



# Stensby Inlet Fast Ice study

2023-VIC\_Baffinland Project E-5

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## Table of Contents

Task description .....	4
Prevalent condition in the Steensby Area .....	4
Data analysis .....	9
Data sources .....	9
Canadian Ice Service – Ice data.....	9
ECMWF – ERA5-Land .....	9
Evaluated parameter - Distance to ice edge .....	9
Methodology.....	9
Results .....	12
Location of fast ice edge .....	12
Distance along ship track .....	16
Discussions .....	17
Evaluated parameter – Cumulative Freezing Degree Days (temperature).....	19
Methodology.....	19
Calculation of Cumulative Freezing Degree Days .....	19
Results .....	19
Discussion.....	23
Evaluated parameter - Snow thickness.....	24
Methodology.....	24
Results .....	24
Discussion.....	27
Evaluated parameter - Ice thickness .....	28
Methodology.....	28
Discussion.....	28
Evaluated Parameter – Polynya.....	30
Methodology.....	30
Results .....	30
Establishment and breakup of floe edge in polynya zones .....	31
Verification of presence of polynyas.....	32
Polynya width .....	34
Statistical analysis.....	35
Implications for shipping operations.....	37
Implications induced by climate change .....	37
Further work.....	38
Methodology for update process.....	39
References.....	39

## Table of Figures

Fig. 1. The fast ice located at Stensby Inlet and approaches. The proposed shipping route is indicated by the black line. ....	5
Figure 2: The North Water polynya between Greenland and the Ellesmere Island, satellite image provided by Sentinel-2 L2A on 11.05.2023. ....	6
Figure 3: Sentinel2 L2A image taken 14 April 2023 showing the area the dynamic pack ice, the open water and the fast ice edge at the approaches to Stensby Inlet. The proposed route is indicated as a black line. ....	7
Figure 4: Sentinel-2 L2A with 10 meter resolution from 14 March 2023, showing details of the fast ice edge. ....	8
Figure 5: Section of charts (pdf-format) utilized for the period 1996 to 2006. ....	10
Figure 6: Illustration where Form of Ice (FA) is defined as Fast ice with a value of 08. Illustration based on ice charts provided in a GIS format. ....	11
Figure 7: Points generated where the proposed route enters the fast ice. ....	12
Figure 8: Stensby Inlet with probabilities (%) for the first week of December. ....	13
Figure 9: Stensby Inlet with probabilities (%) for the first week of February. ....	13
Figure 10: Stensby Inlet with probabilities (%) for the first week of April. ....	14
Figure 11: Stensby Inlet with probabilities (%) for the first week of June. ....	15
Figure 12: Location of fast ice edge during the first week of April. ....	16
Figure 13: Maximum annual distance from the Steensby Inlet port to landfast ice edge along the ship track. ....	17
Figure 14: The dependance of the distance to ice edge on winter severity measured by the maximum CFDD. Note that the bottom left corner is not origin. ....	18
Figure 15: Daily Temperature plotted versus the day number starting first of January [oC]. ....	20
Figure 16: Annual Average Temperature Trend ....	21
Figure 17: CFDD for each winter in the database. ....	22
Figure 18: The maximum CFDD value for each winter in the database. ....	22
Figure 19: Comparison of measured (black line) and ERA5 (red line) temperature from the Steensby Inlet for year 2022. ....	23
Figure 20: Daily Snow Depth Water Equivalent [m]. The blue stars represent the average cumulative precipitation in Hall Beach according to the Weather and Climate home page. ....	25
Figure 21: Average Snow depth Water Equivalent. ....	26
Figure 22: The maximum snow cover water equivalent for each winter. ....	26
Figure 23: The maximum snow cover thickness versus the maximum CFDD for each winter. Note that the origin is not in the bottom left corner. ....	27
Figure 24: The maximum level ice thickness for each winter. ....	28
Figure 25: Polynyas identified in the vicinity of the route. ....	31
Figure 26: Maximum Polynya width as a function of ambient air temperature. ....	34
Figure 27: The extreme value fits for annual maximum values, plotted versus the return period. Fit for maximum top and for minimum bottom. ....	36

## Task description

The planned port at the Steensby Inlet is located in an area of the northern Foxe Basin where there is landfast ice for a major part of the winter.

The purpose of this work is to obtain a better understanding of the governing factors for landfast ice regime in the port area and its approaches. This is obtained through updating the baseline ice and weather information for landfast ice using a long-term dataset, (28 years), and with information on inter-annual variation.

Fast ice also known as landfast ice is ice that is anchored to the shore or ocean bottom. This ice is typically found in protected waters inshore archipelago or over shallow ocean shelves at continental margins. Fast ice is defined by the fact that it does not move with the winds or currents. Landfast ice area is described mainly by its texture – landfast ice is essentially level ice that is not broken. No or very limited ridges nor leads occur in landfast ice area. Thus the main parameters to describe landfast ice is its areal extent, its thickness and possibly the thickness of snow cover on ice.

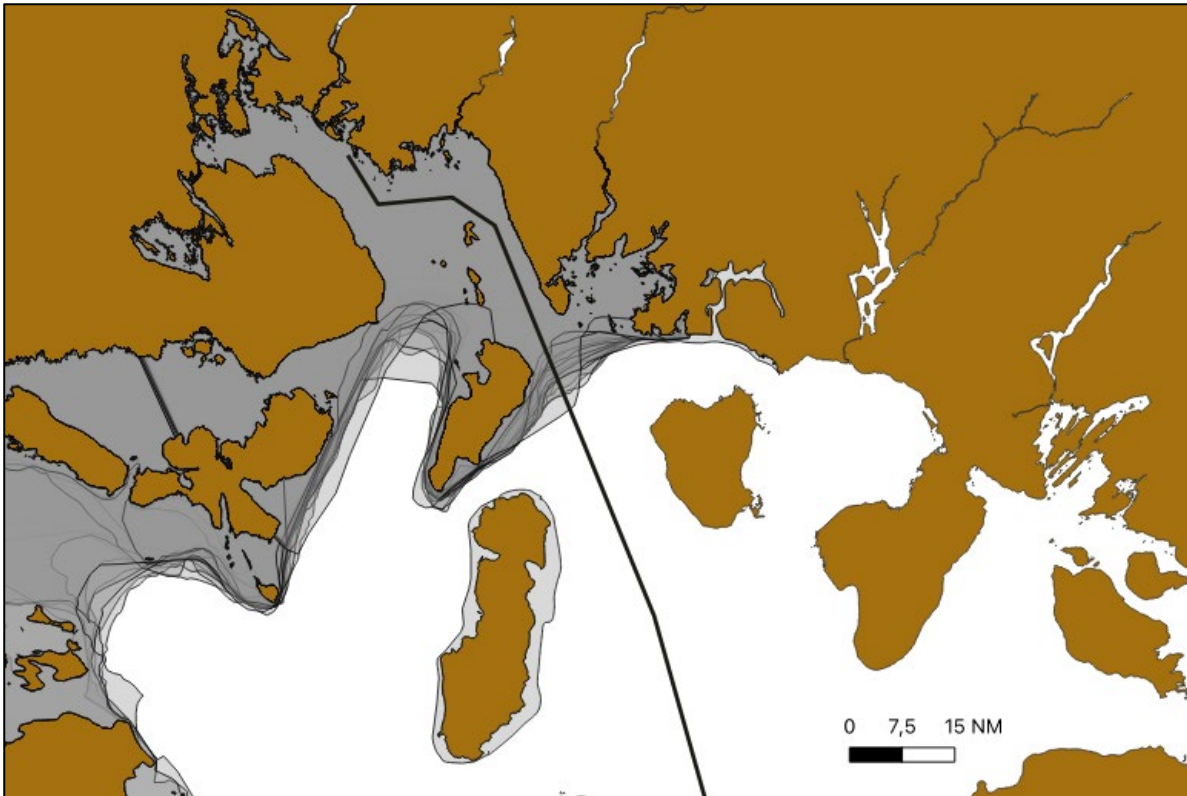
For this study to describe the fast ice close to the Steensby Inlet port, the extent of fast ice is deduced from ice charts. The temperature and snow cover are obtained from ERA5 archive – the snow cover is given only as a water equivalent. The temperature is used to calculate the level ice thickness. As the fast ice extent is used to determine the distance along the ship track in fast ice, there are five parameters obtained to describe the fast ice area:

- Distance in fast ice along the ship track ( $D$ ),
- temperature in the fast ice area  $T$
- and the cumulative temperature based on temperature data calculated for each winter (CFDD),
- water equivalent of snow and the resulting snow cover thickness ( $h_s$ )
- and finally the calculated level ice thickness ( $h_i$ ).

The results from the analysis for landfast ice can be updated annually using annual sea ice data (floe size, cover, concentration) as well as temperature data. This data set will be synthesized and reported according to the most appropriate management plan.

## Prevalent condition in the Steensby Area

Steensby Inlet is located in the northern part of the Foxe Basin in the Canadian Arctic. The inlet is protected by several islands. Koch Island is located outside (south) of the inlet. The protected waters combined with low ambient air temperatures is the prerequisite for the yearly generation of fast ice. Fast ice is essentially level ice that is attached to shore – thus it is often called shorefast or landfast ice. Usually the outer boundary of shorefast ice is outside the outermost islands towards open sea. Typically the boundary is outside the islands at a water depth curve (isobath) of 10 – 15 m depth. This also indicates that the boundary is determined by the action of dynamic i.e. drifting ice at the sea basin which is outside the fast ice area. The fast ice edge obtained from ice charts is shown in Fig. 1.



*Fig. 1. The fast ice located at Stensby Inlet and approaches. The proposed shipping route is indicated by the black line.*

The area south of the fast ice is dominated by thick first year drifting ice during the winter months. The dynamic nature of the drift ice generates a high concentration of ridges and hummocks as well as open water patches.

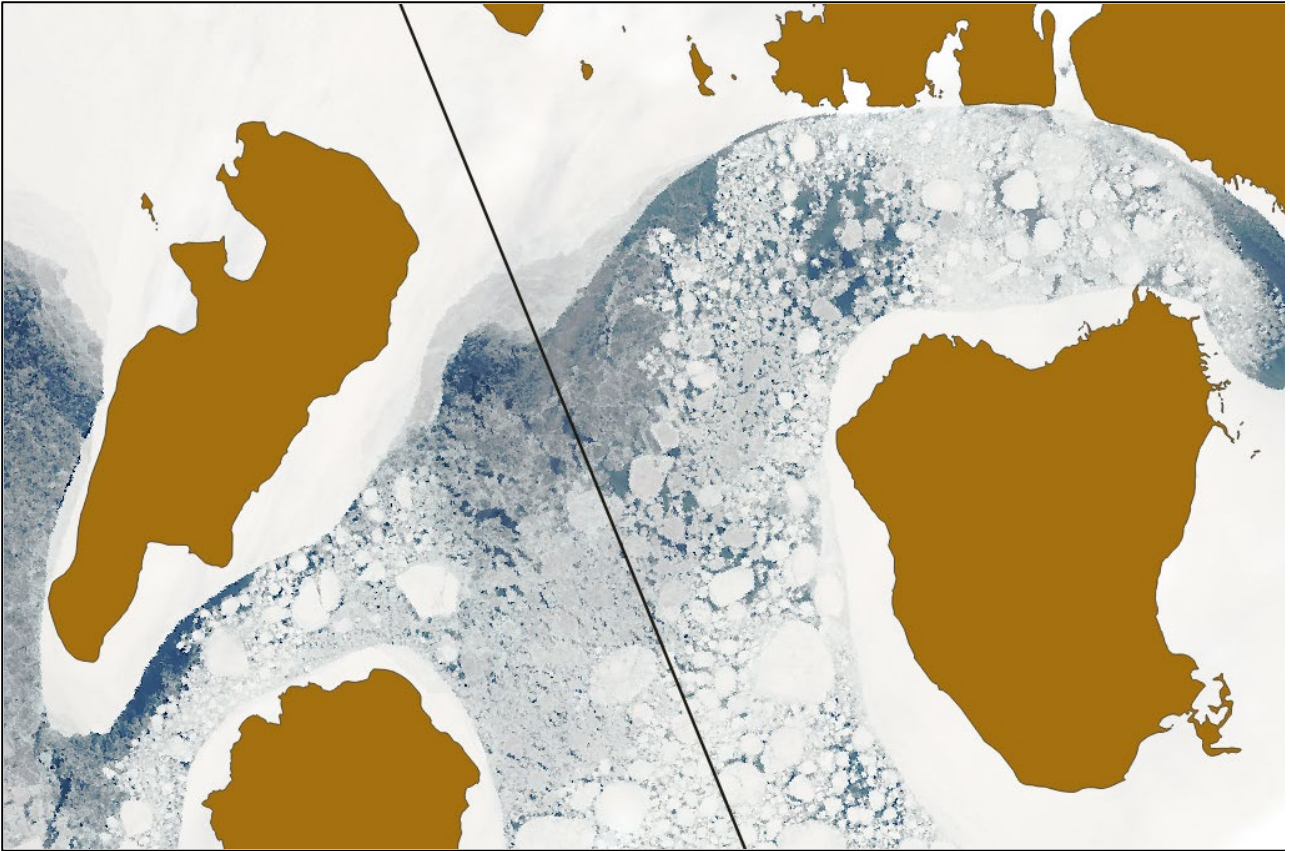
During the winter, drift ice will exert pressure on the edge of the fast ice. This contributes to large ice deformations and areas with brash ice. Just outside of the fast ice edge there is often found open water polynyas. This is due to the combination of the predominant ocean currents and wind. Open water polynyas are typically known to be highly productive areas for flora and fauna. An example to quite stationary open water area is in the southern part of the strait between Greenland and the Ellesmere Island called the North Water, see Fig. 2.



