the flow. In March the first inflow period ocurres when the sea level elevation is negative, while in April the most of the inflow occurs when the sea level elevation is positive. There does not seem to be any relation between the sea level elevation and the offshore wind field. The lack correlation between the wind and the sea level elevation could be due to the distance between where each property is measured.

Why the temperature first drops when the outflow begins, and then increases after some time during the outflow is unclear.

5.6 Short term variability

In January 2004 there was an additional survey in Sognefjorden in January, and some CTD measurements were made along the fjord. The CTD stations were taken at the same location as at the main cruise in February, Fig.5.14 and Fig.4.2c. This additional survey was conducted at 22^{nd} and 23^{rd} of January, about one month before the main cruise.

Fig.5.15 show the vertical salinity distributions at three locations in the outer half of the fjord in January . Only the upper 250 meters are shown.

The surface is coldest and least saline in February. From Fig.5.16 it is seen that there was increased flow of water at the unregulated station Gilja in the first week of February, while in at the regulated station Stuvane the flow of water seems to be less in February than in January. The increase at Gilja could indicate that there was an period of warm weather with rain increasing the amount of fresh water in the fjord. But the flow of water at Gilja is much less than at Stuvane, so probably it is the regulated rivers controlling the fresh

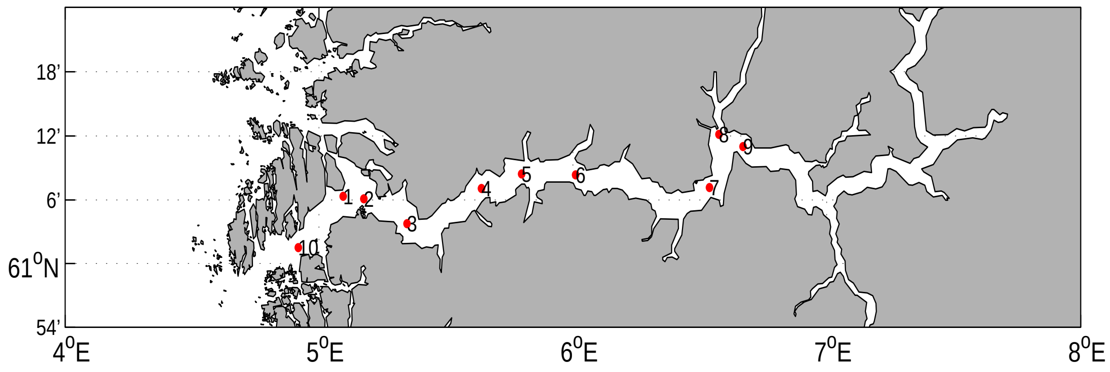


Figure 5.14: Locations of CTD stations from the auxiliary cruise, January 2004

water discharge to the fjord in February and January. It is not obvious if the variability in the flow of water has had any impact on the distribution or not.

At the two outermost stations, Fig.5.15a and Fig.5.15a, the upper 50 meters has become more stratified in both temperature and salinity. From the offshore wind field, Fig.5.4 it is seen that the were strong winds at the coast around January 22nd, while the wind conditions are calmer around February 22nd. Thus the differences in the upper 50 meters could be due differences in wind mixing. Since the differences at the innermost station is smaller, this part of the fjord might be less exposed to wind than the outer parts of the fjord.

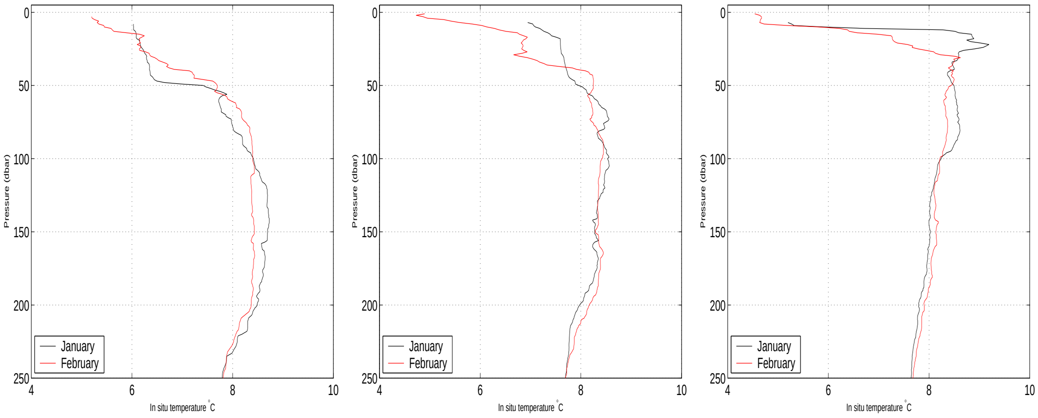
Below 50 meters depth the changes are small in the two innermost stations. At the outermost station the changes are greater. This could be caused by tidal mixing close to the sill. It can also be caused by changes in the pressure field at the sill, preventing steady flow structure from developing and thus coastal water masses would not reach very far into the fjord.

