

Observations of ice conditions and properties in Norwegian fjords during the winter of 2018 and implications for oil spill response

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As the arctic opens to more development and increasing ship traffic, coastlines are at greater risk of oil pollution resulting from these operations. Fjords are one feature common throughout the arctic, with many dotting the coast of Norway. While these fjords often remain ice free year-round, some fjords in both southern and northern Norway (notably Oslofjorden for the former) can experience variations in ice extent from year to year. The properties of this ice, including porosity, can differ from that of the sea ice found in the open ocean given the influence of various factors including freshwater input, bathymetry, and climatic and oceanographic conditions. Given these variations, oil would likely interact with the ice in a way different from that expected with either sea ice or fresh water ice. To begin understanding the causes and extent of these variations and their potential impact on oil movement through the ice, observations of ice conditions and measurement of ice properties were made in fjords throughout northern Norway between January and May 2018. Results reveal significant variations in ice properties between fjords located geographically near to each other. The data provide a starting point to improve our understanding of why ice extent and properties vary between fjords and our ability to predict ice conditions on a more detailed scale in fjords and along arctic coastlines.

Introduction

Fjords are generally defined as glacially carved basins partially filled with seawater. They can vary in depth and experience differing combinations of currents, tides, fresh water flux, and atmospheric conditions. In addition, even fjords located within close proximity to each other can often be influenced by different oceanic conditions. In arctic and sub-arctic environments, the interaction of these variables will influence the formation of ice.

The fjords dotting the coast of mainland Norway occupy a distinct place in the larger field of fjord oceanography. While many are located in the arctic based on latitude, they lack the influence of glaciers and the seasonal ice cover found in regions like Svalbard (Cottier et al., 2010). They also cannot be grouped with lower latitude fjords where conditions are warmer and sea ice consistently does not form (Inall & Gillibrand, 2010). While measurement campaigns have been undertaken to better understand the oceanic conditions specific to these regions, these works have not addressed sea ice formation (e.g. Cushman-Roisin, Asplin, & Svendsen, 1993; Eilertsen & Skarðhamar, 2006; Tverberg, Cushman-Roisin, & Svendsen, 1991; Svendsen, 1995; Mankettikkara, 2013; Skarðhamar et al 2018). It is in studies focused on the Baltic sea where the factors important to ice formation in norwegian fjords (e.g. freshwater flux) are often addressed more thoroughly (Granskog et al., 2005).

The presence of ice in fjords can influence a number of physical processes - it can disrupt the impact of wind and currents, slow the transfer of heat from air to ocean and reverse, lower the amount of solar radiation penetrating the water column. These physical impacts often have repercussions for the

biological and geochemical processes within these areas as well. In addition, ice can act both as a tool and a disturbance to humans. Allowing easier access by foot and motor vehicles for certain activities while creating a challenging obstacle for others. For example, shipping, where ice can pose a risk both in terms of the ships themselves and obstacle it presents if an emergency arises. In particular, ice will greatly alter how one might respond to an oil spill given the various ways it impacts the movement, degradation, and eventual cleanup of pollutants (Transportation Research Board and National Research Council, 2014).

In Fig. 1, the different ways in which oil interacts with ice and ways it may reach the surface are displayed. The two main ways in which oil emplaced under ice will reach the surface is either through leads, cracks, and fractures in the ice or percolation upward through the ice pore space. As seawater freezes, solute rejected from the pure ice matrix form a pore space of concentrated brine. This pore space differentiates sea ice from fresh water ice. In the winter time, these pores are disconnected from one another. In the spring as temperatures rise however, pores will begin to connect enabling vertical fluid flow. It is during this time that oil emplaced under or possibly encapsulated in the ice would be able to travel to the surface. In ice frozen from seawater of a lesser salinity (average values in the open ocean are around 32 ppt) or subjected to fluctuations in freezing conditions which affect the structure of the ice, the connectivity of pore space and eventual rise of oil to the surface may be altered. In this study we focus on one such environment where ice conditions will likely vary from those in the open ocean. Through examination of measurements of ice thickness, extent, and properties we aim to better understand if and how ice in fjords differs from the open ocean applying our findings to better understand how oil could be potentially recovered. While Norwegian fjords are the focus, this research may apply to any coastal region where ice growth is impacted by variables not present in the open ocean, e.g., fresh water flux from the coast. Our goal is to show that fjord environments are diverse and can require different oil spill response measures even within a small area and in a broader context, that greater focus should be placed on ice properties when formulating methods for oil spill response.

Methods

Six fjords were chosen to obtain measurements of ice thickness, extent, and properties in addition to measurements of snow depth, temperature and salinity of the water below the ice, and water and ice samples for analysis of stable isotopes. The fjords were chosen based on the knowledge that they held ice as well as similarities in bathymetry, surrounding topography, and/or exposure to climatic conditions. Time series and transects were measured in one fjord while in five fjords, measurements were made and samples gathered at only one point in each fjord. The location was chosen to be approximately in the middle of the ice cover that remains floating ice during low tide, both across fjord and up/down fjord. At each sampling site, the location of the ice edge was also observed and noted.

