POAC'25
St. John's, Newfoundland and Labrador, Canada

Proceedings of the 28th International Conference on Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador
Canada

Ice thickness formation and growth of fjord ice in Hjellbotn in the Trondheim fjord, Norway

Knut V. Høyland[1], Vegard Hornnes[1], Hanno D. Vetter[1] and Blandine Duprat[1], Alexandra Pliss[1] and Max Wilmink[1]
[1] NTNU, Norway

ABSTRACT

Ice thickness and physical properties were measured over several weeks in Hjellbotn, far north in the Trondheim fjord in four seasons (2021/2022-2024/2025). The measurements reported in this paper include ice and snow thicknesses, freeboard, temperature, salinity and density as well as ice texture. The ice formed from low-saline top water layer resulting from precipitation (snow and rain) and river run-out. This water layer beneath the ice was about 0.5 to 1 m thick. The ice cover was partly layered due to high amounts of precipitation and modest FDDs. The full thickness ranged from 21 to 50 cm, while the only-ice layer ranged from 21 to 25 cm. The ice was almost iso-thermal most of the season because of precipitation and flooding. Salinity was mostly below 1 ppt. Finally, the prediction of ice thickness for practical applications is challenging as the physics behind the standard models is diffe rent than the real physical processes.

KEY WORDS Fjord ice; Ice thickness; Physical properties; Stratification; Ice growth.

INTRODUCTION

Sea ice is *Any form of ice found at sea which has originated from the freezing of sea water* (WMO, 1970}. It does not state how long the water must have been in the sea before it becomes sea water. We define fjord ice as the ice that forms from the water in the fjord, even if the water has only been in the fjord a few hours. In many Norwegian fjords ice forms, in some every winter and in some others only in some winters. Fjord ice is not well mapped or described in Norwegian coastal waters, even though O'Sadnick et al. (2022) addressed fjords in Northern Norway and has provided mapping (https://ndat.no/fjords/). But, in many other Norwegian fjords no mapping or investigations of fjord ice has been done. More have been done in Arctic fjords such as on Svalbard and on Greenland, see for example Gerland and Hall (2006), Høyland (2009) and Swirad et al. (2024). The ice-covered area was about 2 km times 4 km (Figure 1) which is smaller than a typical area captured by operational remote sensing services. This means that only optical sensors could be used. These only work in cloud free weather and when satellites pass over so that we could not rely on remote sensing to capture the ice formation.

An ice cover has important practical consequences, both for the ecology and for infrastructure. The design and operation of bridges is governed by the standard from the Norwegian Road administration (N400). The ice thickness, the ice area and the duration of the ice cover are essential input to estimation of ice action on bridges. Safety when crossing floating ice requires knowledge about the ice thickness and the strength of the ice cover. Guidelines are given by NVE (https://www.nve.no/english/), but only for lake and river ice. A fjord ice cover insulates the water from the atmosphere and is vital for the ecology. Further fjord ice is used for transport, and leisure activities such as fishing and ice skating. All in all, the extent, duration and thickness of a fjord ice cover is relevant information.

The estimation of ice action on infrastructure and bearing capacity requires a quantification of the ice cover strength. It is mostly given by the ice thickness and its temperature/ porosity. But what is the ice thickness? In areas with limited *FDD (Freezing Degree Days)* and enough precipitation the ice cover may consist of layers of ice and slush in between Hornnes et al. (2023). The Norwegian site (https://www.varsom.no/is/) explains the basic physics in ice layers in lakes. All formulas and standards assume one solid ice cover, and it is not clear how strong a layered ice cover will be.

SITE AND EXPERIMENTAL SET-UP

Figure 1 shows map of the site. The maximum vertical tidal variability is about 3.5 m, and Figure 2 shows pictures at high and low tide. Two rivers run out, but most of the water comes from the river *Moldelva* in the north-east. It is a famous place for ice fishing, ice forms every year and stays for 3 - 5 months. The ice cover is level ice and is somewhat thinner close to the coast. Meteorological and hydrological data are taken from respectively Steinkjer weather station (seklima.no) and the river coming through Steinkjer (sildre.nve.no).

