Interannual variations of freshwater content in Hornsund

Master Thesis in physical oceanography
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Abstract

Salinity measurements have been used to calculate the freshwater content in Hornsund for the years 2001 to 2014. In 2011 there was significantly higher freshwater content in the fjord, compared to the other years, with a total freshwater content of 1.08 km^3, when calculated with a reference salinity of 34.2. The high freshwater content in 2011 was attributed to the inflow of sea ice and sea ice meltwater of Barents Sea origin, that had been advected into the fjord from the shelf. The lowest amount of freshwater was found in July 2014. No good relashionship between estimations of variations in terrestial runoff and freshwater content in the fjord was found. The distribution of freshwater in Hornsund seems to be governed by wind conditions and the rotational dynamics in the fjord. The fractional contributions of meteoric water, sea ice meltwater, and seawater was calculated based on $\delta^{18}O$ and salinity measurements in September 2013. Significant amounts of meteoric water was found in the surface waters of the bays Burgerbukta and Brepollen. The $\delta^{18}O$ in Brepollen, the innermost bay of Hornsund, showed unusually high values compared to other $\delta^{18}O$ measurements taken in and around Svalbard. This was attributed to the possible existence of a hydrothermal vent or significant amounts of sea ice meltwater in the bay.

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Knut Ola Dølven
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Contents

1 Introduction

Freshwater plays several important roles in the Arctic Ocean. For one, it suppress the upward transfer of heat by supporting the vertical stratification in the halocline, which separates the warm and saline Atlantic Water (AW) from the surface waters (Rabe et al., 2011). The halocline insulates the surface waters from the warm AW and significantly affects the formation of sea ice in the Arctic Ocean (Macdonald, 2000). Studies have also shown that the export of freshwater from the Arctic Ocean to the Nordic seas can affect the intensity of deep water formation and the large scale circulation in the Atlantic Ocean (Aagaard and Carmack, 1989; Rabe et al., 2011). The freshwater input to the Arctic Ocean can therefore have a direct climatic impact on both regional and global scales (Häkkinen S., 1999). Due to the important roles of freshwater in the Arctic Ocean and possible consequences for the climate, it has been of large interest to monitor and understand the freshwater budget in the Arctic (e.g. Aagaard and Carmack, 1989; Broecker et al., 1990; Dickson et al., 2007; Rabe et al., 2011; Korhonen et al., 2013).

The most important freshwater inputs to the Arctic Ocean is river runoff from Eurasia and North America, the Norwegian Coastal Current (via the Eurasian shelves), precipitation, ice melt, and inflow from the Pacific Ocean through the Bering Strait (Rabe et al., 2011). The most significant output of freshwater from the Arctic Ocean is export through the Fram Strait, the Canadian Arctic Archipelago, and the formation and export of sea ice (Rabe et al., 2011).

Concerning the freshwater balance, an estuarie can be defined as: "*A semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with freshwater*" (Cameron and Pritchard, 1963). By this definition, the whole Arctic Ocean can be interpreted as an estuarie, however, a more traditional perception is that an estuarie is a near-shore zone with low salinity in the proximity of a terrestial freshwater source (Macdonald, 2000). Fjords are typically long and narrow estuaries, often with a complex bathymetry formed by advancing and retreating glaciers through time. In addition to being a link between terrestial freshwater sources and the oceans, changes in the freshwater content in fjords may also affect the living con-

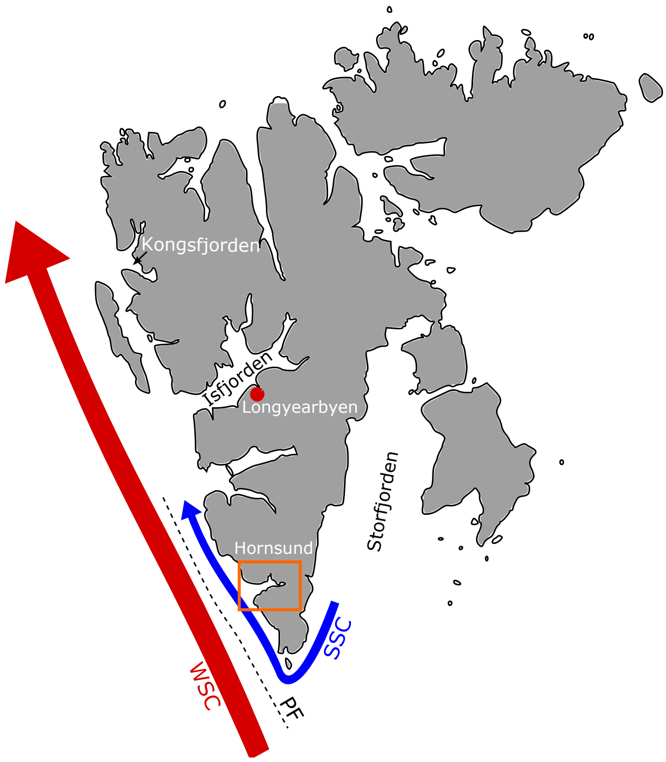


Figure 1.1: Map of Spitsbergen. Hornsund is marked by the orange square, the red arrow is a conceptual representation of the West Spitsbergen Current and the South Cape Current is indicated by the blue arrow.

ditions for the marine biotas in the region (Ruthger and Wing, 2006). A distinguishing feature of arctic fjords is that they usually has a seasonal sea ice cover (Cottier et al., 2010). This sea ice can act as a source of freshwater when the sea ice melts and a sink of freshwater when the sea ice is formed (Macdonald, 2000). Hence, the freshwater budget in arctic fjords has an additional source and sink of freshwater, compared to fjords which are not influenced by sea ice melt and sea ice formation (Macdonald et al., 1995).

Hornsund is an arctic fjord on the west coast of Spitsbergen and is located between 76^{o}54' and 77^{o}6' N and 15^{o}00' and 16^{o}41' E (Figure 1.1). There are two source waters that dominate the conditions west of the fjord. The South Cape Current (SCC) brings relatively cold and fresh water masses from the Barents Sea and Storfjorden. Further west, off the shelf break, the West Spitsbergen Current (WSC) brings relatively saline and warm water masses to the region (Walczowski, 2013). Due to the heat contribution from the WSC, the waters to the west of the shelf are essentially free of sea ice. The atmospheric climate in Hornsund is typical for West Spitsbergen (Marsz and Styszyńska, 2013), with a relatively mild climate despite its high latitude location due the large heat contribution from the WSC (Błaszczyk et al., 2013)

There are few studies that has investigated the freshwater content and distribution from an ocenaographical perspective in Hornsund. The water masses in Hornsund were first described in 1985 by Swerpel (1985). He described that the fjord was influenced by the mixture of the warm water masses transported to the region by the WSC and less saline water masses of Barents Sea origin, in addition to a significant seasonally dependent input of freshwater. Weslawski et al. (1991) did an estimation of the freshwater content in Hornsund based on salinity measurements in the fjord from 1987 and Beszczynska-Möller et al. (1997) did a freshwater content estimation based on salinity and sediment measurements from 1996. Different estimations of freshwater input from land has been done based on glaciological and meteorological measurements and were compiled in Weslawski et al. (1995), which showed that the main freshwater input to the fjord was from the melting of glacier ice.

This study aims to get a better understanding of the variations in the freshwater content in Hornsund and investigate parameters that may effect the amount and distribution of freshwater in the fjord. To do this, the variations in freshwater content will be described based on hydrographical measurements, mainly from July, in the years 2001-2014. Also, the percentage contributions from sea ice meltwater and meltwater derived from glacier melt, river runoff and precipitation will be quantified by using $\delta^{18}O$ and salinity measurements.

In the following chapter we introduce the general hydrographic conditions of fjords on West Spitsbergen and Hornsund in particular. In Chapter 3, the main sources of freshwater to Hornsund will be described and the method of tracing freshwater sources utilizing $\delta^{18}O$ measurements will be introduced. The data used in this study is presented in Chapter 4 and in Chapter 5 the methods used to analyze these data is explained in detail. The results are presented in Chapter 6 followed by a discussion in Chapter 7. In Chapter 8, the main results and findings will be summarized.

2 Hydrographic Conditions

The first investigation of the hydrography in Hornsund was the study conducted by Swerpel (1985), which was based on measurements from 1979 and 1980. In addition to this, Prominska et al. (prep) examined interannual variations in the summer hydrography of the fjord. Apart from these two studies, there are not many hydrographical investigations in Hornsund. However, it should be expected that Hornsund shows similar characteristics as other fjords on West Spitsbergen with similar bathymetric features, thus the hydrography in Hornsund will be described in the context of the hydrographic properties of similar fjords on West Spitsbergen.

2.1 Hydrography of fjords on West Spitsbergen

The fjords on West Spitsbergen are unique in the Arctic due to the fact that they are strongly influenced by the relatively warm and saline AW, carried by the adjecent WSC (Cottier et al., 2010). Along the shelf of West Spitsbergen, the SCC carries less saline and colder Arctic Water (ArW) from the Barents Sea and Storfjorden (Figure 1.1). Between these two water masses there is a front referred to as the Polar Front (Walczowski, 2013). The water masses on the shelf of West Spitsbergen is often a mixture of these two water masses and freshwater input from Spitsbergen (Hagen et al., 2003). The water masses of fjords on West Spitsbergen are characterized by the mixing of the water masses from the shelf and freshwater from land (MacLachlan et al., 2007), and the effect of sea ice formation and melting during winter season and spring season, respectively.

Farmer and Freeland (1983) describes the typical arrangement of water masses in a silled fjord to be composed of three layers: A fresh surface layer, an intermediete layer and a below sill layer. There are few silled fjords on Svalbard, but Cottier et al. (2005) and Nilsen et al. (2008) stated that the non-silled fjords Isfjorden (Nilsen et al., 2008) and Kongsfjorden (Cottier et al., 2005) still show this three layer structure during summer (see map in Figure 1.1). In this three layer structure, the surface layer shows large variations in salinity and temperature, but is usually characterized by relatively high temperatures due to heat fluxes from the atmosphere and a low salinity due to freshwater discharge from rivers and glacier ablation (Nilsen et al., 2008; Cottier et al., 2010). The dominance of freshwater in the formation of a clearly defined surface is usually weakened towards the fjord mouth (Cottier et al., 2010). The intermediate layer is usually composed of shelf water advected from outside of the fjord, being a mixture of AW and/or ArW and freshwater input from land (Cottier et al., 2010). The relatively dense bottom water has two possible origins: It can be locally produced in the winter season by brine release during the formation of sea ice, or it can be AW advected into the fjord which has undergone significant cooling during winter season (Nilsen et al., 2008). The composition of the three layered structure can vary from year to year, depending on the water masses created the previous winter, variations in inflow, and amount of freshwater discharge (Cottier et al., 2010).

When the summer season ends, the air surface temperatures decrease and events of strong winds are more common (Cottier et al., 2010; Styszynska, 2013). Reduced temperatures in the upper water mass weakens the bouyancy in the water column, which results in a water column that is more prone to vertical mixing. The increased wind forcing on the surface layer and the reduced bouyancy in the water column during autumn facilitates vertical mixing with underlying water masses and results in a deeper and colder surface layer (Cottier et al., 2007). The colder water mass created due to these processes during autumn and wintertime is often termed Local Water (LW) (Svendsen et al., 2002; Nilsen et al., 2008). As the undelying water masses initially has a significantly higher density due to higher salinity, cooling of the surface layer itself is often not sufficient to create mixing to the bottom of the fjord (Cottier et al., 2010). The depth of convection due to cooling is dependent on the thickness of the freshwater layer present at the end of summer (Cottier et al., 2010).

The upper water mass usually reach the freezing point in November or December (Nilsen et al., 2008) and continued surface cooling results in ice formation and brine release. Sea ice formation intensifies the densification of the surface waters due to the inceasing salinity from the added brine and may result in convection to the bottom of the fjord. The cold and saline water mass that can be created by cooling and brine release in winter, is often referred to as Winter Cooled Water (WCW) (Nilsen et al., 2008). The water column will gradually become more and more homogeneous due to this density driven convection and the late winter water column is often characterized by weak stratification (Svendsen et al., 2002; Nilsen et al., 2008). Whether the density driven convection during winter reach the depth of the fjord is dependent on the salt flux from freezing and the depth of the fjord (Nilsen et al., 2008).

At the end of the winter season, the fast ice that may be present in parts of the fjord usually has a thickness of about 1 meter (Cottier et al., 2010). The sea ice usually starts to melt between May and July and is highly dependent on swell, the sea ice conditions outside of the fjord, and wind strength and direction (Cottier et al., 2010). When the sea ice has melted, the summer pycnocline is now gradually re-established due to atmospheric heating and freshwater input from the melted sea ice, glacier meltwater, and river discharge. The result is eventually the previously described three layered arrangement of the water column, which is fully developed during summer season.

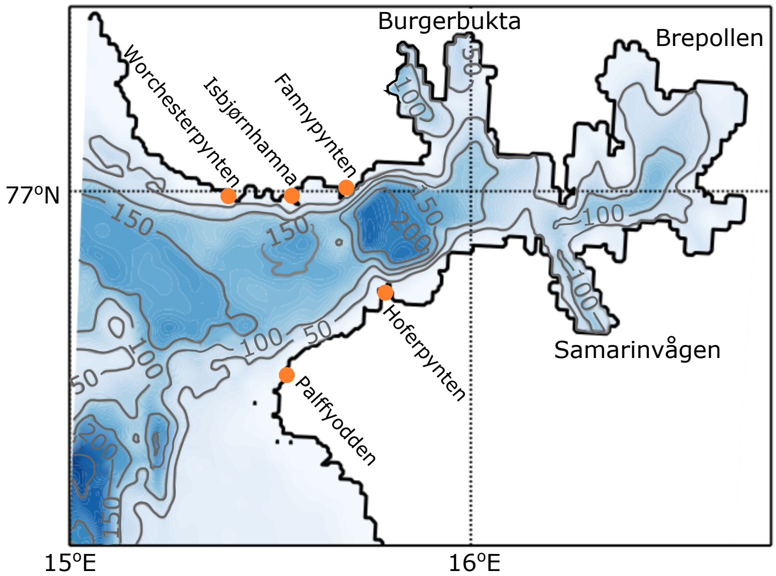


Figure 2.1: Bathymetric map of Hornsund based on data provided by the Norwegian Polar Institute.

2.2 Hydrography of Hornsund

Hornsund is about 30 km long and oriented in an east-west direction, with a 20^o northward inclination (Moskalik et al., 2013)(Figure 2.1). The width of the fjord varies between 2 and 12 km and the fjord has an estimated area of 303 km^3, with the fjord mouth defined by a straight line between Worchesterpynten and Palffyodden (Błaszczyk et al., 2013). The present study will utilize the same fjord mouth definition as Błaszczyk et al. (2013). The averaged depth of the fjord is 93 meter and the maximum depth is 262 meter in the middle of the main basin (Moskalik et al., 2013). In front of the fjord there is a trough which has a leading effect on the ArW and AW that can be present outside of the fjord mouth. The fjord has four secondary bays: Brepollen, Vestre and Austre Burgerbukta, and Samarinvågen. A sill is separating the main basin from Samarinvaagen and Brepollen. However, the fjord has no distinct shallow sill at the fjord mouth, so there is no strong topographic barrier to prevent exchange between water masses in the fjords interior and water masses at the shelf.

Being a non-silled fjord on the west coast of Spitsbergen, the three-layer structure described above should be applicable to describe summer hydrography also in Hornsund. To simplify the description of the hydrography in Hornsund and preserve conformity with previous studies of fjords on West Spitsbergen, the different water masses for Hornsund is adopted from Svendsen et al. (2002) and Nilsen et al. (2008), and are presented in Table 2.1.

The first description of summer hydrography in Hornsund were made by Swerpel (1985), whose study shows similarities with the descriptions of hydrography in Isfjorden and Kongsfjorden. A fresh surface layer with considerable seasonal changes from spring to autumn was described. The surface layer had relatively warm water close to the surface (>1^oC) and colder water masses deeper down with a minimum temperature (in the surface

Table 2.1: Definition of water masses

Water mass	Acronym	Temperature [C°]	Salinity
Arctic Water	ArW	< 1.0	$34.0 - 34.8$
Atlantic Water	AW	> 3.0	> 34.9
Intermediate Water	IW	> 1.0	$34.0 - 34.7$
Local Water	LW	< 1.0	-
Surface Water	SuW	> 0.0	< 34.0
Transformed Atlantic Water	TAW	> 1.0	$34.7 - 34.9$
Winter Cooled Water	WCW	< -0.5	> 34.4

Water masses in Hornsund, adopted from Svendsen et al. (2002) and Nilsen et al. (2008)

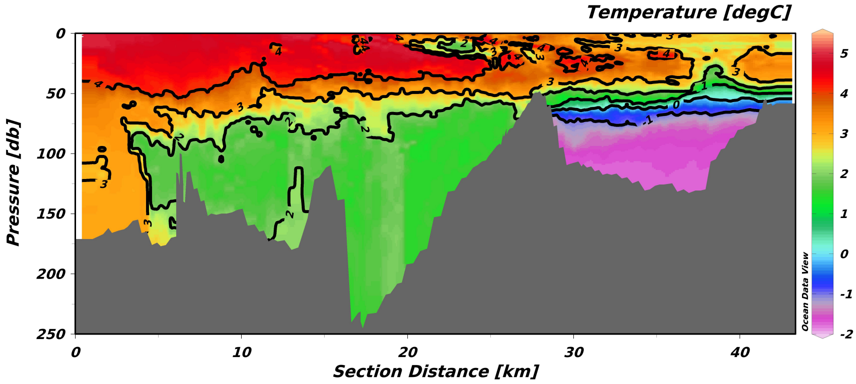
layer) at about 7-15 meters during summer.

An intermediate layer was found below the surface layer, and its development was assumed to be due to the mixture of the cold and fresh water in the bottom of the surface layer and a warmer and more saline mixture of AW and ArW (as defined in Table 2.1), that was present deeper down. Below the intermediate layer, most of the outer and central part of Hornsund was occupied by water masses with temperature and salinities corresponding to the definition of ArW or TAW. During late summer and autumn this three layered structure in Hornsund was vanishing (Swerpel, 1985).

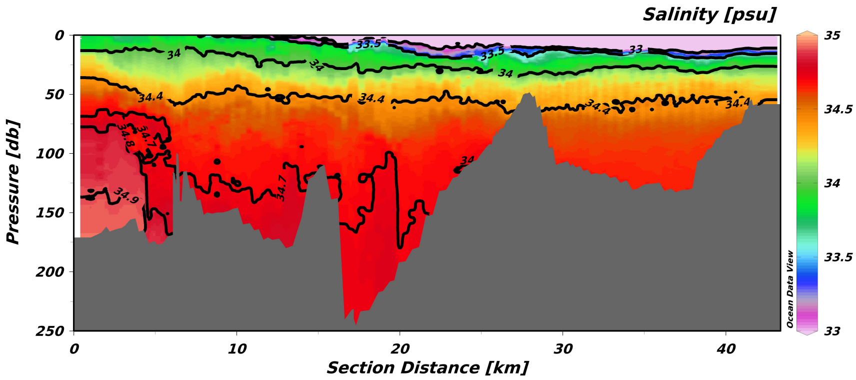
In the innermost bay of Hornsund, Brepollen, different hydrographical conditions was found (Swerpel, 1985). Compared to the central and outer parts of the fjord, Brepollen had a relatively saline water mass at freezing point temperature at the bottom, also during summer. Swerpel (1985) suggested that the origin of this cold and saline water mass was formation of WCW during the winter season, similar to what was described by Cottier et al. (2010) for other fjords on West Spitsbergen. Another possibility of the origin of this water mass mentioned by Swerpel (1985), was water mass exchange between Hornsund and Storfjorden under the Hornbreen glacier. Swerpel (1985) suggested that the circulation regime in Brepollen was governed by a clockwise rotational circulation pattern in the surface layer of Brepollen and a counter-clockwise circulation in the bottom water. He also suggested that warm waters entered Brepollen from the central parts of the fjord below the surface layer, underwent cooling from the glacier fronts and went down to deeper depths, resulting in a layer of relatively cold (~0^oC) and saline water mass above the even colder and saline WCW at the bottom.

Interannual variations in the hydrography of Hornsund for the years 2001-2014 is being described by Prominska et al. (prep). They found that winter conditions prevailed in Hornsund until May or June, with only LW and WCW present in the fjord. The formation of the surface layer starts due to freshwater input, normally in June and the continued decrease of salinity during summer generally results in a salinity below 30 in July. The fresh surface layer increased in thickness during summer and the salinity values that were present at the surface in May, were found at depths of 50-100 meter in July/August.

The described summer hydrography by Swerpel (1985) fits well with what observed in the hydrographical data used in the present study. An example of how the temperature



(a)



(b)

Figure 2.2: Distribution of temperature (a) and salinity (b) from a section along the fjord axis of Hornsund from late July 2002. Brepollen is located to the right and the fjord mouth is located to the left.

and salinity distribution may look like are shown in Figure 2.2, which shows hydrography in Hornsund at a section along the fjord axis in July 2002. The three layered structure of the summer hydrography in Hornsund can be seen, with a layer of surface water that is separated from a layer of intermediate water by a pycnocline. The bottom water of the main basin is composed of TAW, and the WCW/LW that may have been present in spring, has probably been exchanged with water masses from the shelf. AW is only present just outside of the fjord mouth. In Brepollen, WCW is present behind the sill and a layer of IW separates the surface layer and the bottom water.

3 Freshwater sources

The freshwater input to Arctic fjords can either be derived from precipitation, glacier melt, river-runoff, melting of sea ice, and/or it can be advected into the fjord from the shelf (Nilsen et al., 2008). Estimations of freshwater input to fjords can be based on both hydrological and oceanographical investigations. In Arctic fjords, the formation and melt of sea ice may act as both a source and sink of freshwater and the complete freshwater budget of an arctic fjord cannot be determined by only investigating the freshwater input from land based freshwater sources and precipitation. The application of oxygen isotopes is a useful approach to separate between the freshwater sources from land/precipitation and source/sink effect of sea ice melt and sea ice formation. The following chapter describes the freshwater sources to Hornsund and introduce the concept of using oxygen isotopes to trace freshwater sources.

3.1 The freshwater sources in Hornsund

The following section describes the different possible freshwater sources to Hornsund, being river runoff, precipitation, glacial ablation/calving, sea ice, and/or freshwater contained in water masses advected from the shelf.

