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Background on Foxe Basin

Foxe Basin is a shallow, semi-enclosed basin with strong tidal currents that is seasonally ice-covered. A majority of the area is covered by shallow tidal flats, except for the relatively deep Foxe Channel to the south.

Sea ice is present year-round, with a complete ice cover from October to July, and is comprised almost entirely of seasonal ice. The ice cover is notoriously **dirty** and **deformed** (Campbell & Colin, 1958) *"Clean ice is rarely observed"* & *"The most severe ice conditions in the Canadian Arctic"*

Data products from ICESat-2 suggest the ice cover in Foxe Basin is as thick and deformed as the ice pack along the northern Canadian Arctic, an area with the thickest and oldest ice in the Arctic (Petty et al., 2023; Duncan and Farrell, 2022).

Polynyas are present in the northwest, due to the prevailing westerly winds, and east, due to tidal currents (Markham, 1986). Ice growth in polynyas has been linked to Deep Water Formation (Defossez et al., 2008) and a local Carbon Pump (FOXESIPP - PI: Else).

To date, there has not been a dedicated study of this uniquely dirty, deformed and thick, yet seasonal ice pack in Foxe Basin. Recently, there is increased interest in this ice pack as Baffinland has proposed a new port facility in Steensby Inlet from which iron ore will be exported near year-round through Foxe Basin and Hudson Strait to global markets.