*Figure 2: The North Water polynya between Greenland and the Ellesmere Island, satellite image provided by Sentinel-2 L2A on 11.05.2023.*

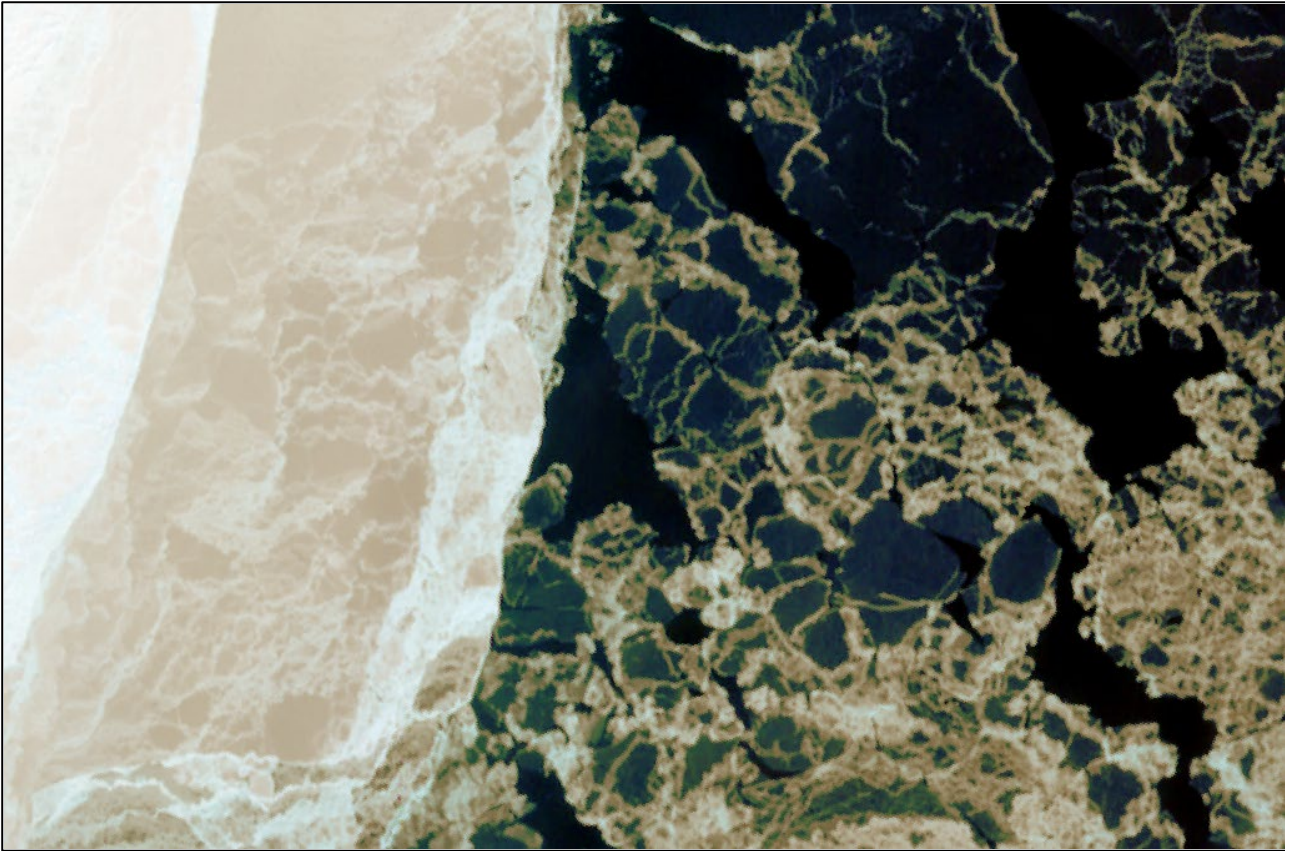
The degree of open water located outside the fast ice edge at Steensby is dependent on the local predominant wind direction. At times there are relatively large bodies of open water outside the fast ice area, while other times the dynamic pack ice is pushed towards the stationary fast ice edge. This is illustrated in Fig. 3.





*Figure 3: Sentinel2 L2A image taken 14 April 2023 showing the area the dynamic pack ice, the open water and the fast ice edge at the approaches to Stensby Inlet. The proposed route is indicated as a black line.*

When looking closer it is evident that new ice is forming in the open water just outside the floe edge. This ice can at a later stage be pushed towards the fast ice edge, consolidating, possibly generating severely deformed ice, see Fig. 4.



*Figure 4: Sentinel-2 L2A with 10 meter resolution from 14 March 2023, showing details of the fast ice edge.*

When zooming in on a Sentinel-2 L2A image from 14 March 2023 (see figure above) it is evident that a new fast ice edge is being developed indicated as a vertical grey band of ice in the image. In the fast ice ridges and deformed ice is visible as white lines/features. The ridges have typically a width of about 30 meters. To the bottom right in the image we see drift ice is being pushed in, deforming the fast ice edge. To the top right in the image we see new, frazil ice is being formed.



## Data analysis

To obtain an in-depth understanding of the factors governing the fast ice regime prevailing at the Steensby Inlet, several parameters of interest and methodologies were utilized. The different approaches required different sources of data, and addressed different aspects of the fast ice regime.

### Data sources

There are two main data sources that were utilized for the analysis. The two main data suppliers were Canadian Ice Service providing ice data and the European Centre for Medium-Range Weather Forecasts (ECMWF) providing ERA5-Land data.

#### Canadian Ice Service – Ice data

The Canadian Ice Service (CIS) is the leading authority for ice and iceberg information in Canada's navigable waters. It is part of Environment and Climate Change Canada's Meteorological Service. The CIS provides accurate and timely information on ice and icebergs in Canada's navigable waters most in form of ice charts published at least weekly. The ice charts from 2006 to 2023 were downloaded from NSIDC (National Snow and Ice Data Center), and the charts from 1996 to 2006 were downloaded directly from CIS.

#### ECMWF – ERA5-Land

ERA5-Land is a reanalysis dataset providing consistent weather variables over several decades. The reanalysis combines model data with observations from across the world into a globally complete and consistent dataset based on meteorology theory. Reanalysis produces data that goes several decades back in time, providing an accurate description of the climate of the past.

The ERA5-Land dataset, as any other simulation, provides estimates which have some degree of uncertainty. The uncertainty of model estimates grows as we go back in time, because the number of observations available to create a good quality atmospheric forcing is lower.

The temporal and spatial resolutions of ERA5-Land make the dataset useful for land surface applications. The temporal and spatial resolution of this dataset, the period covered in time, as well as the fixed grid used for the data distribution at any period enables more accurate information on land states.

## Evaluated parameter - Distance to ice edge

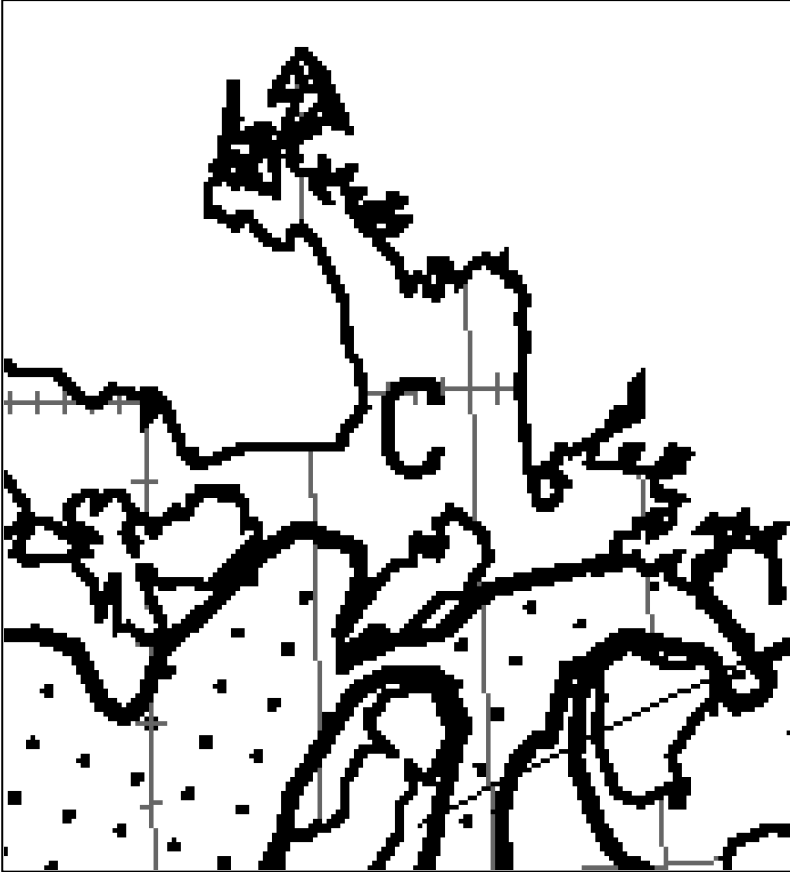
### Methodology

Weekly Regional Ice Charts for the Eastern Arctic (available in Graphics Interchange Format (GIS), Shapefile and E00) were extracted from the ftp server at National Snow and Ice Data Center (<https://nsidc.org/home>). Charts in a GIS format is preferred for the analysis, and charts from 2006 until 2023 were extracted.

For years 1996 to 2006, black and white charts (pdf format) were downloaded directly from CIS. Geo-referencing the charts to a degree of accuracy sufficient for our analysis proved to be challenging due to the inaccuracy associated with land features and projection. The data of

relevance was extracted from the charts based on manually re-drawing of the features of interest. An example shown in Fig. 5.

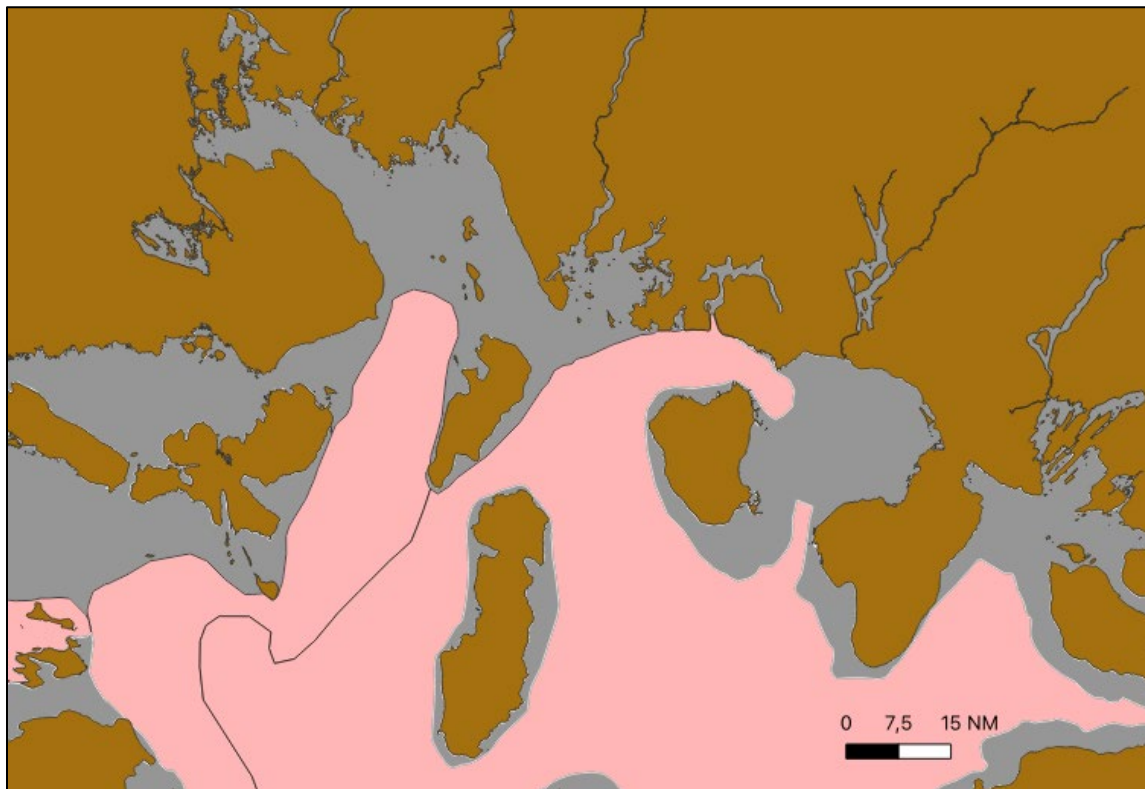
The charts provided information for all of the Eastern Arctic, and we were zooming in, only utilizing a marginal fraction of the canvas. When zooming in it proved that the lines utilized for drawing of the ice chart proved to be up to 2 nautical miles wide. This naturally influences the accuracy of estimating the location of ice edge.



*Figure 5: Section of charts (pdf-format) utilized for the period 1996 to 2006.*

When investigating the charts on this level of detail it also proved that there were uncertainties associated with the manual drawing/definition of the different ice features.

The naming convention associated with the landfast ice also proved to vary through out the time period of interest. Sometimes it was classified as a “Concentration” of 10/10 (SIGRID CODE 92) at other times it was classified as “Form of ice” as “Fast Ice” (SIGRID CODE 08), see Fig. 6.