The small changes below 50 meters during one month suggests that the process causing the variability in the temperature and salinity distribution in the fjord could occur several months prior to the surveys. It also suggests that the flow structure discussed in Section 5.3 is not maintained for longer periods of time.

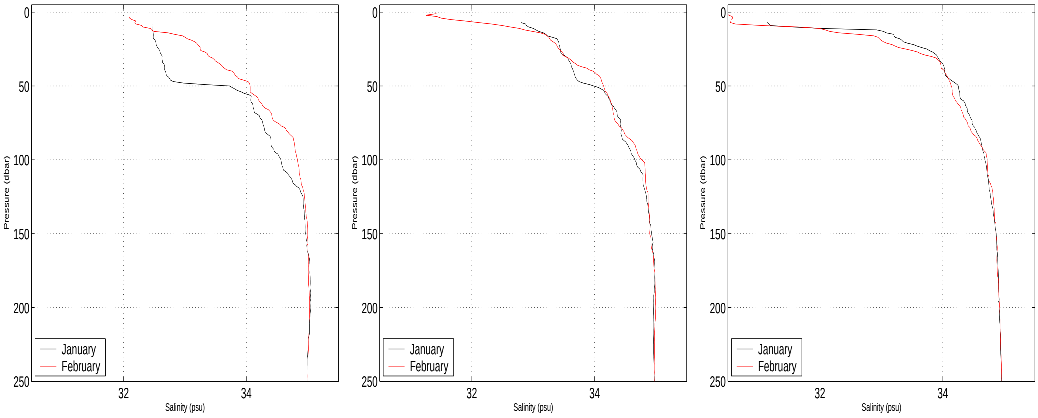
5.7 Fjærlandsfjorden

In 2002 and 2003 CTD surveys were conducted in Fjærlandsfjorden, one of the larger fjord arms in of Sognefjorden, see Fig.5.17 and Fig.2.1 for location. The temperature and salinity distributions are shown Fig.5.18 and Fig.5.19, respectively.

The distributions in Fjærlandsfjorden is very similar to the distributions in the innermost parts of the main fjord. And as in the main fjord, it is colder in 2003 than in 2002, especially in the surface. The thermocline is strongest in



(a) Temperature, 3 vs 106 (b) Temperature, 6 vs 109 (c) Temperature, 9 vs 112



(d) Salinity, 3 vs 106 (e) Salinity, 6 vs 109 (f) Salinity, 9 vs 112

Figure 5.15: a, b and c are temperature(°C) profiles, and c, d and f are salinity(psu) profiles. The black and red curves are the profiles from January 22^{nd}-23^{rd} and February 22^{nd}, respectively.

2003. The temperature maximum in Fjærlandsfjorden 2002 is about the same as at the head of the main fjord, but it is found at greater depth in Fjærlandsfjorden. The thermocline is much stronger in 2003.

The surface salinity gradients are stronger in 2003, but the 34.5 psu isohaline is found at greater depths in 2003 than in 2002.

Wind observations at the head of Fjærlandsfjorden, Fig.5.20, shows that the wind conditions in January 2003 were calmer than in January 2002. The calm conditions in 2003 is probably one of the reasons why the surface is strongly stratified in 2003.