Before ice samples were removed, any snow on the surface was shoveled away to provide a clean area from which to drill ice cores. Three cores were gathered at each location. A stratigraphy core for transport back to our home office for subsequent thin sectioning and analysis of ice crystal structure, a core to measure ice temperature, and a core to measure of ice salinity. To measure temperature, small holes were drilled 0.05 m apart upon the removal of the core. Next, a Fluke 54IIB thermometer having an accuracy of $\pm 0.05\% + 0.3\text{ }^{\circ}\text{C}$ and resolution of $0.1\text{ }^{\circ}\text{C}$ was placed into the hole and held for approximately 15 seconds before a stable temperature reading was obtained. For salinity measurements, the core was removed and laid horizontal immediately to minimize brine drainage. Using a saw, the core was next

sliced into 0.05 m sections and double bagged. Samples were next melted at room temperature before salinity was measured using a YSI Pro30 salinometer with accuracy of $\pm 1\%$ or ± 0.1 ppt (whichever is greater) and resolution of 0.1 °C. To obtain a value of brine volume fraction, also known as porosity, equations presented by Cox and Weeks (1983) were applied for ice having temperatures below -2 °C. For ice with a temperature between -2 °C and 0 °C, equations by Leppäranta and Manninen (1988) were used.

Slush was next removed from one of the holes created by the core removal, before lowering a Castaway CTD to the bottom of the fjord. When measuring temperature, the CTD has a resolution of 0.01 °C and accuracy of 0.05 °C; for salinity (converted from conductivity), resolution is 0.01 ppt with an accuracy ± 0.1 ppt; for depth (converted from pressure), resolution is 0.01 m and accuracy is $\pm 0.25\%$ of the measured value. Two casts were made at each location to ensure that consistent measurements were obtained. The data presented here comes from the raw data of pressure and conductivity that were then converted to depth and salinity using the Unesco equations (Fotonoff & Millard, 1983). As the CTD sampled at a frequency of 5 Hz, the measurements presented were obtained by binning measurements every 0.05 m and averaging their values. Only measurements made during the upcast were used as slush and ice sometimes influenced readings when initially lowering the instrument. In addition, the top 1 m and bottom 1 m of measurements were not included. The former due to suspected mixing that occurred during core extraction which produced inaccurate measurements, and the latter because of scatter associated with the CTD sitting on the ocean floor.

For each location, samples of water under the ice and the remaining seawater from the melted ice samples were placed in glass bottles with cone liners and stored at 4 °C for isotopic analysis. Results from these samples along with analysis of ice crystallography from the stratigraphy cores were not yet available for this study.

Values for average daily air temperature, daily fresh snowfall, and rain and snow melt were obtained through seNorge (www.senorge.no; Lussana et al., 2016). All values are based off spatially interpolated weather data provided by the Norwegian Meteorological Institute and snow data from Norwegian Water Resources and Energy Directorate (NVE). Images from the Terra Surface Reflectance 8-Day Global 500m dataset, a MOD09A1 V6 product, were also used in combination with Google Earth Engine to determine where ice may be forming during the 2018 season (Vermote, 2015). Lastly, maps of norwegian fjords to determine bathymetry and calculate ice area were provided through Kartverket and available at www.norgeskart.no.

Results

In Fig. 2 and Fig.3, the location of each measurement is shown along with a closer look of each fjord, the ice extent (marked with a black line) and bathymetry in each fjord. A comparison of ice thickness and snow depth is provided in Fig. 4. Ice extent was determined through personal observation when visiting the fjord. Through analysis of the MODIS images and temperature data, it appears that measurements were obtained near to the maximum ice extent before the onset of melt and break up. In addition, ice appeared to be nearing or at the end of the growth phase given that the skeletal layer was thin, if present at all. The date of ice freeze-up was only observed in one fjord, Beisfjord, and occurred on 29 January 2018. As no MODIS images are gathered during the dark, winter period, it is not known when ice began to form in the other five fjords. In Fig.5 and Fig. 6, average daily air temperature and daily fresh snowfall are presented. From this data, we estimate that ice also formed some time during January in all

other fjords. This is based on the lack of granular, snow ice in all cores which would align with ice not forming until after the last big snowfall in December. Further examination of the ice crystallography however is planned to confirm this hypothesis.

In Fig. 7, measurements of ice temperature, salinity, and calculated brine volume fraction are presented. Between the six fjords examined, variations in all properties are evident with ice temperature ranging from -4 °C to just below 0 °C and bulk salinity between 0.1 to 5 ppt. These variations lead to values for brine volume fraction from 1 % to greater than 35%. Measurements of temperature and salinity of the seawater gathered from CTD casts are presented in Fig. 8a. At each sampling location, little variation is seen throughout the water column, however, between samples temperature varies from 0 °C – 4 °C and salinity 32 – 33.5 ppt. These differences are more evident when comparing temperature to salinity and as shown in Fig. 8b. Beisfjord and Lavangen appear to be outliers primarily due to warmer temperatures while the remaining four fjords, located approximately 150 km to the north, show similarity in salinity and temperature. To note however is that water density between the six fjords is relatively consistent ranging only between 1025.5 and 1026.5 kg/m³.

From average daily air temperatures provided by seNorge (Fig.5), the number of freezing degree days (FDD, negative sum of temperatures on days with mean air temperatures below 0 °C) between 1 November 2017 and 30 April was calculated. These values are presented in Fig.9 in comparison to ice thickness, snow depth, and rain fall/melt. For FDD versus ice thickness and snow depth (Fig.9a & 9b), a negative relationship is apparent while FDD shows a positive relationship to rainfall/melt (Fig.9c).