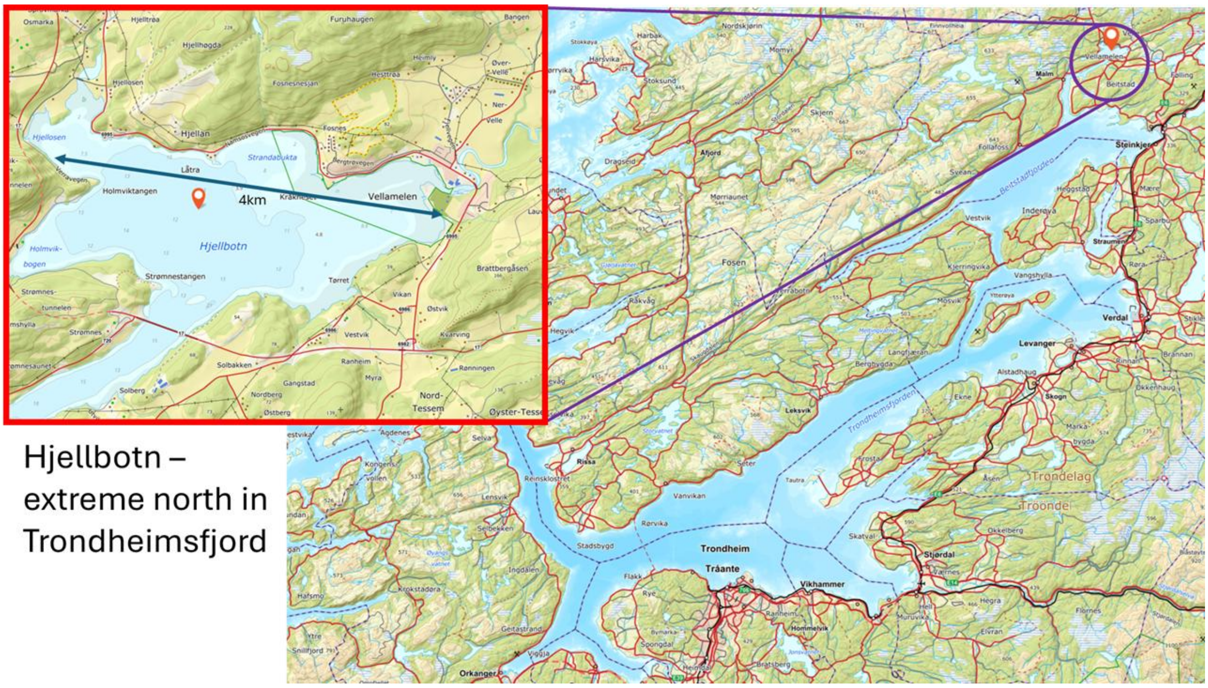

Figure 1. Map of Trondheim's fjord and zoom-in on Hjellbotn (top left)

The coastal ice (deformed by the vertical tidal water-level variations) can either be thicker or thinner than the free-floating landfast ice. Investigations from the Svea Bay on Svalbard where there is permafrost, cold water and cold winters (Blæsterdalen et al., 2016) showed thicker coastal ice. Whereas in Hjellbotn where winters are mild and there is no permafrost the coastal ice is thinner than the landfast ice (Figure 2). Ice forms when the surface water becomes equal to its freezing point ($T_{water}=T_f\ (S_i)$). Norwegian fjords are often strongly exposed to the North Atlantic Coastal current that brings in warm and saline water every tidal cycle. In Trondheim fjord the sea surface temperature (SST) is about 4-8°C during the winter https://www.seatemperature.org/europe/norway/trondheim.htm). In other words, far too warm for ice formation. Ice only forms when there is a fresh surface water-layer and the air temperatures are below zero.

a) b)

Figure 2. The beach at a) High tide and b) Low tide.

Table 1 gives an overview of the measured parameters. The ice thickness was measured with manual drilling together with freeboard and snow depth. Ice cores were taken, the layers were examined, and samples were taken home for salinity, density and ice texture quantification. One, or two one-meter long thermistor-sticks (GEOPrecision) were installed and recorded the temperature in the air, through the snow and ice and into the water underneath every hour. The temperature and salinity of the upper water layer was measured manually with a probe lowered down in a hole in the ice. Borehole Jack tests were done with the NTNU jack Hornnes et al. (2024) and will be presented and discussed in another paper. In 2022 we installed bi-axial pressure sensors in the ice, but as the ice was almost isothermal the measured stresses were low.

RESULTS

Level ice thickness, snow and ice layers

Table 2 gives a summary of ice and snow thicknesses. The distinction between full ice thickness and only-ice thickness is explained in Hornnes et al. (2023) and illustrated in Figure 3 where the only-ice was about 0.12 m and full ice thickness (including slush layer) was up to 0.2 m. The only-ice layer was also layered (Figure 3c), but without slush or gaps in-between layers. As the table shows ice thickness varied strongly in-between years. In 2022 the precipitation was mostly snow and several layers developed. The other years there was also sufficient rain to melt and refreeze the snow. The snow thickness varied strongly in-between seasons and also throughout the different seasons. Figure 4b shows ice and snow thicknesses throughout the 2024 measurements.