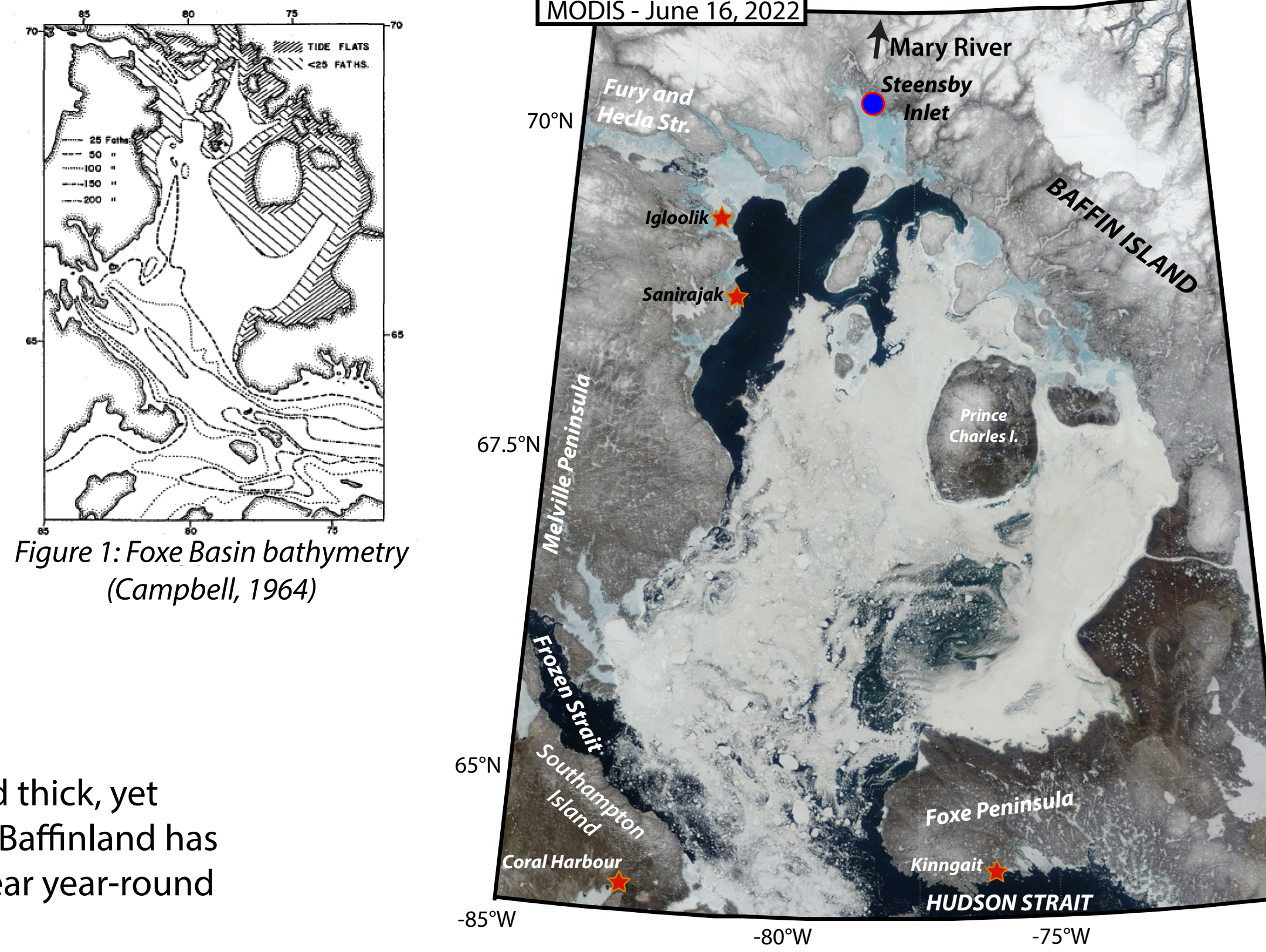


Figure 1: Foxe Basin bathymetry (Campbell, 1964)

Figure 2: Map of Foxe Basin with dirty ice in June 16, 2022 from MODIS

Steensby Inlet and a new shipping route in Foxe Basin

The Mary River mine is located on Baffin Island and exports 6 MT of iron ore through Eclipse Sound annually.

In their Phase 2 development plan Baffinland, the operator of Mary River, has proposed to build a railway to and port facility in Steensby Inlet to export an additional 6 MT of ore per year with near year-round access by ships.

Currently, Deception Bay in Hudson Strait is the only Arctic port that operates near year-round. Due to the dynamic ice cover, ships routinely become beset and delayed by ridges and compressed ice (Babb et al., 2022). Similar conditions may be expected in Foxe Basin, though very little is known about the ice.