Discussion

The fate of oil in an icy fjord will depend on several factors including ice thickness, ice extent, and the properties of the ice itself. The measurements gathered combined with examination of climatic data, provide an initial look into the how and why these factors differ between fjords located geographically near to each other. The following provides an overview of possible correlations that may assist in predicting ice conditions in fjords and their impact on the response to an oil spill.

Freezing Degree Days

In general, ice thickness increases with FDD as FDD indicate the amount of thermal cooling from the surface. A common cause for this relationship to be altered is the addition of a snow cover insulating the surface and resultantly slowing ice growth. Our results in Fig.9 therefore show an unexpected relationship with less FDD correlating to thicker ice and fjords with more ice having a thicker layer of snow. What might account for this finding? First, from examination of modeled snowfall (Fig. 6) it is evident that little snow fell in all fjords studied during the ice growth phase (i.e., in February and March). The snow on the surface during the time of measurement therefore likely resulted from a snow event a few days prior to observation. As a result, the insulative effects of the snow likely did not have a substantial impact on the overall ice thickness.

Next to be considered are other climatic factors such as rainfall and snow melt before and throughout the ice season. Part of what makes a fjord environment different from the open ocean is the influence of freshwater from river runoff. In talking with locals, it is a common knowledge that years with more rain lead to greater ice formation in certain fjords. In the open ocean, the entire water column must be cooled to a temperature below freezing before ice begins to form on the surface. It is well known that in a fjord environment however, a fresh water 'lid' can form on the surface due to freshwater flux from

surrounding rivers. When a freshwater 'lid' exists, it is only within this layer that temperature needs to decrease to freezing for ice to appear. Given that the freezing temperature is higher for freshwater and the layer itself may be relatively thin, ice can appear earlier in a fjord with a freshwater input than an area without. Our findings support that this process was present in the fjords studied and relatedly, may play an important role in the overall ice extent and thickness in a fjord. In addition, this finding points to the importance of precipitation and run-off events in understanding and predicting ice coverage in fjord environments. Lastly, such events are likely to impact the properties of the ice, for example porosity. All three of these factors, ice extent, thickness, and properties, play a key role in determining how one might respond to an oil spill in coastal regions of the arctic where ice is present.

Bathymetry and surrounding topography

An obvious outlier when comparing ice thickness to FDD, snow, and precipitation/melt event is Nordkjosbotn. To further investigate, we compared ice thickness to ice extent in Fig. 9d and examined the surrounding topography and bathymetry. For the fjords studied, a greater ice thickness is related to a smaller area of ice. In Nordkjosbotn this may be due to a narrowing in the fjord which ice does not appear to have grown past this winter season. We hypothesize that this constraint acted to stymie further ice growth outward and contributed to the ice thickening quicker than in other fjords. A connection between ice edges and characteristics of the bathymetry and surrounding topography appear in other fjords as well. A few weeks prior to measurement, ice in Beisfjord extended slightly past the mark shown in Fig. 3 to a similar narrowing in the fjord where depth also decreased quickly. In addition, Storfjord was both the widest of the fjords studied and had the greatest ice area, but thinnest ice. How bathymetry and topography are related to ice formation within the fjord is likely tied to oceanographic processes, i.e- currents, in the fjord and a topic under closer examination now.

Ice and Water Properties

Bulk ice salinity provides a record of ice formation, including for example the flux of fresh water into the fjord, snowfall, and surface melt. All samples had bulk salinities lower than that expected for typical sea ice found in the open ocean, where values in first year sea ice often range between 5 – 8 ppt (Fig.7). Kattfjord stands out having the lowest values of bulk salinity, between 0 and 1 ppt, consistently through the depth of ice. In first year sea ice, the typical mode of desalination that may lead to lower values of bulk salinity is through the drainage of surface melt in the spring time. We, however, hypothesize that the values measured are not the result of desalination but from ice forming from fresh or brackish water. This would be consistent with the high rainfall and/or snow melt experienced in Kattfjord (Fig.9c). The highest values of bulk salinity, between 3 – 4 ppt, were measured in Storfjord and Beisfjord. These two fjords however differed from each other in all other characteristics presented thus far- thickness, FDD, snowfall, and precipitation/melt. It is clear that drawing correlations between these factors is not trivial. Stable isotopic analysis of melted ice samples is currently being performed to better define the origin of the water in the ice. The aim of the analysis is to address if ice forming in fjords can hold layers, if not be entirely composed, of ice originating from fresh water sources. If layers of brackish and/or fresh ice are present, it has important implications on the interaction between oil and ice.

Between the fjords measured, there was one consistency- the water underneath the ice had properties close to that of sea water found in the open ocean (Fig.8). While small differences did exist in salinity and temperature, the water density was relatively consistent between all fjords. Therefore, while seawater between fjords can be similar, the ice sitting on the surface can still differ in its properties of salinity and

brine volume fraction. The most extreme example is Kattfjord and Storfjord. Both held water of similar salinity although differing slightly in temperature. The ice on the surface of Kattfjord however was fresh while Storfjord had saltwater ice.