Table 1. Overview of the field work in Hjellbotn 2022-2025.

Year	Drilling			Sampling			Water		Thermistor-stick	Mechanics	
	h_i	*FB*	h_s	T_i	S_i	ρ_i	T_w	S_w	$T_i(z,t)$	*BHJ*	$p(x,y,t)$
2022	x	x	x	x	x	x	-	-	-	x	x
2023	x	x	x	x	x	x	-	-	-	x	-
2024	x	x	x	x	x	x	x	x	x	-	-
2025	x	x	x	x	x	x	x	x	x	x	-

Table 2. Overview of the field work in Hjellbotn 2022-2025.

Year	h_i^{max} full	h_i^{max} only ice	h_s snow	Precipitation	FDD (negative / all)*
	[cm]	[cm]	[cm]	-	[ºC·days]
2022	50	25	0	Snow	284/146
2023	23	23	5	Snow (rain)	328/220
2024	31	31	5	Rain (snow)	524/353
2025	21	21	0	Rain	166/25

- FDDs were calculated by: a) adding all daily negative average temperatures (negative) or by adding all average daily temperatures after assumed freeze-up (all)

Temperatures and physical properties

A relatively less saline upper water-layer of about 0.5 to 1 m was present. It was almost fresh and close to the freezing point, and we did not capture any variability with tide. Figure 4a shows a typical example from 2024, where the transition depth was between 0.6 and 0.8 m. The ice salinities were between 0.1 and 0.7 ppt and the corresponding ice temperatures were mostly above -0.5°C. The snow, flooding and rain kept the ice close to isothermal most of the season. Data from the thermistor-sticks confirms this and Figure 5 shows examples from 2024 season. The ice texture was granular, and this confirms the high amount of top ice growth.

a) b) c)

Figure 3. Ice samples, a) and b) 10.03.2023 showing full thickness including slush layer, c) from 14.02.2024 showing only-ice.

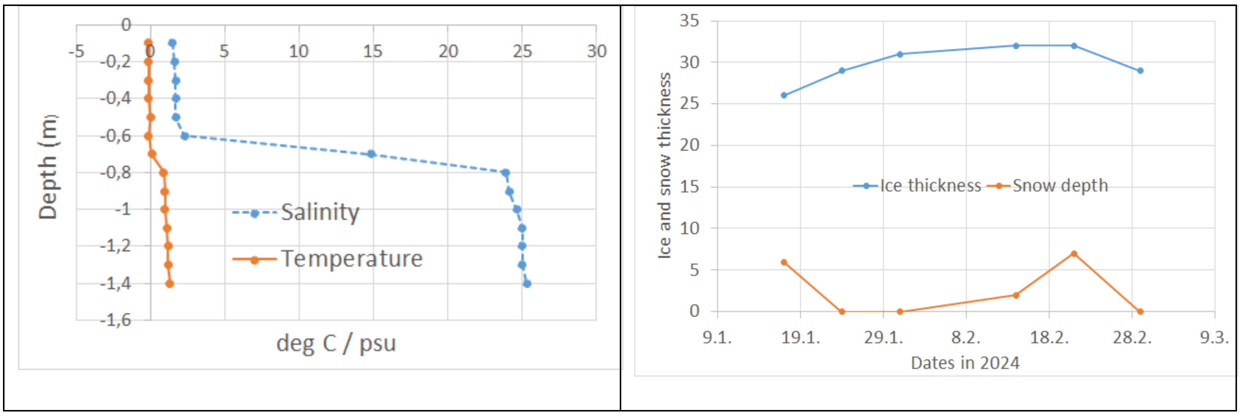

Figure 4. a) Vertical profile of water temperature and salinity under the ice 31.01.2024 and b) Ice and snow thickness over the campaign in 2024.