3.1.1 River runoff

The drainage area of Hornsund is approximately 1200 km^2 (Figure 3.1). This area has a glacial coverage of about 67%, where 97% of this glaciated area is composed of tidewater glaciers (Błaszczyk et al., 2013). A tidewater glacier is a glacier terminating directly into the sea, with terminus either floating or grounded below sea level (Cogley et al., 2011). The glaciers terminating in the sea has a direct freshwater input to the fjord at the terminus of the glacier. Hence, the input of freshwater from glaciers to rivers is low in the catchment area of Hornsund and the river runoff is highly dependent on the seasonal melt of snow and precipitation in the watershed. In general, the river runoff on Svalbard mainly occurs during the summer months (June to September) (Killingtveit et al., 2003). This is also true for Hornsund and Weslawski et al. (1995) stated that the freshwater contribution from rivers in the Hornsund area is of secondary importance. However, it can be significant in spring and early summer due to the melting of snow. The largest rivers entering the Hornsund fjord are Revelva, Lisbethelva, and the rivers entering Gåshamna which drains water from Gåsbreen (Figure 3.1).

3.1.2 Precipitation

Precipitation can act as a direct freshwater source on the fjord and increase the runoff in the catchment area. The seasonal contribution to runoff from snow melt is dependent on the winter precipitation (Marsz and Styszyńska, 2013). The average precipitation at the weather station at the Polish Reasearch Station in Isbjørnhamna was 434.4 mm for the period 1979-2009 and varied between 230.7 mm in 1987 and 635.9 mm in 1996 (Lupikasza, 2013). There is generally more precipitation during winter than in summer and winter precipitation contributes with about 60% of the total precipitation during an average year (Lupikasza, 2013).

3.1.3 Glacier ablation/calving

The most dominant freshwater source to fjords on Spitsbergen is glacial ablation and calving (e.g Weslawski et al., 1995; Svendsen et al., 2002; MacLachlan et al., 2007). Weslawski et al. (1995) stated that the freshwater flux from glaciers contributed with about 70% of the total freshwater flux to Hornsund annually. Hagen et al. (2003) estimated the annual mean freshwater input to fjords from glaciers on Svalbard. These estimations showed a total runoff from glaciers of about 800 mm per unit glaciated area. However, there are both interannual variations and variations between different drainage basins, depending on the topography and the type of glaciers in the topical watershed (Hagen et al., 2003). For instance, as described above, in the Hornsund drainage basin, 97% of the glacial coverage are composed of tidewater glaciers, whereas the proportion of tidewater glaciers for the whole of Svalbard is just above 60% (Blaszczyk et al., 2009). This may result in a higher freshwater input in Hornsund from glaciers than the general estimations for Svalbard by Hagen et al. (2003), due to a higher freshwater input from glacial calving and the possibility of freshwater discharge during winter.

The glacial cover in Hornsund is most prominent in the three basins Burgerbukta, Samarinvaagen, and Brepollen. Brepollen, the innermost basin in Hornsund, is almost entirely surrounded by the tidewater glaciers Storbreen, Hornbreen, Hyrnebreen, Svalisbreen, Chomjakovbreen, and Mendeleevbreen (Moskalik et al., 2013). Many of the glaciers in Hornsund are defined as surge-type glaciers. A surge-type glacier can be described as a glacier which exhibits "quiescent" phases, typically lasting some decades, during which velocities are lower than in a non-surge-type glacier, and "surge" phases, when the glaciers has an abnormally fast flow over a period of a few months to years, during which the front of the glacier advances substantially (Cogley et al., 2011). A tidewater glacier in "surge" phase has an increased calving rate and hence increased freshwater flux due to the rapid

Figure 3.1: Topographic map of the Hornsund watershed, based on map from the Norwegian Polar Institute and Błaszczyk et al. (2013). The watershed is indicated by a black line.

advance of the glacier front (Błaszczyk et al., 2013). Only one surge has been reported during the measuring period for this study, which was the surge of Mendelejevbreen that was surging in the period 1995-2002 (Błaszczyk et al., 2013).

Since many of the glaciers in Hornsund are polythermal, there is also a possibility for freshwater input from glaciers to the fjords during winter (Hagen et al., 2003). A polythermal glacier is defined as a glacier containing some cold ice (temperatures below pressure melting point) and some temperate ice (temperatures at or close to pressure melting point) (Cogley et al., 2011). In a polythermal glacier, a basal layer of temperate ice is overlain by a cold ice layer which is covered by a surface layer of thickness between 10-15 meter which can be heated to melting point seasonally (Cogley et al., 2011). These glaciers contain water in the temperate parts, which may drain during winter and thus these glaciers usually has a runoff also during winter (Hagen et al., 2003). On land based polythermal glaciers, the water released during winter usually refreeze as it leaves the glacier and hits frozen ground. However, in tidewater glaciers, heat contribution from warmer intermediate or deep level waters can result in a freshwater discharge into the fjord also during winter season (Hagen et al., 2003). This freshwater contribution leads to a bouyant plume of freshened ambient water (Sciascia et al., 2013). The plume will rise vertically close to the ice-ocean interface and the result is a near surface current with relatively fresh water which moves away from the glacier. Weslawski et al. (1995) observed diminished salinity down to 80 meters in glacier-influenced bays in Hornsund, which was attributed to bottom discharge from tidewater glaciers. Even though the polythermal glaciers terminating in the fjord usually has a winter freshwater contribution, the hydrological impact of freshwater flux from glaciers are, like the river runoff, also to a great extent related to seasonal variations and most of the freshwater discharge occures during summer season (Hagen et al., 2003).

3.1.4 Sea ice

The amount of sea ice in Hornsund varies from year to year, but fast ice cover is usually confined to the innermost parts of the fjord (Błaszczyk et al., 2013). Sea ice normally starts to form in late autumn in Brepollen and the inner parts of Burgerbukta and Samarinvågen (Gerland and Hall, 2006). Measurements of sea ice thickness in Burgerbukta and at the entrence to Brepollen done by Gerland and Hall (2006), showed thickness varying between 0.99 and 1.43 meter.

Based on observations from the winter season in the years 1992-1994, the storage of freshwater in fast ice in Brepollen was estimated by Weslawski et al. (1995) to be 0.05 km^3. However, relatively large interannual variations in fast ice cover was found by Muckenhuber et al. (prep), based on satellite image analysis. To quantify the sea ice coverage they defined the concept "Days of fast ice coverage" (DFI), which is calculated by taking the sum of the fast ice area relative to the total area (of the fjord) of all the days in the study period. The DFI was calculated by Muckenhuber et al. (prep) from the 1st of March to the end of the sea ice season. The DFI in Hornsund for this time period in each year from 2001-2014 are presented in Figure 3.2.

The results from Muckenhuber et al. (prep) showed a DFI varying between 40 and 60 for most years, except for 2006, 2012, and 2014 when the DFI was lower. In 2012 and

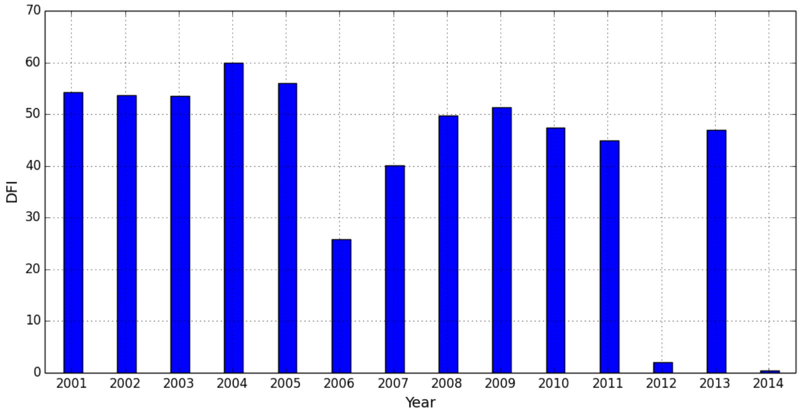


Figure 3.2: Days of fast ice cover (DFI) in Hornsund for the period 1st of March to the end of the sea ice season for the years 2001-2014. Courtesy to Muckenhuber et al. (prep) for providing data.

2014 there was almost no fast ice in the fjord after the 1st of March.

3.1.5 Advected freshwater from the shelf

The last possible source of freshwater input to Hornsund is freshwater advected from the shelf. Hornsund is usually free of sea ice during summer, except for ice bergs and brash ice from calving glaciers (Błaszczyk et al., 2013). However, sea ice drifting with the SCC from the Barents sea, can enter the fjord in summer during favorable wind conditions (Błaszczyk et al., 2013). In addition to the freshwater provided by the eventual melting of the drift ice that enters the fjord, it should be expected that there is a significant amount of sea ice meltwater contained in the water mass carrying this ice. How often this inflow occurs is unknown, but the pravailing wind direction in Hornsund is easterly (>80%, Błaszczyk et al., 2013), which is non-favorable for the inflow of drift ice and its presumably fresh ambient water mass.

Although the surface inflow of sea ice from the SCC is dependent on wind conditions, the inflow of water masses from the SCC at intermediate depths are observed both in Swerpel (1985) and in the data set used in the present study. The SCC is a prolongation of the East Spitsbergen Current and containes relatively fresh water, compared to the water masses in the WSC. The freshwater content in the SCC is dependent on the sea ice melt in the Barents Sea and both the terrestial freshwater input and sea ice melt in Storfjorden and the coastal areas south and east of Hornsund. How much freshwater that is contained in this current is not known, but will probably exhibit both seasonal and interannual variations.

3.1.6 Estimations of freshwater input to Hornsund

Some estimations of freshwater input to Hornsund can be found in litterature. Weslawski et al. (1995) compiled data from Leszkiewicz (1987), Weslawski et al. (1991), and Jania and Pulina (1994) on freshwater flux to Brepollen. They estimated the freshwater input to the bay to be 1.313 km^3 annually, where 1.113 km^3 came from glacial ablation/calving, 0.102 km^3 from rain water collected in the watershed, 0.007 km^3 from direct rainfall on fjord, 0.18 km^3 from melted snow, and 0.051 km^3 melting of fast ice, based on data collected during the years 1992-1994. Based on the compiled data, they found that most of the freshwater input occured during July and August with 1.026 km^3 of freshwater. In Brepollen, the freshwater input prior to August was 0.598 km^3 (Weslawski et al., 1995). The freshwater input for the whole of Hornsund was estimated by Jania and Pulina (1994) to be about 1.8 km^3 anually, but the fractional contribution from the different sources was not described.

3.2 The use of δ^{18}O as a tracer for freshwater sources

In arctic fords, sea ice can act as a source of freshwater when the sea ice melts and a sink of freshwater when the sea ice is formed (Macdonald, 2000). To calculate the freshwater contribution from precipitation, runoff, and glacial ablation/calving versus the freshwater contribution from sea ice meltwater, the isotopic composition of the water molecules has proven as a useful tool (e.g. Östlund and Hut, 1984; Macdonald et al., 1999; Frew et al., 2000). In the following section, the use of oxygen isotopes in the tracing of freshwater sources will be introduced and how this method is suitable for tracing freshwater sources in Hornsund.

3.2.1 Variations in the isotopic composition of water

The net difference in solar energy supply between higher and lower latitudes drives the large scale atmospheric circulation on earth. Large heat contribution at low latitudes creates widespread evaporation (Bengtsson, 2010) and the atmospheric circulation, driven by the heat-generated pressure differences, transports the evaporated water poleward (Wallace and Hobbs, 2006). Rate of condensation is dependent on the relative humidity and thus temperature of the considered air parcel, thus, during this poleward transport, condensation of water vapor occurs and there is a mean transport of water through the atmosphere from the equator to higher latitudes (Wallace and Hobbs, 2006).

Oxygen atoms comes in three stable isotopical variations ^{16}O, ^{17}O and ^{18}O. Oxygen isotope ^{16}O is by far the most common ($>$ 99% of oxygen in the oceans) (Dansgaard, 1964), followed by the ^{18}O isotope. Water molecules with the ^{18}O isotope has a lower vapor pressure than water molecules with the ^{16}O isotope and demands more energy to be evaporated (Humlum, 2005). A consequence of this is that water molecules with the ^{18}O isotope condense more easily, compared to water molecules with the ^{16}O isotope. This leads to a progressive depletion of the ^{18}O oxygen isotope in water, during poleward atmospheric transport (Frew et al., 2000).

A standard method to describe variations in the ^{18}O/^{16}O isotopic composition in water are to report the results in del units relative to Vienna Standard Mean Ocean Water (VSMOW):

$$\delta^{18}O = \left(\frac{(\frac{^{18}O}{^{16}O})_{sample} - (\frac{^{18}O}{^{16}O})_{VSMOW}}{(\frac{^{18}O}{^{16}O})_{VSMOW}}\right) \cdot 1000 \tag{1}$$

where $\frac{^{18}O}{^{16}O}_{sample}$ is the measured ratio between the ^{18}O and ^{16}O isotopes, and $\frac{^{18}O}{^{16}O}_{VSMOW}$ is the ratio of the two isotopes in VSMOW. The change in the ratio between these isotopes from the VSMOW value are multiplied by 1000 to get the permil value. VSMOW is an international measurement standard with a known $\frac{^{18}O}{^{16}O}$ ratio, used for stable isotope analysis (IAEA, 2009).

3.2.2 δ^{18}O as an oceanographical tracer

The use of high precision δ^{18}O measurements in the tracing of water masses were introduced by Epstein and Mayeda (1953), who linked the decrease in δ^{18}O values in the high latitude oceans to melting of snow and ice. The work by Epstein and Mayeda (1953) demonstrated that the isotopic variations in oxygen could be used as a tracer for water masses (Frew et al., 2000). Craig and Gordon (1965) did high precision isotopic measurements of different parts of the global ocean and found that though the isotopical variations in the deep oceans were small, they suggested that the use of oxygen isotopes was a suitable oceanographical tool to investigate the genesis of deep water in the ocean. The use of the isotope-salinity relashionship to separate sea ice meltwater from freshwater of atmospheric origin were introduced by Fairbanks (1982).

The use of δ^{18}O as a tracer to determine the sources of freshwater in the Arctic Ocean is well documented (e.g. Östlund and Hut, 1984; Macdonald et al., 1995; Alkire et al., 2010). Oxygen isotopes are especially powerful as a tracer in the Arctic Ocean, due to the above described progressive depletion of ^{18}O in water molecules in the atmosphere as water vapor is transported from lower to higher latitudes This results in a very low δ^{18}O value in polar precipitation, compared to the δ^{18}O values in the water masses advected to the Arctic in the large scale ocean currents. During sea ice formation, there is a small increase in δ^{18}O of +(1.6‰ to 2.8‰) as the ice matrix preferentially incporporates water molecules with the ^{18}O isotope (Frew et al., 2000). The increase in δ^{18}O as sea ice forms is small and positive, while the reduction in salinity is large, thus these two tracers are decoupled when sea water freeze (Frew et al., 2000). Based on the above, three different water types can be separated and traced by salinity and δ^{18}O measurements in the Arctic. These are defined as: Meteoric water (MW), which is a combination of precipitation, river-runoff, and glacial ablation/calving, sea ice meltwater (SIM), and seawater (SW).

The use of δ^{18}O as a tracer to separate MW from SIM in the Arctic Ocean was partly limited by low sampling rates until Östlund and Hut (1984) decoupled SIM from MW in the Arctic Ocean halocline. The study by Östlund and Hut (1984) focused on large spacial scales in the Arctic Ocean. The use of oxygen isotopes to separate the freshwater contribution from MW and SIM in estuaries, was introduced by Macdonald et al. (1995).

Water masses in estuaries are usually a mixture of freshwater and the seawater present outside of the fjord (Macdonald et al., 1999). In estuaries without sea ice formation, the fractional contribution from the seawater source and the freshwater source can be calculated using the salinity of the seawater source and the salinity of the freshwater source (which usually is zero) (Macdonald et al., 1999). However, the sources of freshwater in a typical arctic fjord includes the melting of sea ice, and sea ice formation/melt confounds this two endmember model by changing the properties of the water column due to brine release during winter, and by playing the role of a freshwater source in summer, when the sea ice melts (Macdonald et al., 1999). These two processes are decoupled in space and time, thus sea ice can act as a source or sink of freshwater even though the net freshwater input of the sea ice formation/melt cycle is zero (Alkire et al., 2010). By calculating the amount of SIM contained in the water column, water masses influenced by brine rejection during sea ice formation and water masses influenced by the melting of sea ice can be detected, as this would yield a negative and positive contribution of SIM, respectively. The application of $\delta^{18}O$ as a tracer, in addition to salinity, should therefore be both a useful and suitable tool to give additional information on the freshwater origins in Hornsund.

4 Data

To calculate the freshwater content in Hornsund and to distinguish between freshwater of meteoric origin and sea ice meltwater, salinity and δ^{18}O measurements was used. An overview of the data obtained are presented in the following Chapter.

CTD data

Salinity data was obtained from Conductivity-Temperature-Depth (CTD) measurements taken in July each year from 2001 to 2014 (exept 2004 and 2005), during cruises with R/V Oceania conducted by the Institute of Oceanology Polish Academy of Science (IOPAS), and from CTD measurements taken on cruises conducted by the University Center in Svalbard (UNIS) in September 2013/2014 with R/V Håkon Mosby (Table 4.1).

During the IOPAS cruises the CTD measurerents were obtained by using a towed CTD profiling system. In 2001, 2002, 2003 and 2006, an Idronaut 316 profiling at 8 Hz was used (Idronaut, 2006), while in the other years the measurements were taken with a Seabird SBE49 (Sea-bird, 2015), profiling at 16 Hz. By using standard procedured, the data were averaged and filtered every 1 db. The CTD data from R/V Håkon Mosby were collected using a Seabird SBE911plus CTD system. The SPE911plus has a sampling frequency of 24 Hz and the data were averaged every 1 db (Sea-bird, 2014). Raw data were transformed using Seasoft V2 . The accuracy of the instruments that was used is presented in Table 4.2.

δ^{18}O data

To obtain δ^{18}O data, water samples were collected during the cruise with R/V Håkon Mosby in September 2013. Water samples were collected at bottle target depths of 5, 10, 15, 20, 30, 40, 60, 80, 100 and 125 meter. The water samples were analyzed at the Department for Earth Science at the University of Bergen using the CO_2 equilibrium method, with an accuracy of 0.004‰.

Table 4.1: Overview of data

Year	Date(s)	Collected by	Type
2001	29-30.07	R/V Oceania (IOPAS)	CTD
2002	22.07	R/V Oceania (IOPAS)	CTD
2003	23-26.07	R/V Oceania (IOPAS)	CTD
2006	22-23.07	R/V Oceania (IOPAS)	CTD
2007	26.07	R/V Oceania (IOPAS)	CTD
2008	25-26.07	R/V Oceania (IOPAS)	CTD
2009	22-23.07	R/V Oceania (IOPAS)	CTD
2010	23.07	R/V Oceania (IOPAS)	CTD
2011	26-27.07	R/V Oceania (IOPAS)	CTD
2012	31.07 - 01.08	R/V Oceania (IOPAS)	CTD
2013	26-27.07	R/V Oceania (IOPAS)	CTD
2013	04-05.09	R/V Håkon Mosby (UNIS)	CTD and $\delta^{18}O$
2014	31.07	R/V Oceania (IOPAS)	CTD
2014	02.09	R/V Håkon Mosby (UNIS)	CTD

No data were collected in 2004 and the data from 2005 were considered erraneous and will not be used.

Table 4.2: Accuracy of instruments

Instrument	Conductivity [Sm^{-1} cm^{-1}]	Temperature [^{o}C]	Pressure [% of full scale]
Idronaut 316	0.003	0.003	0.060
SBE49	0.0003	0.002	1.000
SBE911plus	0.0003	0.001	0.015

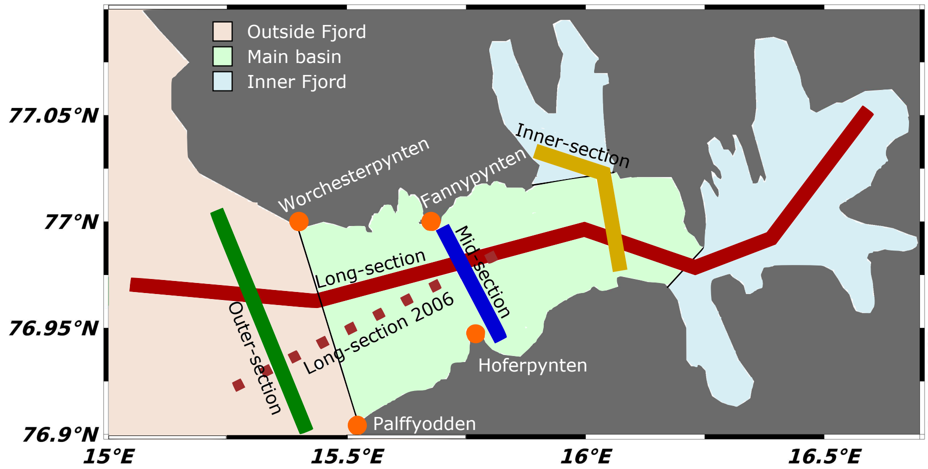
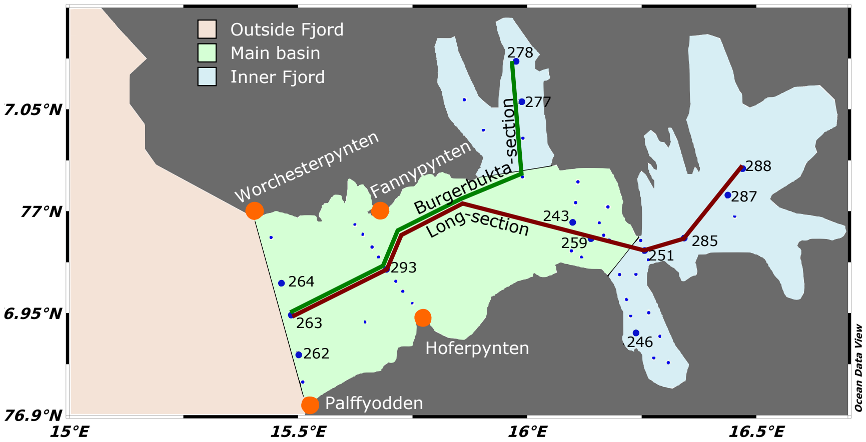


Figure 4.1: Map showing transects for the data collected in July by IOPAS. The data from 2006 has a more southerly direction than the other years. The Long-section, Inner-section, Mid-section, and Outer-section are shown with red, yellow, blue, and green colours, respectively and the three defined areas, the Inner-fjord, Main basin, and Outside-fjord area are indicated by blue, green, and pink shadings, respectively.