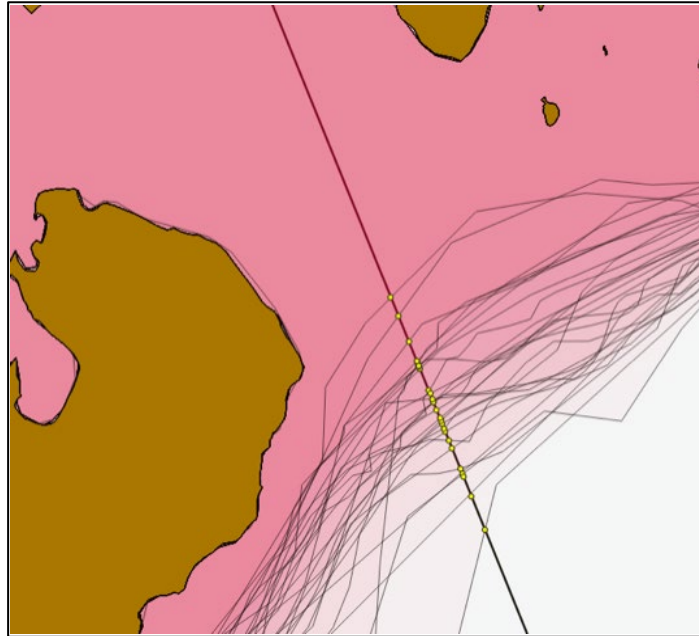
*Figure 6: Illustration where Form of Ice (FA) is defined as Fast ice with a value of 08. Illustration based on ice charts provided in a GIS format.*

Ice information describing the fast ice was extracted for the date issued closest to the following dates:

- First week of December
- First week of February
- First week of April
- First week of June.

The polygons describing the landfast ice were extracted and merged into one layer. A layer for each individual period (e.g. first week of December) was generated. This layer contained one polygon per year for the addressed weeks. The number of overlapping polygons describes the probability of ice being present, e.g. ice being present in an area 28 of 28 years indicate 100% presence of landfast ice in the area. Fig. 7 shows the interpretation of the ice edge for different years.

The points where the proposed route entered into the fast ice were identified. The distance required sailing in fast ice (distance from port to drift ice) was calculated for the individual years and for the weeks of interest.



*Figure 7: Points generated where the proposed route enters the fast ice.*

## Results

### ***Location of fast ice edge***

The location of the fast ice edge varies from year to year. Based on the obtained data the following plots were developed, see Figs. 8 - 11:

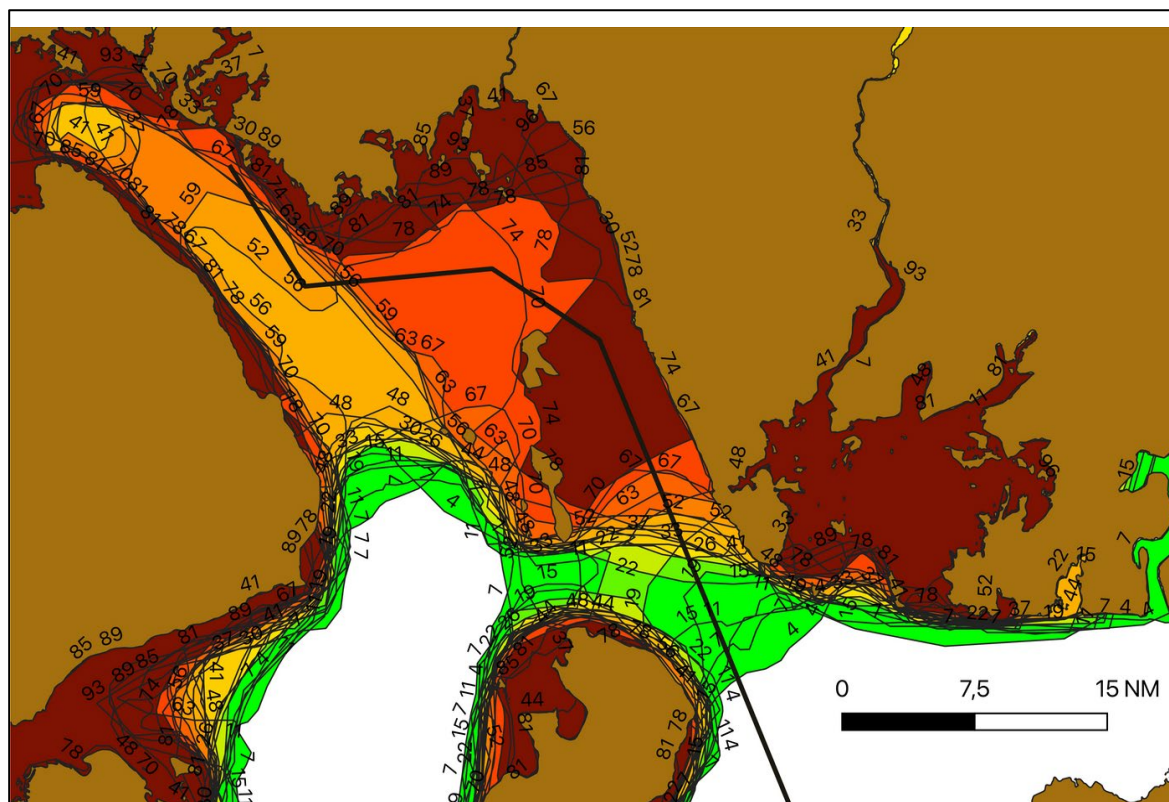


Figure 8: Stensby Inlet with probabilities (%) for the first week of December.

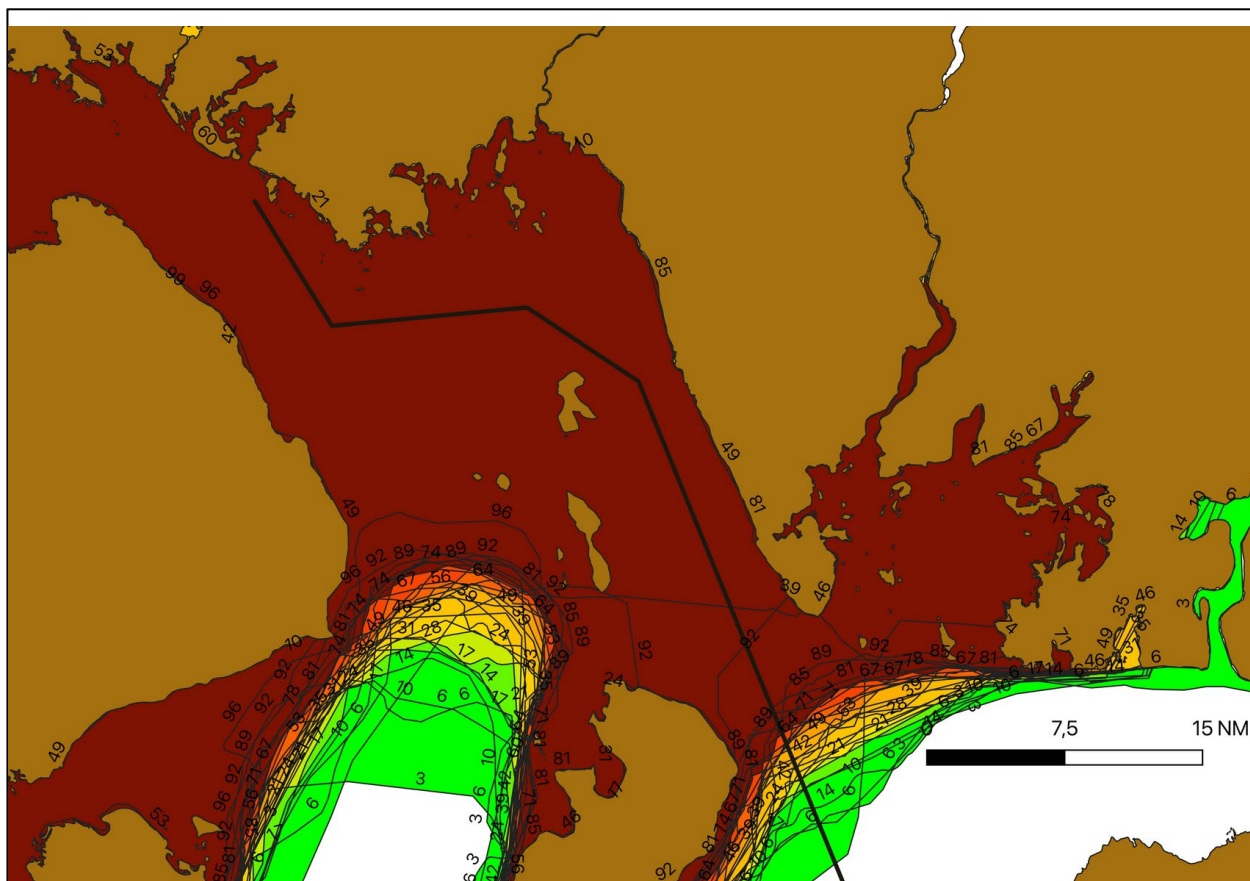


Figure 9: Stensby Inlet with probabilities (%) for the first week of February.



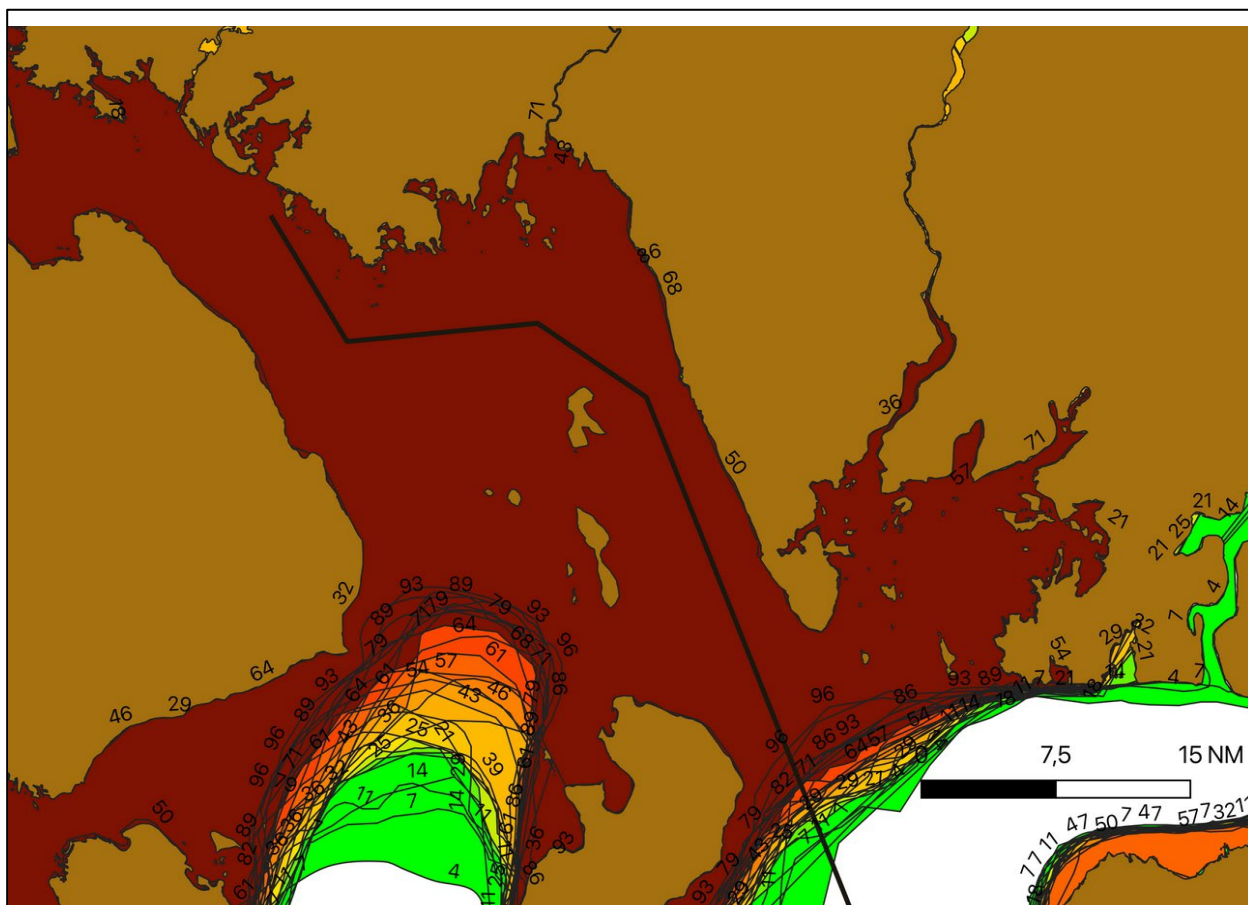
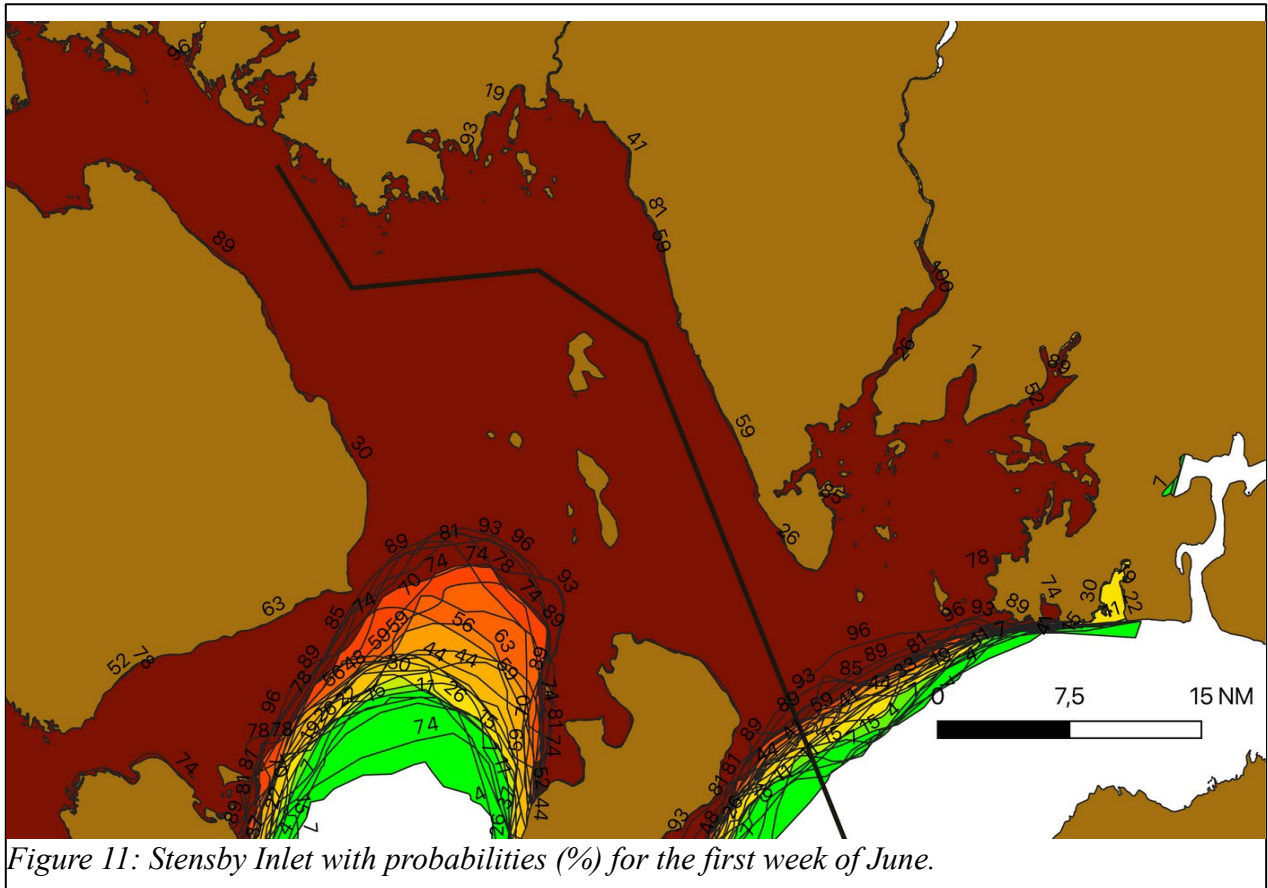


Figure 10: Stensby Inlet with probabilities (%) for the first week of April.