Figure 3: Ice Breaker in Hudson Strait (FedNav)



Figure 4: Dirty ice in Foxe Basin - August 2024

Dirty ice / Foxey Ice

Sediment can be entrained within sea ice two ways:

- > **Suspension Freezing:** sediment is resuspended by tidal currents and trapped in new ice forming in polynyas or flaw leads.
- > **Anchor Rafting:** Larger material (rocks) entrained when the ice touches the seafloor.

Dirty ice is observed in Hudson Bay and throughout the Arctic, but Foxe Basin is notorious for its discoloured ice with dirty ice even being called *"Foxey Ice"*.

Due to the dynamics with suspension freezing, dirty ice is associated with thick, deformed ice.

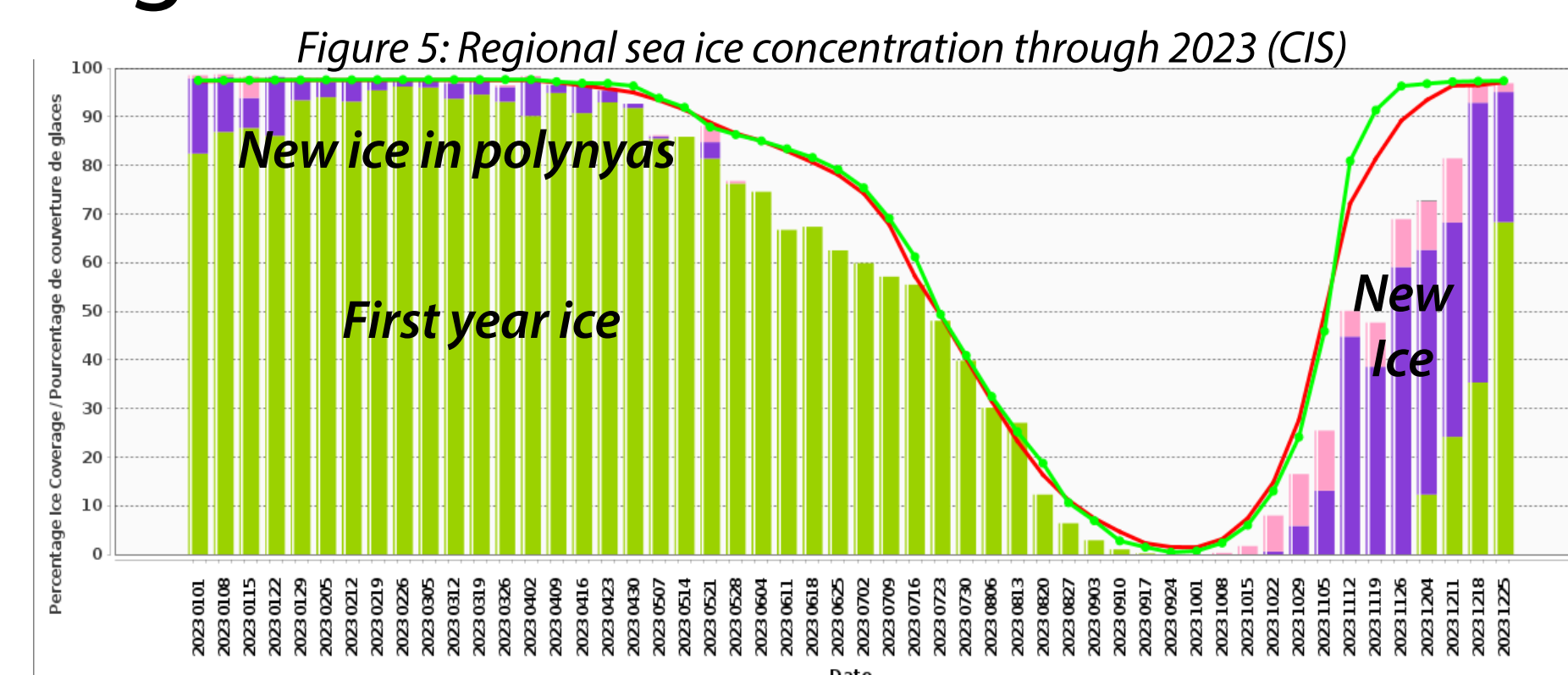
The ice cover in Foxe Basin is seasonal, yet it becomes very thick, deformed and discolored.