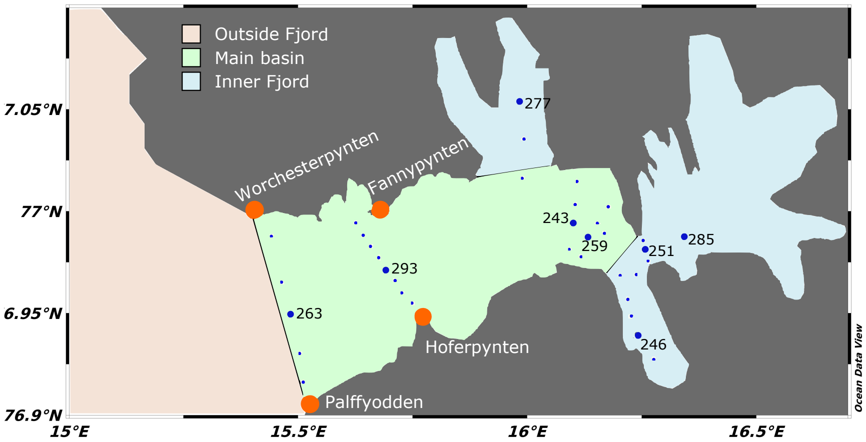
Transects and station positions

The positions of the CTD profiles taken by IOPAS followed four transects (Figure 4.1). The sections and number of stations taken by IOPAS varied from year to year. The only section taken every year is the section along the axis of the fjord, from the inner part of the fjord (Brepollen) to outside of the fjord mouth, reffered to as the Long-section. This section is almost identical for all years except in 2006 when the transect had a more southerly direction at the western part of the section (marked by a dashed line in Figure 4.1). The Inner-section cross Burgerbukta and then the main basin, the Mid-section goes from Fannypynten into Gåsebukta and the Outer-section goes across the fjord axis, outside of the fjord mouth, as defined by the line between between Worchesterpynten and Palffyodden. Three areas of the fjord are defined. The Inner-fjord comprise Brepollen, Burgerbukta, and Samarinvågen. The Main basin has its borders defined by the borders of the Inner-fjord and the fjord mouth and the Outside-fjord area comprise the stations taken outside of the fjord mouth. The different areas are indicated by colored shadings in Figure 4.1.

The position the sections and the CTD stations taken by UNIS in September 2013 and 2014 are shown in Figure 4.2. The Long-section are to resemble the Long-section from July in the best possible manner, with the stations that were available. In addition to the Long-section, a section following the Long-section, but then deviaties into the eastern bay of Burgerbukta is defined as the Burgerbukta-section. The sections are shown in Figure 4.2. The areas defined for the July data is used for September 2013 and 2014 as well, in addition to certain indicated stations.



(a)



(b)

Figure 4.2: Map showing the position of the stations (indicated by blue dots) and the transects used for the data collected with R/V Håkon Mosby in September 2013 (a) and September 2014 (b). The Long-section and the Burgerbukta-section is indicated by a red and a green line, respectively. The three defined areas, the Inner-fjord, Main basin, and Outside-fjord area are indicated by blue, green, and pink shadings, respectively.

5 Methods

This chapter describes how the calculations of the FWC and the contributions from MW, SIM, and SW in Hornsund was done and how the reference and endmember values were chosen.

5.1 Calculation of freshwater content

A change in salinity S for an observed water body with an initial given salinity will be a result of mixing with either fresher water or more saline water, if the salt exchange between the atmosphere and the ocean surface and salt diffusion in the ocean is considered negligible (Korhonen et al., 2013). The addition of freshwater to a water body decrease the salinity and to calculate the freshwater content (FWC), the measured salinity relative to a reference salinity (S_{ref}) is integrated over the water column, as shown in Equation 2,

$$FWC = \int_z^0 \frac{S_{ref} - S}{S_{ref}} dz \tag{2}$$

where FWC represents the height of the freshwater portion of the water column, S_{ref} is the reference salinity, S is the measured salinity and z is the depth. Equation 2 is then discretizised to calculate the FWC from the data set. All data points with salinities above the reference salinity is considered to have no freshwater and is excluded from the calculation to avoid negative contributions to the freshwater content calculation. The salinity measurements were given with a vertical spacial distribution of one meter, thus the discretizised depth integration are done by doing a sum operation on each salinity profile, resulting in the following equation:

$$FWC = \sum_{z=z_0}^{n} \frac{S_{ref} - S_n}{S_{ref}} \tag{3}$$

where FWC is the calculated height in meters [m] of pure freshwater in the profile, S_{ref} is the reference salinity, S_n is the measured salinity of point n in the profile, and z_0 is the depth to which the integration is done, i.e. where $S = S_{ref}$ or the bottom of the fjord. The plots of FWC distribution each year were made by using weighted average interpolation in Ocean Data View (Schlitzer, 2015).

Definitions of regions in the fjord

To quantify certain aspects concerning the distribution of the freshwater, the averaged FWC was calculated for three different areas. These are defined as: The Inner fjord, which encompass Brepollen, Burgerbukta, and Samarinvaagen, the Main basin, and the Outer part, which is defined as the part of the Long-section outside of the fjord mouth, as defined by the arbitrary line between Worchesterpynten and Palffyodden (See map in Figure 4.1). There are different amounts of data available for different years/months, for instance the availability of data from Burgerbukta and Samarinvaagen in the July data are poor and since it is desired to be able to do a valid comparison between different years, only the Long-section data are being used for these calculations in July. In the September data, the FWC is calculated for all regions mentioned above, except the Outside-fjord area.

5.1.1 Reference salinity

To be able to do these calculations, an appropriate reference salinity (S_{ref}) for Hornsund must be found. Two reference salinities was used in this study. There are multiple approaches to find a suitable reference salinity for Hornsund. The possible approaches considered here are: 1) The winter conditions in the fjord, 2) The water masses on the shelf, and 3) Reference salinities previously used for FWC calculations in the Arctic Ocean.

The winter conditions in the fjord

The freshwater input to fjords on Spitsbergen has large seasonal variations (Hagen et al., 2003) and the freshwater contribution during the winter season can be considered negligible compared to the total annual freshwater influx. Indeed, in the compiled data of seasonal freshwater influx to Brepollen presented in Weslawski et al. (1995), only 6‰ of the total annaual freshwater input were reported to be discharged into the fjord prior to June (see Section 3.1.6). In addition to this, Alkire et al. (2015b) suggested that the residence time of freshwater in fjords on Spitsbergen were short and that almost all the freshwater were flushed out of the fjords prior to the freezing season. It can therefore be argued that the winter conditions would be a good initial state representation of a fjord on West Spitsbergen before the onset of the seasonal freshwater influx to the fjord. The best measure of the winter conditions in the fjord available are data collected along the Mid-section in April 2012 and May 2011 and 2013 (Figure 5.1). Prominska et al. (prep) suggested that winter conditions were prevailing to May or June in Hornsund and taking the freshwater flux estimations by Weslawski et al. (1995) mentioned above into account, this should prove a valid representation of the winter conditions. Figure 5.1 shows some influence of mixing with freshwater in 2012 and 2011 and these data points are not consirered. There are clearly interannual variations in the spring hydrography of the fjord

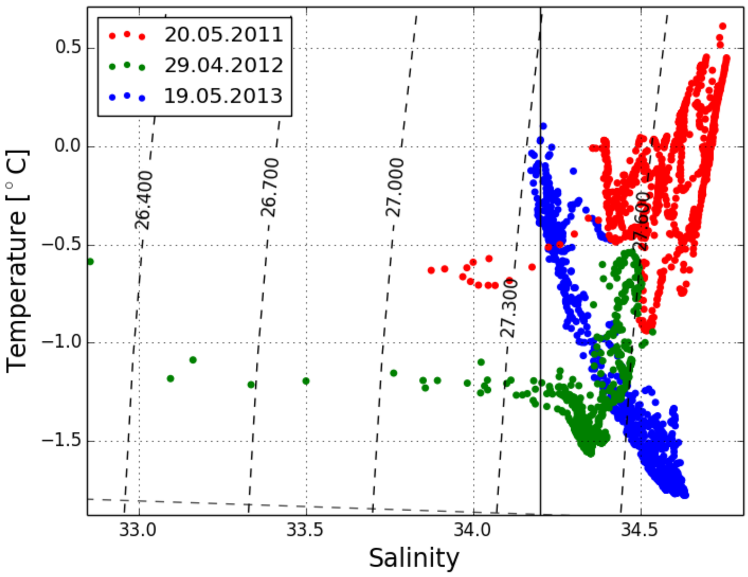


Figure 5.1: The temperature and salinity relashionship for April/May in the years 2011-2013 at the Mid-section

and it could be argued that the reference salinity should be determined independently for each year based on the spring hydrography. However, it is desired to use only one reference value, since several years are to be compared and hydrographical data from spring are not available for most of the years. If the spring hydrography is to represent a fjord without freshwater, a freshwater calculation should yield approximately zero FWC for all these years, and based on this argument the reference salinity is chosen to be 34.2. Another aspect that leads towards this choice, is the fact that this is a suitable value for examination of FWC in the surface layer, as the 34.2 isohaline is lying in the pycnocline for July in all the years. This is seen in Figure 5.2 which shows depth profiles at the intersection point between the Mid-section and the Long-section in July.

The water masses on the shelf

Another possible approach for choosing a good reference value is to consider the water masses present at the shelf during summer, as these water masses usually replace the water masses present in spring below the surface layer (Prominska et al., prep). There are two possible water masses entering the fjord, this is ArW carried by the SCC or AW carried by the WSC, or a mixture of these two and/or terrestial freshwater input from land (Section 2.2). The ArW has by the definitions used in this study a salinity ranging from 34.0-34.8, and is considered to be a water mass that has been affected by freshwater input in the Barents Sea and Storfjorden due to sea ice melt and terrestial freshwater sources. To include the freshwater contribution in the SCC, it would be suitable to use the properties of AW as the second reference salinity, as this is the least modified, most saline water mass that can possibly enter the fjord. Weslawski et al. (1991) and Beszczynska-Möller et al. (1997) used a reference salinity based on the least modified water mass present at

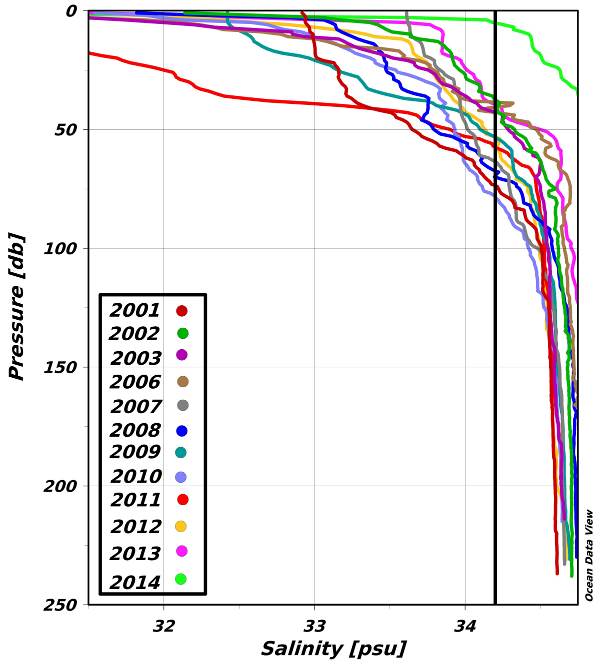


Figure 5.2: Salinity profiles from the station at the intersection point between the Long-section and the Mid-section (see Figure 4.1) for July in the years 2001-2014. The chosen reference salinity of 34.2 is marked by a black vertical line.

the shelf, disregarding the reduced salinity of the ArW carried in the SCC and determined this salinity to be 35.23. However, this salinity was not found in the shelf waters during the years 2001-2014, and the second reference salinity used in this study will be based on the lower limit of AW in the water mass definitions presented in Table 2.1 and is thereby set to be 34.9. As will be seen in the following paragraph, this reference salinity does also have a higher conformity with the reference values used in previous studies in the Arctic Ocean.

Reference salinities previously used for FWC calculations in the Arctic Ocean

Reference values used for FWC calculations in the Arctic that was found in the litterature, has mainly been used for large scale calculations in the Arctic Ocean. These are summarized in the following paragraph, as well as a short description of what they were used for. All the reference values mentioned and where they were used are presented in Table 5.1.

Aagaard and Carmack (1989) established a freshwater budget for the Arctic Ocean and the Nordic Seas and used a reference salinity of 34.8 for the Arctic Ocean and a reference salinity of 34.93 for the Nordic Seas based on the mean salinity value in these seas. Zhang and Zhang (2000) did a ocean/sea-ice model to examine heat and freshwater budgets and pathways in the Arctic and used a reference salinity of 34.8. Dickson et al. (2007) investigated freshwater flux through Arctic and subarctic seas and used two reference salinities to calculate freshwater flux. These were 34.8 to comform with existing literature and 35.2 which should represent the inflow of Atlantic Water to the Arctic.

Table 5.1: **Reference salinities previously used in the Arctic**

Region	Value	Used by
Arctic Ocean	34.8	Aagaard and Carmack (1989)
Nordic seas	34.93	Aagaard and Carmack (1989)
Hornsund	35.23	Weslawski et al. (1991)
Arctic Ocean	34.8	Zhang and Zhang (2000)
Arctic Ocean	34.8	Dickson et al. (2007)
Arctic Ocean	35.2	Dickson et al. (2007)
East Greenland Current	35.0	Nilsson et al. (2008)
Arctic Ocean	34.8	McPhee et al. (2009)
Beaufort Gyre	34.8	Proshutinsky et al. (2009)
Arctic Ocean	35.0	Rabe et al. (2011)
Beaufort Gyre	34.7	Giles et al. (2012)
Arctic Ocean	34.9	Korhonen et al. (2013)

Nilsson et al. (2008) investigated liquid freshwater transport and polar surface water characteristics in the East Greenland Current and used a reference salinity of 35.0. McPhee et al. (2009) examined the rapid change in the freshwater content of the Arctic Ocean and used a reference salinity of 34.8. Proshutinsky et al. (2009) investigated the freshwater reservoir of the Beaufort Gyre and calculated the changes in freshwater content of the water column bounded by the 34.8 isohaline, and used this as a reference salinity value. Rabe et al. (2011) examined the Arctic Ocean freshwater content changes from the 1990s to the 2006-2008 period and used a reference salinity of 35.0 to calculate the freshwater content. Giles et al. (2012) investigated how the wind-driven spin-up of the Beaufort Gyre affected freshwater storage, and used a reference salinity of 34.7. Korhonen et al. (2013) examined time and space variability of freshwater content in the Arctic Ocean from 1991 to 2011, they choosed a reference salinity of 34.9, based on the salinity of the Fram Strait outflow.

5.1.2 The total volume of freshwater

The total freshwater content, i.e. the volume of pure freshwater in the fjord (FWC$_{total}$), was calculated by averaging the height of the freshwater column (FWC) for different areas and multiplying this averaged value with the topical area. The areas used for these calculations are defined in Figure 4.1. The FWC of the Outside fjord area was neglected in this calculation, as this region is by our definition outside of the fjord and does not have a well defined area. The resulting equation used to estimate the total volume of freshwater in the fjord is given in Equation 4,

$$FWC_{tot} = \overline{FWC}_{Main} \cdot A_{Main} + \overline{FWC}_{Inner} \cdot A_{Inner} \tag{4}$$

where FWC_{tot} is the total freshwater content, $\overline{FWC}_{Main} \cdot A_{Main}$ is the averaged height of the freshwater column multiplied with the area of the Main basin, and $\overline{FWC}_{Inner} \cdot A_{Inner}$ is the average height of the freshwater column multiplied with the area of the Inner fjord.

The two areas were estimated to be 151 km^2 and 152 km^2 for the Inner fjord and the Main basin, respectively, based on a satelite image from July 2009. This adds up nicely to the estimation of the total area of the fjord by Błaszczyk et al. (2013) of 303 km^2. In the July data, only the Long-section data was used, as this is the only section that was taken each year. In the September data, these calculations were based on station 246, 277, and 285 for the Inner fjord, and 243, 251, 259, 263, and 293 for the Main basin (see Figure 4.2).

5.2 Calculation of the contributions from Meteoric water, Sea ice meltwater, and Seawater

The freshwater in Hornsund can have multiple origins and two specific freshwater sources has been defined: Meteoric water (MW) and Sea Ice Meltwater (SIM). These two fresh source waters are mixed with a third endmember, reffered to as Seawater (SW). As described in Section 3.2, the use of oxygen isotopes together with salinity should prove a suitable method to calculate the fractional contributions from MW, SIM, and SW in the fjord.

5.2.1 Calculation of the fractions of the source waters

To determine the contributions from each of the three source waters, a method presented by Östlund and Hut (1984) was used. The method requires simultaneous solving of three equations and the two tracers δ^{18}O and salinity. The equations are the mass balance, salt balance, and $\delta^{18}O$ balance of the topical water body. This gives the following set of equations:

$$f_{SW} + f_{SIM} + f_{MW} = 1 \tag{5}$$

$$f_{SW}S_{SW} + f_{SIM}S_{SIM} + f_{MW}S_{MW} = S_{observed} \tag{6}$$

$$f_{SW}\delta^{18}O_{SW} + f_{SIM}\delta^{18}O_{SIM} + f_{MW}\delta^{18}O_{MW} = \delta^{18}O_{observed} \tag{7}$$

where Equation 5 is the mass balance, Equation 6 is the salt balance, and Equation 7 is the $\delta^{18}O$ balance. The fractions of SW, SIM, and MW are represented by f_{SW}, f_{SIM}, and f_{MW}, respectively. S_{SW}, S_{SIM}, and S_{MW} are the endmember salinity value of SW, SIM, and MW, respectively. $\delta^{18}O_{SW}$ is the endmember $\delta^{18}O$ value of SW, $\delta^{18}O_{SIM}$ is the $\delta^{18}O$ endmember value for SIM, and $\delta^{18}O_{MW}$ is the endmember $\delta^{18}O$ value of MW. Solving these equation with known endmember values of the source water masses, gives the contribution from each of the source waters at given point. This can be done by eliminating f_{SW} and f_{SIM} from Equation 7, which gives the fractional contribution of MW in the data point,

$$f_{MW} = \frac{O_{observed} - O_{SIM} + (\frac{S_{SIM}-S_{observed}}{S_{SW}-S_{SIM}}) \cdot O_{SW} + (\frac{S_{observed}-S_{SIM}}{S_{SW}-S_{SIM}}) \cdot O_{SIM}}{O_{MW} - O_{SIM} + \frac{S_{SIM}}{S_{SW}-S_{SIM}}O_{SW} - \frac{S_{SIM}}{S_{SW}-S_{SIM}}O_{SIM}} \tag{8}$$

The SW fraction can then be calculated by eliminating f_i from Equation 6 which gives,

$$f_{SW} = \frac{S_{observed} - S_{SIM} + f_{MW} S_{SIM}}{S_{SW} - S_{SIM}} \tag{9}$$

And the SIM fraction is then calculated from Equation 5,

$$f_{SIM} = 1 - f_{SW} - f_{MW} \tag{10}$$

Sea ice can act as both a source of freshwater during melting and a sink during freezing due to brine release. Even though the total end product of freezing and melting of sea ice is concervative, these two processes can be decoupled in both space and time and result in a net contribution at the time and point of measurement. The SIM contribution can show both positive and negative solutions due to melt and formation of sea ice, respectively (Macdonald, 2000). The negative contribution from SIM is an analogue to net salinification of the water mass due to brine release (Östlund and Hut, 1984). Negative values for SW and MW are not meaningful and could indicate erraneous endmember values.

To solve the equations to calculate the fractional contribution from the different sources, appropriate source values have to be found. MW has a significantly reduced δ^{18}O value in the Arctic due to the depletion of ^{18}O during poleward atmospheric transport, and has a salinity of 0. The SIM has a reduced salinity due to salt expulsion during freezing but is also affected by a small positive fractionation in the δ^{18}O, resulting in sea ice having a higher δ^{18}O than the water mass from which it was formed (Macdonald et al., 1995). The reported increase in δ^{18}O as water freeze is varying slightly (e.g. Macdonald et al., 1995, 1999; Frew et al., 2000; Alkire et al., 2015b), but lies within the borders of +1.6‰ to +2.8‰. In estuaries, the water mass that the sea ice is formed by is usually a mixture of the MW endmember and the SW endmember. The δ^{18}O and salinity properties of the sea ice varies depending on this mixing ratio (Macdonald, 2000). In Figure 5.3 the SIM endmember is defined as ice formed of pure SW, thus any ice in the topical estuary is to be regarded as a two component mixture of ice formed by MW and ice formed by SW and can exhibit properties dictated by the mixing line between the SIM endmember, and the MW endmember. The theoretical mixing lines between the three endmembers are shown in Figure 5.3.