In all fjords, measured temperature and salinity were relatively homogeneous from about 2 m depth downwards. Given that measurements in the upper 1 m were discarded, in future years, we aim to better resolve the salinity in these upper meters as it might be where the influence of freshwater flux is most extreme. In addition, from continuous measurement of water temperature in Beisfjord, tidal cycles have been found to impact temperature measurements up to 1 °C. Obtaining measurements continuously or at approximately the same point in the tidal cycle would make direct comparison more accurate.

Predicting the fate of oil in a fjord environment

Ice thickness and extent can impact oil spill response activities greatly. The presence of ice, no matter the thickness, can dampen the surrounding waves thereby decreasing the weathering of oil. As it increases in thickness, it can slow or prevent the access of ships to attend to an oil spill. In addition, how much ice and where it is located influences where the oil may travel- potentially pooling between floes of ice or flowing underneath the ice. It is this latter scenario where the properties of the ice, primarily porosity, play an important role in planning how to respond and prepare for an oil spill.

Ice porosity depends on both bulk salinity and temperature. Since ice temperature profiles are sensitive to snow depth and air temperature at the time of measurement and were found to differ considerably between measurement sites, we calculated ice porosity from the measured bulk salinity profiles and ice temperature profiles calculated for specific cases of air temperatures and snow depths. Three different scenarios were considered: (a) Surface temperature = -5 °C, ice/ocean interface = -1.8 °C; (b) Surface temperature = -1 °C, ice/ocean interface = -1.8 °C; and (c) Surface temperature = -1 °C, ice/ocean interface = -0.5 °C. For each a linear temperature profile was assumed from the surface to the ice/ocean interface allowing for the calculation of ice temperature at specific depths. Using measured values of bulk salinity, brine volume fraction was then calculated. The results are presented in Fig. 10. A dashed line marks where oil percolation has been observed to begin, at about 10% porosity although in some scenarios oil did not reach the surface until ice reached a porosity of 15% (Karlsson et al., 2011; NORCEL). In scenario (a), only ice extracted from Beisfjord and Storfjord is found to have porosities above this threshold in the bottom layers. In scenario (b) Beisfjord and Storfjord are the only samples above the threshold, although one layer in the Storfjord sample dips below. It is only in scenario (c) that samples from Beisfjord and Storfjord lie firmly above the 10% threshold while samples from Nordkjosbotn, Sørbotn, and Lavangen however, jump above and below. In Kattfjord, porosity remains very low except in the very bottom layers. These findings are useful in determining in what fjords and at what temperatures oil percolation upward might be possible. While two cores would theoretically have oil percolation to the surface, in the remaining samples oil could reach impermeable layers, preventing or at least lengthening the time before oil appears on the surface and clean up can begin. Knowing where and when such layers exist is challenging given that ice properties at the top and bottom would indicate the ice is saline and thus allow for the eventual flow of oil upward. With a greater knowledge of how and why internal layers of fresh and brackish ice form, we can increase our knowledge of ice in coastal regions in general as well as assist in adapting spill response programs to coastal areas of the arctic.

Conclusions and Future Work

Through our observations of ice conditions made during the 2017-2018 season in six northern Norwegian fjords, it is evident that a variety of factors including fresh water flux, bathymetry, and climatic and oceanographic conditions influence ice thickness and extent as well as the ice properties. Examination of ice cores collected reveal ice having salinity lower than ice found elsewhere in the arctic with one fjord, Kattfjord, having ice with properties similar to freshwater ice. In addition, within ice cores gathered, vertical bulk salinity and relatedly brine volume fraction curves differed from predicted values for sea ice with similar surface temperatures, the result potentially of oceanographic, meteorologic, and topographic factors changing throughout the winter season. Lastly, despite being geographically located near to each other and holding ocean water of relatively the same temperature and salinity, the ice observed varied noticeably between different fjords. These points are all important to consider when deriving potential methods to use in the case of an oil spill in a coastal area. While ice thickness and extent will control where oil may initially spread, ice properties will play an important role when determining how and when oil may eventually surface. The present study gave a first impression of the range of ice conditions that can be expected in fjords. Future work should also consider:

- 1) Repeat visits to every fjord during the season and transects across each fjord.
- 2) Analysis of stable isotopic data to determine the origin of the water from which the ice is frozen.
- 3) Including wind, current, and tidal factors in the analysis.
- 4) Inclusions of fjords in different regions south.
- 5) Laboratory studies of fjord ice to observe how oil would move through naturally grown fjord ice of different bulk salinities.