What is driving the formation of this unique ice cover? How does it affect the underlying ocean? What risk does it pose to ships along the proposed route?

We seek to provide the first detailed study of this unique ice cover in Foxe Basin.

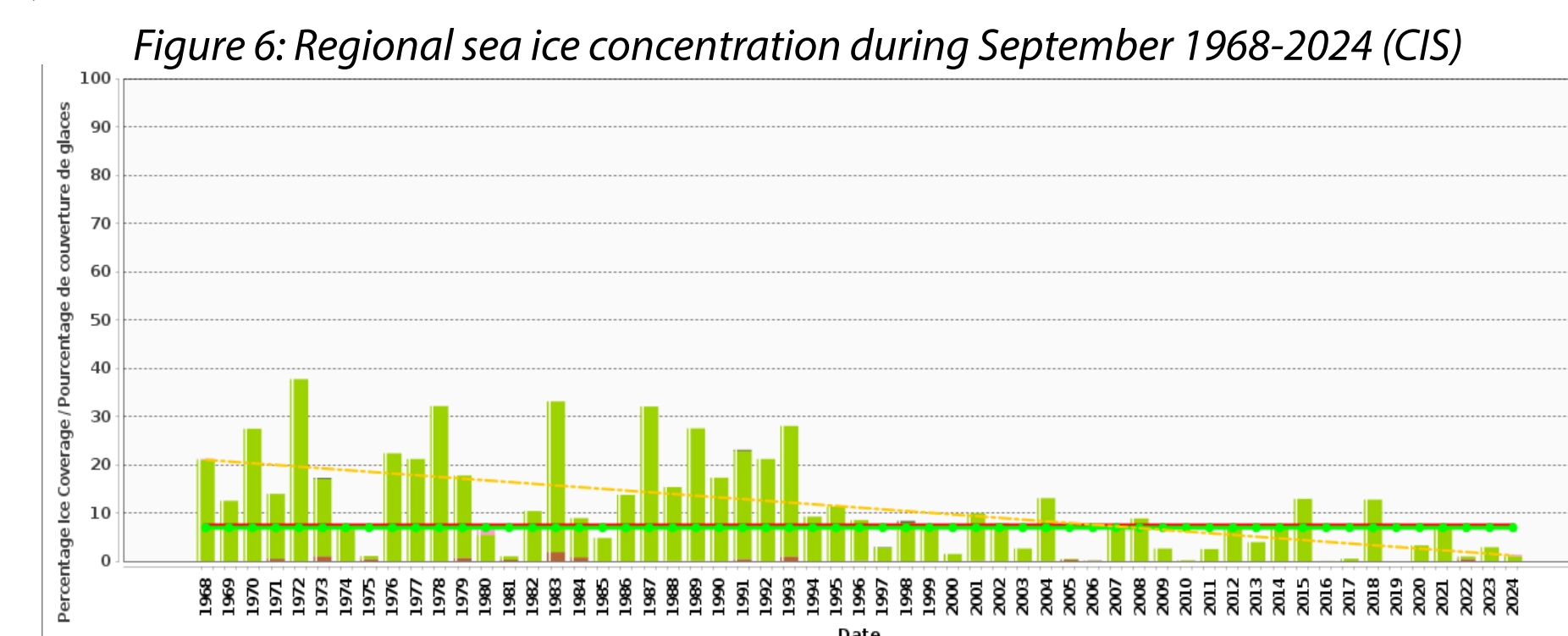
Early Results

Regional Sea Ice Cover



Foxe Basin undergoes a near-complete freeze-melt cycle annually. Ice-free in September/October. Fall freeze-up with new ice. Complete ice cover from December to April. New ice during winter (~5%) highlights polynyas!

Historically, some traces of multiyear ice from ice surviving in Gulf of Boothia and drifting through Fury and Hecla, but no more.

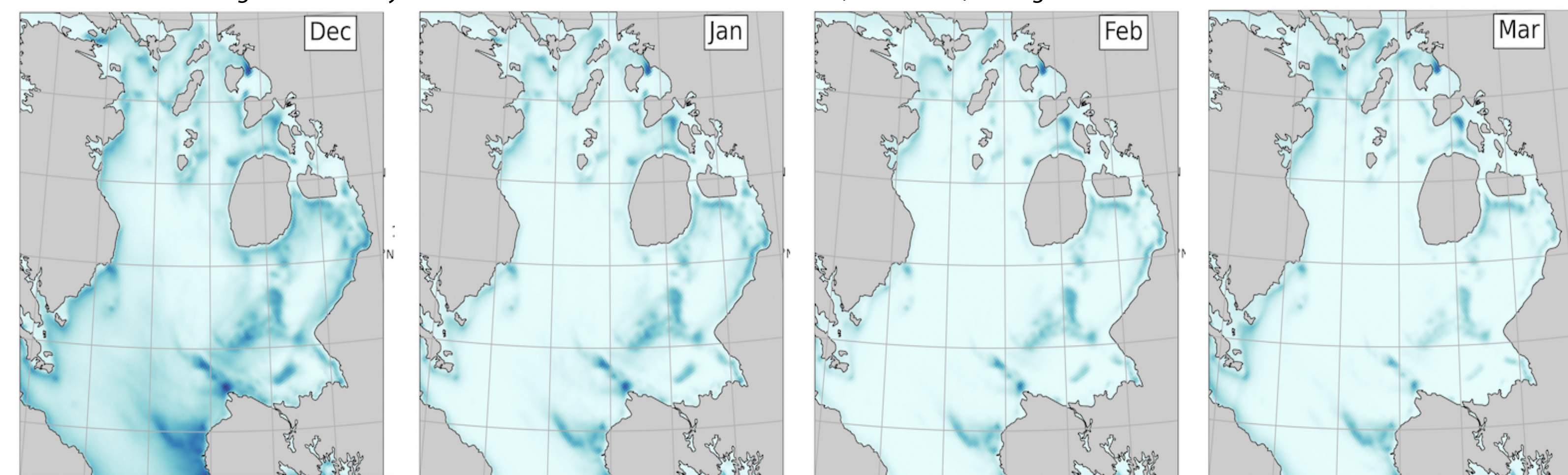


Decline in summer sea ice cover leading to longer open water season.
 July: - 2.2%/decade - earlier breakup
 August: - 5.3%/decade
 September: - 3.5%/decade
 October: no trend - ice-free
 November: - 5.3% decade - later freeze-up

Sea Ice Concentration and Polynyas

Maps of the monthly mean sea ice concentration show that the northwest polynya is not overly prominent. Instead there are persistent polynya features in the east, near Foxe Peninsula. Suggested to be due to strong tidal currents in the shallow areas of eastern Foxe Basin, but why such a stable pattern?

Figure 7: Monthly mean sea ice concentration from AMSR-2 (12.5 km res) during winter months from 2012-2023



Sea Ice Thickness

First, there are no in situ observations of ice thickness from the pack ice in Foxe Basin.