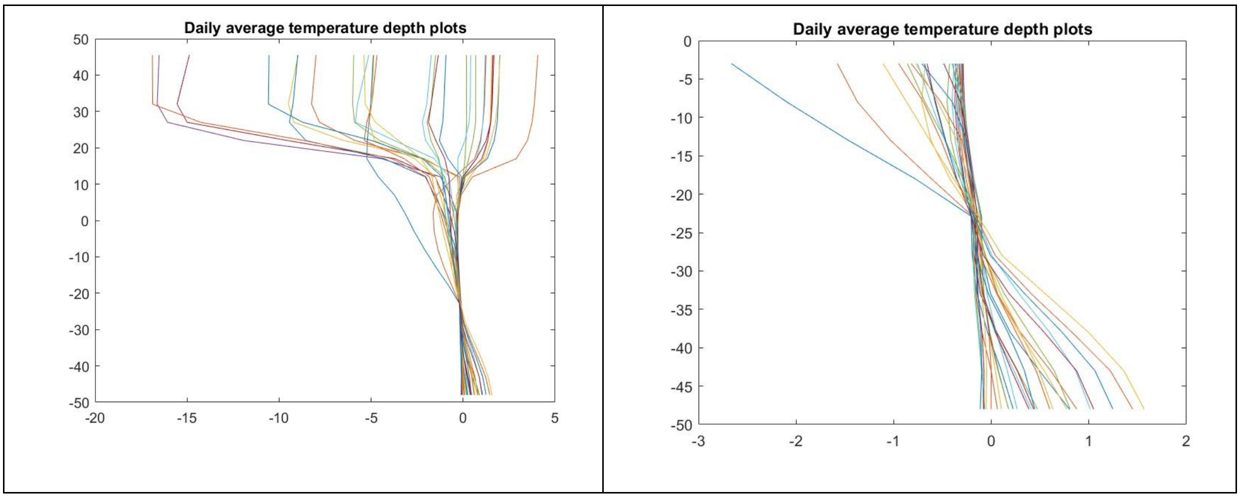

Figure 5. Daily averaged temperatures versus depth from thermistor-sticks in 2024. a) from air, down through snow and ice and into the water, b) only in the ice and the water.

DISCUSSION

Conditions for ice formation

The captain on one of the boats that is used to break the ice in the area over many years stated that *The ice usually came with the mild weather*. We also experienced this in 2023-2024 season. In November and December 2023, it was very dry and cold, all the lakes in the area had ice covers and there was little water in the rivers. There was no fjord-ice 8 December and the water had high salinity. In late December precipitation came and ice formed. This shows that the conditions for ice formation is a stable relatively fresh surface water layer. The river run-out must be sufficient, it must stay inside the sub-basin and it must not be mixed down by waves and currents. Hjellbotn is connected to Beistadfjorden by a long and narrow part, and it seems that the river-run out is not transported out of the area. A simple calculation of required river run-out during three days to form a 0,5 m freshwater layer over the 2 km x 4 km area of our sub-basin is about 15 m^3/s. There is no data on the local river, but the number is not unreasonable. The area of the sub-basin also gives a limited fetch for waves to form in the critical period with cold weather and fresh surface water layer. The stability of the fresh low saline surface water layer of thickness H and with a density of ρ_{sw} on top of a denser water body ($\Delta\rho = \rho_w - \rho_{sw}$) with a current ($v_c$) is given by a critical value given by the Richardson number ($Ri>1/4$):

$$R_i = \frac{\Delta\rho g H}{\rho_w v_c^2} > \frac{1}{4} \quad \Leftrightarrow v_c < 2\sqrt{\frac{\Delta\rho}{\rho_w} gH} \qquad [1]$$

This gives a critical current velocity between 0.5 and 1 m/s. The local current is a function of tidal and local bathymetry. We have neither measured nor modelled the tidal current, but if the Richardson number criteria is correct is should be less than 0.5 – 1 m/s. The need for fresh surface water was also observed by O'Sadnick et al. (2022) in several fjords in Northern Norway.

Prediction of ice thickness

As the ice thickness is a key property in many applications it is essential to be able to predict it. Table 4 shows predictions of maximum ice thickness from some different models. Most of the models give conservative estimates, both for full thickness and only-ice thickness. However, the level of precision is not very good. If we would use some of these to predict ice thickness for ice actions on a vertical bottom-fixed structure, it would either be very conservative, or very uncertain. The first challenge is that there are no well-known models (hardly any at all) that can be used to find ice action from a layered ice cover.

Table 4. Ice thickness measurements and corresponding predictions with different versions of Stefan's law. Only negative air temperatures were used in the FFDs.