From the temperature measured at the head of Fjærlandsfjorden, the autumn 2002 where colder than the autumn of 2001. In January the temperature is about the same in 2002 and 2003, while February 2003 is colder than Febru-

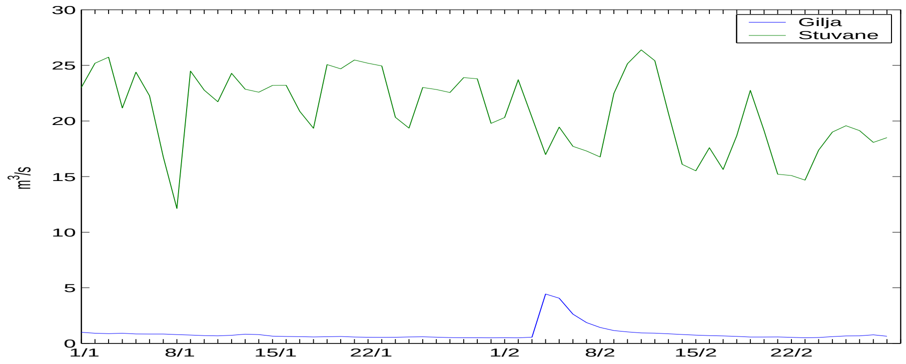
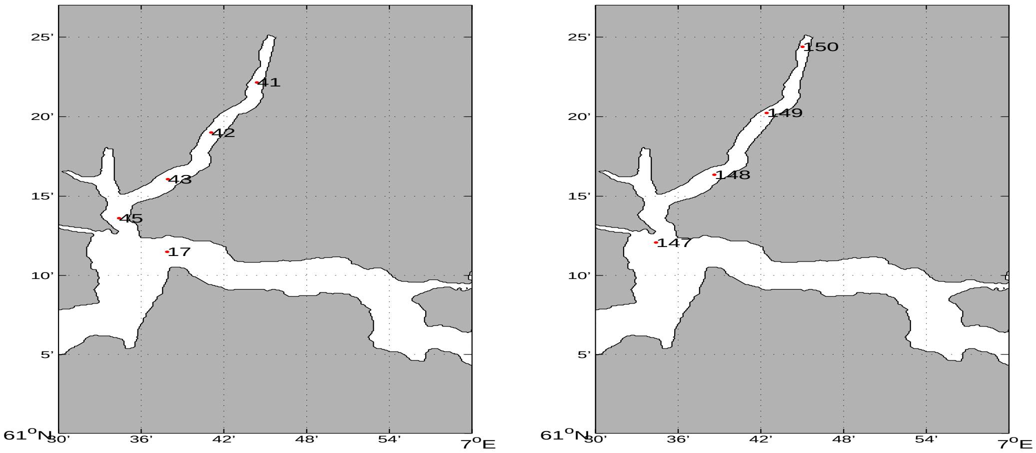


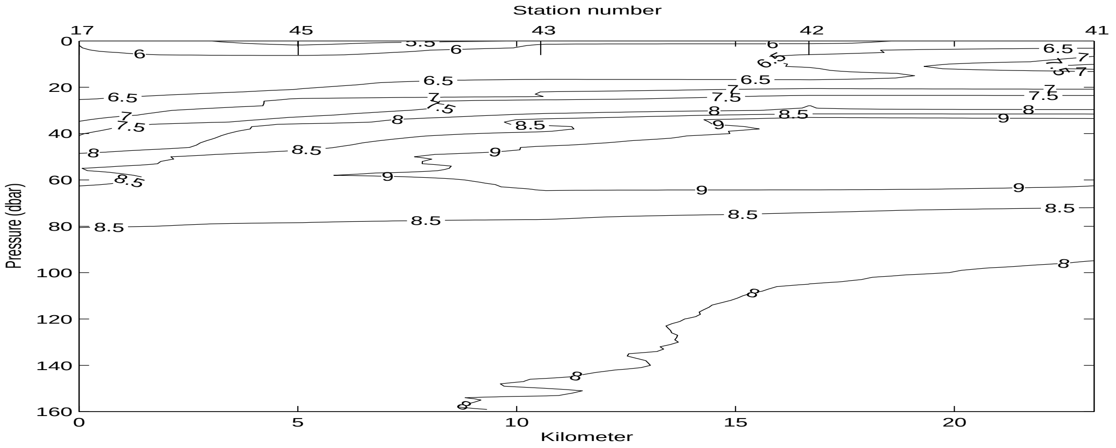
Figure 5.16: Day to day variability in flow of water at Gilja and Stuvane(m^3/s) in January and February 2004