Observations of ice thickness are limited to the landfast ice near communities (Hall Beach and Igloolik), which show the seasonal cycle and growth to 2m by end of winter (Candlish et al., 2019).

Freeboard from ICESat-2

ICESat-2 is a laser altimeter that measures the elevation of the earth's surface. For sea ice it differentiates between the ice (snow) surface and the water level in leads, providing freeboard and letting us estimate thickness.

ATL-10 is the standard ice thickness product produced by NASA, however it has difficulty identifying the sea level in areas near land and with strong tides... For example Foxe Basin!

We developed a new approach based on the continuity of the ocean surface that improves upon assumptions of sea surface height in areas where strong tides create strong gradients in sea surface heights.

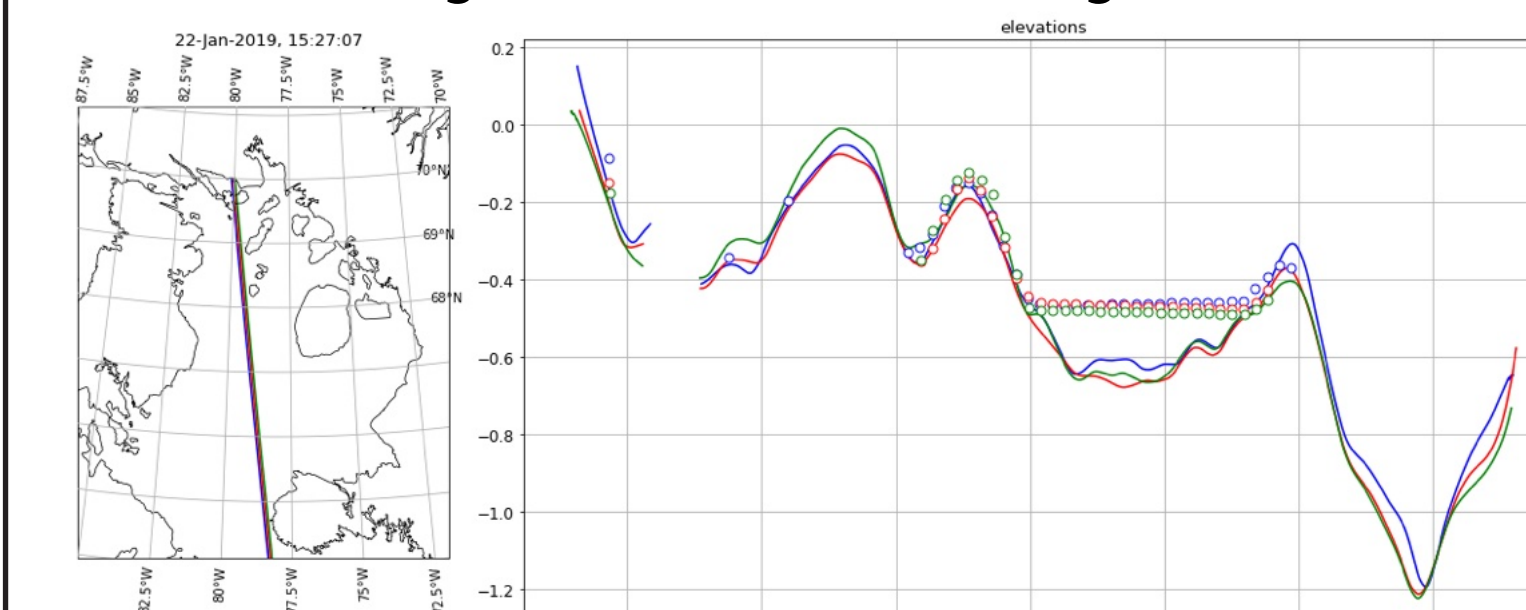


Figure 9: Example comparing ATL-10 (circles) and our estimates of sea surface elevation across Foxe Basin