If there are only MW and SW in the mixture of a water body, a linear fit can be applied to the data points. The zero salinity intercept of this linear fit would correspond to the MW endmember value and the equation for the linear fit would resemble the equation for the theoretical mixing line beteen these source waters (Alkire et al., 2010). However, sea ice melt and sea ice formation changes the properties of the underlying water masses and confounds this two endmember model. When SIM is added to the system, points are pushed up and left, as the SIM has a significantly reduced salinity and an increased δ^{18}O value due the above mentioned fractionation when sea ice forms (Macdonald, 2000). Correspondingly, when sea ice is formed, points in the δ^{18}O-salinity space is pushed down and right, due to the high salinity and lower δ^{18}O value in the released brine. The effect of brine release to the underlying water mass can, by pushing the points to the right in δ^{18}O-salinity space, result in highly negative intercepts when a linear mixing line is applied (Alkire et al., 2010). The effect of SIM on the other hand has the opposite effect,

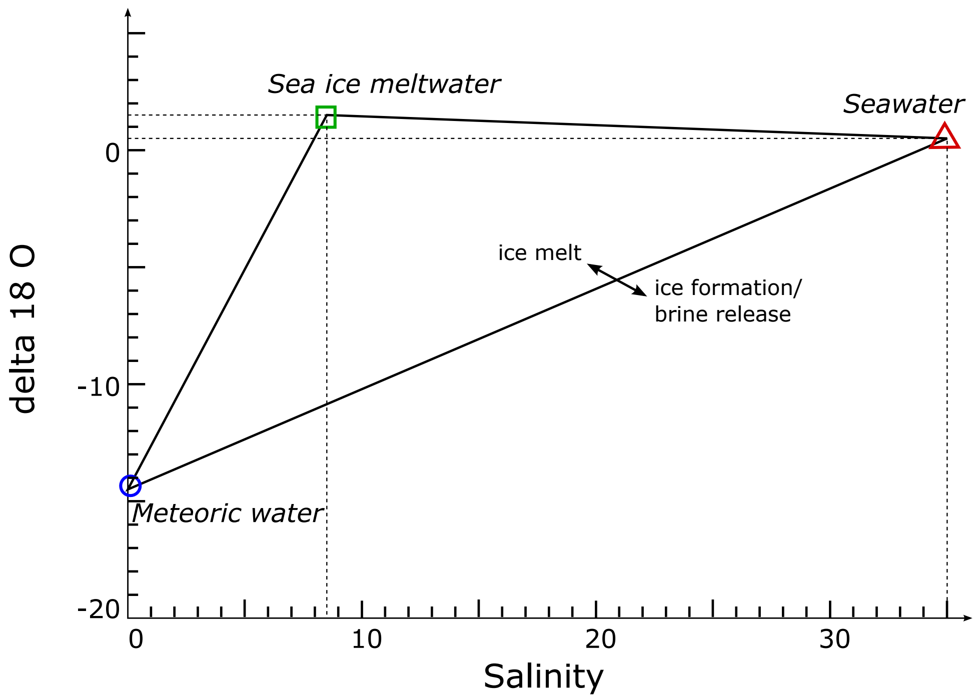


Figure 5.3: Concept figure showing the δ^{18}O and salinity properties of the three water masses, MW, SIM, and SW. The reference values and their theoretical mixing lines are shown by dotted and purple lines, respecively. The effect of sea ice formation and melt is shown by the double arrow across the mixing line between MW and SW.

resulting in a more positive zero salinity intercept when a linear fit is applied. Thus, the extrapolation of a linear mixing line to zero salinity is not a valid method to determine the isotopic composition of the MW endmember when sea ice formation/melt occurs (Granskog et al., 2011) and both the above mentioned processes can result in non-linear mixing lines in the δ^{18}O-Salinity space (Alkire et al., 2010).

An uncertainty analysis was applied to the calculations, due to the fact that the endmember values had to be chosen based on relatively few measurements and that they can vary significantly both seasonally and spacially. The uncertainty analysis was based on a Monte Carlo approach (see e.g. Ayyub and McCuen, 2003; Cohen and Cohen, 2008), similar to what used in Alkire et al. (2015a). The endmember values were randomly selected within the uncertainty range of each endmember value, and calculated 10000 times to provide 10000 MW, SIM, and SW fractions for the complete dataset (n=396) resulting in a $3\times396\times10000$ matrix (3 water type fractions, 396 data points, and 10000 values at each data point for each water type fraction). The average value and standard deviation for the three water masses was then calculated based on the results of all the iterations at each data point, giving a 4×396 matrix containing the fractional values and the standard deviation at each data point. The average of the standard deviation was used as an estimate of the uncertainty.

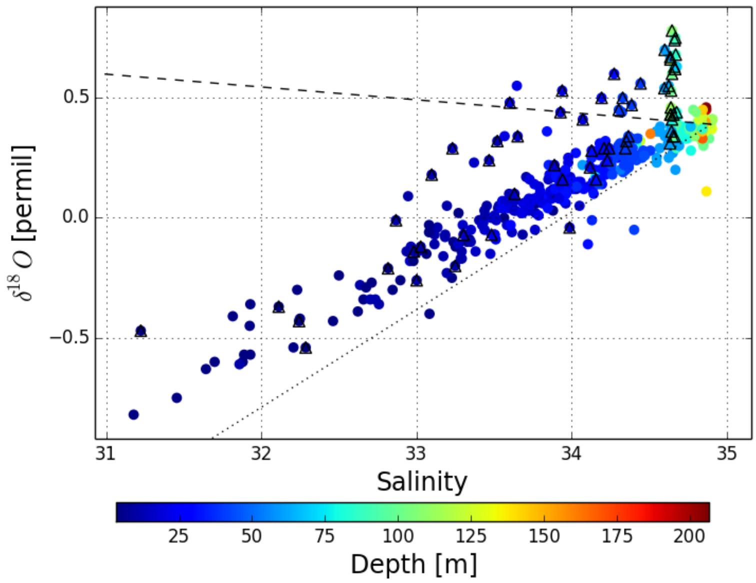


Figure 5.4: The δ^{18}O-Salinity relashionship for Hornsund in September 2013. Triangles represents measurements from Brepollen. The color of the marks indicates the depth of the measurments. The dotted line represents the theoretical mixing line between the SW endmember and the MW endmember and the dashed line represents the theoretical mixing line between the SW endmember and the SIM endmember.

5.2.2 Endmember values for meteoric water, sea ice meltwater and seawater

The determination of the endmember values is partly based on the interpretation of the δ^{18}O-salinity relashionship in Hornsund and isotopic measurements of sea ice and sources of MW.

Determination of endmember salinity and δ^{18}O value for meteoric water

MW is defined as a combination of water derived from precipitation, river-runoff, and glacial ablation/calving. The determination of the $\delta^{18}O$ endmember value for MW is challenging as it comprise both precipitation that has fallen during different times of the year and glacial melt, which can have different isotopical compositions. In an area without sea ice, the δ^{18}O value of the MW endmember could be determined by extrapolating a linear fit to the data in δ^{18}O-salinity space to zero salinity (See section 5.2.1). However, this is not suitable in Hornsund, as this would discount the presence of SIM. Hence, the determination of the MW endmember should be based on performed oxygen isotope measurements in river water, precipitation and glacier ice. Measurements of river water in Hornsund were done during summer 2014 in Lisbethelva and Fuglebekken and showed an average value of -8.90‰. Unfortunately, measurements of precipitation and glacier ice in Hornsund is not available and to determine a suitable combined endmember value for MW in Hornsund we must turn to litterature.

The canonical δ^{18}O value for MW in the Arctic Ocean has been set to -18.8‰ (Alkire et al., 2010), but there are significant regional variations (as seen in e.g. Macdonald et al., 1995; Azetsu-Scott and Tan, 1997; MacLachlan et al., 2007), depending on the properties of the topical drainage basin, such as glacier cover, amount of river runoff and topography. In addition to this, the δ^{18}O in precipitation exhibits large seasonal variations. Dansgaard (1964) stated that temperature is a main control on the δ^{18}O values in precipitation and that the average value of δ^{18}O in precipitation can be described by a linear relationship. The linear $\delta^{18}O$-temperature relashionship for Longyearbyen was investigated by Humlum (2005), based on precipitation data collected in November-December 1999 and is presented in Equation 11,

$$\delta^{18}O = 0.575T_s - 12.12‰ \tag{11}$$

where T_s is the surface temperature. The values presented in Humlum (2005) ranged between -30‰ and -5‰ and had an average of -14.75‰. Monthly precipitation data from Ny-Ålesund in Kongsfjorden (see map in Figure 1.1) showed δ^{18}O values varying between 5.23‰ to -22.93‰ during the years 1990-2002, with an average value of -11.55‰ (MacLachlan et al., 2007). The lower average value reported in Longyearbyen can at least partly be attributed to the seasonal variations, as the data presented in Humlum (2005) was collected in months that has lower average temperatures than the annual mean temperature.

Glacial meltwater is derived from water that has been stored over a certain period of time, and transported from a certain elevation. As temperature decrease with altitude, the δ^{18}O values of glacier ice can vary, depending on the altitude at which the ice was formed and also depending on the age of the ice (MacLachlan et al., 2007). Oxygen isotopes in glacier ice has been measured in Kongsfjorden (MacLachlan et al., 2007; Alkire et al., 2015b) and Billefjorden (a branch of Isfjorden) (Alkire et al., 2015b). MacLachlan et al. (2007) obtained several measurements of δ^{18}O in glacier ice in Kongsfjorden, which showed an average value of -15.85‰, with a range of -17.69‰ to -14.62‰. The samples collected by Alkire et al. (2015b) showed a δ^{18}O value of -15.0‰ in glacier ice collected in Kongsfjorden and -15.9‰ in Billefjorden.

Due to the fact that there are considerable differences in the δ^{18}O values of precipitated water, river-runoff, and glacier ice, the contributions from the different sources to the fjord should be taken into account. MacLachlan et al. (2007) did this and found the combined δ^{18}O value for MW in Kongsfjorden to be -14.69‰, based on an estimation of the annual input from precipitation and glacier meltwater by Svendsen et al. (2002), and the isotopic composition of these two freshwater sources. They also found good agreement between the estimated value for MW based on hydrological data and the δ^{18}O value at the zero salinity intercept of the linear regression line in δ^{18}O-salinity space, based on oceanographical data, which showed a value of -14.35‰.

As no measurements were taken of glacier ice in Hornsund, the value of -15.85‰ for glacier ice from MacLachlan et al. (2007) will be used for glacial meltwater, since Kongsfjorden has a closer resemblance to Hornsund in topography and proximity to the coast, compared to Billefjorden. Weslawski et al. (1995) stated that 70% of the freshwater influx to Hornsund was from glacial ablation (see Section 3.1). Since the Hornsund drainage basin has undergone significant changes due to retreating glacier fronts the last 25 years (Błaszczyk et al., 2013), this number must be treated with some caution, however, it is the best measure of the relative freshwater contribution from glacial melt versus precipitation and river-runoff available. The river water that was used, was collected in rivers with non-glacier origins and can be assumed to contain precipitated water or snow melt and no glacier meltwater. Using the δ^{18}O value of -15.95‰ for glacier ice from MacLachlan et al. (2007), the measured δ^{18}O of river water in Hornsund of -8.90‰, and the fractional value for freshwater flux from glaciers in Weslawski et al. (1995) of 70%, the combined MW value for Hornund was calculated to be -13.8‰ (Table 5.2). The uncertainty in this value is significant, as it is based on multiple assumptions, measurements from other drainage basins, and the fact that it can vary spacially in the fjord, depending on what the dominent source of MW is at the measuring site. A range of $\pm$7.0‰ is therefore applied for the uncertainty analysis of the estimation of the contribution from MW in Hornsund.

Determination of endmember salinity and $\delta^{18}O$ value for sea ice meltwater

The SIM in Hornsund has two possible origins: It can be the result of the melting of locally produced sea ice, or it can be SIM or sea ice that melts locally, which has been carried in the SCC and then advected into the fjord from the shelf. The SIM from locally produced sea ice and the sea ice/SIM that is carried in the SCC can have different values for both δ^{18}O and salinity, due to the fact that the sea ice produced in the different regions is formed from different water masses.

The best solution of finding the δ^{18}O-salinity properties of the locally produced sea ice is to measure the values directly, however, there are no δ^{18}O values of sea ice available for Hornsund. Ice in an estuary may be formed by both MW and SW or (usually) a mixture of these two water masses, and the δ^{18}O and salinity properties of the sea ice in estuaries may vary, depending on the amount of MW and SW contained in the ice. However, Alkire et al. (2015b) did an analysis of MW content in sea ice in different fjords on Spitsbergen, which showed small influence of meteoric water ($\simeq$4‰) in most cores. From these results, Alkire et al. (2015b) suggested that the MW is flushed out before the onset of ice formation in fjords on Spitsbergen. If this can be assumed to be the case for Hornsund as well, the results from Alkire et al. (2015b) is probably the best measure to indicate a suitable endmember value for SIM in Hornsund. The results from Alkire et al. (2015b) showed that the average salinity of these cores were 8.5 with a standard deviation of 1.8 for all cores, except one core from Tempelfjorden which had a significant outlier value for δ^{18}O. The averaged δ^{18}O value for these cores was 1.4‰ with a standard deviation of 0.3‰. These measured values of δ^{18}O and salinity in sea ice will be used as the SIM endmember value in Hornsund (Table 5.2). However, for the uncertainty analysis, two standard deviations will be applied instead of one, due to the fact that these measurements were done in other fjords on Spitsbergen and that some of the SIM in Hornsund may be derived from sea ice or SIM carried by the SCC.

Determintation of endmember salinity and $\delta^{18}O$ values for Seawater

In the application of δ^{18}O isotopes in this study, it is desired to be able to detect SIM contained in the SCC that can enter the fjord. Hence, the endmember salinity value should represent the least modified version of AW that can possibly enter the fjord. From the temperature-salinity relashionship in September 2013 (Figure 5.5) it can be seen that

Table 5.2: **Endmember values**

Water mass	δ^{18}O[‰]	**salinity**
Meteoric water	-13.80±7.20	0.0
Sea-ice meltwater	1.40±0.60	8.5±3.6
Sea water	0.37±0.24	34.85±0.5

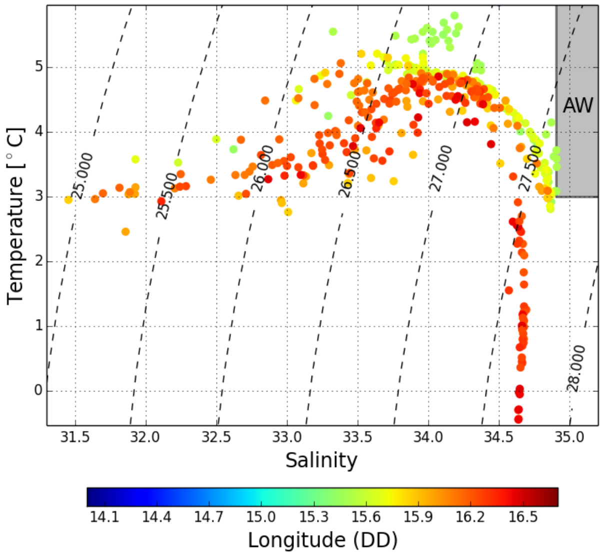


Figure 5.5: The temperature-salinity relashionship in September 2013 for the data points where δ^{18}O were measured. The colors of the marks represents the longitude of the measurement, thus high longitude marks represents measurements taken in the innermost part of the fjord.

AW is present at the fjord mouth and TAW has entered the fjord. Based on these data, the salinity of the SW endmember is chosen to be 34.85±0.5. The averaged δ^{18}O value corresponding to this salinity is 0.37‰, with values ranging from -0.05 to 0.78 and with a doubled standard deviation 0.24, which is used as the range of uncertainty (Table 5.2).

6 Results

The FWC and estimated contributions from MW, SIM, and SW in Hornsund are presented in the following chapter. The FWC is presented in Section 6.1 and the contribution from the different source waters are presented in Section 6.2.

6.1 Freshwater content

The FWC was calculated for the years 2001-2014 (except 2004 and 2005) as described in Section 5.1, based on data collected by IOPAS with R/V Oceania (July) and UNIS with R/V Håkon Mosby (September). The FWC are presented in two ways: FWC distribution and total freshwater volume (FWC_{total}). In addition to this, salinity profiles at the intersection points between the cross-sections and the Long-section are presented for July 2001. These profiles were taken at almost the exact same position, with relatively short measuring intervals and are included to examine variations at small time scales.

6.1.1 FWC distribution

The calculations of FWC were done with two reference salinities: 34.2 and 34.9. However, only the results from the calculations done with a reference salinity of 34.2 are used to describe the distribution of FWC in the fjord. If the reference salinity is set to 34.9, the distribution of FWC is in general similar, however, the FWC is higher and the distribution shows more freshwater in the deeper parts of the fjord compared to the more shallow parts. This is due to the fact that this reference salinity incorporates larger parts of the water column, hence the change in FWC between the calculations done with the two reference values is largest where the water column is deep.

The FWC in Hornsund changes from year to year, but usually varies from about 0 to about 2 meter, depending on whether it is a year with high or low FWC (Figure 6.1 and Figure 6.2). The year 2011 strikes out as a special year, with considerably larger amounts of freshwater compared to the other years. The highest recorded FWC in Hornsund was found this year, in the inner part of the Main basin with a FWC of 4.23 meter. The spacial variations, i.e. the difference between the highest and lowest recorded FWC within Hornsund in a single year do also vary, from less than 0.5 meter in 2007, to about 2.5 meter in 2011.

It can also be seen that there are usually more freshwater in the inner parts of the fjord than the outer parts. To quantify this difference, the mean FWC for the three previously defined areas; the Inner fjord, the Main basin, and the Outside fjord area (Figure 4.1) and the difference between the averaged FWC in the Inner fjord area and the Outside fjord area was calculated (reffered to as the I-O value, Table 6.1). In most years, the Inner fjord had highest FWC (Table 6.1, the highest values are highlighted in red) and in the other years, the Main basin had highest FWC. The largest difference between the FWC in Inner fjord and the Outside fjord area was found in 2003, when the difference between the Inner fjord and the Outside fjord area was 1.52 meter. In 2001 and 2009, the I-O values are negative, which means that the Inner fjord had lower averaged FWC than the Outside fjord area in these years. In September, there are no values in the Outside fjord area, as no stations were taken in this area in September.

A north-south variation can be seen in most of the years, when cross-fjord sections were taken (Figure 6.1 and 6.2). The Mid-section was taken in all years except 2006 and 2007 and generally show cross-fjord variations with more freshwater at the northern side of the fjord, compared to the southern side. This is also the case for the results from September 2013 and September 2014. The largest difference was found in 2011, when the northernmost station at this section had a FWC of 4.10 meter compared to 2.74 meter at the southernmost station. For the years with Outer-section data from July, a north-south variation is observed in 2003, 2010, 2011, and 2013. The difference between the northernmost and southernmost station in this section was about 0.5 meter in 2003, 2010, and 2013 and about 1 meter in 2011, with more freshwater on the northern side. In the other years, this difference was less than 0.2 meter and in 2002 it was slightly more freshwater at the southern side compared to the northern side (Figure 6.1). There was a north-south variation in September 2013 and September 2014 as well, with a FWC of about 0.7 meter at the northern side and about 0.2 meter on the southern side of the section taken across the fjord mouth, in both years (Figure 6.2).

The changes in FWC that took place between July and September is different in 2013 than in 2014 (Figure 6.2). In 2013, the FWC in both the Inner fjord and the Main basin showed higher FWC in July than in September. During this time interval, the averaged FWC was decreasing from 1.35 meter to 0.74 meter in the Inner fjord and from 0.77 to 0.58 meter in the Main basin. In 2014, the FWC was increasing from July to September in both the Inner fjord and the Main basin, from 0.64 meter to 0.95 meter in the Inner fjord and 0.36 to 0.47 meter in the Main basin (Table 6.1).

6.1.2 Variations on small time scales

At the intersection points between the cross-sections and the Long-section (Figure 4.1), there were stations taken at almost exactly the same position with measuring intervals ranging from a few hours to days. These stations can provide information on how fast the

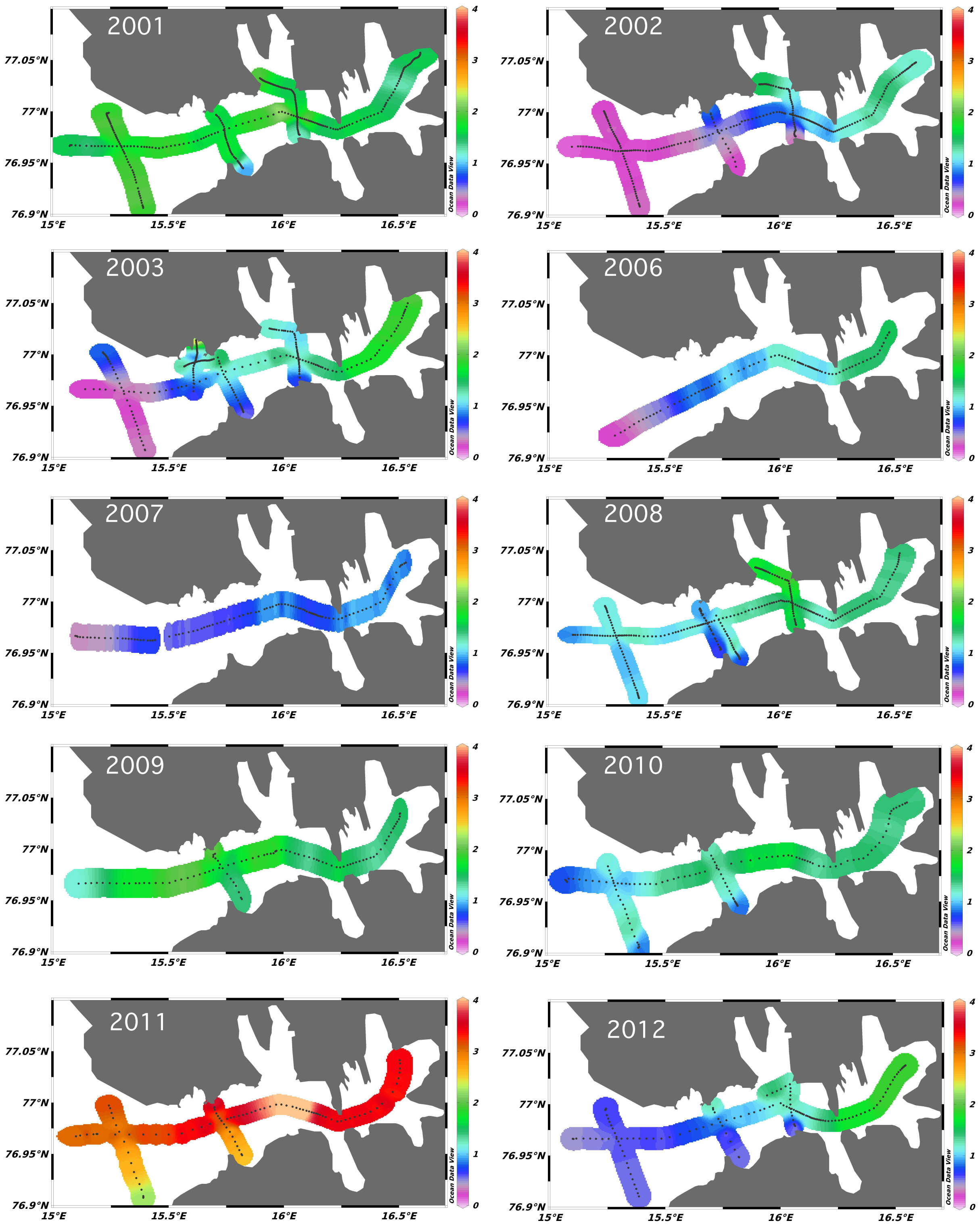


Figure 6.1: Distribution of FWC in Hornsund for July in the years 2001-2012, except 2004 and 2005. Values are given in meter [m] of pure freshwater in the water column. The FWC was calculated with a reference value of 34.2.