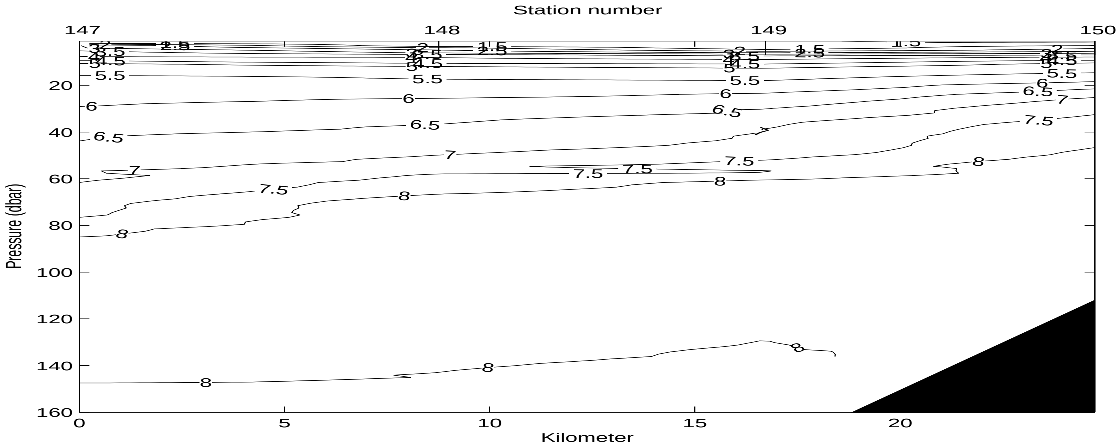
(a) 2002

(b) 2003

Figure 5.17: Map of Fjærlandsfjorden and locations of CTD stations in Fjærlandsfjorden in 2002 and 2003.