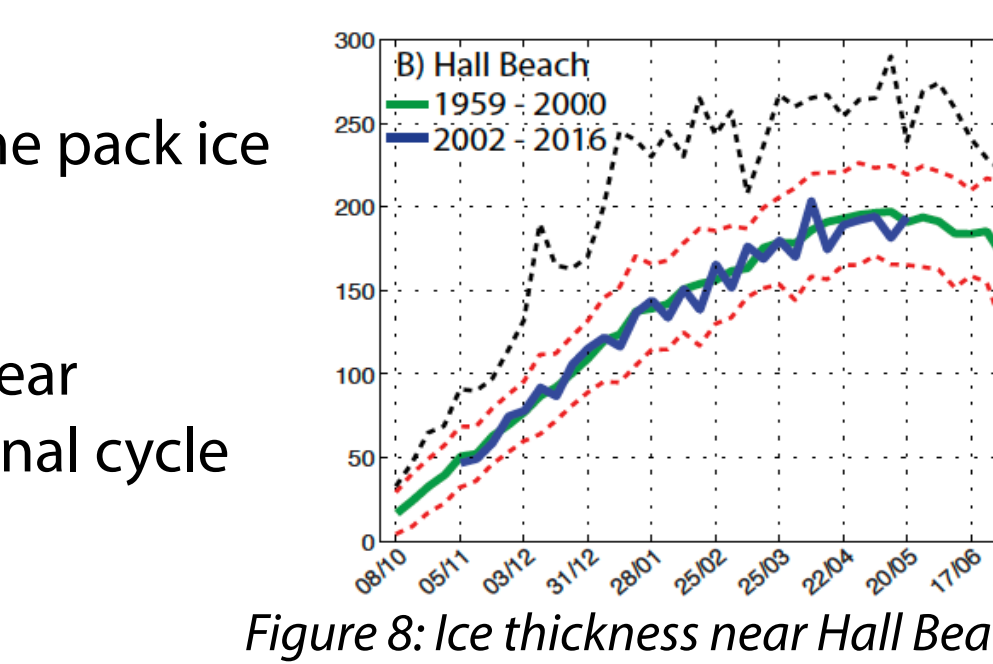


Figure 8: Ice thickness near Hall Beach (CIS)

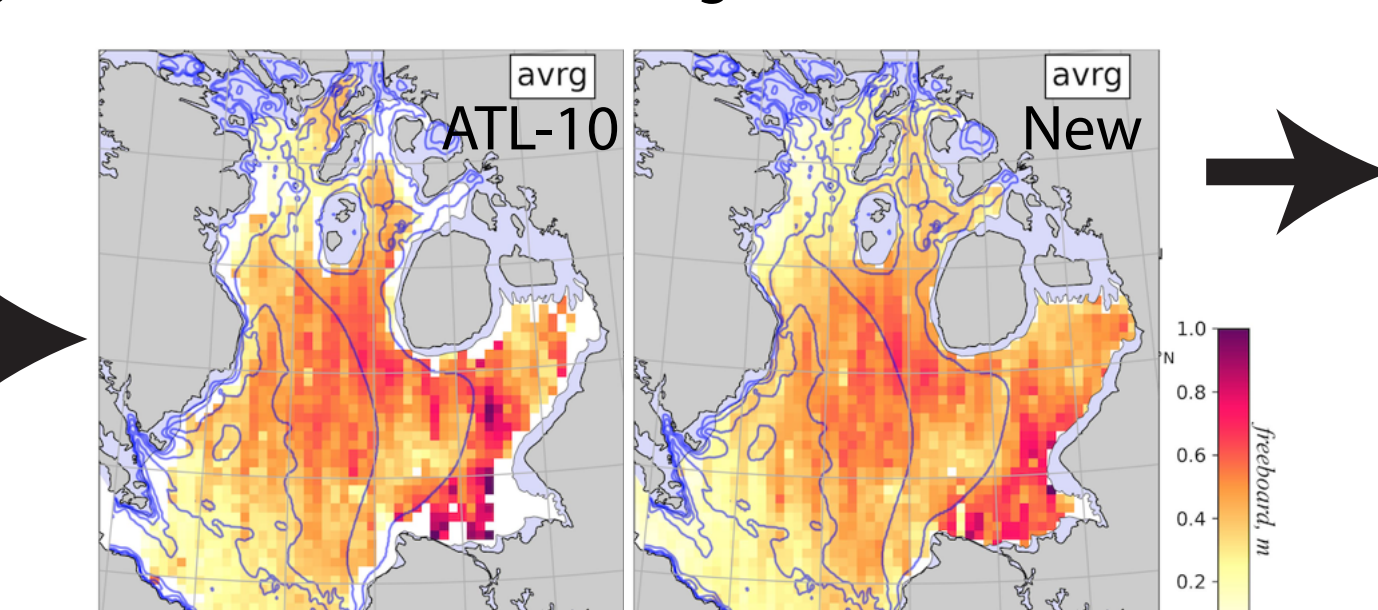


Figure 10: Comparing the average freeboard in Foxe Basin from March to May over 2019-2023 between the two approaches