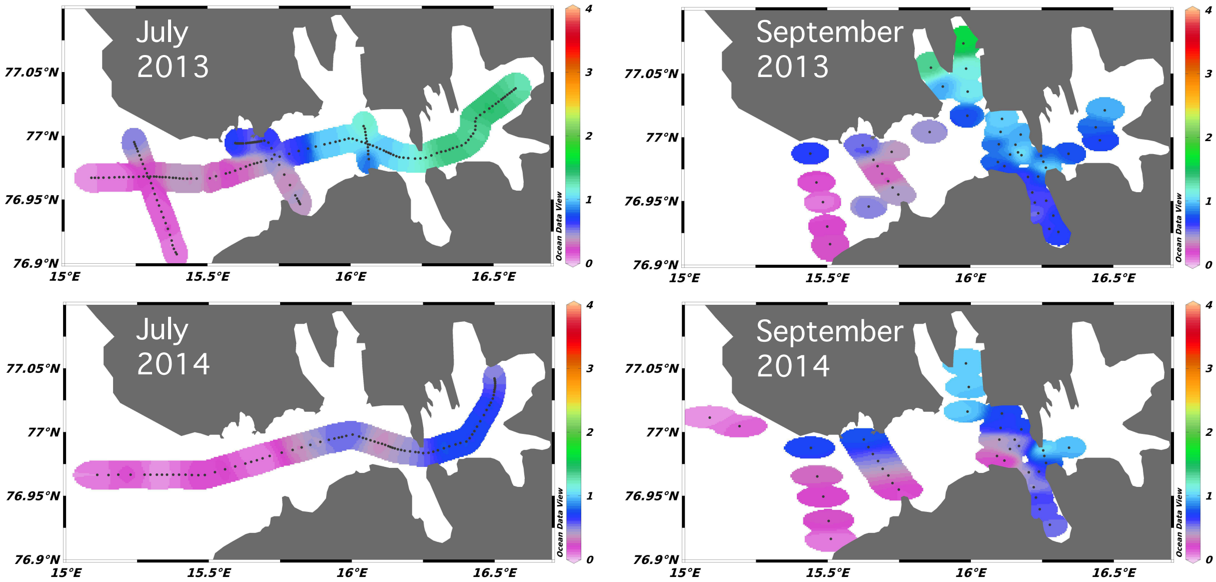
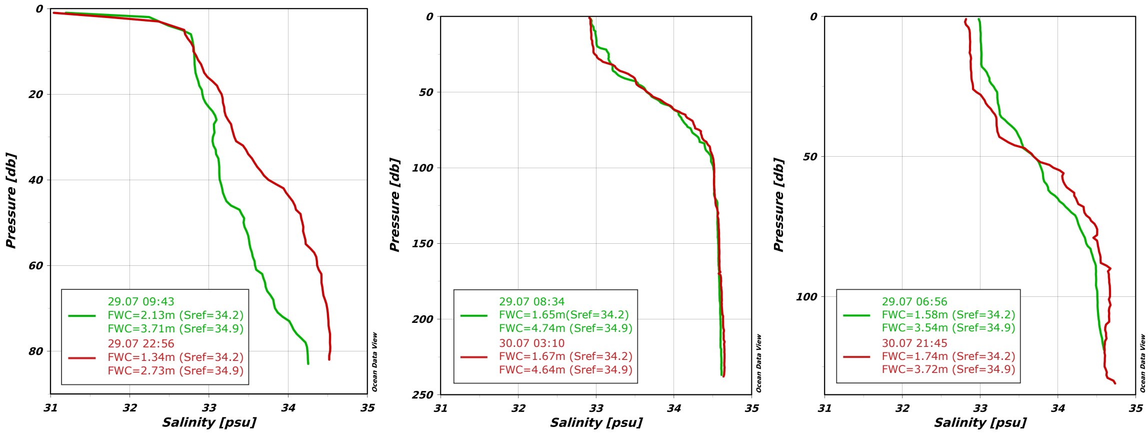


Figure 6.2: Distribution of FWC in Hornsund for July and September for 2013 and 2014. Values are given in meter [m] of pure freshwater in the water column. The calculations are based on salinity data collected by "R/V Oceania" (July) and R/V Håkon Mosby (September) and the FWC was calculated with a reference value of 34.2.

Table 6.1: Estimated averaged FWC in different areas of Hornsund

Month	Year	Outer[m]	Main[m]	Inner[m]	I-O[m]
July	2001	1.60	1.80	1.49	-0.11
July	2002	0.17	0.70	1.25	1.08
July	2003	0.28	1.18	1.80	1.52
July	2006	0.33	0.97	1.44	1.11
July	2007	0.51	0.71	0.89	0.38
July	2008	1.09	1.24	1.37	0.28
July	2009	1.54	1.67	1.42	-0.12
July	2010	0.93	1.45	1.40	0.47
July	2011	3.08	3.70	3.40	0.32
July	2012	0.52	1.12	1.81	1.29
July	2013	0.23	0.77	1.35	1.12
Sept	2013	-	0.58	0.74	-
July	2014	0.10	0.36	0.64	
Sept	2014	-	0.47	0.95	-

Averaged height of pure freshwater column (FWC) in each of the previously defined areas (Figure 4.1), calculated with S_{ref}=34.2. The areas with highest FWC are highlighted in red. I-O[m] is the averaged FWC in the Inner fjord area minus the averaged FWC in the Outside fjord area.



(a) (b) (c)

Figure 6.3: Salinity profiles at the intersection points between the Inner-section/Long-section (a), the Mid-section/Long-section (b), and the Outer-section/Long-section (c), taken at different times of the day/different days.

hydrographic conditions and hence FWC can change in the fjord. The changes in FWC were usually not that large and usually showed a change of less than 0.2 meter. However, in 2001 the changes were more significant (Figure 6.3).

At the intersection between the Long-section and the Inner-section, it can be seen that there is almost no changes in the salinity profile in the upper 10 meters, but below this depth the salinity has increased during the 13 hour interval (Figure 6.3a). The FWC at at 09:43 was 2.13 meter when calculated with S_{ref}=34.2 and 3.71 when calculated with S_{ref}=34.9, while at 22:56 the FWC was 1.34 meter for S_{ref}=34.2 and 2.73 for S_{ref}=34.9. Hence, there was a decrease in the FWC during this 13 hour interval of 0.79 and 0.98 meter for S_{ref}=34.2 and S_{ref}=34.9, respectively, at this position. Changes at the intersection point between the Mid-section and the Long-section were not significant (Figure 6.3b). At the intersection point between the Long-section and the Outer-section, there was a slight increase in the FWC of 0.16 meter for S_{ref}=34.2 and 0.18 meter for S_{ref}=34.9, during a 38 hour interval (Figure 6.3c). There was also an increase in the salinity gradient at about 50 meter, i.e. the salinity above this depth was decreasing and the salinity below this depth was increasing.

6.1.3 Total FWC

To see how the amount of freshwater in July varied between each year, the total volume of freshwater (FWC_{total}) in Hornsund was calculated for each year. The FWC_{total} is presented as the sum of the FWC_{total} in the Inner fjord and the FWC_{total} in the Main basin (Figure 6.4, Table 6.2). The calculations were done by taking the averaged FWC in the Inner fjord and in the Main basin (Figure 4.1) and multiplying each of these averages with its topical area, as described in Section 5.1.2.

In general, the FWC_{total} was varying between about 0.2 km^3 and 0.6 km^3, when a reference value of 34.2 was used and about 0.6 km^3 and 1.0 km^3 when calculated with a

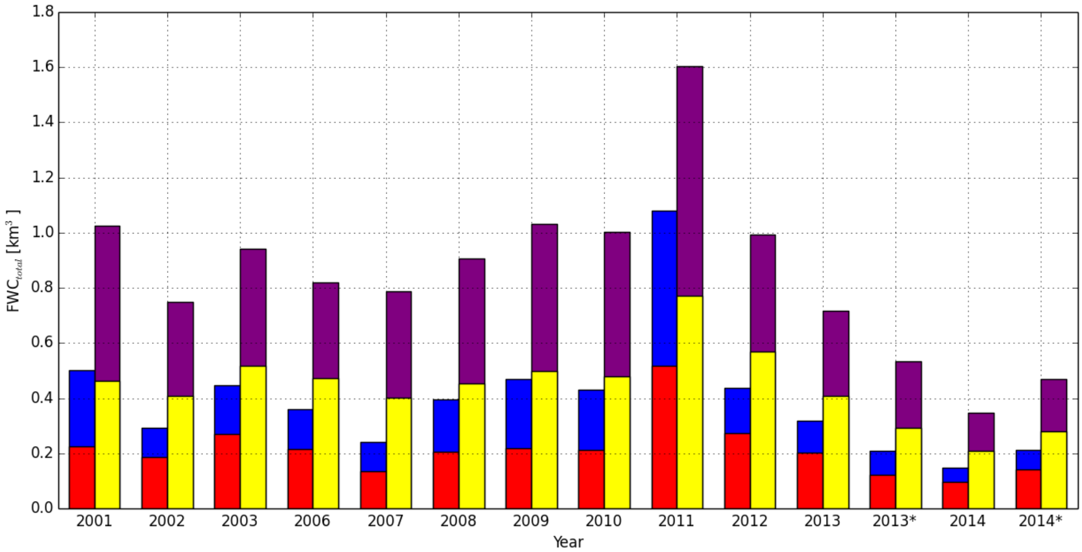


Figure 6.4: Total freshwater volume (FWC_{total}) in Hornsund based on Long-section data taken in late July and station 243, 246, 251, 259, 263, 277, 285, and 293 in September 2013 and 2014. The FWC_{total} calculated with a reference salinity of 34.2 is represented by the red and blue column and the FWC_{total} calculated with a reference salinity of 34.9 is represented by the yellow and purple column. The red and yellow part of the columns represents the FWC_{total} in the Inner fjord (Brepollen, Burgerbukta and Samarinvågen), and the blue and purple part of the columns represents the FWC_{total} of the Main basin for S_{ref}=34.2 and S_{ref}=34.9, respectively. The total height of each column represents the FWC_{total} in the whole of Hornsund. The results from September is indicated by a star (*).

reference salinity of 34.9 and the average FWC_{total} was 0.43 km^3 and 0.91 km^3 for the two reference salinities, respectively. The year with most freshwater was 2011, which showed significantly higher FWC_{total}, with a FWC_{total} of 1.08 km^3 for S_{ref}=34.2 and 1.61 km^3 for S_{ref}=34.9. The year with lowest FWC_{total} was 2014, which had a FWC_{total} of 0.15 km^3 when calculated with S_{ref}=34.2 and 0.35 km^3 when calculated with S_{ref}=34.9. The calculations with the two different reference salinities show similar variations from year to year, but the calculations done with a reference value of 34.2 naturally show lower FWC_{total} compared to the calculations done with a reference value of 34.9. The difference in FWC_{total} between the calculations done with the two reference values was varying from 0.46 km^3 and 0.57 km^3 for all the years, except 2013 and 2014, when this difference was lower. In 2013 the total FWC decreased between July and September, while it increased during the same time interval in 2014.

Table 6.2: Estimated total freshwater content in Hornsund

		$\mathbf{FWC_{tot}[km^3]}$	
Month	**Year**	$\mathbf{S_{ref}=34.2}$	$\mathbf{S_{ref}=34.9}$
July	2001	0.50	1.03
July	2002	0.30	0.75
July	2003	0.45	0.94
July	2006	0.37	0.82
July	2007	0.24	0.79
July	2008	0.40	0.91
July	2009	0.47	1.03
July	2010	0.43	1.00
July	2011	1.08	1.61
July	2012	0.45	0.99
July	2013	0.32	0.72
September	2013	0.21	0.53
July	2014	0.15	0.35
September	2014	0.21	0.47

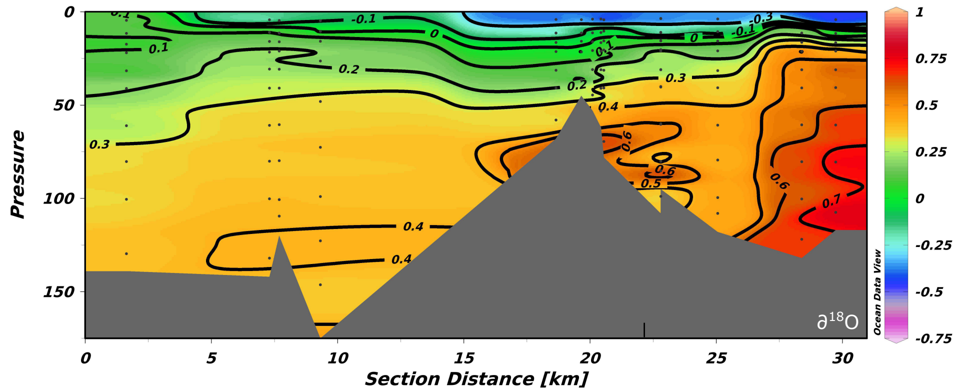
Total volume of freshwater in Hornsund based on Long-section data (see Figure 4.1) taken in late July and station 243, 246, 251, 259, 263, 277, 285, and 293 in September 2013 and 2014 (see Figure 4.2).

6.2 δ^{18}O and contributions of MW, SIM, and SW in Hornsund

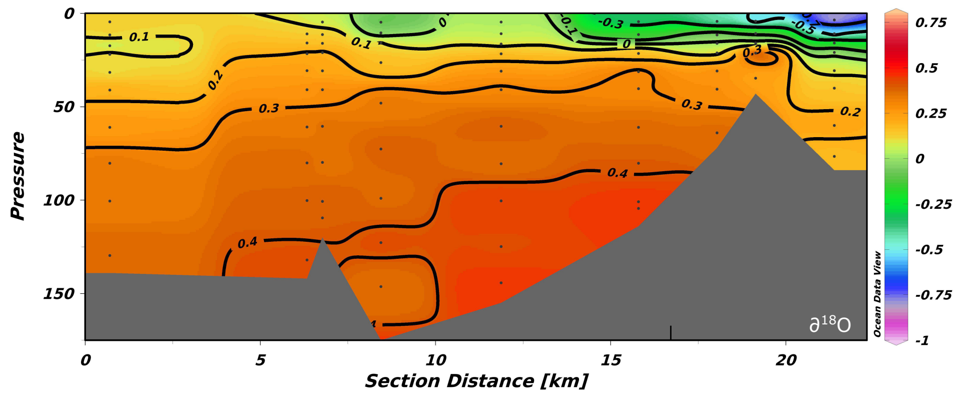
The estimations of the fractional contributions from MW, SIM, and SW was done based on water samples collected by UNIS with R/V Håkon Mosby in September 2013. The description of the method and endmember values that were used are presented in Section 5.2. The measured values of δ^{18}O are shown for the Long-section and the Burgerbukta-section, as well as salinity and δ^{18}O depth profiles and the δ^{18}O-salinity relashionship for selected stations. The calculated fractional contribution from the different freshwater sources are shown at the Long-section and the Burgerbukta-section.

6.2.1 $\delta^{18}O$ and depth profiles

The vertical distribition of δ^{18}O at the Long-section (Figure 6.5a) shows that the δ^{18}O values in the surface water increase towards the fjord mouth, from -0.47‰ at the innermost station, to positive values about 5 km from the fjord mouth. There is also a relatively strong increase in δ^{18}O with depth in Brepollen, from -0.47‰ at the surface to 0.78‰ below 100 meter at the innermost station. The rapid increase in δ^{18}O with depth in Brepollen is getting slightly less significant when moving towards the sill. There is an increase in the δ^{18}O values with depth outside of the sill as well, however, the increase with depth is significantly weaker in this region.



(a)



(b)

Figure 6.5: Vertical distribution of $\delta^{18}O$ in Hornsund, beginning of September 2013 along the Long-section (a) and the Burgerbukta-section (b). The inner part of the fjord (Brepollen/Burgerbukta) is located to the right. The entrance to Burgerbukta is located at about 17 km and the entrance to Brepollen is located at about 22 km, indicated by a black vertical line. The measuring points are marked by black dots.

In the Burgerbukta-section, the surface water values are decreasing towards the fjord mouth as well. There are even lower values in the surface layer in Burgerbukta than what observed in Brepollen, reaching -0.82‰ in the surface waters of the innermost station (Figure 6.5b). As observed in Brepollen, there is a relatively rapid increase in the δ^{18}O values with depth in Burgerbukta, however, the values do not reach as high values as observed in Brepollen and below about 40 meter the values are varying between 0.15‰ and 0.36‰.

From Figure 6.6a) it can be seen that the δ^{18}O values are similar in the surface water in Brepollen and Burgerbukta. However, in Brepollen they are increasing more rapidly with depth and at 20 meters depth the values in the two bays differ significantly, with about 0‰ in Burgerbukta and about 0.4‰ in Brepollen. At the stations in the center of the fjord mouth, the surface values are higher, but the increase in δ^{18}O with depth is weaker than in the two bays and shows similar values as what observed in Burgerbukta from 40 meters and down to the bottom.

The salinity in the surface water are lower in Burgerbukta and Brepollen compared to the stations at the Mouth-section. There is a significant increase in salinity with depth in both Brepollen and Burgerbukta and this increase is similar for the two bays in the upper 20 meters (Figure 6.6b). Below this depth, the values in the innermost part of Burgerbukta shows lower values than what observed in Brepollen. At the center of the fjord mouth, the increase in salinity with depth is weaker and below 20 meter, the salinity at the fjord mouth shows similar values as what observed in Brepollen.

The δ^{18}O-Salinity relashionship for the three areas (Figure 6.6c), shows that most values lies above the mixing line between SW and MW. The δ^{18}O values in Brepollen shows generally higher values than in the two other areas. In Burgerbukta and at the fjord mouth, the values follows a linear trend with a slightly gentler slope than the theoretical mixing line between SW and MW. However, in Brepollen, the high salinity values lies on an almost vertical line in δ^{18}O-salinity space, with δ^{18}O values above the endmember δ^{18}O value for SW. From this vertical line, there is a similar linear trend as seen for Burgerbukta and at the center of the fjord mouth.

6.2.2 Contributions of MW, SIM, and SW

Figure 6.7 and 6.8 show the percentage contributions from MW, SIM, and SW, at the Long-section and the Burgerbukta-section, respectively, for September 2013. The uncertainty of the calculation had an average of ±0.9% for MW with a maximum of ±2.9%, ±1.2% for SIM with a maximum of ±3.8%, and ±0.4% for SW with a maximum of ±1%. The uncertainty was in general highest in the surface water of Brepollen and Burgerbukta. There was also relatively high uncertainties at depth in Brepollen, with about ±1% for MW, ±1.4% for SIM, and ±0.5% for SW.

From the Long-section, it can be seen that the amount of MW is decreasing in the surface water towards the fjord mouth, from 6% in the innermost part of the section to about 2% at the fjord mouth (Figure 6.7a). In Brepollen, the amount of MW are decreasing rapidly with depth and reach a negative contribution already at a depth of about 30 meter. Negative contributions from MW are not meaningful (see Section 5.2.1) and some of the MW found at depth in Brepollen are outside of the uncertainty range.

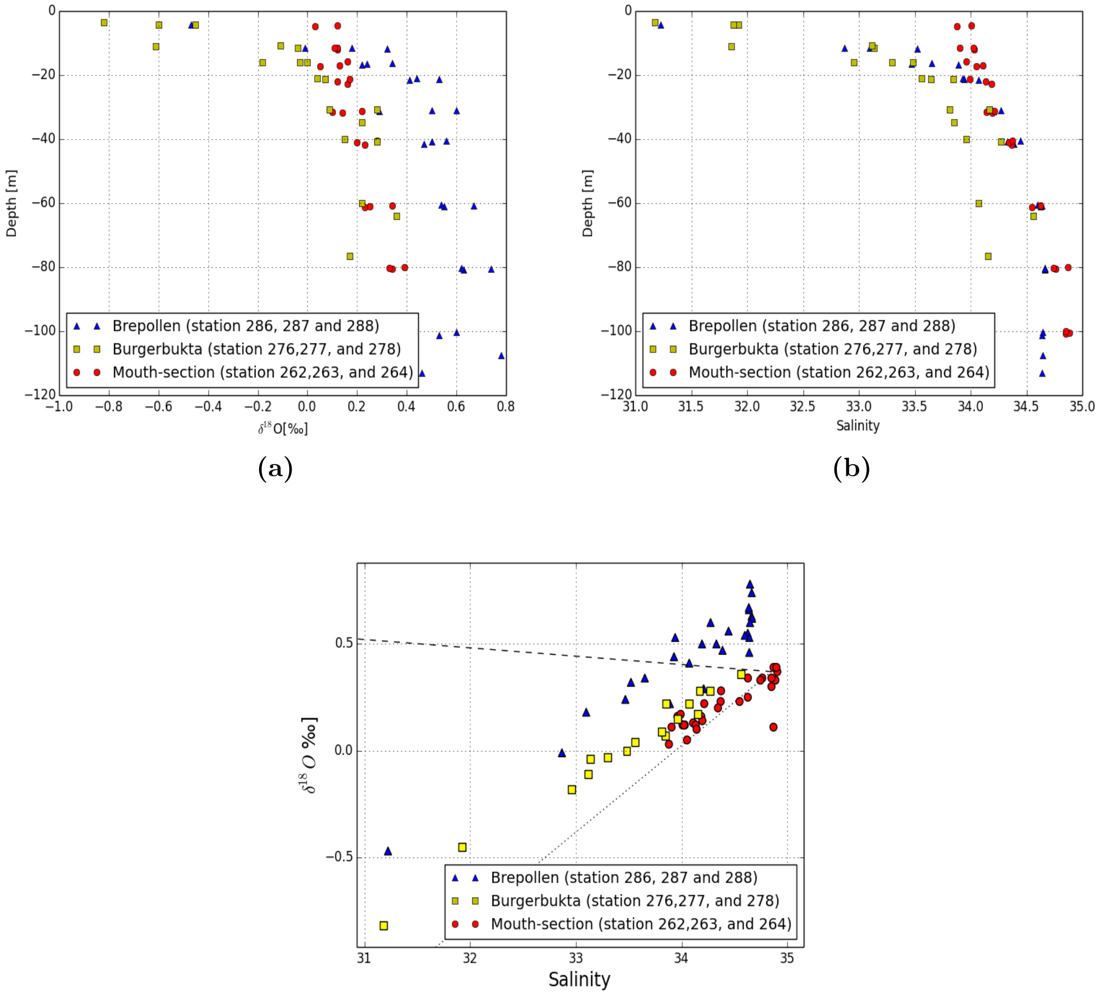


Figure 6.6: Depth profiles of δ^{18}O (a) and salinity (b) and the δ^{18}O-Salinity relashionship (c) in Brepollen, Burgerbukta, and the three station in the center of the fjord mouth (see Figure 4.2 for the position of the stations). The dashed line represents the theoretical mixing line between SW and SIM and the dotted line represents the theoretical mixing line between SW and MW.