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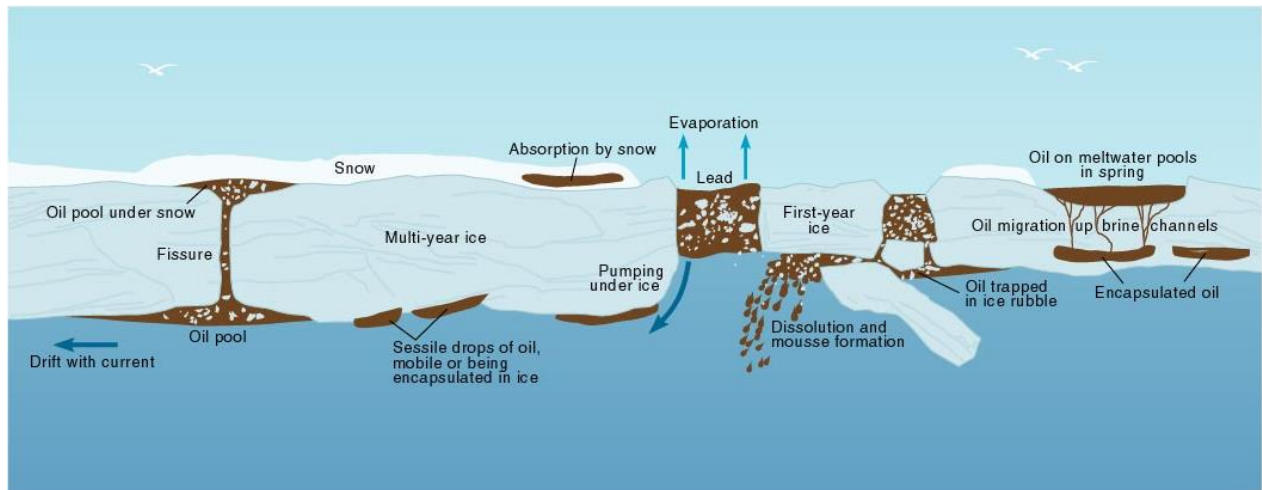


Fig. 1: Sequence of oil and ice interactions (AMAP,1998)

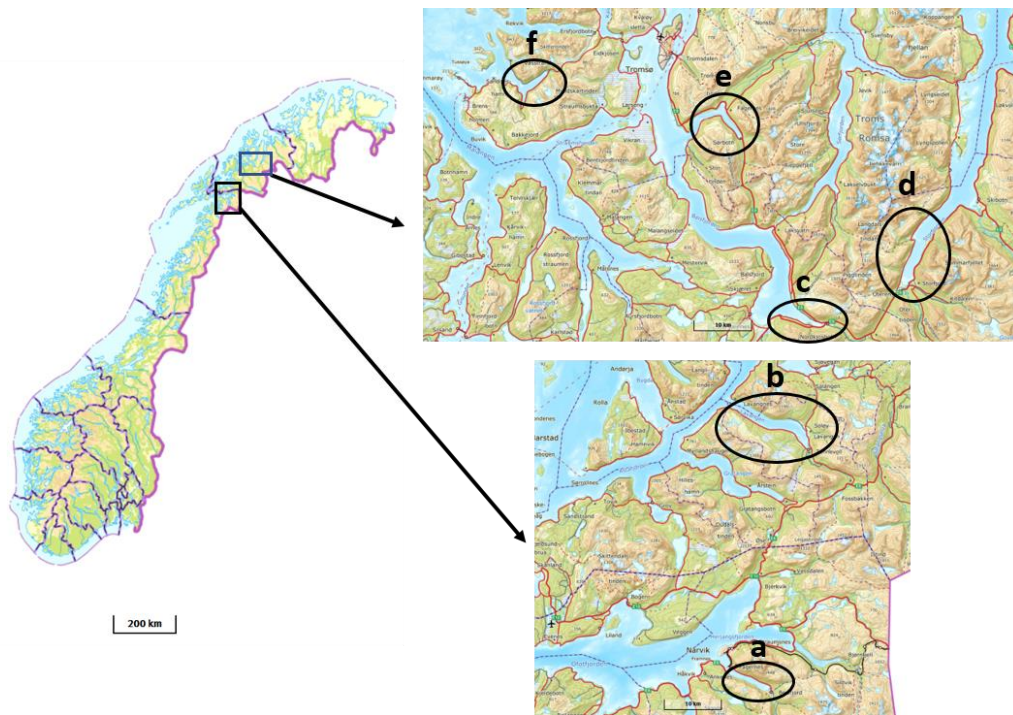


Fig. 2: Location of fjords where measurements were gathered. a) Beisfjord, b) Lavangen, c) Nordkjosbotn, d) Storfjorden, e) Sørbotn, f) Kattfjord