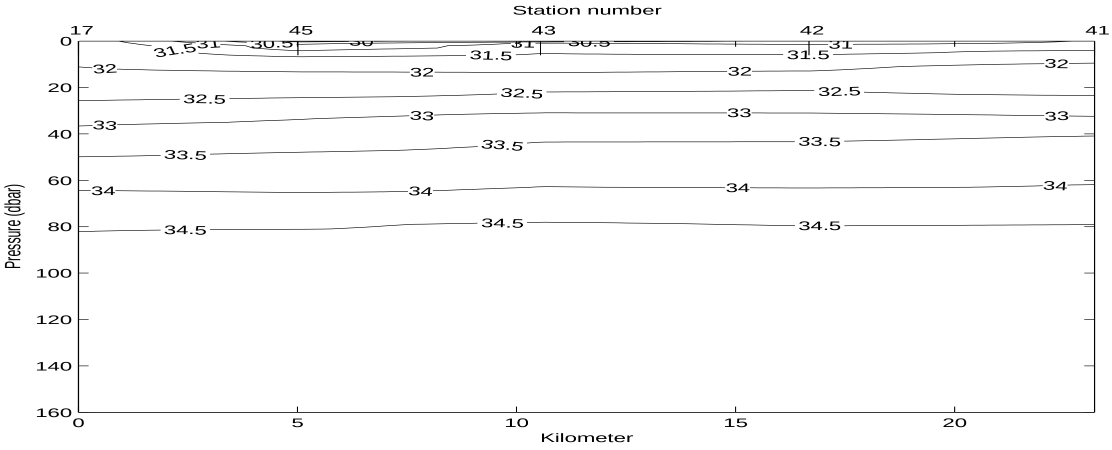
(a) Temperature(°C), 2002



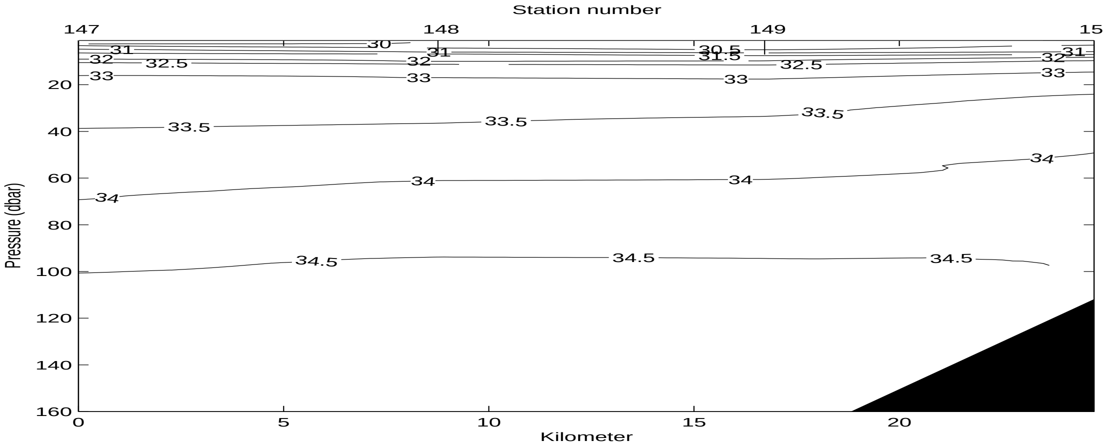
(b) Temperature(°C), 2003

Figure 5.18: Temperature along Fjærlandsfjorden in the upper 160 meters in 2002 and 2003. Head of the fjord is on the right hand side.

ary 2002. It is possible that the air temperature in the autumn might be contributing to the different temperature distribution, but it will not explain the the differences in salinity. Most of the differences is probably due to advection.

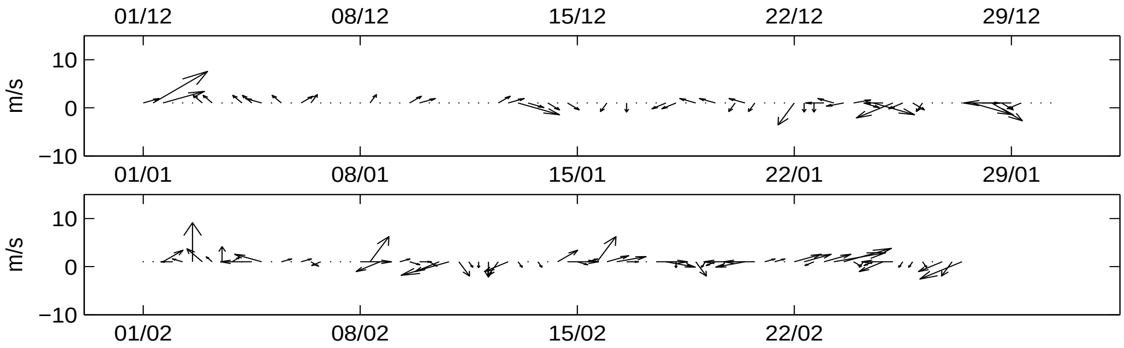


(a) Salnity(psu), 2002

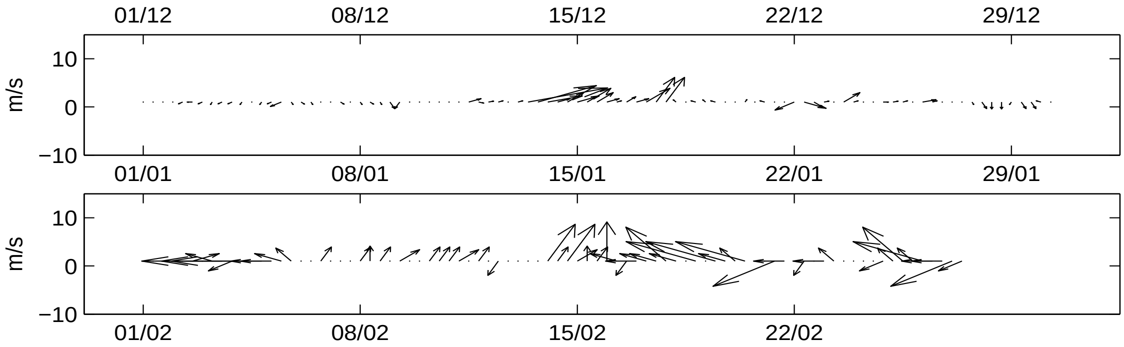


(b) Salnity(psu), 2003

Figure 5.19: Salinity along Fjærlandsfjorden in the upper 160 meters in 2002 and 2003. Head of the fjord is on the right hand side.