Further out, in the Main basin, the contribution from MW is higher below 25 meters than in Brepollen and the 1% contribution line is found at 50 meters in the Main basin, compared to about 25 meters in Brepollen. There are slightly negative contributions of MW below 100 meters in the Main basin, but these are all within the uncertainty range.

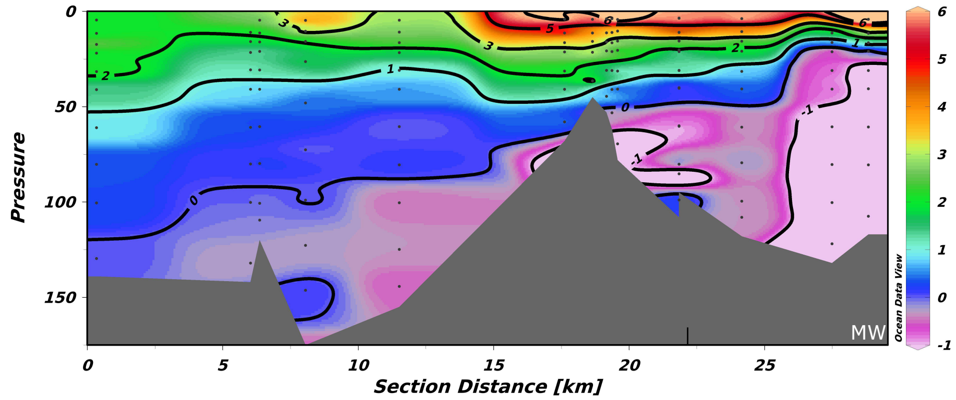
The contributions from SIM are highest in the innermost part of the Long-section, where the whole water column shows much higher SIM content than the rest of the fjord (Figure 6.7b). The highest contributions was found both in the surface water and at approximately 100 meter depth with a contribution of 4.5%. However, the uncertainty of the SIM estimations at the measuring point in the surface water are relatively large, with a value of $\pm 2.8\%$, compared to the uncertainty at 100 meters which shows an uncertainty of $\pm 1.4\%$. The SIM contribution is relatively uniform with depth in the whole area inside of the sill, but are decreasing horizontally from the innermost part of the section towards the sill. There are in general less SIM in the areas outside of the sill and at the fjord mouth there are almost no SIM at all.

The amount of SW in the upper 30 meters has a wedge-like shape, with increasing amounts of SW when moving towards the fjord mouth in the surface water (Figure 6.7c). In the innermost part of the Long-section, the 97% contribution line is found at a depth of about 30 meter, whereas at the fjord mouth the amount of SW is above 97% at the surface. The lowest amount of SW are found in the surface water at innermost part of the section, with a contribution of 88.5%. The amount of SW increase with depth and in the Main basin the contributions of SW are above 99% below about 50 meters. In the innermost part of Brepollen, the values are slightly lower below this depth. Below 90 meters at the fjord mouth there is no influence of freshwater at all (SW=100%).

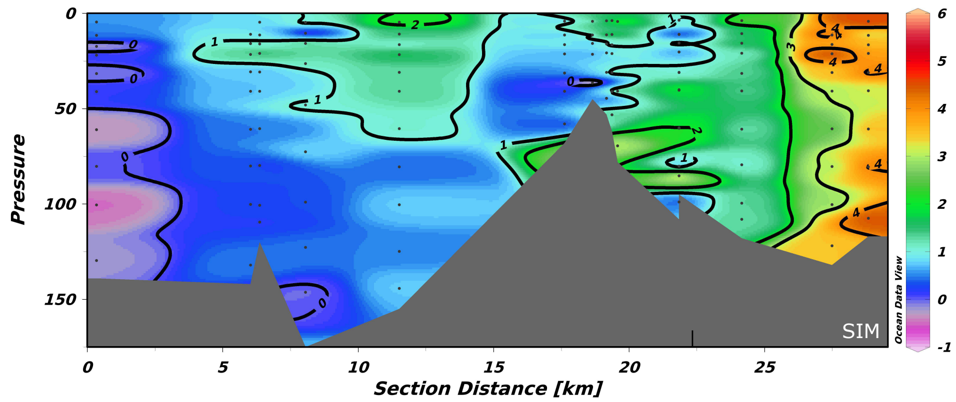
In the Burgerbukta-section (see map in Figure 4.2), the amount of MW is highest close to the surface of the innermost part of the section, with contributions reaching 9.5% at the innermost station (Figure 6.8a). The amount of MW in the surface water is decreasing horizontally when moving out of Burgerbukta to the Main basin and reach a contribution of about 2% at the fjord mouth. There is a relatively rapid decrease in the MW contribution with depth also in Burgerbukta. However, this decrease is significantly weaker than what observed in Brepollen and the contributions of MW at the innermost station of the Burgerbukta-section show values above 1% throughout the water column, with no negative values.

The contribution of SIM is less prominent in Burgerbukta compared to Brepollen (Figure 6.8b). The surface water contains around 2% of SIM, while below 60 meter the contribution was found to be 0.5%. The highest amount of SIM observed in this section was found close to the surface at the station just outside of the bay, where the SIM contribution was 3.2%.

As observed in the Long-section going into Brepollen, the amount of SW in the Burgerbukta-section are lowest close to the surface of the innermost part of the section, with a minimum value of 89.1% at the innermost station (Figure 6.8c). The distribution of SW has a similar shape as observed in the Long-section, with increasing contributions in the surface water towards the fjord mouth and higher amounts of SW with increasing depth througout the section. Behind the small sill in the innermost part of Burgerbukta, the amount of SW is lower than in the Main basin, with contributions varying between 97.5% and 97.9% below 50 meters, compared to above 99% in the Main basin.



(a)



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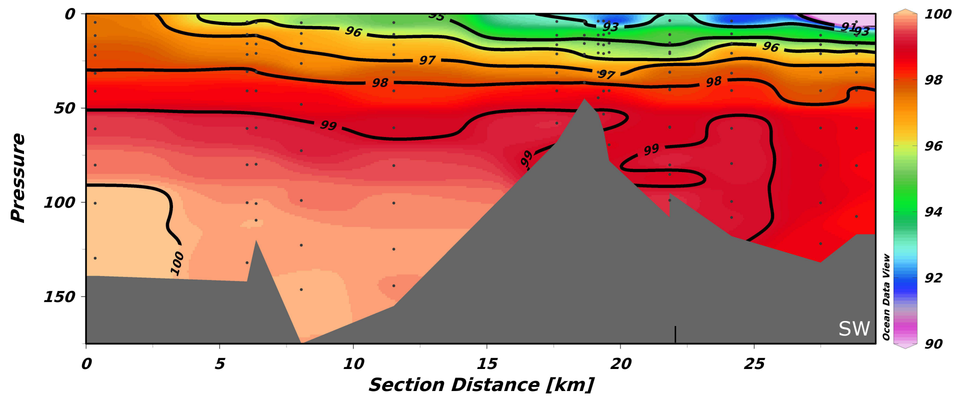
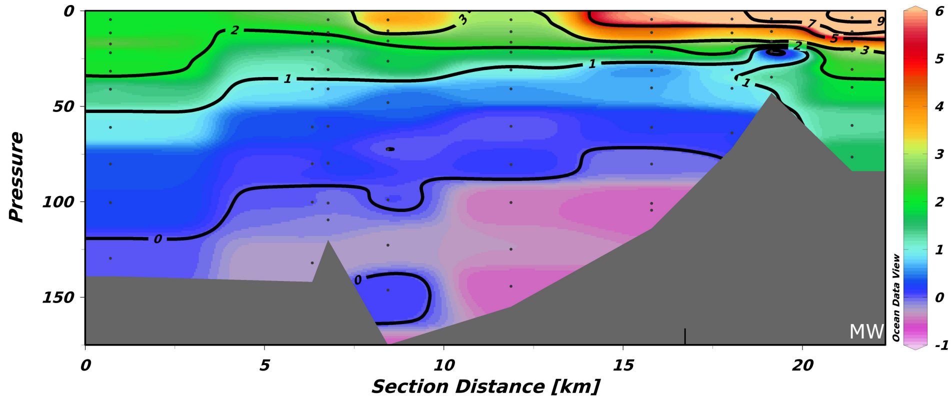


(c)

Figure 6.7: Percentage contribution from meteoric water (a), sea ice meltwater (b), and seawater (c) at the Long-section in Hornsund, September 2013. Brepollen is located to the right and the fjord mouth is located to the left. The endmember values used in the calculations are presented in Table 5.2. The measuring points are marked by black dots. The entrance to Brepollen is located at about 24 km, indicated by a short black vertical line.



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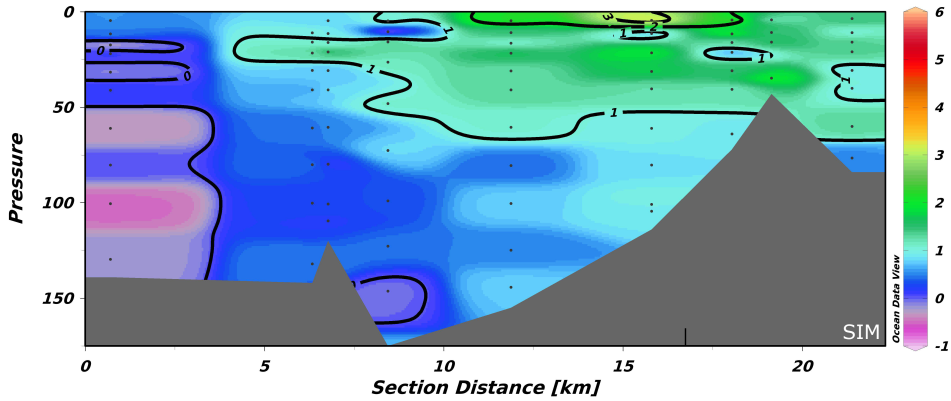

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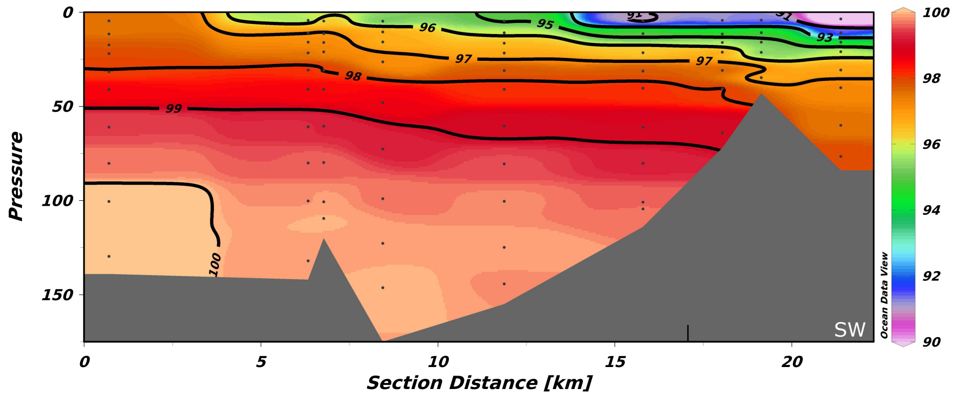


(c)

Figure 6.8: Percentage contribution from meteoric water (a), sea ice meltwater (b), and seawater (c) at the Burgerbukta-section in Hornsund, September 2013. Burgerbukta is located to the right and the fjord mouth is located to the left. The endmember values used in the calculations are presented in Table 5.2. The measuring points are marked by black dots. The section follows the Long-section to about 12 km and the entrance to Burgerbukta is located at about 17 km, indicated by a short black vetical line.

7 Discussion

The following chapter will discuss the different factors that may affect the freshwater content in Hornsund as well as the contributions from MW, SIM, and SW.

7.1 Freshwater content in Hornsund

There are three features of the freshwater content distribution that will be discussed. These include the in-fjord/out-fjord variation, the cross-fjord variation, and the changes from July (mid-summer) to September (autumn). Additionally, the changes at small time scales will be described further and the interannual variations in the FWC_{total} of the fjord will be discussed. To more easily be able to do this, the main results from the FWC calculations are summarized in Table 7.1, in addition to information on the inflowing water masses from the shelf, atmospheric parameters, and the DFI index for the different years. The atmospheric parameters are based on data collected at the weather station in Isbjørnhamna (see map in Figure 2.1), retrieved from the Hornsund GLACIO-TOPOCLIM database.

Table 7.1: FWC in Hornsund and paramteres that may affect the total FWC and distribution of FWC

			FWC$_{tot}$[km^3]		AW/TAW			Atmospheric conditions					Sea ice
Year	**Month**	**I-O[m]**	**S_{ref}**	**S_{ref}***	**T_{max}[^{o}C]**	**S_{max}**	**D_{min}[m]**	**PDD_L**	**PDD_S**	**P[mm]**	**U_d**	**$\overline{U^2}$[(ms^{-1})^2]**	**DFI**
2001	July	-0.11	0.50	1.03	-	-	-	186	95	-	out	28.0	54.3
2002	July	1.08	0.30	0.75	1.54	34.71	173.0	236	116	-	in	4.3	53.6
2003	July	1.52	0.45	0.94	-	-	-	185	93	-	in	12.7	53.5
2006	July	1.11	0.37	0.82	3.20	34.82	65.3	214	94	35.8	in	1.4	25.8
2007	July	0.38	0.24	0.79	-	-	-	183	85	11.0	out	6.9	40.1
2008	July	0.28	0.40	0.91	1.93	34.74	148.0	180	88	25.2	out	2.5	49.8
2009	July	-0.12	0.47	1.03	-	-	-	215	107	2.8	out	32.8	51.4
2010	July	0.47	0.43	1.00	-	-	-	148	79	-	out	3.1	47.4
2011	July	0.32	1.08	1.61	-	-	-	189	78	-	in	14.6	44.9
2012	July	1.29	0.45	0.99	-	-	-	160	96	7.6	in	13.4	2.0
2013	July	1.12	0.32	0.72	2.24	34.81	97.0	227	109	50.4	in	3.6	47.0
2013	Sept.	-	0.21	0.53	4.07	34.87	75.0	340	54	68.3	out	21.5	47.0
2014	July	0.54	0.15	0.35	4.49	34.93	29.7	224	112	33.9	in	0.5	0.4
2014	Sept.	-	0.21	0.47	3.98	34.92	44.0	305	45	11.0	in	0.7	0.4

FWC$_{tot}$[km^3] is the total volume of freshwater in the fjord, calculated with a reference salinity of 34.2 (S_{ref}) and 34.9 (S_{ref}*). I-O[m] is the averaged FWC (in meters of pure freshwater) in the Inner fjord area minus the average FWC of the Outside fjord area (as defined in Figure 4.1). T_{max}[^{o}C]) is the maximum potential temperature and S_{max} is the maximum salinity for AW/TAW (S>34.7,T>1.0^{o}C) and are obtained from a CTD station at the intersection between the Mid-section and the Long-section. D_{min} refferes to the minimum depth where the TAW or AW was present. In years with no values neither TAW nor AW present at the station at the time of measurement. PDD_L and PDD_S is the Positive Degree Day sum for two months and three weeks prior to the measuring dates, respectively. P[mm] is the total precipitation three weeks prior to the measuring period. U_t[d] and $\overline{U^2}$[(ms^{-1})^2] is the wind direction and averaged squared wind speed of the along fjord wind component for the three days prior to the measuring dates. The atmospheric data is retrieved from the weather station at Isbjørnhamna. The sea ice (DFI) data is data based on satellite image analysis (Muckenhuber et al., prep).

7.1.1 The distribution of freshwater in Hornsund

There are two main findings in the distribution of FWC that will be discussed, these are the in-fjord/out-fjord variation and the north/south variation. Additionally, the rapid changes in the FWC that occured in the inner part of the Main basin in 2001 will be further described.

The in-fjord/out-fjord variation

The observations showed a general trend of more freshwater in the inner parts of the fjord compared to the outer parts (Figure 6.1 and 6.2). This can be explained by the fact that the freshwater influx from land is largest in the inner parts of the fjord and that the inner bays of the fjord has a relatively smaller area compared its associated drainage basin (Figure 3.1). Additionally, the outer parts of the fjord are more prone to inflow of seawater from the shelf that can dilute the freshwater.

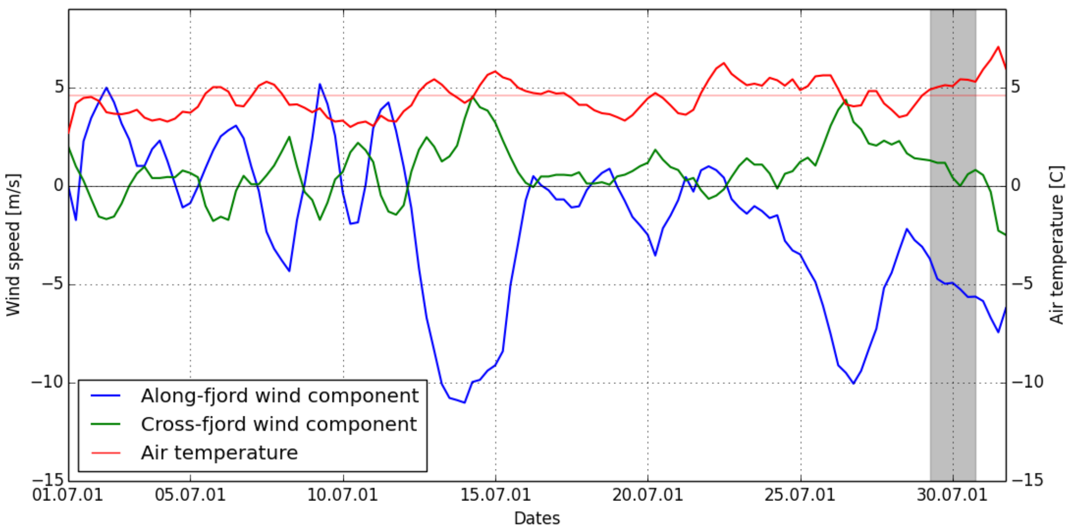
Even though the Inner fjord showed higher FWC than the outer parts of the fjord in most years, there are interannual variations in the magnitude of this difference. The I-O values, i.e. the averaged FWC in the Inner fjord minus the averaged FWC in the Outside fjord area, were generally positive. However, in 2001 and 2009, there was higher averaged FWC in the Outside-fjord area than in the Inner fjord, with negative I-O values (Table 7.1, highlighted in red in). These two years were also years with considerable wind forcing and both years had strong out-fjord winds prior to and during the measuring period. Wind data from July 2001 (Figure 7.1a), showed consistant out-fjord winds from the 23rd of July that lasted beyond the measuring period (29-30th of July). This wind event has probably induced a wind driven flow, that has resulted in an increased advection of freshwater out of the fjord. The fact that there was higher averaged FWC in the Outside fjord area compared to the Inner fjord area this year, indicates that the advection of freshwater out of the fjord was larger than the terrestial freshwater influx to the Inner fjord. The upper 50 meters of the water column was also relatively well mixed (Figure 6.3), which fits well with the depiction of a fjord that has been under the influence of significant wind stress, as this probably has enhanced the vertical mixing in the fjord.

The wind event in 2009 started closer to the measuring period than the wind event in 2001 and had an onset about 1 day before the measuring period (Figure 7.1b). Previous studies on fjords on Svalbard have shown that the response time to wind forcing on the surface layer flow can be almost instant (e.g. Skarðhamar and Svendsen, 2010). The fact that the fjord showed similar in-fjord/out-fjord variation in FWC in 2009 as in 2001 already after about 1 day of wind forcing, indicates that the response time of the surface layer flow to wind forcing is rapid also in Hornsund.

The results from the years 2001 and 2009 indicates that out-fjord winds can significantly change the in-fjord/out-fjord distribution in Hornsund and that the response time can be almost instant. The wind forcing applied to the ocean surface can be approximated by using a bulk formula for the wind stress as shown in Equation 12 (Smith, 1988),

$$\tau = \rho_{air} C_D U_{air}^2 \tag{12}$$

where τ is the wind stress, ρ_{air} is the density of air, C_D is a drag coefficient and U_{air} is the wind speed at a certain reference height. The only varying parameter in this



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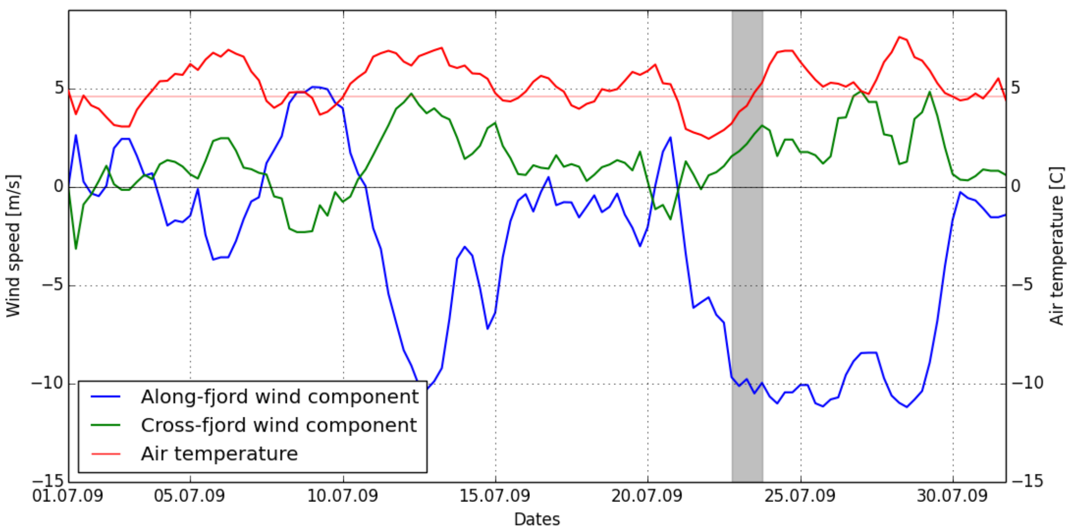


(b)

Figure 7.1: Weather data for July 2001 (a) and July 2009 (b) from the weather station at Isbjørnhamna, retrieved from the Hornsund GLACIO-TOPOCLIM database. The measuring period is marked by the shaded area. Positive values indicates in-fjord winds or winds from the southern border of the fjord for along-fjord component and cross-fjord component, respectively. The red horizontal line represents the averaged air temperature in July for the years 2001-2014. The gray shaded area represents the measuring period. The data is smoothened by using a running mean function with a period of 24 hours.