Based on the plots above it is evident that the ice edge starts to develop in December, and is well established by the first week of February. There is a large variability (indicated as probabilities for presence of fast ice in the plot) in December. This variability is a result of annual variation for ice growth.

It is further evident that the location of the ice edge where the route enters the fast ice is relatively constant throughout the winter. The annual variation in the location of the ice edge is observed to be in the range of only a few nautical miles. The relatively static location of the fast ice edge is most likely a result of local geographical and metocean conditions (mainly the current) being relatively constant throughout each season, see Fig. 12.

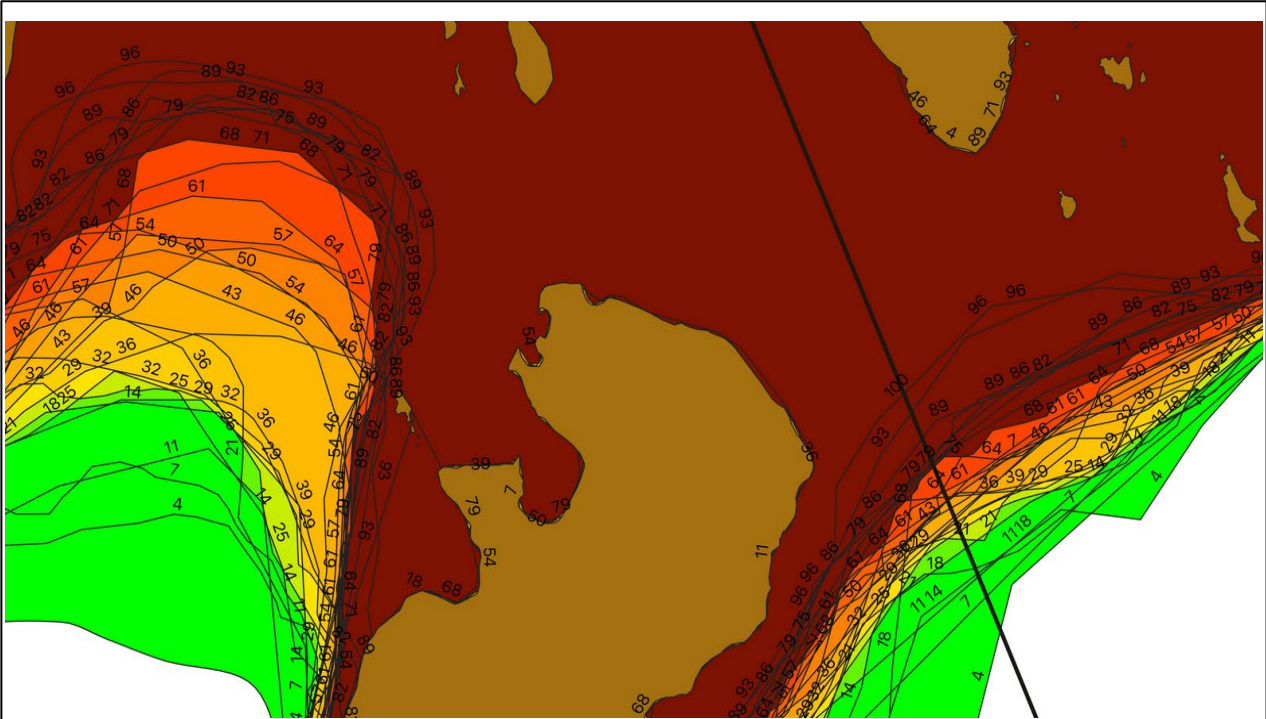
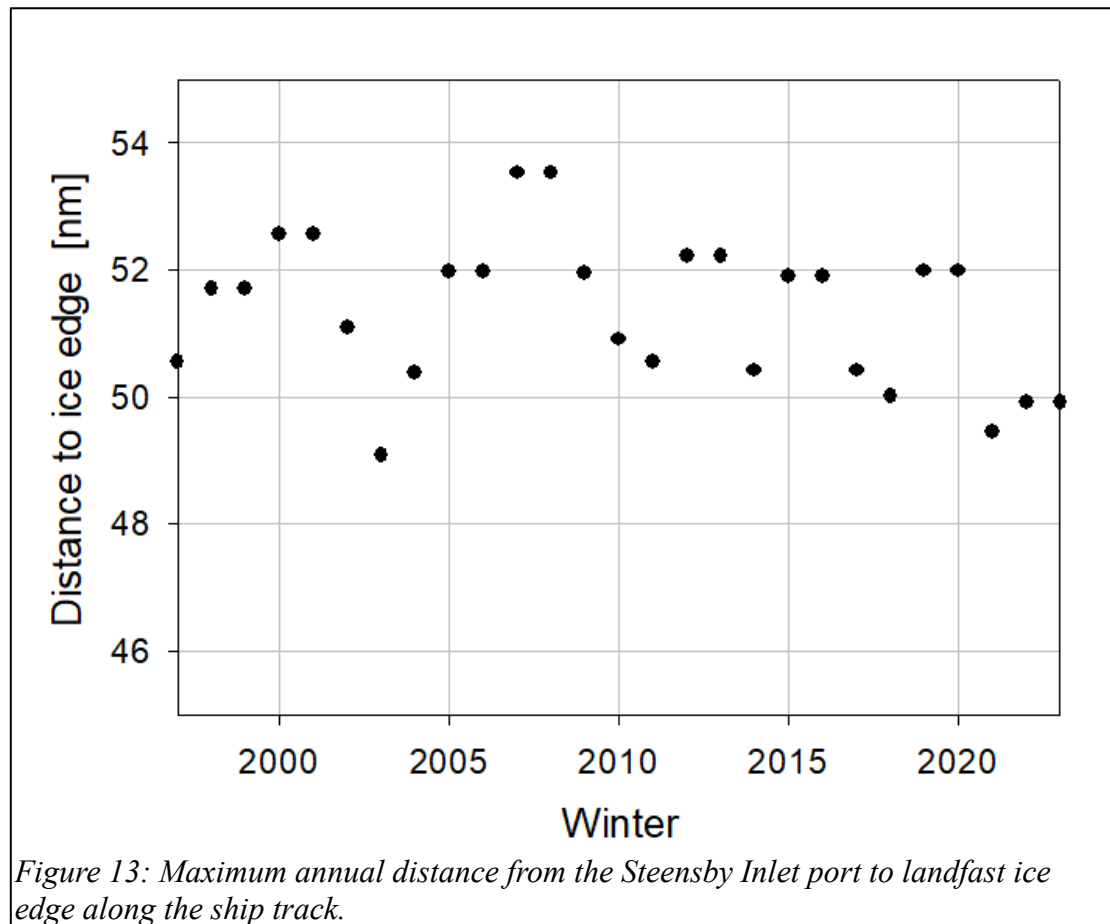


Figure 12: Location of fast ice edge during the first week of April.

The location of the fast ice edge on the West side of Koch Island shows a variability of about 15 nautical miles throughout the period examined. During most years the fast ice edge on the west side of Koch Island is located further North than on the East side of the island.

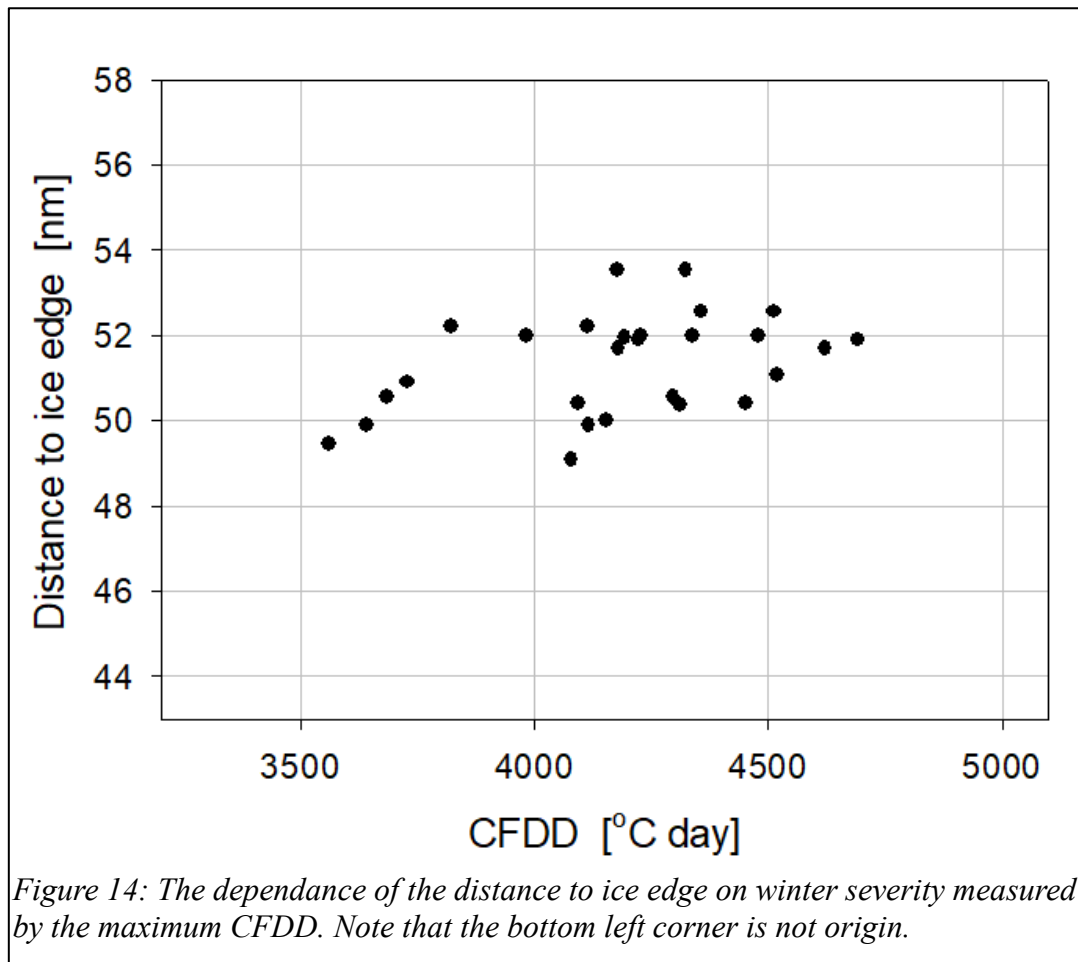
### ***Distance along ship track***

The annual maximum distance along the ship track from the Steensby Inlet port to the landfast ice edge is shown in Fig. 13. A slight decreasing trend can be discerned – a linear fit gives an annual decrease of 0.04 nm.



## Discussions

The variation in the distance to landfast ice edge is very small between different winters. This is understandable as the ice edge location is mostly determined by geographical factors. The effect of winter severity does not seem to influence the distance as Fig. 14 shows (this result anticipates the CFDD results which are shown in a later chapter). There may be a very slight trend to increased distance versus the annual maximum CFDD (Cumulative Freezing Degree Days).





## Evaluated parameter – Cumulative Freezing Degree Days (temperature)

### Methodology

Estimation of Cumulative Freezing Degree Days (CFDD) is based on temperature data. The temperature data was obtained from the ERA5-Land model, and the parameter “2m temperature” was used. “2m temperature” is defined as follows:

*“Temperature of air at 2m above the surface of land, sea or in-land waters. 2m temperature is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.”*

The temperature was extracted for each day at 00:00, 06:00, 12:00 and 18:00, and averaged to provide a daily average temperature. 365 days for each year were utilized in the study.

### Calculation of Cumulative Freezing Degree Days

Cumulative Freezing Degree Days (CFDD) was calculated based on the daily average 2m temperature, denoted  $T$ . The cumulative temperature is calculated summing the temperature difference  $T_f - T$ , where  $T_f$  is sea water freezing temperature taken here as  $-1^\circ\text{C}$ . The summing started in summer during the positive temperatures – here the start is made in the beginning of September. Thereafter the sum is made to the end of winter – and if the temperature difference is less than zero, it is put to zero exactly. This is based on the observation that small positive temperatures do not melt ice. Also the start of the summing may be discussed as often ice does not start to form immediately when the temperature is below freezing. These assumptions produce only very small differences in results. Thus the CFDD is defined as

$$CFDD = \sum_{i=1}^N (T_f - T_i)$$

where  $T_i$  is the average temperature on day  $i$  and the sum is over consecutive days.