Year	h_i^{max} full	h_i^{max} only ice	h_s snow	Stefan, Ta =Ts	Stefan ω=0.4	Stefan snow	Danish rules
	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
2022	47	25	8	58	37	22	40
2023	23	23	5	62	39	33	45
2024	31	31	5	79	50	48	62
2025	21	21	0	44	28	28	24

Secondly, the governing assumptions behind Stefan's law and other similar empirical modes (including Zubov and Lebedev's equations) are stable cold winter where the ice forms on the ice bottom as heat is pulled up though the ice cover. With increasing air temperatures and precipitation two things happen. One is that the air temperature during winter oscillates around the freezing point, and another is that the increasing snow layer makes the ice warmer and increases the top ice formation. Let us look at the oscillating air temperatures first. It is not clear how to deal with these as high air temperatures do not directly melt ice. They may melt the surface snow which drizzles down in the snow-pack and re-freezes. Now the snow is warmer, but also thinner so the net effect on the vertical heat transport is not obvious. If one simply adds all (also positive) air temperatures to the FDD, the ice thickness may be too small so that one may underestimate the ice actions. By using only the negative ones one should be on the safe side.

Then about the snow, flooding, rain and top ice growth. These give different physical processes governing ice growth than those assumed in Stefan's law. And it is of course questionable to use models that assume different physical processes than those governing the reality. Models that simulate snow ice formation exist and are included in some large-scale models. There are challenges with the models themselves, such as the diffusion of brine. But perhaps even more difficult is the prediction (or measurement) of the snow thickness and density. The statistics of precipitation and snow cover on sea ice is much more uncertain than the statistics of air temperatures (giving FDD). To our knowledge no accepted guidelines are available on the estimation of how snow affects ice thickness for design of structures (or bearing capacity).

In the end it is the cold atmosphere that drives the freezing, so even if the ice does not form from the ice bottom from heat being pulled up through the ice thickness, the colder it is (more FDDs) the more snow ice will form. As a summary we may mention some unsolved challenges with ice thickness prediction in a changing climate with substantial top ice formation:

- Which ice thickness is important for the problem at hand?
- How should one deal with positive air temperatures?
- How should top ice growth be predicted? Can Stefan's law models make any sense?

CONCLUSIONS

We have done four years of field investigations about the ice conditions and properties in Hjellbotn in Trondheimsfjord in Norway. Some of the data are presented and discussed in other papers and in this paper we have focused on ice formation and growth. The main conclusions are:

• The ice forms from freshwater layer from river run-out, and the ice cover depends on the stability of the freezing-point water layer beneath the ice.

• The high amount of precipitation and modest *FDD*s means the ice becomes low-saline and warm.

• High fraction of ice growth is top ice. Snow gives more layered ice cover.

• The prediction of ice thickness for practical applications is challenging as the physics behind the standard models is different than the real physical processes.

ACKNOWLEDGEMENTS

Thanks to Lia Francisca Herrmannsdörfer and Yuan Zhang for helping in field. The authors wish to acknowledge the support from the Research Council of Norway through the two projects RareIce (326834) and IceWise (352996) and the support from all industry partners. Finally, we should thank Eldar Asp who allows us to park on his ground, install our equipment and so on.

REFERENCES

Blæsterdalen, B., Wrangborg, D., Marchenko, A. and Høyland, K.V. 2016. Geometry and Thermo-Mechanical Properties of Coastal Ice in a Micro-Tidal Climate in Svalbard, Part I, Permeability and Geometry. Proc. of the 23 Int. Symp. on Ice (IAHR), Ann Arbor, USA, June 2016, paper 4878716.

Gerland, S., Hall, R., 2006. Variability of fast-ice thickness in Spitsbergen fjords. Annals of Glaciology (44), 231-239.

Hornnes, V., Høyland, K. V., John, J., 2023. Layered ice thickness - exmaple from Norwegian fjords. In: Proc. of the 27 Port and Ocean Engineering under Arctic Conditions (POAC), Glasgow, Scotland. Vol. ISBN.

Høyland, K. V., 2009. Ice thickness, growth and salinity in the Van Mijen fjord on Svalbard, Norway. Polar Research (28), 339-352.

O'Sadnick, M., Petrich, C., Brekke, C., Skardhamar, J., Øystein Kleven, 2022. Ice conditions in northern Norwegian fjords: Observations and measurements from three winter seasons 2017 to 2020. Cold Regions Science and Technology (204), 103663.

Swirad, Z. M., Johansson, M., Malnes, E., 2024. Extent, duration and timing of the sea ice cover in Hornsund Svalbard from 2014 2023 . The Cryosphere 18 (895-910).

WMO, 1970. WMO sea ice nomenclature, (supplement No. 5, 1989). Tech. Rep. MO No. 259.TP.145, World Meteorological Organization, Geneva, Switzerland.