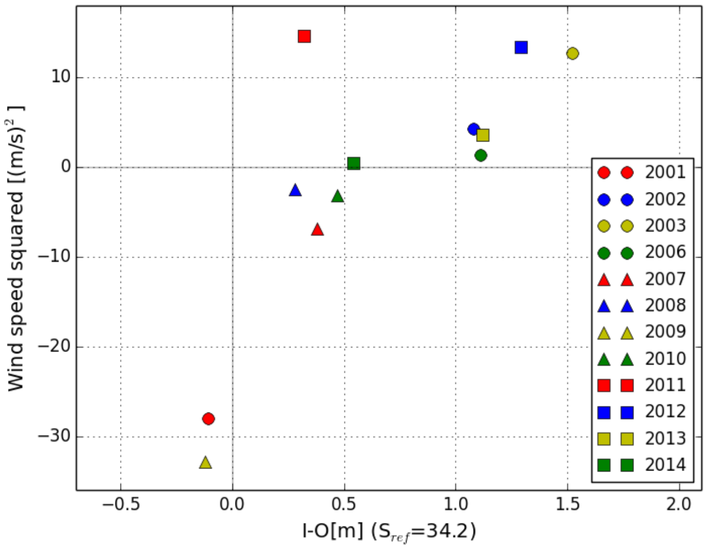


Figure 7.2: Averaged squared along fjord wind component from the three days prior to the measuring period each year and the difference between the averaged FWC in the Inner fjord and the Outside fjord area (I-O) (see Table 7.1 for exact values). Negative values for the averaged squared wind represents out-fjord winds and positive values represents in-fjord winds.

approximation to the wind stress is the wind speed. To investigate the effect of wind stress on the I-O variation in the fjord for all the years, the averaged squared along fjord component of the wind velocity for the three days prior to the measuring period are calculated for each year (Table 7.1). From Figure 7.2 it can be seen that there are in general a relatively good correlation between the variations in the along fjord wind stress and the variation in the I-O values for the different years. When the wind forcing has been in-fjord, the I-O values are in general higher and when the wind forcing has been out-fjord, the I-O values are usually lower. The most significant deviation from this relashionship is the year 2011, which was a year with a relatively low I-O value despite in-fjord wind stress prior to the measuring period. This can be explained by the inflow of sea ice and sea ice meltwater from the shelf, which occured prior to the measuring period in 2011. This will be further discussed in Section 7.1.2.

Significant wind events are numerous in Hornsund, and the prevailing wind direction in Hornsund is easterly (Section 3.1). The winds are enhanced by the east-west angle of the fjord axis, resulting in quite strong winds with more than 40 days with wind speeds > 15 ms^{-1} each year on average (Styszynska, 2013). The in-fjord/out-fjord variation in FWC in Hornsund seems to be strongly related to wind forcing and due to the numerous significant wind events, wind forcing is suggested as a crucial factor for the distribution of freshwater in the fjord. Alkire et al. (2015b) suggested that the residence time for freshwater in fjords on West Spitsbergen was low and that most of the freshwater was flushed out prior to ice formation in late autumn. Taking the strong seasonal variations in freshwater input to fjords on West Spitsbergen into account (Section 3.1) and the increasing number of significant wind events in autumn, the low residence time suggested by Alkire et al. (2015b) may well be explained by the increased advection of freshwater out of the fjord during these wind events.

North-south variation

A north-south variation in the distribution of FWC are shown in most years when cross-section data were available, with usually higher FWC towards the northern border of the fjord (Figure 6.1 and 6.2). There are two factors that can contribute to the explanation of this feature. The first is the fact that the northern part of the drainage basin to Hornsund is larger and has a higher degree of glacial coverage than the southern part of the drainage basin (Figure 3.1). A larger drainage basin collects more precipitation, due to the larger area and the glaciers provides a constant freshwater flux in the summer months due to the melting of glacier ice. This probably results in a higher terrestial freshwater influx to the northern border of the fjord, compared to the southern border in the summer months.

The second factor concerns the possibility of a rotational character in the circulation of the fjord. It is often normal to characterize fjords as "wide", where rotational effects (Coriolis effect) are significant, or "narrow", where rotational effects are negligible (e.g. Stigebrandt, 1981; Farmer and Freeland, 1983). Whether rotational effects are important or not is dependent on the width of the fjord and the stratification and will therefore vary with seasonal variations in the hydrography of the fjord. One way to determine whether the circulation in the fjord is influenced by rotational dynamics, is to compare the width of the fjord with the internal Rossby radius of deformation (see e.g. Cushman-Roisin and Beckers, 2011). The Rossby radius for fjords on Spitsbergen was estimated by Cottier et al. (2010) to be ranging from 3.5-6 km during summer/autumn, and rotational effects are shown in both Kongsfjorden (Svendsen et al., 2002) and Isfjorden (Nilsen et al., 2008). Calculations based on a rough two layer approach to the vertical density distribution in July during the years 2001-2014 in the Main basin of Hornsund, showed a Rossby radius ranging from ~2 km to ~6 km (based on f=1.45·10^{-4} s^{-1}, 5 m<$H_{surface}$ <60 m, 110 m<H_{low} <170 m, and 1.0 kgm^{-3} < $\Delta\rho$ <2.2 kgm^{-3} for the different years). This is lower than the width of the Main basin, which has a width varying between ~6 km and ~10 km. These calculations indicates that the circulation in the Main basin of Hornsund was affected by rotational dynamics at the time of measurement. A result of rotational dynamics is that the surface layer flow will be deflected to the right hand side relative to the direction of the flow (Cushman-Roisin and Beckers, 2011). The consequence of this is that the freshwater that enters the fjord (of which mostly is situated in the surface layer), will tend to flow along the borders of the fjord. In Hornsund which has a head to the east, the inflow will tend towards the southern border and the outflow will tend towards the northern border. The terrestial freshwater influx will increase the FWC of the inflowing current progressively as it travels along the borders of the fjord and the outflow at the northern border will thus have a higher FWC.

The effect of rotational dynamics has also an important effect when wind forcing is applied to the surface waters, as Ekman transport will push water masses to the right of the wind direction. This may be an explanation of another feature of the FWC distribution in 2001, when there was strong out-fjord winds in Hornsund (Figure 7.1a). In this year, there was relatively higher FWC in Burgerbukta compared to Brepollen, which may be explained by an intensified right trending surface current as freshwater enters the Main basin from Brepollen and an accumulation of freshwater in front of Burgerbukta. This freshwater may have acted as a barrier that could have reduce the outflow of freshwater from Burgerbukta. A similar response to out-fjord winds as hypothesized in 2001, was portrayed by Ingvaldsen et al. (2001) in the Kongsfjorden-Krossfjorden system. Ingvaldsen et al. (2001) described an increased surface layer flow during out-fjord winds, which was steered by rotational dynamics from Kongsfjorden towards the mouth of the more northern situated Krossfjorden, thereby affecting the outflow from Krossfjorden. The study by Ingvaldsen et al. (2001) was partly based on model simulations and the deployement of drifters in Kongsfjorden and Krossfjorden. The deployement of drifters outside of the mouth of Brepollen and in Burgerbukta during periods of out-fjord winds could provide useful information to investigate this hypothesis further.

The fact that the highest FWC was found in Burgerbukta in July 2001 may also be explained by a north component in the wind direction (Figure 7.1a), thus the wind direction in Burgerbukta may be more in-fjord than out-fjord, considering the north-south angle of Burgerbukta. If the wind direction in Burgerbukta was in-fjord, the Ekman transport would push the surface waters towards the eastern border of Burgerbukta. However, the cross section at the mouth of Burgerbukta (section plot not shown, but the position of the transect is shown in Figure 4.1) showed that the western border of Burgerbukta had about 2.0 meter of FWC, while the eastern border had about 1.5 meter of FWC. If the wind forcing in Burgerbukta had been in-fjord prior to the measuring period, it should be expected that the difference in FWC between the western and eastern border was less or even of an opposite character, considering the Ekman transport due to this wind forcing. However, as described above, this was not observed and indicates that the wind forcing was out-fjord also in Burgerbukta.

Variations on small time scales

The salinity profile and FWC at the intersection point between the Inner-section and the Long-section in 2001, showed considerable changes on relatively short time scales (see Figure 6.3a). The fact that the FWC at this site was decreasing with 0.79 meter (S_{ref}=34.2) and 0.98 meter (S_{ref}=34.9) during the 13 hour interval suggests that there was a significant advection of freshwater out of this area, which was higher than the freshwater input from the inner basins. A possible explanation of these changes could be the increase in the out-fjord wind speeds from the 27th of July, combined with reduced temperatures from the 26th to the 28th. This could have increased the outflow of freshwater and reduced the terrestial freshwater input which may have resulted in a negative freshwater budget at the measuring site. However, sensitivity and response time of changes in terrestial freshwater input to temperature changes has not been investigated, thus this hypothesis has to be considered with carefulness.

Another explanation that may have affected the FWC at this site is that more saline water masses is advected into the fjord at depth. The change in FWC was largest when calculated with a reference salinity of 34.9 and there was almost no changes in the salinity profile in the upper 10 meters of the water column. Increased flow and vertical mixing due to wind forcing could result in an increased entrainment and outward advection of the ambient water of the surface layer. To compensate for this increased outflow, an inceased inflow of deeper water masses i needed. Additionally, there is a possibility of upwelling of deeper water masses in the inner parts of the fjord due to the increased outward advection of the surface water. Considering the upward slope towards the inner parts of the fjord at this measuring site, the uppwelling of deeper and more saline water may also explain the significant changes in the FWC during this measuring interval.

Outside of the fjord mouth, the salinity was decreasing in the upper 50 meter of the water column, while it was increasing below this depth (Figure 6.3c). This might indicate that more saline water masses are advected towards the fjord at depth, while there is an increase of freshwater in the upper part of the water column due to significant advection of freshwater out of the fjord.

Anyhow, the rapid changes in FWC that was observed indicates that the FWC of the fjord can change significantly on small time scales, especially when the wind forcing is strong. This should be kept in mind when conclusions are inferred between parameters that affects the amount of freshwater in the fjord on larger time scales.

7.1.2 Interannual variation in FWC$_{total}$

The interaunnual variations of FWC$_{total}$ showed a general variation between about 0.2 km^3 and 0.6 km^3 when calculated with a reference salinity of 34.2 and about 0.6 km^3 and 1.0 km^3 when calculated with a reference salinity of 34.9 (Figure 6.4, Table 6.2 and 7.1). Variations in the FWC$_{total}$ for the two different reference salinities are in general the same. However, the amount of freshwater differs significantly when calculated with the two reference salinities. This illustrates the importance of choosing a suitable reference salinity, when the total volume of freshwater in the fjord is to be quantified and compared to e.g. runoff rates or freshwater contributions from the shelf.

The total volume of freshwater in July was calculated based on the FWC at the Long-section and the area of two different regions of the fjord (Section 5.1). By applying this method, it is assumed that the FWC at the Long-section is representative for the rest of the area. This can result in both an overestimation and an underestimation of the actual volume of freshwater in the fjord. The rotational dynamics of the fjord was described in Section 7.1.1 and there was usually more freshwater at the northern border of the fjord, compared to the stations located at the Long-section. This may result in an underestimation of the actual FWC$_{total}$ in the fjord, especially during periods with out-fjord winds, as the Ekman transport of the surface water would confine the outflow even more towards the northern border. When the FWC$_{total}$ is calculated with a reference salinity of 34.9, the whole water column is usually integrated. This probably results in a general overestimation, due to the fact that the fjord is deeper at the Long-section, compared to the average depth of the fjord.

The factors that may affect the FWC$_{total}$ in Hornsund that will be discussed in the following sections include the variations in the meteoric water input to the fjord, the variations in inflow from the shelf in the surface and at depth, and the local sea ice conditions. Additionally, the results from the FWC$_{total}$ in this study will be compared to previous estimations of FWC in Hornsund.

Surface water contributions from the shelf

The effect of winds on the distribution of freshwater was described in Section 7.1.1 and it was indicated that the wind direction had a significant impact on the advection rate of

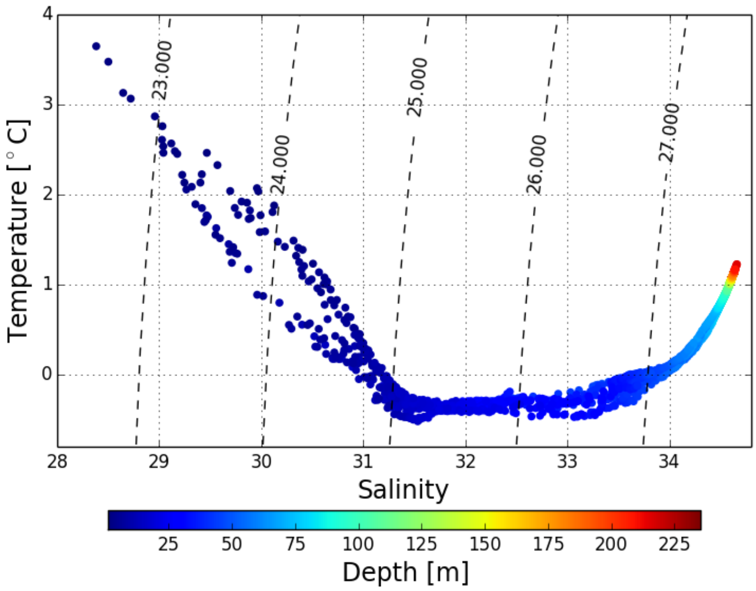


Figure 7.3: The temperature-salinity relashionship at the Mid-section in July 2011.

freshwater out of the fjord. However, the two years that was most significantly affected by out-fjord winds (2001 and 2009) did not show low levels of FWC$_{total}$. The wind forcing in 2009 had an onset about 1 day prior to the measuring period, and it could be argued that a large portion of the freshwater had not yet been advected out. However, the wind event in 2001 had persisted for several days prior to the measuring period and the FWC$_{total}$ were still relatively high. Considering the other years, there is no good relashionship between the along fjord wind stress inside of the fjord the FWC$_{total}$ (see Table 7.1). However, the wind forcing on the shelf may have an influence on the FWC$_{total}$ as this may act as an important factor that affects the inflow of water masses from the shelf.

The highest value of FWC$_{total}$ in Hornsund during the measuring period were July 2011, which showed a significantly higher freshwater content compared to the other years. This can be explained by advection of drift ice and fresh water masses from the shelf. Scientists aboard "R/V Oceania" observed large amounts of drift ice that had entered the fjord, during their cruise (personal communication with Agnieszka Prominska, autumn 2014) and it can be assumed that the ambient water masses advected with this drift ice contained significant amounts of sea ice meltwater. From the temperature-salininity relashionship in the Main basin (Figure 7.3), it can be seen that there was a very thick, fresh, and relatively cold surface layer. This fits well with a strong freshwater input from sea ice melt, which would create a fresh, but cold watermass. Synoptical charts from the days prior to the measuring period (not shown) indicated that the winds prior to the measuring period was southerly. This has probably facilitated this inflow, both by Ekman transport of surface waters towards the coast and the fact that the local wind direction inside of the Hornsund fjord was in-fjord, due to topographic steering.

The FWC$_{total}$ in July 2011 had 0.62 km^3 more freshwater than average (S$_{ref}$=34.2). If 2011 is assumed to be an "average" year with respect to other parameters that govern the FWC$_{total}$ in the fjord, the freshwater contribution from the inflow of sea ice and sea ice meltwater is highly significant this year. This might indicate that the advection of sea ice and sea ice meltwater occasionally can act as the dominant freshwater source in Hornsund. In the freshwater influx estimation from Weslawski et al. (1995), an annual influx of 1.313 km^3 to the Brepollen bay was suggested, while the influx to the whole of Hornsund was estimated to be 1.8 km^3 (Jania and Pulina, 1994). In the study by (Weslawski et al., 1995), it was estimated that 0.598 km^3 of the freshwater was discharged prior to August in Brepollen (Section 3.1.6). This is about half of the total volume of freshwater in Hornsund in July 2011, when calculated with a reference salinity of 34.2. Hence, if hydrographical data are to be used to estimate e.g. the changes in the runoff rates in the Hornsund drainage basin, it is important to account for the possible significant impact of advected freshwater and sea ice into the fjord by the SCC.

It is challenging to ascertain how often these events of sea ice inflow occures based on the data used in the present study, due to the seemingly short residence time of freshwater in Hornsund. Anyhow, taking the significant impact of this event into account, the freshwater influx from advected sea ice and sea ice meltwater could possibly act as a considerable annual freshwater source. This could be further examined by analysis of satellite images from the fjord, and possibly using the FWC in July 2011 as an indicator for the contribution of freshwater during an event of sea ice inflow.

Variations in input of meteoric water

The perhaps most intuitive parameter that can affect the FWC_{total} is the freshwater influx to the fjord from glacial ablation and river runoff. Weslawski et al. (1995) stated that 70% of the freshwater influx to Hornsund was due to glacial ablation and that this was the dominant freshwater source to the fjord. The variations in freshwater influx from glacial ablation/calving from glaciers are dependent on the energy balance at the glacier surface, if surge events are neglected (see Section 3.1). The energy balance is governed by several parameters, such as air temperature, cloud cover, snow cover, and humidity (Cuffey and Paterson, 2010). Due to the restricted availability of these data, our best measure to investigate variations in the energy balance from year to year, is the air temperature from the weather station in Isbjørnhamna.

A simple model that can be used based on these data is a degree day model (see e.g. Knight, 1999). This model assumes that a certain depth of snow or ice is melted for each degree celsius above zero degree celsius. By adding up the daily averaged temperatures above zero degree celsius over a certain period of time, reffered to as the Positive Degree Day sum (PDD), the energy available for melting of snow and ice during this time interval can be estimated. The PDD for Hornsund was calculated based on temperature data collected at the weather station at Isbjørhamna. As the residence time for freshwater in Hornsund remains undetermined, the PDD was calculated for two periods to examine how the FWC_{total} varies with the PDD. The first period was two months prior to the measuring period each year (see Table 4.1 for dates) and the second was three weeks prior to the measuring priod each year (results are shown in Table 7.1). It could be expected that a high PDD would result in a higher FWC_{total} in Hornsund, due to the fact that a high PDD would indicate higher melt rates of the glaciers and that this would increase the terrestial freshwater influx to Hornsund. However, the correlation between FWC_{total} and the PDD is poor for both periods (Figure 7.4) and may suggest that the PDD approach

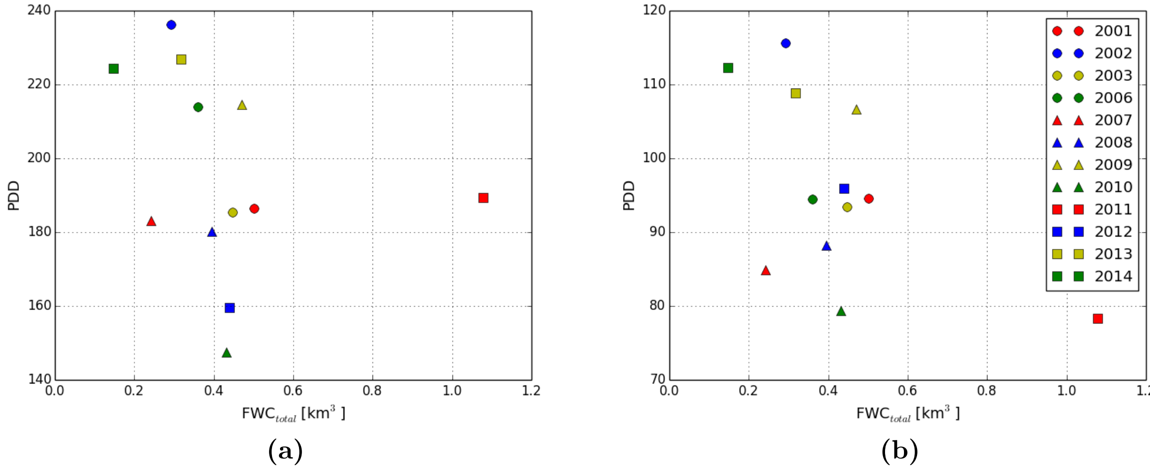


Figure 7.4: The relashionship between the FWC$_{total}$ calculated with a reference value of 34.2 and the calculated positive degree days from the beginning of June (a) and from the beginning of July (b) to the measuring period for each year.

is too crude to estimate the variations in terrestial freshwater influx to the fjord and/or that there are other mechanisms in the fjord itself or at the shelf, that are more important for the FWC$_{total}$.

Precipitation may also increase the freshwater influx to Hornsund. The accumulated precipitation for the three weeks prior to the measuring period each year, is presented in Table 7.1, for the years when this data was available. The year with most precipitation during the three weeks prior to the measuring period was 2013 with an accumulated precipitation of 50.4 mm. If all this precipitated water has drained into the fjord during these three weeks it would result in a freshwater contribution of 0.08 km^3, based on the catchment area estimation by Błaszczyk et al. (2013) (Section 3.1). This is about 24% of the total freshwater in the fjord in July this year, when calculated with a reference value of 34.2. However, to assume that all the precipitated freshwater is contained in the fjord at the time of measuerement is not a realistic situation. The freshwater is continously advected out of the fjord, and the precipitated freshwater is not supplied instantly, as most of the precipitated water will be an addition to the total terrestial runoff. The large glacier cover of the drainage basin complicates this even further, as the freshwater flux change from glaciers due to precipitation at the glacier surface is not straightforward to estimate (see e.g. Cuffey and Paterson, 2010). Still, the decrease in FWC$_{total}$ from July to September in 2013 may be explained by a relatively large freshwater contribution due to precipitation prior to the measuring period in 2013 and that this freshwater has been advected out of the fjord in the time interval between July and September. The variation from July to September in July 2014 were of an opposite character, which fits well with the idea that the higher FWC$_{total}$ in July 2013 compared to September 2013 was due to an isolated event of freshwater influx that occured close to the measuring period.