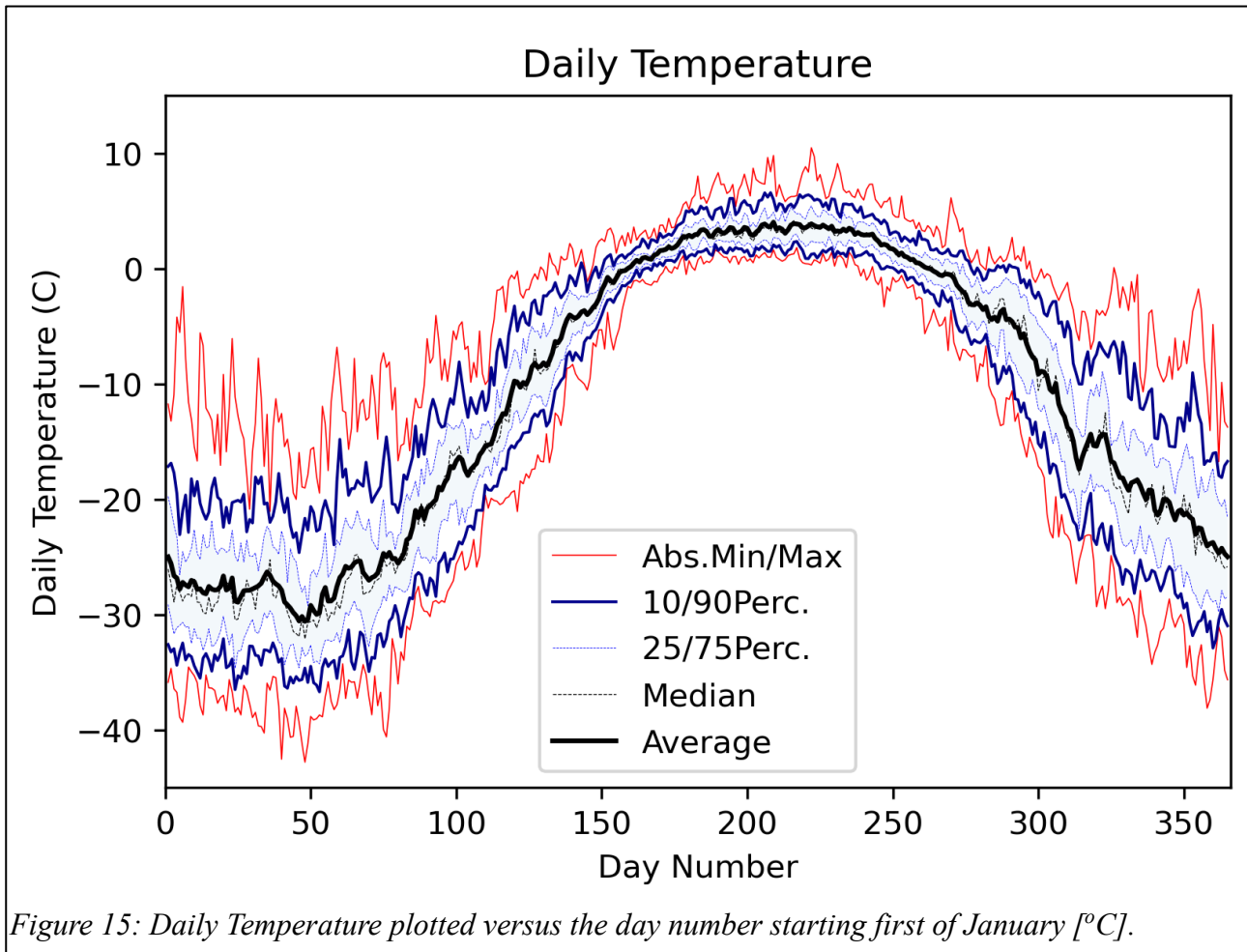
The CFDD data is provided per winter where the sum starts in the beginning of previous year September and ends in summer of the following year. Thus for example the Winter 2000 is the period from September 1999 to August 2000.

### Results

The average daily temperatures were accumulated and plotted. The plot contained the following statistical parameters:

- Absolute maximum/minimum temperatures – The absolute maximum and minimum temperatures recorded for the individual days during the period of interest.
- 10/90 percentile – The 10/90 percentile temperature values observed in the dataset.
- 25/75 percentile - The 25/75 percentile temperature values observed in the dataset.
- Median – The median temperature values for each day.
- Average - The average temperature values for each day.

The results are shown in Fig. 15.



Based on the figure above it is evident that there are larger fluctuations in daily temperatures during the winter months than during the summer. In the winter temperature variations of more than 20 degrees were observed, while during the summer the fluctuations were in the order of a few degrees.

When plotting the Annual Average Temperature shown in Fig. 16, it becomes evident that there is a general warming trend. For the period of interest there is observed a linear annual average temperature increase of 0.058 degrees pr. year.

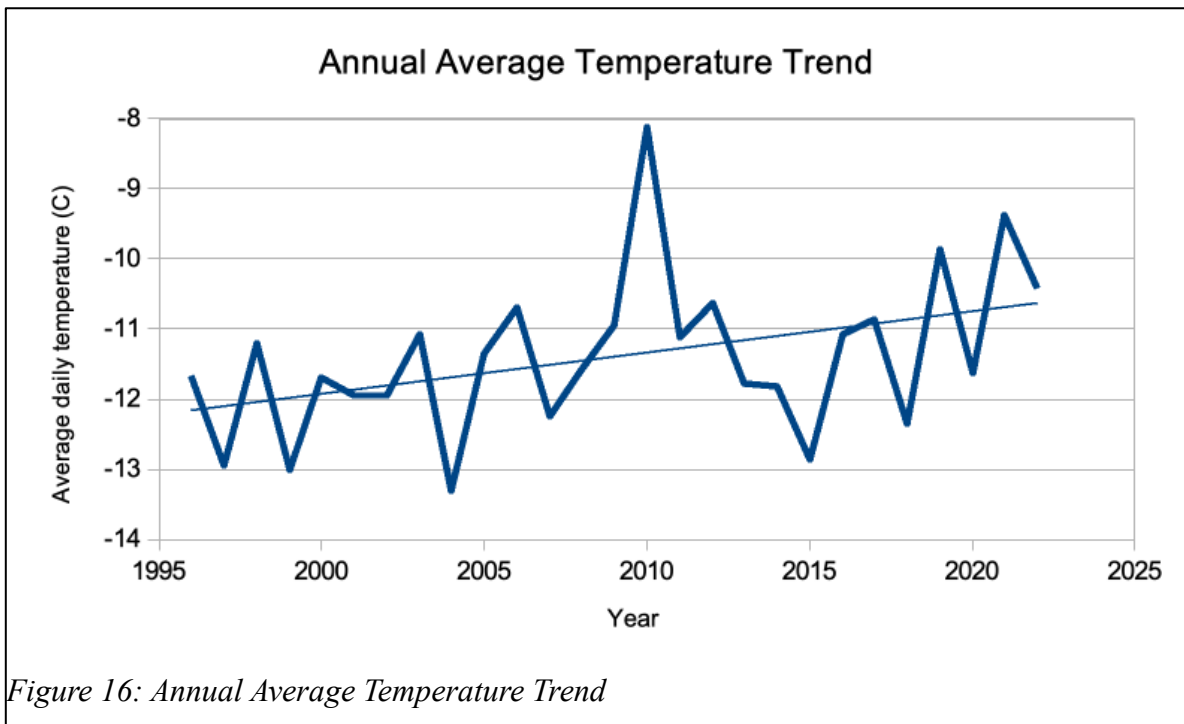
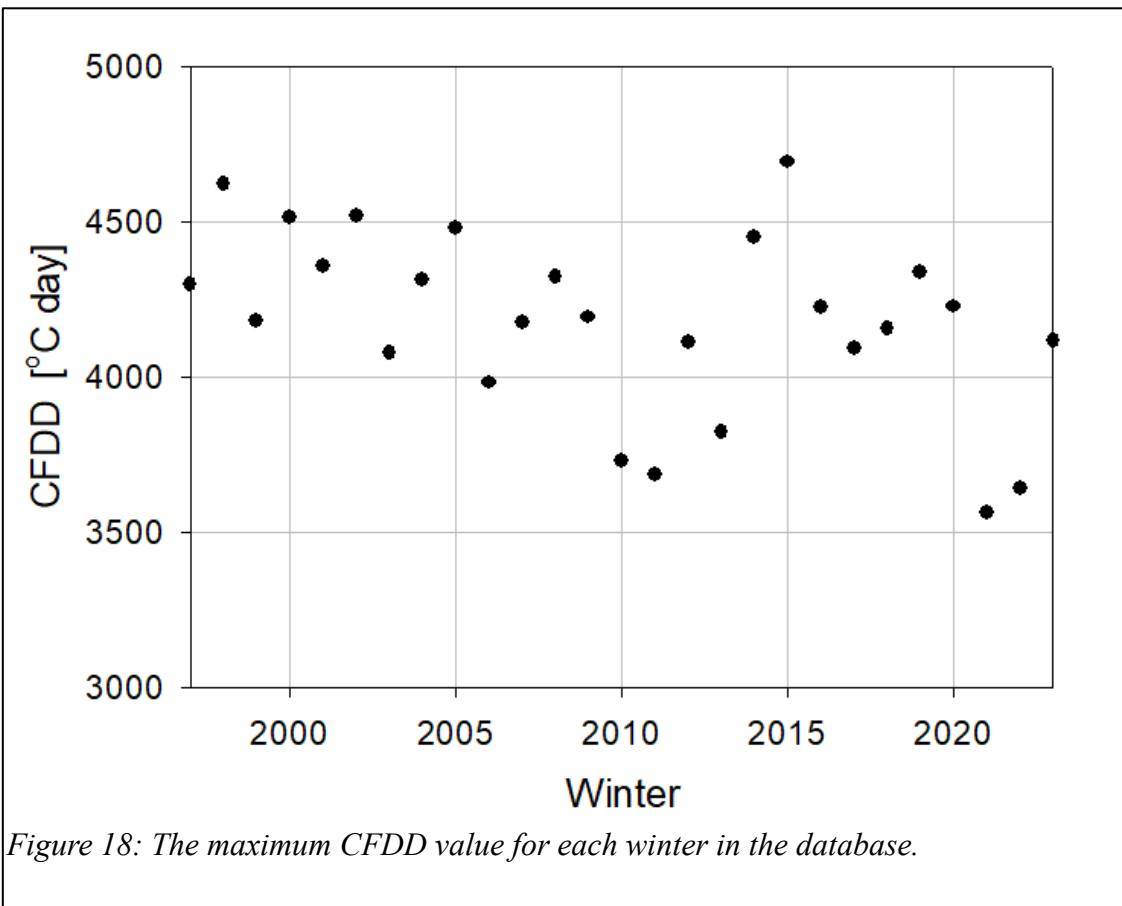
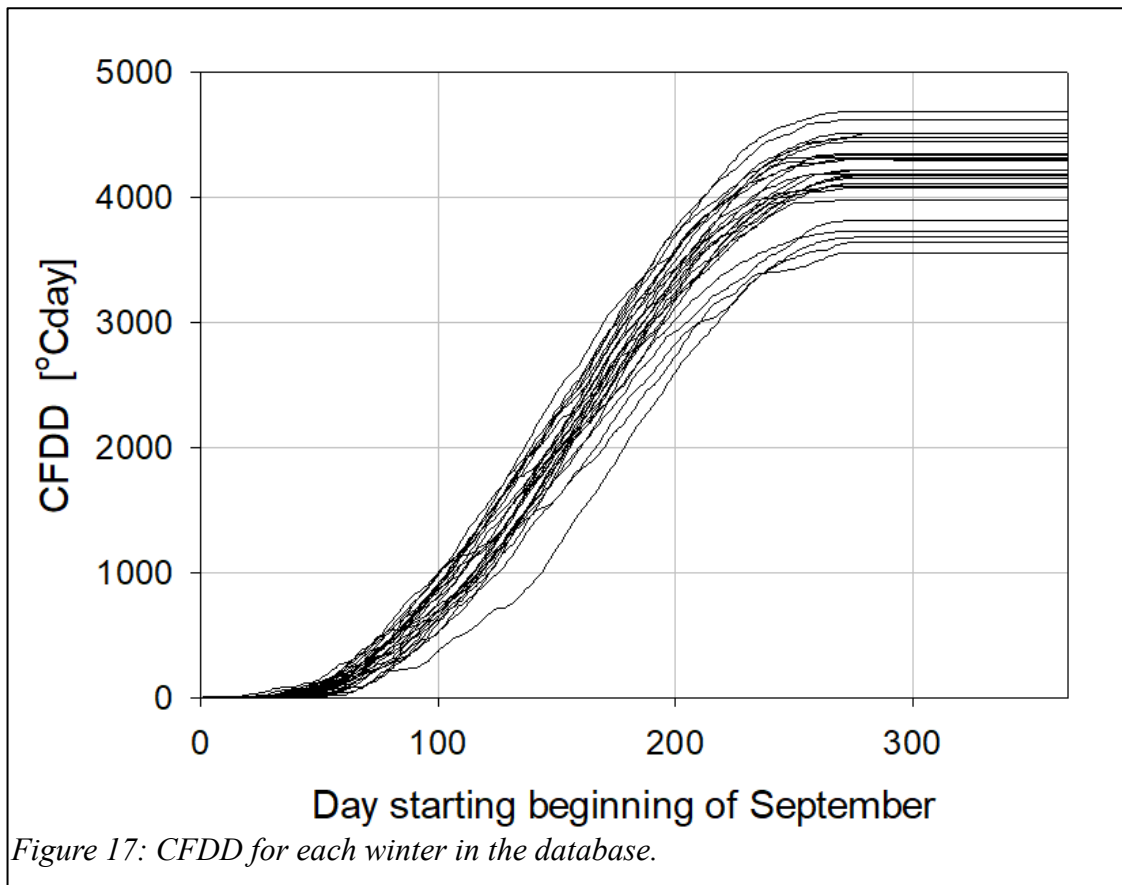


Figure 16: Annual Average Temperature Trend

The CFDD is analysed per winter as this can be used to calculate the level ice thickness. The collected results are shown in Fig. 17. The CFDD plot shows that there are several very mild winters where the maximum CFDD is clearly less than 4000 °C·day. The average CFDD over this period of 27 winters is 4180 °C·day. The warming trend that was shown in annual temperature averages is also present – naturally – in CFDD values, see Fig. 18. The decreasing trend in the CFDD is annually 16.1 °C·day based on a linear regression ( $r^2 = 0.186$ ). Thus during the observation period, the expected CFDD has decreased almost 500 °C·day.