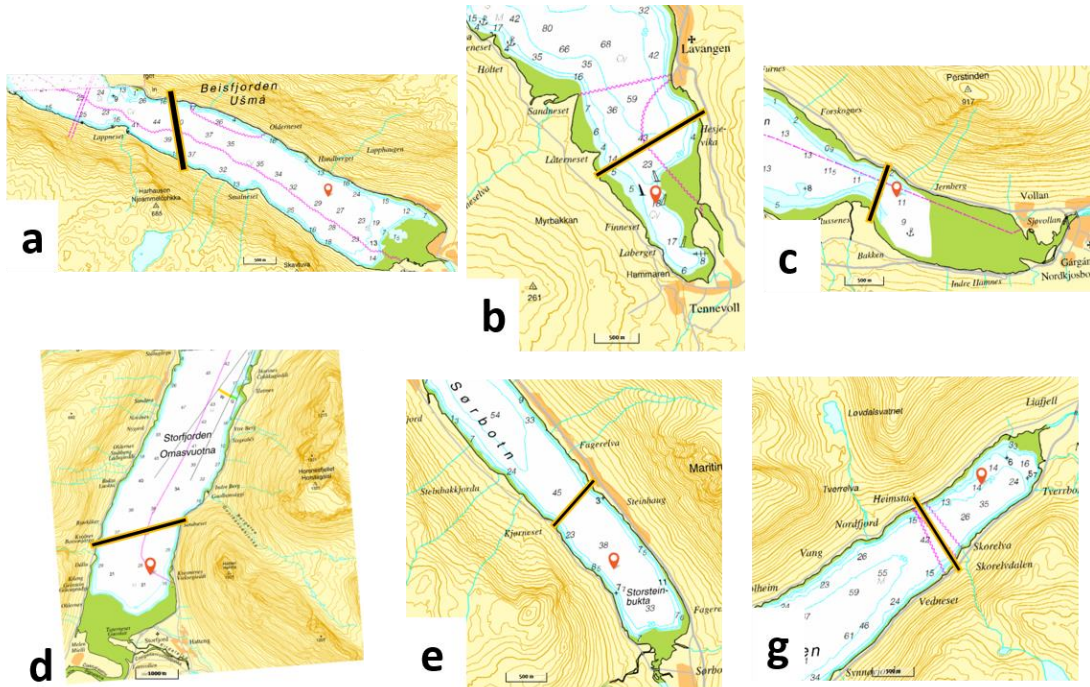


Fig. 3: Close up of fjords where measurements were gathered. a) Beisfjord (13 March), b) Lavangen (23 March), c) Nordkjosbotn (20 March), d) Storfjorden (20 March), e) Sørbotn (20 March), f) Kattfjord (21 March). Depths refer to low tide and are given in meters. Black and gold line marks the approximate ice extent on the date of measurement. Sample location is marked by a red/white dot.

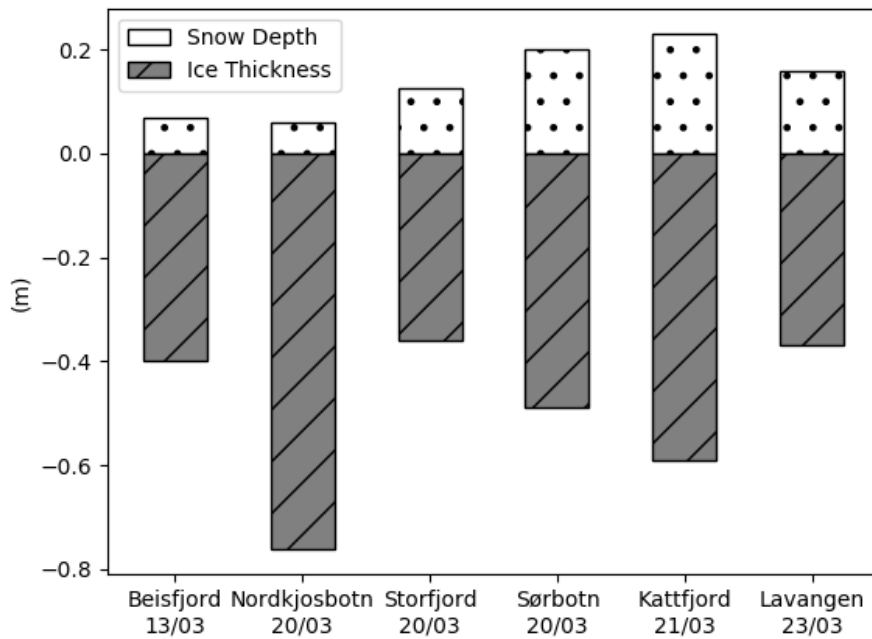


Fig. 4: Measurements of snow depth and ice thickness gathered at each sampling location.

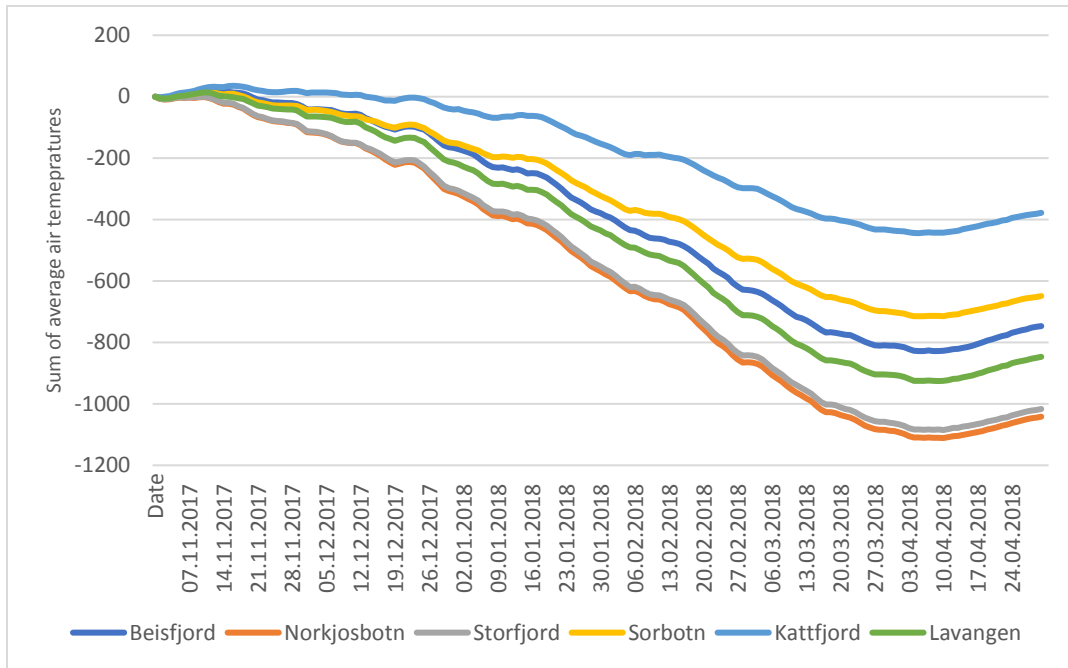


Fig. 5: Sum of average daily air temperatures from 1 November 2017 to 30 April 2018. Values of temperature provided by seNorge.