(a) Wind, December 2001 - February 2002



(b) Wind, December 2002 - February 2003

Figure 5.20: Wind measured at the head of Fjærlandsfjorden

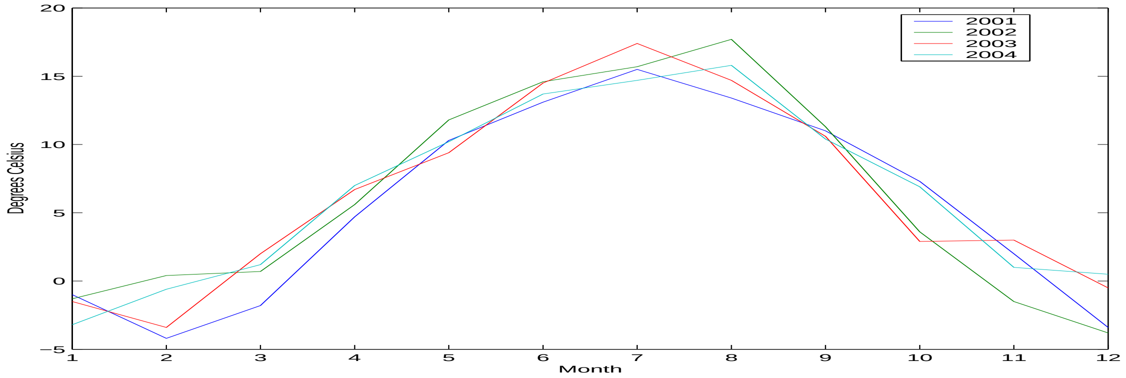


Figure 5.21: Monthly mean air temperatures measured at the head of Fjærlandsfjorden

Chapter 6

Conclusion

Summary The temperature and salinity distribution in Sognfjorden in February show large variations, both in the brakish water and the intermediate water. The variability in the brakish water was expected since this water mass is under influence of atmospheric forcing. In Fjærlandsfjorden the surface stratification has been related to atmospheric forcing. It is not possible to explain the variability in the brackish water in the main fjord from the available river runoff data, but it is also possible that the available runoff data is not representative for the total fresh water input to the fjord. But in the winter months it is probably the local wind field and temperature along the fjord which determines the distributions in the brackish water masses. The offshore wind field might also be causing variability in brackish layer.

From calculations of the Richardson numbers, shear induced turbulence is likely to occur in Sognefjorden.

Variability in the coastal water and the offshore wind field have been studied in order to explain the variability in the temperature and the salinity distributions in the intermediate water. The variability could be caused both by variations in the offshore wind field and by variations in the coastal water, but a firm conclusion cannot be made from the data available.

The circulation is found to be related to the stratification, and variability in the circulation pattern can be related to the variations in the stratification.

Geostrophic flow has been found to have similar layers as the measured flow. Thus it is possible that the baroclinic pressure fields inside the fjord is driving the circulation.

The pressure differences between Sognesjøen and the fjord is found to have relatively large variations during the winter months. It can be related both to wind field and variations in the Norwegian Coastal Current, but the exact relationship is not possible to determine. The flow structure can to some degree be related to salinity differences between Sognesjøen and Sognefjorden. The flow at the sill can also to a certain degree be related to the offshore wind field.

Future work In order to further increase the knowledge of the physical oceanography of Sognefjorden, more measurements are needed. From the work of this paper, there are some topics which could be subject for further investigations in Sognefjorden. The first topic is the year-to-tear variability. The get a better understanding of the variability, more knowledge of surface elevation, offshore and local wind field and river runoff. The sea surface variation can easily be measured by some pressure gauges around the sill, while wind may be modelled on a fine scale from hindcast data. More information about river runoff might be obtained through NIVA. Together with detail information of inflow/outflow at the sill from a bottom moored ADCP, it should be possible to determine the cause for the variations. Another option to determine the year-to-year variability is to apply a numerical ocean model like ROMS(Regional Ocean Modelling System). A combination of extended knowledge of the mentioned variables and a model setup would off course provide an even better result.

Another feature which could be investigated further is the shear stability. By use of a stationary ADCP and CTD measurements with short intervals, better estimates of the Richardson number may be achieved. Direct measurements of turbulence would also be useful.

It would also be interesting to go make further investigations of the cross fjord variations, in order to get a better understanding of the importance of the rotational effects in fjords.

Bibliography

[1] L. Asplin, K. Boxaspen, and A.D. Sandvik. Modelled distribution of sea lice in a norwegian fjord. Technical report, ICES, 2004.