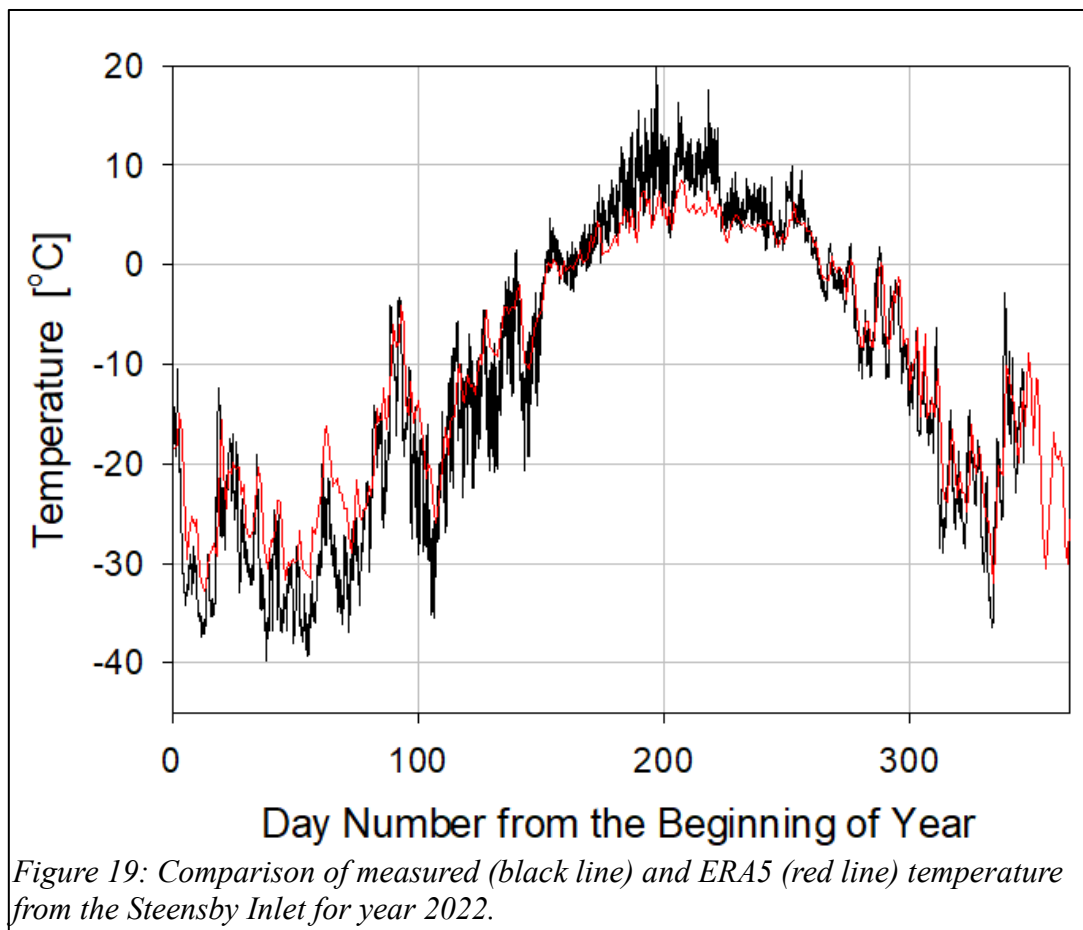


## Discussion

The temperature dataset shows that the minimum observed temperature in the Steensby area is about  $-42^{\circ}\text{C}$  (mid-February) and the highest temperature about  $+10^{\circ}\text{C}$  in July/August. Summer period when average temperature is above zero is from beginning of May to beginning of October. In a severe year the summer period may be some weeks shorter.

The average CFDD value is  $4180^{\circ}\text{C}\cdot\text{day}$  with a minimum observed value of  $3560^{\circ}\text{C}\cdot\text{day}$  (winter 2021) and maximum  $4690^{\circ}\text{C}\cdot\text{day}$  (winter 2015). Two out of the three very mild winter where the maximum CFDD was less than  $3800^{\circ}\text{C}\cdot\text{day}$  occurred in this decade (winters 2021 and 2022).

The accuracy of ERA5 data is good but the local variations may alter the picture somewhat. A comparison of ERA5 temperatures with those measured at the Steensby Inlet is shown in Fig. 19. The measured temperature data supplied to us from the Steensby Inlet was consistently  $3\text{--}5^{\circ}\text{C}$  lower in winter and some  $3^{\circ}\text{C}$  higher in summer than the ERA5 data. This emphasizes the importance of local measurements. The difference is not, however, very large.





## Evaluated parameter - Snow thickness

### Methodology

For the analysis of snow thickness the ERA5 parameter “Snow depth water equivalent” was utilized. The parameter is in a gridded format, with a time resolution of 1 hours. The values from 00:00, 06:00, 12:00 and 18:00 was utilized in the study. ERA5 describes the parameters in such a way:

*“Depth of snow from the snow-covered area of a grid box. Its units are metres of water equivalent, so it is the depth the water would have if the snow melted and was spread evenly over the whole grid box. The ECMWF Integrated Forecast System represents snow as a single additional layer over the uppermost soil level. The snow may cover all or part of the grid box.”*

The values were averaged over each day to eliminate the effect of large and non-representative snowfalls. It was assumed that each year had 365 days, starting from first of January.

The snow cover thickness is more important for ice growth than the water equivalent of snow. In order to determine the snow cover thickness from the water equivalent, the snow density must be known. In this description of conditions, the snow density is assumed to be 300 kg/m<sup>3</sup>. This corresponds to slightly wind packed settled snow.

### Results

The average daily water equivalent of snow levels were accumulated and plotted. The plot, Fig. 20, contains the following statistical parameters:

- Absolute maximum/minimum – The absolute maximum and minimum snow depth water equivalent values recorded for the individual days during the period of interest.
- 10/90 percentile – The 10/90 percentile snow depth water equivalent values observed in the dataset.
- 25/75 percentile - The 25/75 percentile snow depth water equivalent values observed in the dataset.
- Median – The median snow depth water equivalent values for each day.
- Average - The average snow depth water equivalent values for each day.

The plot of the daily snow depth water equivalent indicates that the large daily variability is found in the middle of the year (around day 150). This is probably due to annual variations in accumulated snow cover in combination with annual variation in commencement of the spring melting season.

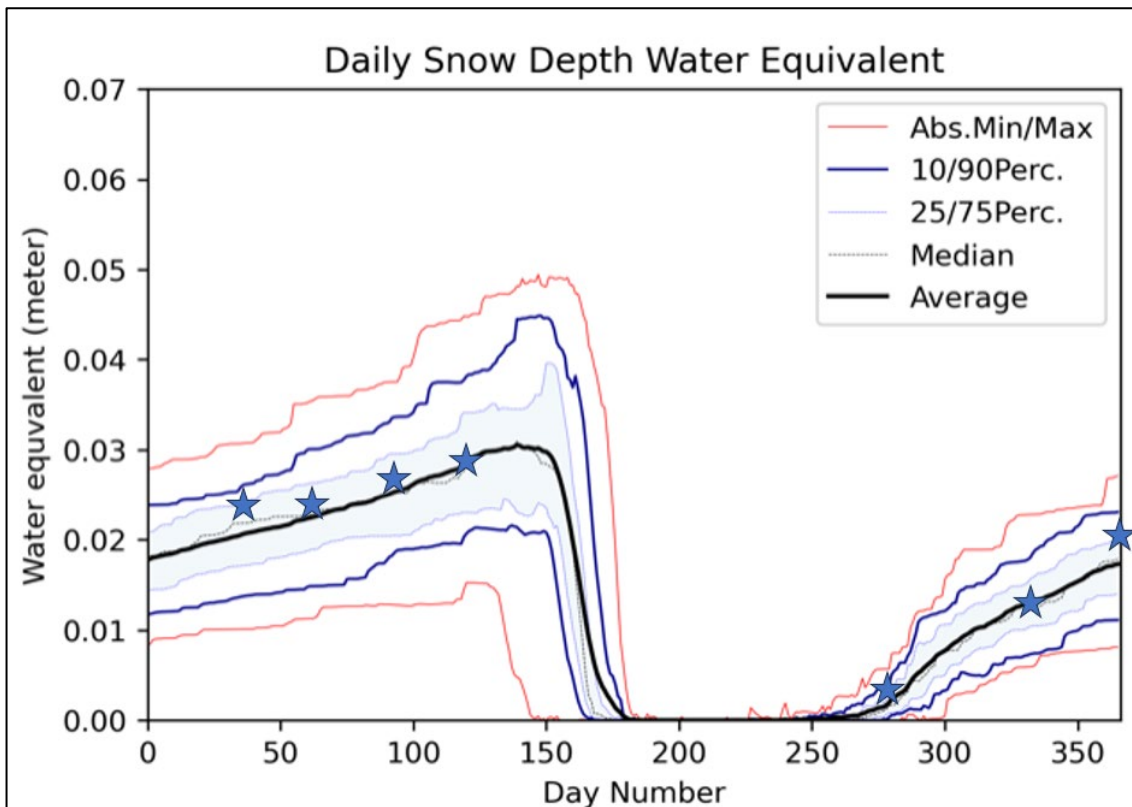
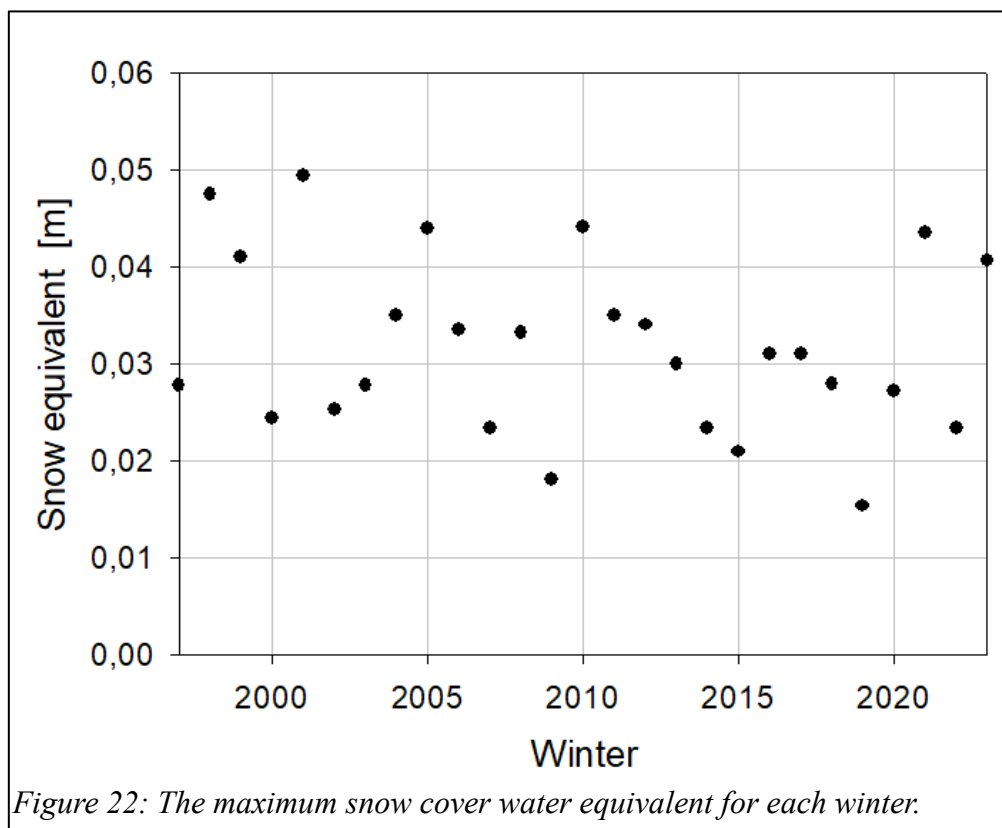
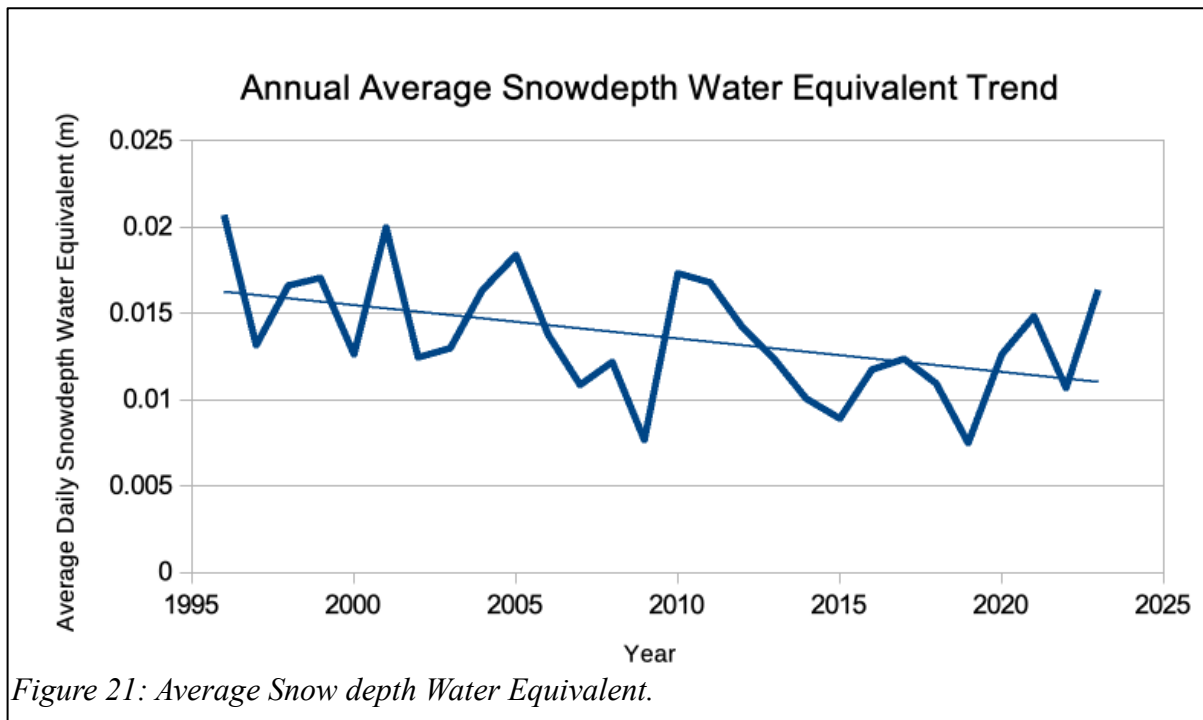