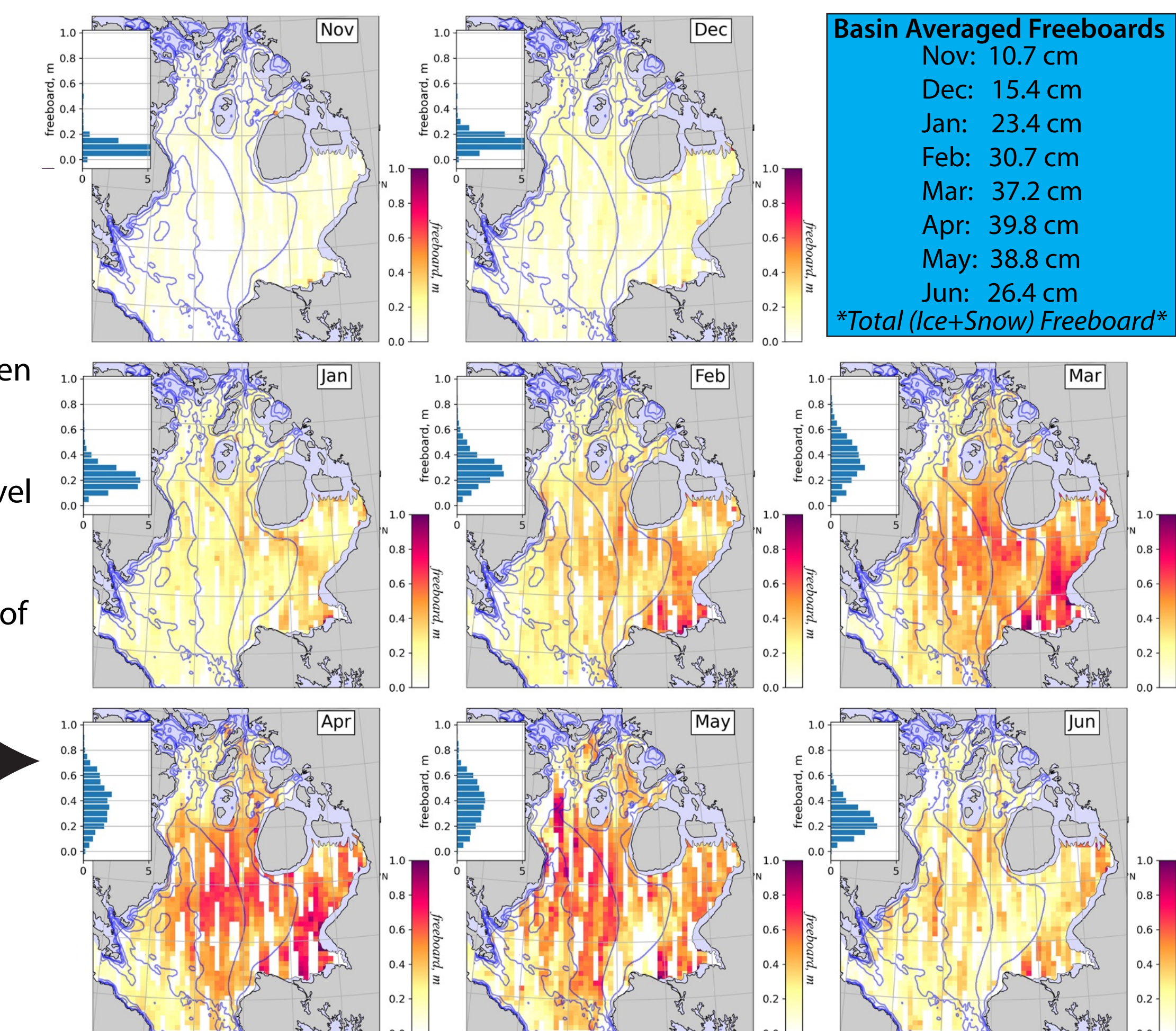


Figure 11: Monthly mean evolution of freeboard in Foxe Basin from 2019-2023.