[2] J. Aure, S. Erga, and L. Asplin. Increased biological productions in fjords by artificial upwelling. In J. Aure, editor, *Fisken og Havet*, 2000. Institute of Marine Research, Bergen, Norway.

[3] J. Aure, J. Molvær, and A. Stigebrandt. Observations of inshore water exchange forced by a fluctuating offshore density field. *Marine Pollution Bulletin*, 33:112–119, 1996.

[4] J. Aure and A. Stigebrandt. Aquaculture and fjords, analysis of environmental effects in 30 fjords in møre and romsdal. Technical report, Institute of Marine Research, Bergen, Norway, 1989.

[5] J. Berntsen, D.L. Aksnes, and A. Foldvik. Production enhancement by artificial upwelling: a simulation study. *Hydrobiologia*, 484:177–190, 2002.

[6] I.K Eliassen, Y. Heggelund, and M. Haakstad. A numerical study of the circulation in saltfjorden, saltstraumen and skjerstadfjorden. *Continental Shelf Research*, 21:1669–1689, 2001.

[7] T.H. Ellison and J.S. Turner. Turbulent entrainment in stratified flows. *Journal of fluid mechanics*, 6:423–448, 1959.

[8] D.M. Farmer and H. Freeland. The physical oceanography of fjords. *Progress in Oceanography*, pages 147–200, 1983.

[9] H.G. Gade and A. Edwards. Deep water renewal in fjords. In Freeland et al, editor, *Fjord Oceanography*, 1980. Proceedings of the NATO Conference on Fjord Oceanography.

[10] H.G. Gade and E. Svendsen. Properties of the robert t. long model of estuarine circulation. In J.C.J. Nihoul, editor, *Hydrodynamics of estuaries and fjords : proceedings of the 9th International Liège Colloquium on Ocean Hydrodynamics*, pages 423–437, 1977.

[11] H.O Hermansen. Sognefjordens hydrografi og vannutveksling. 2003.

[12] RD Instruments. Principles of operation: A practical primer. Available from RDInstruments.com.

[13] Statens Kartverk, editor. *Den Norske Los*, volume 3 of *Farvannsbeskrivelse*. Sjøkartverket(The Norwegian coastal mapping authority), 2001.

[14] P.K. Kundu and I.M. Cohen. *Fluid mechanics*. Elsevier Academic press, 2004.

[15] R.R. Long. Circulations and density distribution in a deep strongly stratified two layered estuary. *Journal of Fluid Mechanics*, 71:529–540, 1975.

[16] Arctic Monitoring and Assesment Programme. Amap assesment report: Arctic pollution issues, 1998.

[17] S. Pond and G.L Pickard. *Introductory Dynamical Oceanography*. Butterworth-Heinemann, 2^{nd} edition, 1983.

[18] R. Sætre, J. Aure, and R. Ljøen. Wind effects on the lateral extension of the norwegian coastal water. *Continental Shelf Research*, 8:239–253, 1987.

[19] R. Skogseth, I Fer, and P.M. Haugan. *Dense-Water production and Overflow From an Arctic Coastal Polynya in Storfjorden*, volume 158 of *Geophysical Monograph Series*, pages 73–88. The American Geophysical Unioin, 2005.

[20] A. Stigebrandt. A mechanism governing the estuarine circulation in deep, strongly stratified fjords. *Estuarine, Coastal and Shelf Science*, 13:197–211, 1980.

[21] H. Stommel and H.G. Farmer. *On the nature of Estuarine Circulation*. Mass. Woods Hole Oceanographic Institution, 1952.

[22] H. Svendsen. A study of the circulation in a sill fjord on the west coast of norway. *Marine science communications*, 3(2):151–209, 1977.

[23] H. Svendsen. A study of circulation and exchange processes in the ryfylkefjords. *Geophysical Institute, University of Bergen*, 1981.

[24] H. Svendsen et al. The physical environment of kongsfjorden-krossfjorden, an arctic fjord system in svalbard. *Polar research*, 21:133–166, 2002.

[25] H. Svendsen and N. Utne. Fysisk-oseanografisk undersøkelse i ryfylkefjordene 1972-1975. Technical report, Rådgivende utvalg for fjordundesøkelse, Ryfylkeprosjektet, 1979.