Figure 20: Daily Snow Depth Water Equivalent [m]. The blue stars represent the average cumulative precipitation in Hall Beach according to the Weather and Climate home page.

When estimating the average daily snow depth water equivalent for each day, for each year, Fig. 21, it becomes evident that there is a negative linear trend. This means that there is a less snow cover at the end of the period compared with the start of the period. On average there is a loss of 0.19 mm snow depth water equivalent per day, per year. The maximum snow cover water equivalent for each winter is shown in Fig. 22. There is a similar slight decreasing trend in the maximum snow cover for maxima as for average values. The decrease is only 0.3 mm per year, determined by a linear fit – this corresponds roughly to 1 mm annual decrease of snow cover thickness.

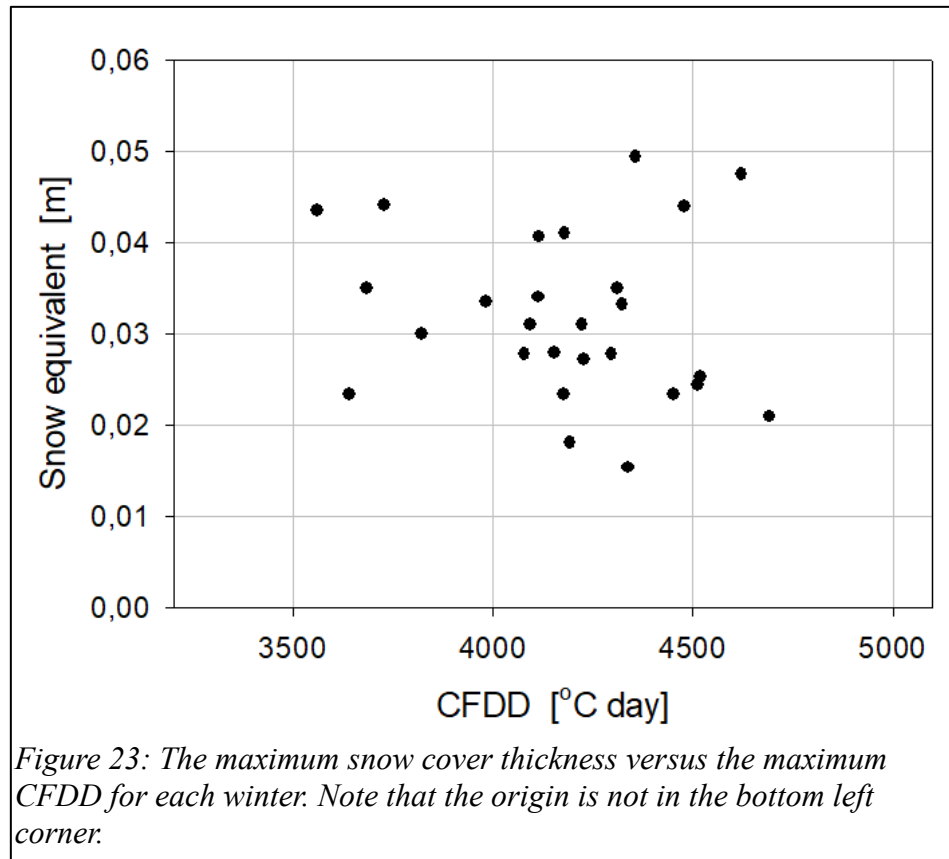


It is difficult to obtain any comparison for snow cover in order to verify the accuracy of ERA5 data. The Canadian statistics from Hall Beach show that the water equivalent in the ERA5 data is very close to observations, see Fig. 20. This still leaves some uncertainty in the actual snow cover thickness.



## Discussion

Snow cover thickness is very small in the area. This is clear as most of the precipitation occurs during summer months. Winter temperatures do not influence the snow precipitation and the snow cover thickness seems to be quite random with no influence by the winter severity, see Fig. 23.



It is difficult to obtain any snow cover thickness values for verification. The Weather and Climate home page states average monthly precipitation values for Hall Beach, the cumulative values starting in October are shown in Fig. 13. These values do not deviate much from the values based on ERA5. As was stated, the snow density can be assumed to be  $300 \text{ kg/m}^3$ . This implies a maximum average snow cover thickness of about 11 cm.

## Evaluated parameter - Ice thickness

### Methodology

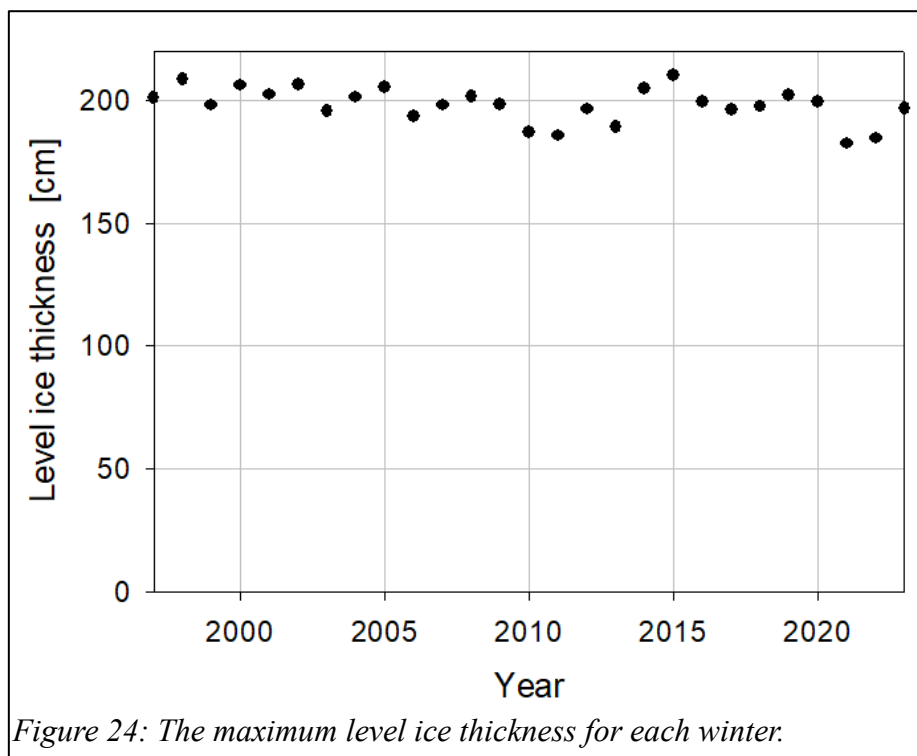
Ice cover thickness is calculated by a modified Zubov equation, see for example Zubov (1963) and Riska & Bridges (2024). which takes into account the snow cover thickness. The average maximum annual snow cover thickness is 10.6 cm. Using this value gives a level ice growth equation as

$$h_i^2 + 11.3h_i - 9.92 \cdot CFDD = 0,$$

in units of cm and °C·day. In calculating the ice thickness, the CFDD values presented above are used.

### Results

The maximum ice thickness for each winter is shown in Fig. 24. The average maximum level ice thickness is 198 cm with maximum value during the investigated winters of 210 cm. Even here a slight decreasing trend can be observed; a linear fit gives an annual decrease of 0.4 cm ( $r^2 = 0.19$ ).



### Discussion

The ice growth equation used here different from the one used in earlier logistic studies, the equation was here calibrated using measured ice thickness data from Hall Beach. The results given by these two equations differ, however, only some by some cm. These calculations can be made even better by input from direct measurement results from the Steensby Inlet area.

The ice growth equation does not take into account the different kind of ice that can form, especially the snow ice forming from freezing slush (snow immersed in water). The water can occur when ice is flooded due to heavy snow cover – but this is unlikely due to small snow cover thickness. Flooding can occur due to wave action or precipitation, but these mechanisms are rare. Only direct observations can verify the presence of different ice types. To obtain comprehensive level ice thickness measurement and observation of ice type a ice test on the fast ice can be quite





easy to obtain as the fast ice is normally accessible from land or by helicopter and do not require an icebreaker to reach the area of interest.

## Evaluated Parameter – Polynya

Polynyas are large, persistent regions of open water and thin ice that occur within much thicker pack ice, at locations where climatologically, thick pack ice is to be expected. Polynyas persist with opening and closing at the same time of the year, and at the same locations.

Open water leads are typically long, linear transient features associated with the pack ice deformation. They are not restricted to a particular location, and generally have a much smaller area than polynyas.

In constricted areas between islands and in straits tidal currents can keep the water in strong motion. This prevents the created ice from covering the area, and thus the sea surface remains open in spite of cooling and the formation of new ice. The sea water in a polynya is directly exposed to a large negative heat flux, with the resultant rapid formation of new ice. This new ice is advected away from the area as fast as it forms, exposing new warm sea water to the cold ambient air temperatures. This results in a large heat loss to the atmosphere causing, cooling and thermal induced vertical currents.

## Methodology

The presence of polynyas is not always evident from the ice charts. In satellite imagery they are visible as areas of open water or areas covered with frazil ice. Polynyas outside the fast ice edge were identified in the satellite imagery.

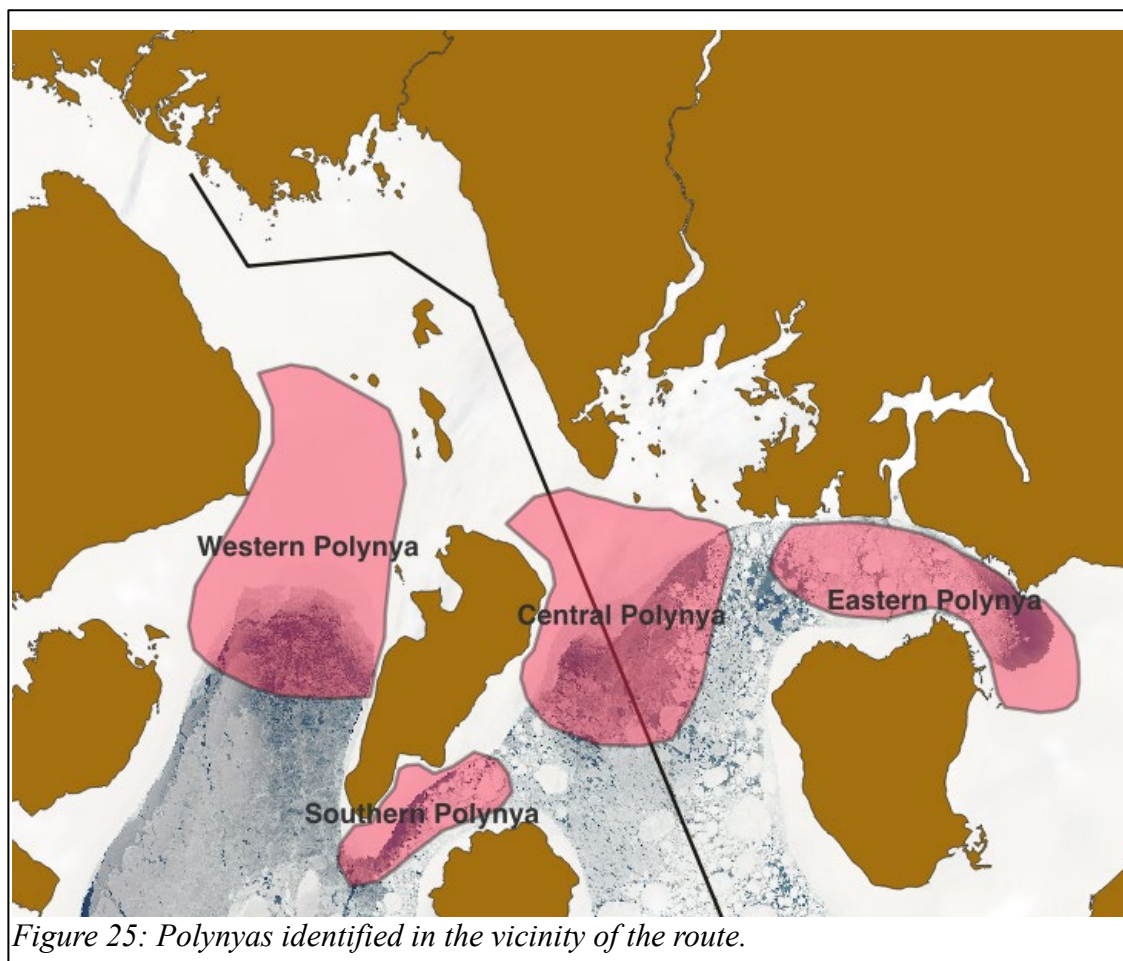
To define the start of the generation of a polynya, the time for the establishment of the fast ice edge at the approaches to Stensby Inlet was utilized. The date of fracture of fast ice in the spring/summer determines end of the season for the polynya.