To describe the relashionship between input from runoff and precipitation and the FWC$_{total}$ in Hornsund has proven a challenging task. However, it could be argued that the methods used in the above discussion are to crude to estimate the variations in the freshwater influx to the fjord. In Kongsjorden, Svendsen et al. (2002) used a precipitation-run-off model (HBV model, see Bergstrøm, 1972) to simulate the daily runoff based on meterorological observations in Ny-Ålesund. This model has successfully been applied to several watersheds on Svalbard (Hagen et al., 2003). The application of a HBV model to the Hornsund watershed could be a reasonable future approach to compare the runoff and FWC in Hornsund and how the FWC in the fjord responds to changes in runoff.

The variation in inflow of deeper water masses from the shelf

A parameter that also may have an influence on the FWC_{total} is the inflow of deeper water masses from the shelf. Cottier et al. (2005) found a relashionship between surface layer depth, which they used as a proxy for the FWC in the fjord, and the inflow of Atlantic influenced water masses into the Konsfjorden-Krossfjorden system. Measurements from September 2000-2003 showed that the years with significant influence of AW in the inflowing water masses (2002 and 2003) had a shallow surface layer compared to the years with less infuence of AW in the inflowing water masses (2000 and 2001). The differences were considerable with a surface layer with depth of almost 50 meters in the years with small amounts of AW in the inflowing water mass, compared to about 20 meter in the years when the influence of AW was more significant (Cottier et al., 2005).

The year with lowest FWC_{total} in Hornsund was 2014, which also was the year with strongest influence of AW, based on data from the CTD station outside of Fannypynten (Table 7.1). The surface layer depth was also significantly shallower this year compared to the other years (Figure 5.2). The temperature and salinity maximum in the AW/TAW water mass was the highest, and TAW was present already at about 30 meter depth, which fits well with the observations from Kongsfjorden presented in Cottier et al. (2005). The other years with observed AW influenced water masses outside of Fannypynten are the years 2002, 2006, 2008, and 2013, of which 2002 and 2013 also showed significantly lower FWC_{total}. The difference in FWC_{total} between the calculations done with the two reference salinities are lowest in these years, which shows that there is less amounts of freshwater contained in the inflowing water mass below the 34.2 isohaline in these years. This emphasize the importance of choosing a suitable reference salinity if the freshwater budget in the fjord is to be examined, as there may be differences in the freshwater content of the inflowing water mass at depth. However, the FWC in 2002, 2013, and 2014 is low regardless of the choice of reference salinity, which fits well with the results from Kongsfjorden in Cottier et al. (2005), where the depth of the 34.0 isohaline was used as a proxy for the FWC. Hence, both the results from Kongsfjorden and the results presented in the present study indicates that the inflow at depth has an effect also on the thickness of the brackish layer and FWC in the uppermost part of the water column.

A possible explanation for this relashionship, is the higher salinity of the AW compared to the ArW and that the end product of mixing between AW and freshwater will have a higher salinity than the end product of mixing between freshwater and ArW. Another factor that may decrease the FWC_{total} when there are large amounts of AW in the fjord, is the higher density of the AW. An increased density difference between the brackish water in the surface layer and the underlying watermasses may supress vertical mixing and counteract a deepening of the surface layer. The inflow of denser water masses may also result in more efficient freshwater advection out of the fjord, as a higher density difference between the surface waters and the underlying water masses may counteract turbulent transfer of momentum between the two layers due to the increased bouyancy of the water column (see Cushman-Roisin and Beckers, 2011).

Locally produced and melted sea ice

The sea ice conditions during the years 2001 to 2014 was described by Muckenhuber et al. (prep), using the DFI index (Section 3.1). The DFI index is not describing the amount freshwater contained in the ice at the end of winter season, but gives an indication on whether there has been any significant amounts of fast ice in the fjord. Hence, the DFI index is only a rough estimate on the amount of freshwater that can be expected to be derived from sea ice melt in spring and early summer. From Figure 3.2 and Table 7.1, it can be seen that there was almost no fast ice in the fjord in 2012 and 2014. Of these years, only 2014 shows significantly lower FWC_{total}. However, as described above, the low FWC_{total} in Hornsund in 2014 may also be explained by a significant inflow of AW from the shelf.

Input of freshwater from the melting of locally produced sea ice was estimated by Weslawski et al. (1995) to contribute with 0.051 km^3 of the freshwater input to Brepollen (see Section 3.1.6). Hence, the contribution of freshwater from melted locally produced sea ice is relatively low, compared to the terrestial freshwater input. Taking the relatively low estimated contribution to the freshwater input from locally produced sea ice and the seemingly low residence time for freshwater in the fjord into account, it is suggested that the amount of freshwater contained in locally produced fast ice in Hornsund is of secondary importance when it comes to the FWC_{total} in July.

Comparison with earlier studies on FWC in Hornsund

Estimation of fresh water content in Hornsund was done based on data collected in August 1987 by Weslawski et al. (1991) and in 1996 by Beszczynska-Möller et al. (1997). Weslawski et al. (1991) used a constant reference salinity similar to the method used in this study. Beszczynska-Möller et al. (1997) defined different layers and set a reference salinity based on the source seawater properties for each layer. The estimations provided by Beszczynska-Möller et al. (1997) yielded a total freshwater volume in the fjord of 0.0757 km^3 in Hornsund and was considered by the author to be an underestimation. The result from Weslawski et al. (1991) with constant reference salinity showed a freshwater content of 0.79 km^3 in Hornsund in August 1987 based on a reference salinity of 35.23. This is relatively low compared to the data from 2001-2014, when the calculations on the data set from 2001-2014 were done with reference value of 35.23, which results in an average of 1.22 km^3.

It is challenging to compare these results due to several reasons. The data in 1987 were collected in August (not July), which may introduce seasonal variations and there are numerous factors that may affect the FWC_{total} on relatively short time scales (some are described in the paragraphs above), which was not considered in the results presented in Weslawski et al. (1991). A factor that may affect the FWC_{total} on longer time scales is the retreat of the tidewater glaciers in the inner basins of Hornsund (Błaszczyk et al., 2013), which can affect both the distribution and the runoff rates due a decrease in the drainage area and an increased fjord area. It is not mentioned in the article what area or volume they used to estimate the total freshwater content, but in Błaszczyk et al. (2013) the estimated area of the fjord were reported to be 264 km^2 in 1990, which differs significantly from the area of Hornsund today.

7.2 The δ^{18}O values and contributions from MW, SIM, and SIM in Hornsund

The measured values of δ^{18}O in Hornsund showed in general isotopically lighter water in the surface and in the inner parts of the fjord, something which would be expected due to the high input of MW with low δ^{18}O values in these areas. The same situation was observed in Kongsfjorden by MacLachlan et al. (2007), where it was found that there was a weak seaward surface salinity gradient that corresponded well with a similar weak gradient in $\delta^{18}O$. In the depth profiles (Figure 6.6), it can be seen that the values from Burgerbukta has low values for both salinity and δ^{18}O, consistent with the depiction of a fresh surface layer with considerable influence of MW. The δ^{18}O at depth was similar in Burgerbukta and at the fjord mouth, indicating exchange of deeper water masses between the Main basin and Burgerbukta. The perhaps most startling feature with the δ^{18}O data, is the high values in Brepollen (Figure 6.6 a). This indicates that the sill acts like an effective barrier, that prohibits exchange of deeper water masses between the parts of the fjord that is inside of the sill and deeper water masses in the Main basin.

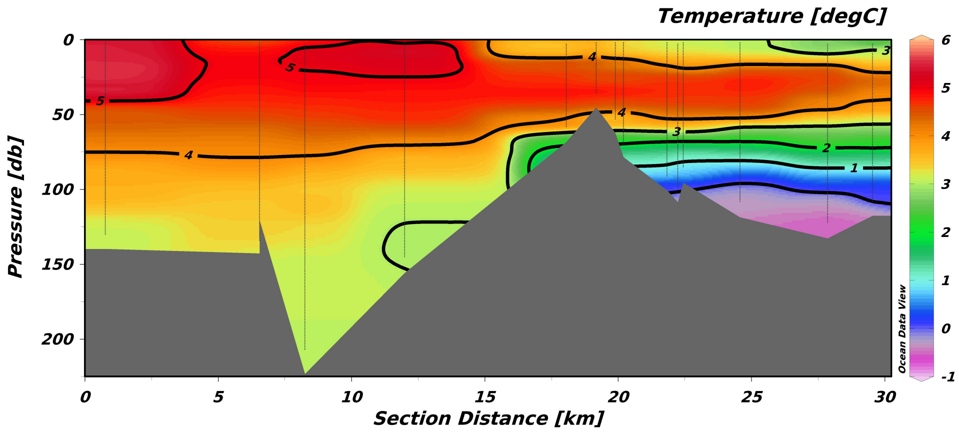
The values at depth in Brepollen do also show significantly higher values than what has been observed in other fjords on Spitsbergen. Measurements of δ^{18}O in the deeper water masses in Storfjorden showed values varying between 0.3‰ and 0.4‰ (Schmidt et al., 1999) and in Kongsfjorden the δ^{18}O at depth in the inner fjord showed values varying between -0.02‰ and 0.21‰ (MacLachlan et al., 2007).

7.2.1 The contributions from MW, SIM, and SW

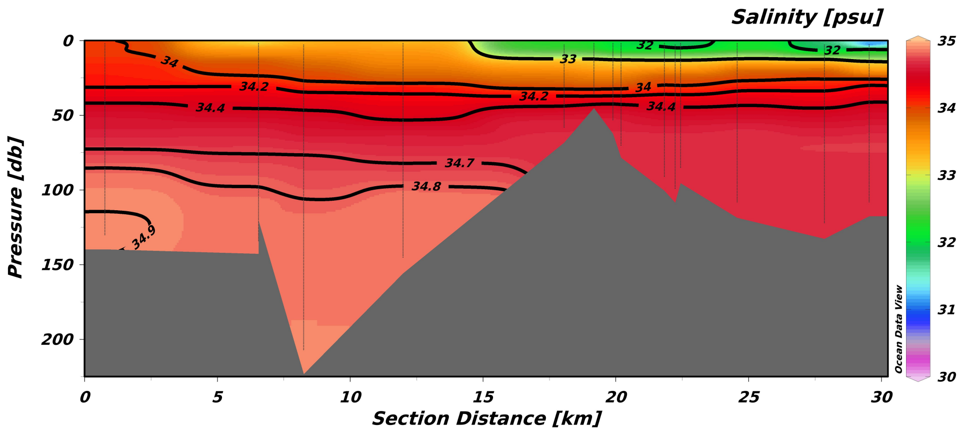
In the Long-section from September 2013, the influence of MW in the surface layer is clearly visible as a plume with increasing depth and decreasing intensity from the innermost part of the section towards the fjord mouth (Figure 6.7). This fits well with the depiction of two layered fjord system, where freshwater input to the inner basins is entraining ambient water masses as it is advected out of the fjord. The amount of freshwater in the deeper water masses in the Main basin is in general low, however, the MW and SIM contributions indicates that the inflowing water masses at depth containes both MW and SIM. In Brepollen, the contributions of SIM are clearly visible at significant depth, while the MW values are negative. The negative values of MW and the significant amounts of SIM in Brepollen will be discussed further in the following sections.

The negative MW values at depth in Brepollen

The contribution from MW showed a rapid transition from positive MW values in the surface, consistent with a significant terrestial freshwater input, to negative values from depths of about 30 meters. Below sill depth, the MW contribution is negative in the



(a)



(b)

Figure 7.5: Temperature (a) and salinity (b) at the Long-section in September 2013.

whole bay (Figure 6.7a). The negative values of MW is not meaningful and can either indicate that the endmember values are erraneous, or that there is an external water mass that enters the bay, which was not considered when the endmember values were chosen.

Several assumptions were done when the endmember values were chosen (Section 5.2.2). Among them was the assumption that the most saline water mass that could enter the fjord was AW and that this water mass was present at the fjord mouth. AW was indeed present at the fjord mouth in September 2013 and can occationally enter the Main basin of the fjord, as observed in 2014 (Table 7.1). However, AW was not observed in Brepollen in any of the years prior to 2013. As seen from Figure 7.5, the water masses present below sill depth in Brepollen has different characteristics in temperature and salinity than what observed at similar depths in the Main basin, thus the choice of the SW endmember value for Hornsund may be an invalid endmember value for SW in Brepollen. The water mass present below sill depth in Brepollen has a temperature and salinity signature of WCW, i.e. a water mass created due to cooling and freezing processes (Section 2.1). The high δ^{18}O of this water mass is therefore a paradox, since brine enriched water masses should show reduced δ^{18}O, compared to the δ^{18}O of the water mass from which the ice was formed (Section 5.2.1). Thus, there is no good physical basis for using the WCW at depth in Brepollen as the endmember value for SW, as this would be based almost solely on the fact that the calculations resulted in a negative contribution from MW.

There is also an uncertainty regarding the MW endmember value, as this value was partly based on measurements done in other fjords than Hornsund. A linear fit to the δ^{18}O-salinity relashionship for Hornsund in September 2013 (Figure 5.4) resulted in an equation of δ^{18}O=0.32S-10.67‰, with a coefficient of determination of 0.82. The deviation in the linear fit from the chosen δ^{18}O endmember value for MW of -13.8‰ at the interception point of the zero salinity line and the relatively low coefficient of determination, indicates that there was an influence of SIM in the water masses of Hornsund in September 2013 (see Section 5.2.1). MacLachlan et al. (2007) examined the δ^{18}O-salinity relashionship in Kongsfjorden and assumed that the dominant freshwater source was MW. They found a good correspondance between the zero salinity line intercept of a linear fit to the data and the chosen endmember value for MW. The linear fit did also show a high coefficient of determination of 0.982, indicating that there was only SW and MW present in the fjord.

The contributions of SIM was calculated to be relatively high in Brepollen compared to Burgerbukta (Figure 6.7 and 6.8). By assuming that the dominant freshwater source in Burgerbukta was MW, a similar approach as was used in MacLachlan et al. (2007) can be applied to evaluate the chosen endmember value for MW in Hornsund. A linear fit applied to the δ^{18}O-salinity relashionship in Burgerbukta (Figure 6.6c) results in an equation of δ^{18}O=0.36S-12.1‰, with a coefficient of determination of 0.987. The zero salinity intercept of -12.1‰ for this linear fit has a higher correspondance to the chosen endmember value of -13.8‰, compared to the zero salinity intercept for the linear fit to the complete data set. Additionally, the higher coefficient of determination adds plausability to the assumption that there are only SW and MW present in Burgerbukta. The zero salinity intercept of -12.1 *permil* is slightly higher than the chosen δ^{18}O endmember value for MW, which may indicate that the chosen endmember value for MW is too low.

The inflow of an external watermass to Brepollen that was not considered in the choice of the endmember values could also explain the negative MW values in Brepollen.

Swerpel (1985) briefly described the possibility of a connection between Storfjorden and Hornsund below Hornbreen and that Brepollen could exchange water masses with Storfjorden through this channel. However, this hypothesis is highly speculative and the fact that δ^{18}O measurements at depth in Storfjorden showed values that are significantly lower than the values found at depth in Brepollen indicates that this explanation is unlikely.

One of the main reasons for the negative values of MW is the exceptionally high values of δ^{18}O in Brepollen. A possible explanation of these high values is the existence of a hydrothermal vent at the bottom of Brepollen. A hydrothermal vent is a fissure in the crust of the earth that release geothermally heated water and the water released from hydrothermal vents usually exhibits very high δ^{18}O values (e.g. Merlivat et al., 1987). Hydrothermal vents are found in Stormbukta, which is located about 30 km south of the fjord and the existence of a hydrothermal vent in Brepollen cannot be outruled (personal communication, Snorre Olaussen, spring 2015).

The SIM contribution in Brepollen

From Figure 6.7b it can be seen that there is a significant contribution of SIM in Brepollen. In the same area, there was also observed a negative contribution from MW which is not meaningful, something which may indicate erraneous choice of endmember values. However, if it is assumed that there are no hydrothermal vents in Brepollen, the only plausible explanation of the high δ^{18}O values are the existence of SIM in the water column, as this is the only source water that can increase the δ^{18}O values to the values observed in Brepollen (see Figure 5.3). There are two possible sources of SIM in Hornsund. The SIM may be a result of the melting of locally produced sea ice, or it may be the melting of sea ice or SIM that has been advected into the fjord from the shelf.

The SIM contribution of locally produced sea ice was discussed in Section 7.1.2 and was considered of secondary importance for the FWC_{total} in July. This was partly due to the apparent low residence time of freshwater in the fjord. If the SIM was produced from the melting of locally produced sea ice, it had to be stored in Brepollen through the whole summer to still be present in September, which is considered to be unlikely. The fact that the SIM is present in the whole water column makes it even less suitable to infer that the origin of this water is the melting of locally produced sea ice, as this would demand vertical mixing with the WCW that is present at the bottom of Brepollen. If surface or intermediate water in spring/early summer that contained SIM had been mixed down, this mixing should also have mixed down MW, since the onset of sea ice melt in spring usually corresponds well in time with the seasonal onset of terrestial freshwater input. However, the MW contributions below 30 meter is negative, thus this hypothesis is considered to be falsified.

As seen in 2011, sea ice and SIM carried in the SCC may be advected into the fjord from the shelf. The fact that there is SIM in the whole water column, also in the parts of the water column in which there is no MW, implies that the SIM must have been mixed down when there was negligible amounts of MW present in Brepollen. A scenario that may explain this is the inflow of SIM from the shelf, after the seasonal halt in terrestial freshwater input from land. As described in Section 3.1.6, most of the terrestial freshwater input to Hornsund occures in the summer months. Additionally, it has been suggested that the residence time of freshwater in Hornsund is low and that the fjord is flushed of freshwater prior to the winter season. Hence, SIM could have been the only freshwater present in Brepollen prior to the onset of sea ice formation, if it had been advected into the fjord after the fjord had been flushed of MW. If this was the case, the relatively low temperature and salinity of the SIM would have facilitated sea ice formation in the fjord. Since the there is no terrestial freshwater input, the freshwater driven flow is negligible and in additional to this, the eventual formation of fast ice would protect the surface water from wind forcing and the residence time of the surface waters in Brepollen would increase, thus the SIM would stay in the bay. The convective mixing processes initiated by the brine release during the sea ice formation could result in convection of this water mass to the bottom of the fjord. As described in Section 5.2.1, sea ice formation gives a negative contribution of SIM, hence, this hypothesis demands that the bay must contain enough SIM prior to the onset of sea ice formation to give a net positive contribution of SIM at the end of winter season.

There was significant amounts of SIM in the surface waters as well and one of the assumptions applied for this explanation was that the residence time of freshwater in the fjord was low during summer, thus one could argue that the SIM in the surface should have been flushed out. However, as described in Section 6.2.2, the uncertainty of the estimations in the surface water was significantly higher than what found at depth.

One way to add additional information to either falsify or make this hypothesis more plausible, is to calculate the inventory of SIM in the water column in Brepollen. This would give information on whether the amount of SIM contained in the bay is comparable to the amount of SIM that can be produced locally. This was not possible based on the results in the present study, due to the negative contribution from MW. However, by taking measurements of the actual sources of SIM and MW in Hornsund, such as glacier ice, locally produced sea ice, and sea ice advected into the fjord, it should be possible to determine the appropriate endmember values in Hornsund with a higher degree of certainty. It would also give an indication on whether the high δ^{18}O values found at depth in Brepollen is due to the presence of SIM or that there is an external source that increase the δ^{18}O values, e.g. a hydrothermal vent.

8 Summary

The freshwater content in July in Hornsund showed significant changes from year to year, both in the distribution of freshwater in the fjords interiour and in the total freshwater volume of the fjord. Several parameters have been associated with these changes. The along fjord distribution of freshwater showed that there were generally higher amounts of freshwater in the inner parts of the fjord, compared to the outer parts of the fjord. However, wind forcing can change this situation to be of an opposite character and a good correlation between the along fjord wind component and the along fjord distribution of freshwater was established. The response time of the surface layer to wind forcing appared to be almost instant. The fjord generally showed higher freshwater content at the northern border of the fjord, compared to the southern border. This is mainly a result of the rotational character of the circulation regime in the Main basin and the larger drainage basin associated with the northern border of the fjord, compared to the drainage basin associated with the southern border.

The highest total volume of freshwater was found in July 2011, which showed a significantly higher freshwater content than the other years. The high freshwater content this year was attributed to the inflow of sea ice meltwater and sea ice contained in the South Cape Current, that had been advected into the fjord facilitated by favorable wind conditions. Occasional inflow of sea ice meltwater contained in the South Cape Current during summer, can therefore be a significant freshwater source to Hornsund that has not been considered in previous studies of the freshwater budget in the fjord. No apparent relashionship was found between the estimated variations in runoff and the total volume of freshwater in the fjord. It is also shown that the amount of Atlantic Water in the inflowing water mass can have an effect on the total volume of freshwater, as this water mass has a higher salinity compared to the Arctic Water that usually is the dominant water mass at depth in Hornsund.

The δ^{18}O measurements from Hornsund showed that Brepollen had unusually high values for the region. This was attributed to the possible existence of a hydrothermal vent or that there was a significant amount of sea ice meltwater in the bay. The fractional contributions from freshwater of meteoric origins and sea ice meltwater was calculated for September 2013. The results showed significant amounts of meteoric water and sea ice meltwater in the surface waters, especially in Burgerbukta and Brepollen, while only minor amounts were found in the in the inflowing water masses. The deeper water masses in Burgerbukta and Brepollen were significantly different. In Burgerbukta there were only minor amounts of sea ice meltwater below around 50 meter, while in Brepollen there was a significant contribution of sea ice meltwater throughout the water column. This higher amount of sea ice meltwater in Brepollen are possible remnants of inflowing sea ice meltwater carried in the South Cape Current, that has entered the fjord from the shelf.

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