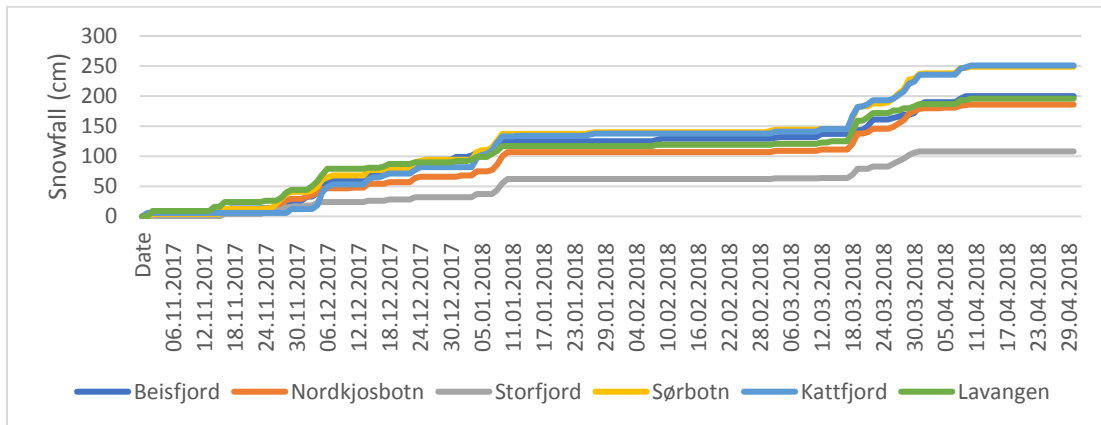


Fig.6: Cumulative snowfall in cm from 1 November 2017 to 30 April 2018. Values of temperature provided by seNorge.

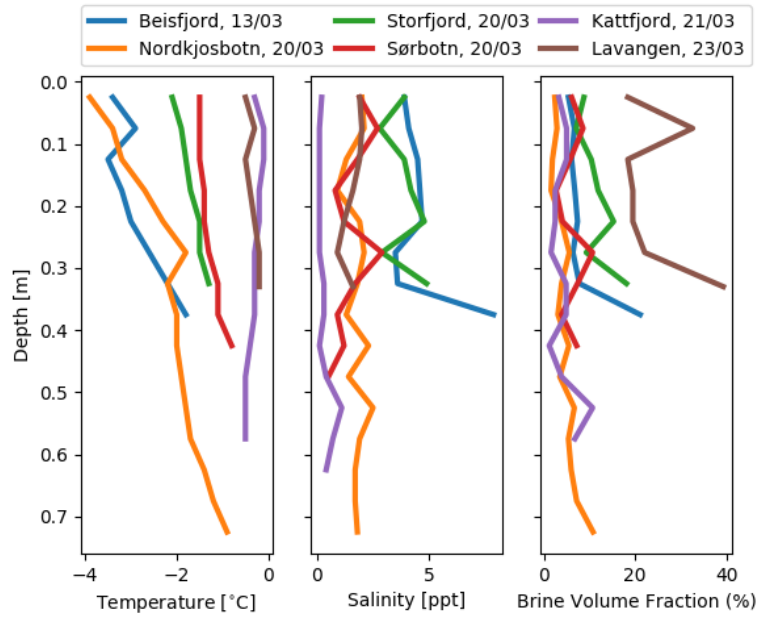


Fig. 7: Measured values of ice temperature and salinity and calculated brine volume fraction for each fjord.

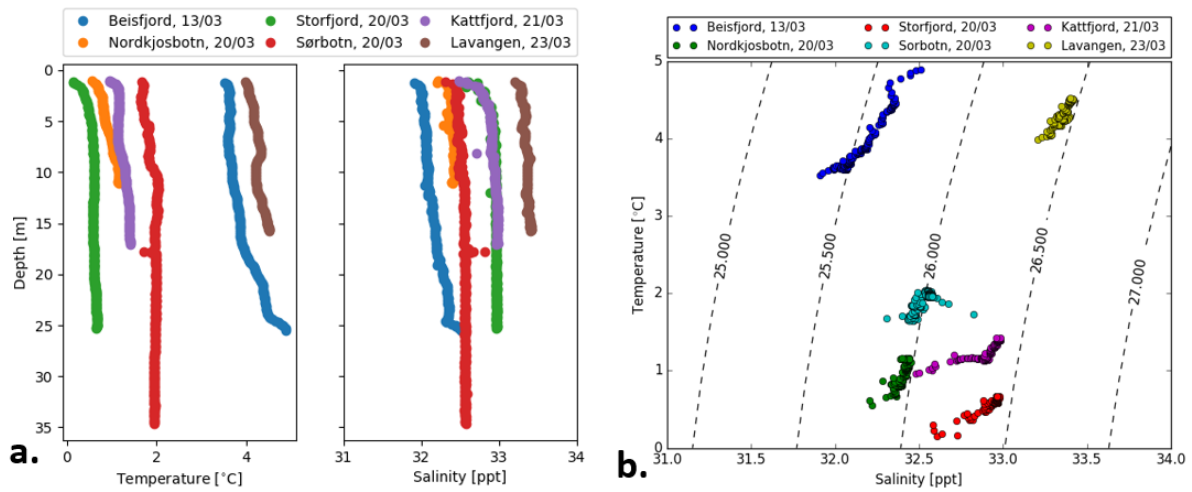


Fig. 8: a) Measurements of temperature and salinity gathered from a CTD lowered to the bottom of each fjord. Values in the top 1.0 m are not included due to an uncertain amount of mixing when cores were removed. b) Comparison of temperature to salinity with density lines plotted.