The data defining establishment of the landfast ice edge and fracture of the landfast ice edge was obtained from the ice charts provided by CIS. The presence of open water with polynya features was verified through images provided by the Sentinel-2 satellite. Due to time constraints, for efficiency, only 5 years (2018, 2019, 2020, 2021 and 2022) were utilized in this study.

## Results

In the vicinity of the route to Stensby Inlet several polynyas were identified. For practical reasons they were labelled:

- Western Polynyas
- Southern Polynyas
- Central Polynya
- Eastern Polynya



### ***Establishment and breakup of floe edge in polynya zones***

The edge of the landfast ice, also called the floe edge, marks the northern boundary zone in the identified polynyas. The time for establishment of a fast ice edge in the areas of interest was based on the ice charts from Canadian Ice Service. When the Form of Ice (Fa) was identified as 08, a fast ice edge was assumed.

The tables 1 and 2 below identify the time of year when the fast ice edge is established. This is defined as the first week of the season when the CIS ice charts shows fast ice (Form of Ice is 08) within the labelled polynya zones.

Table 1. The date when the ice edge for the polynyas is established.

Season	Western Polynya	Southern Polynya	Central Polynya	Eastern Polynya
<b>2018</b>	03.12	03.12	03.12	19.11
<b>2019</b>	23.12	16.12	23.12	23.12
<b>2020</b>	21.12	16.11	11.01 (2021)	21.12
<b>2021</b>	10.01 (2022)	22.11	10.01 (2022)	13.12
<b>2022</b>	28.11	14.11	26.12	28.11

The fracture time is defined as the first week of the season when fast ice is not present within the labelled polynya zones (Form of Ice (Fa) not defined as 08).



Table 2. The date when the polynya ice edge disappears.

<b>Year</b>	<b>Western Polynya</b>	<b>Southern Polynya</b>	<b>Central Polynya</b>	<b>Eastern Polynya</b>
<b>2018</b>	16.07	09.07	16.07	16.07
<b>2019</b>	24.06	24.06	24.06	24.06
<b>2020</b>	13.07	20.07	13.07	13.07
<b>2021</b>	19.07	19.07	12.07	12.07
<b>2022</b>	18.07	11.07	11.07	11.07

### ***Verification of presence of polynyas***

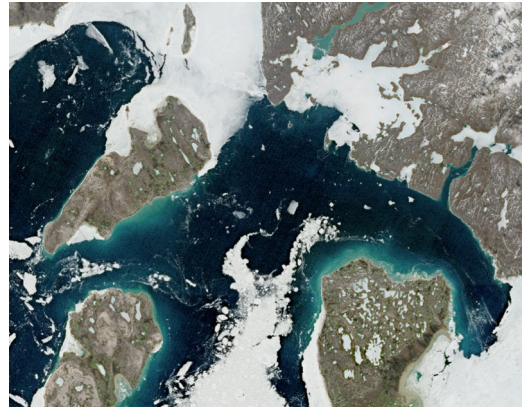
In several cases the CIS ice charts does not accurately portray the presence of the features associated with polynyas. The outreach of the distinct features associated with polynyas varies, depending in wind and local currents.

The Sentinel-2 data is dependent on sunlight and images are not available for the dark season. The images without cloud cover are needed to portray the region of interest. The Sentinel-2 constellation revisits an area every 5 days. As a result of the above constraints, usable images are not available on a regular basis. To verify a presence of the polynyas, Sentinel-2 L2A images were downloaded for a variety of the months for the years of interest, see Fig. 25.



Date	Sentinel-2 L2A Imagery
19.03.2018	A satellite image showing a glacier with a complex, irregular shape. The glacier is light blue/white, indicating snow and ice, with some darker blue areas suggesting meltwater or bare ice. The surrounding area is mostly white, likely snow-covered ground.
03.04.2019	A satellite image showing a glacier, similar in shape to the one in 2018. The glacier appears slightly more compact and has a more uniform light blue/white color, suggesting less meltwater or a different stage of the melt season.
07.05.2020	A satellite image showing a glacier that has significantly melted compared to the previous years. The glacier is now a dark blue color, indicating a large area of bare ice or meltwater. The shape is more elongated and less complex than in previous years.
11.06.2021	A satellite image showing a glacier that has almost completely melted. The remaining ice is a dark blue color, and the surrounding area is a mix of white snow and brownish/tan ground, indicating a significant reduction in ice cover.

03.07.2022



*Fig. 25. Satellite images from the northern part of the Foxe Basin.*

### **Polynya width**

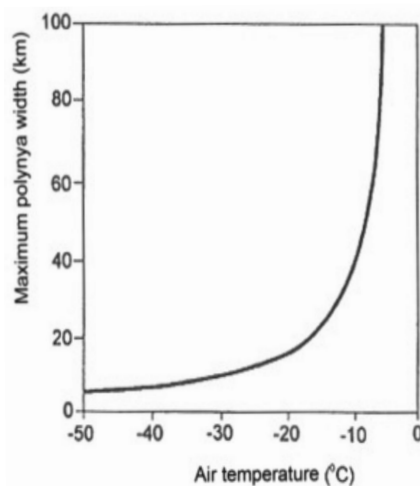
The width (perpendicular to the ice edge/coast) of a polynya is a function of the following parameters:

- Ice velocity ( $V_i$ ) – how quickly the newly formed ice is moved out of the area
- Ice thickness ( $H_i$ ) – how thick the ice is
- Formation rate ( $F_i$ ) – how quickly new ice is forming

The following relationship for the maximum theoretical polynya width was formulated by Pease:

$$\text{Max width} = (V_i * H_i) / F_i$$

The above relationship is visible in the following plot:



*Figure 26: Maximum Polynya width as*

The above plot does not take into consideration local wind forcing or tidal currents, which can alter the width depending on speed, direction and duration. In the winter-time the average ambient temperature in the area of interest is about -30. This correlates with a theoretical width of about 10 km. As the spring approaches, the temperature increases and the theoretical width increases. This effect is clearly visible in the previously shown Sentinel-2 images.





## Statistical analysis

The above data for the distance in landfast ice, snow thickness, CFDD and ice thickness is analyzed by extreme value statistics in order to obtain prediction of maximum and minimum value for a longer time period. The time period used here is 100 years which is typical period for determining the design loads to external parameters in offshore industry. The analysis is done using the Gumbel I distribution and the distributions for predicted maxima and minima are different. An example of results is shown in Fig. 27.

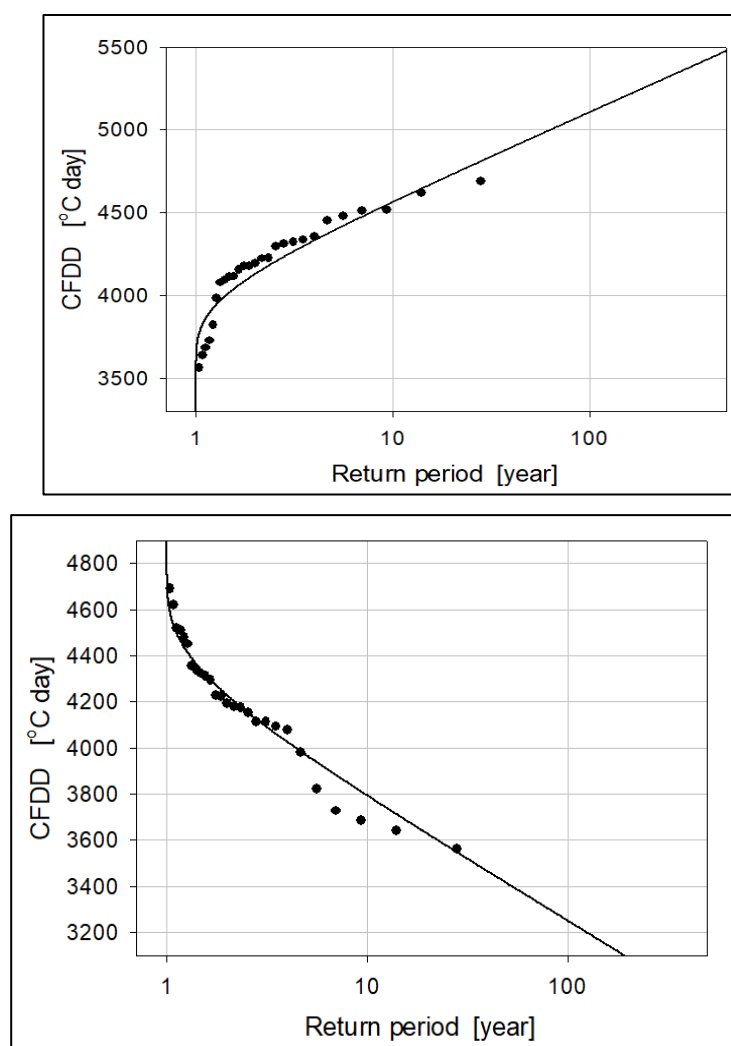


Figure 27: The extreme value fits for annual maximum values, plotted versus the return period. Fit for maximum top and for minimum bottom.

These fits can be used to obtain the expected largest and smallest value a winter once in 100 years. These results are given in Table 5. The difference in 100 years minimum and maximum is not very large for the distance in fast ice but for the other three parameters the variation is considerable, and greatest for the snow cover thickness.

Table 5. The 100 years values for the investigated parameters.

Parameter	Unit	Minimum	Maximum
D	[nm]	47.6	55.0



CFDD	[°C·day]	3240	5110
$h_s$	[cm]	0.8	20.1
$h_i$	[cm]	175	221

## Implications for shipping operations

The fast ice area close to the Steensby Inlet is described in this report using five main parameters:

- Distance to ice edge from the Steensby Inlet port along the ship track
- Cumulative temperature CFDD
- Snow cover thickness
- Polynyas
- Level ice thickness

The first, second and last of these has an effect on shipping. The temperature determines the thickness of brash ice that is forming in old shipping channels. The brash ice thickness determines the ice resistance acting on ships proceeding along the channel and the length of the track settles the time consumed in going through the fast ice area.

## Implications induced by climate change

This study complements many of the previously done studies, conducted with regards to shipping from the new port in Steensby Inlet. Due to longer data series the effects of climate change become visible. It is evident that the effects of climate will impact the operation, especially for a project which has a lifespan of multiple decades. In our study the difference in distance operated in fast ice was observed to be in the range of only a few nautical miles, and the maximum ice thicknesses were relatively constant throughout the years examined in this study. This is mainly due to the fast ice edge location is defined by a combination of the following effects:

- Geographical features
- Ocean current regime
- Non-linear growth of sea ice

It is however not to be disregarded that the climate change forcing is not necessarily following a linear trend. Furthermore, tipping-points affecting larger part of the ecosystem are also a plausible path forward. Assessment of longer time series, indicating possible ice-regime scenarios in the later phases of the project could be a viable option.

## Further work

This study elaborated on the fast ice regime present close to the Steensby Inlet. The Steensby Inlet is located in a relatively remote area, and very limited high quality data describing parameters essential for dimensioning a logistical solution according to commercial, environmental and regulatory requirements are lacking. High quality parameters describing the following topics would be beneficial for the project:

- Ice regime
- Meteorological conditions

Based on the recent developments in the project, the following tasks are recommended:

- Data gathering campaign – The generated meteorology and ice information will be highly valuable for dimensioning of the logistical solution, and reduce the uncertainty associated with the current studies. The study can combine both new technology and a small team to efficiently reduce overhead and achieve the predefined goals.
- Assessment of climate change and the effect on logistic solution. This involves assessment of longer time series of hind-cast data, The purpose is to identify any trends in the historical material stretching further back, e.g. 50 years, and indicate possible future ice regime scenarios. The area of interest is mainly close to the Steensby Inlet and its approaches as this is dimensioning for much of the marine activities required for shipment of iron ore out of Baffinland. The data obtained through such a study will be implemented in the logistical model, providing logistical outlooks for future development paths.
- Desktop study of the polynyas transited by the route. This would include assessment of hind-cast and remote sensing data to quantify potential impacts on the logistical solution, and to prepare the project for possible future regulatory changes.
- The floe edge, where the landfast ice meets the dynamic ice pack, usually consists of highly deformed ice. This includes severe ridging and brash ice belts. These local conditions can represent major hurdles for marine activities. Due to limited availability of data, the floe edge has not been especially addressed in this study, or in any of the other studies. A study assessing ridge concentration and ridge size in this area would be of interest as it is dimensioning for marine activity taking place in the fall/spring season.

## Methodology for update process

The present study is based on data from 28 years (1996 – 2023). This dataset can be complemented by data from the last year annually. This way the database is extended by one year each year – this makes the predictions and conclusions more reliable. As the insight what parameters are more important for the logistics, more focused data gathering can be pursued each new year. This makes the description of ice regime more detailed.

The annual update can occur early in each year when the data from the previous year are available. The data for distance in fast ice, temperature and snow fall are just added to the database, new statistical values calculated, and the updated results are added to the plots. It is also worthwhile to add a new chapter: Description of the Ice Regime in the Previous Year. This way any changes of the typical conditions can be detected.

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