Month	Freeboard (cm)
Nov	10.7
Dec	15.4
Jan	23.4
Feb	30.7
Mar	37.2
Apr	39.8
May	38.8
Jun	26.4
Total (Ice+Snow) Freeboard	

From Freeboard to Ice Thickness

To convert from freeboard to thickness we must account for snow.

Foxe Basin is too small for lagrangian snow products typically used in altimetry, hence we are exploring other approaches.

Coastal observations show ~28cm of snow by end of winter. Regional average total freeboard is 39.8 cm. Suggesting an ice freeboard of 12 cm.

Solving the hydrostatic equilibrium equation, with $\rho_i = 917 \text{ kg/m}^3$, $\rho_s = 300 \text{ kg/m}^3$ and $\rho_w = 1025 \text{ kg/m}^3$. Gives an average end of winter ice thickness of 1.92 m, which is similar to fast ice observations.

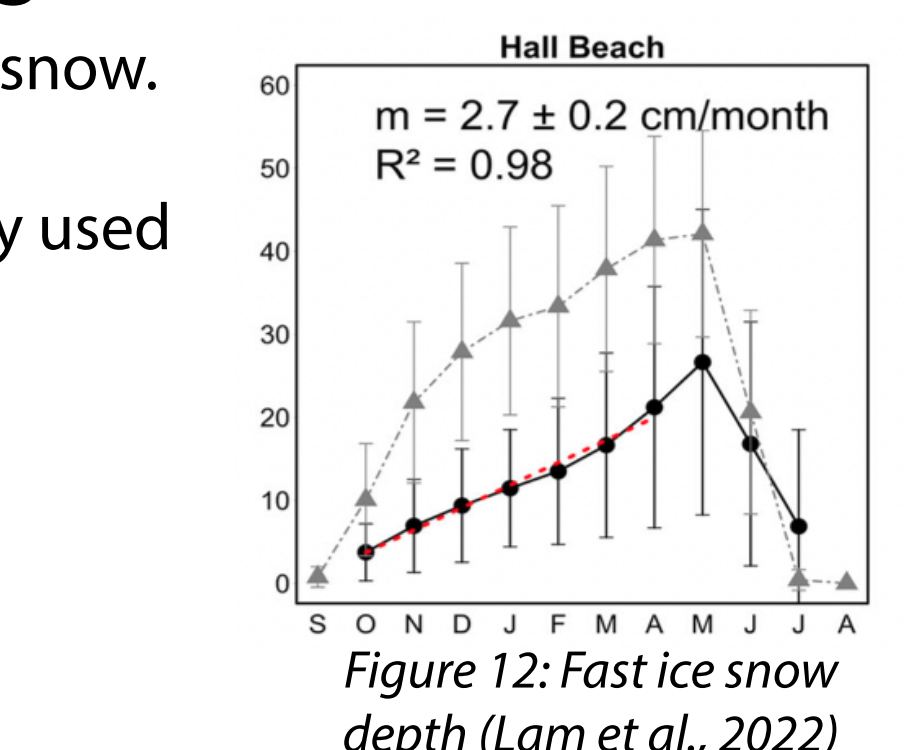


Figure 12: Fast ice snow depth (Lam et al., 2022)

$$H_i = \frac{\rho_w}{(\rho_w - \rho_i)} F_i + \frac{\rho_s}{(\rho_w - \rho_i)} F_s$$

However, total freeboard reaches 60-80cm and snow depth on pack ice may be less due to loss in leads and delayed accumulation. All this to say that the pack ice is thicker and there are some very thick deformed pieces of ice in the ice pack

Summary and ongoing work

Very little is known about the uniquely deformed and discoloured ice pack in Foxe Basin, yet it is now critical to understand as a near year-round shipping route has been proposed.

With limited in situ observations, we use a mix of remote sensing techniques to analyze the ice pack and find the following:

- > The summer ice cover is decreasing, creating a longer open water season.
- > Persistent polynyas are present in eastern Foxe Basin due to tidal dynamics.
- > An improved technique for measuring freeboard with ICESat-2 improves the data quality.
- > Roughly, solving the hydrostatic equation for the average end of winter total freeboard with typical densities and the average end of winter snow depth on fast ice, we estimate an average end of winter ice thickness of 1.92 m, which aligns with fast ice observations.

Ongoing work towards accounting for snow on sea ice, calculating ice production and brine rejection, and extreme ice features in the ice pack are ongoing as we seek to understand this unique ice cover and its role in deep water formation and the risk that it poses to ships.

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