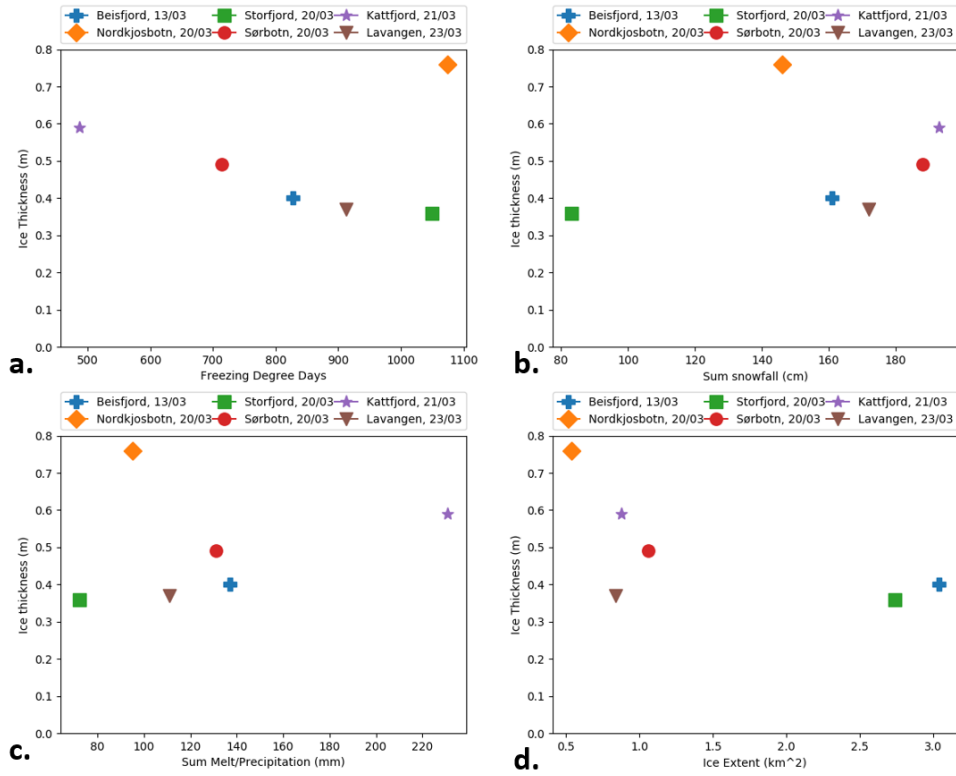


Fig. 9: Comparison of ice thickness to a) freezing degree days, b) cumulative snowfall (cm), c) the sum of melt/precipitation (cm), and d) ice extent (km²)

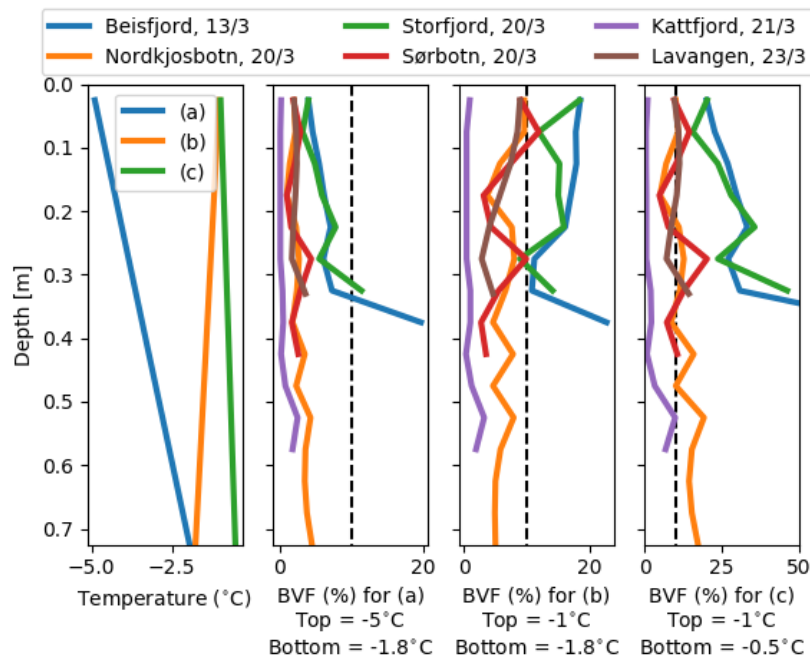


Fig.10: Derived values of brine volume fraction using linear temperature profiles and three different scenarios. Temperature at the top and bottom of ice given below each. Dashed line at 10% is representative of brine volume fraction where oil migration may be initiated.