POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

Long-term observations (2014-2020) of pressure ridges in the Barents Sea

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ABSTRACT

Ice ridges play a key role in the sea ice mass budget, and typically govern sea ice design loads. In this paper results from consistent long-term observations of ice ridge keels by upward looking sonars at five sites in the southwestern part of the Barents Sea ice cover during the period 2014-2020 are presented. The data collection was initiated by the Barents Sea Metocean and Ice Network (BaSMIN). This paper focuses on keel depth and how it relates to level ice draft. In total, 130 708 keels deeper than 2.5 m were detected. The average keel depth is 3.8 m. The 99th percentile is 9.4 m, while the deepest keels extend down to nearly 20 m. The seasonal maximum keel depths are measured in April and May. The ratio between maximum daily keel depth and level ice draft is quantified. The mean ratio between keel depth and level ice is 11.8. The ratio was relatively constant during March and April, but more scattered in May/June. Different melt ratios of ridged and level ice and import of ice from the north are likely explanations of the scatter. For design purposes it is key to correlate parameters and obtain not only univariate maximum values but also their distributions which typically is applied in probabilistic design methods. For this purpose, we established a parametric distribution of keel depth, conditional on level ice draft.

KEY WORDS: Ice ridges; Long-term observations; Extreme value analysis.

Introduction and background

The Barents Sea ice cover is important for the Arctic climate system, and the local ecosystem as well as for economic resources with rich fisheries and hydrocarbon resources. Despite its role in the Arctic climate system and its economic importance, the thickness and presence of pressure ice ridges in the Barents Sea are not well described. Ice ridges play a key role in the sea ice mass budget, and typically govern sea ice loads. Long-term observations of pressure ridges in the Barents Sea were absent prior to the data presently analyzed. In this paper data from consistent long-term observations of ice ridge keels by upward looking sonars at five sites in the southwestern part of the Barents Sea ice cover during the period 2014-2020 are presented. The data collection was initiated by the Barents Sea Metocean and Ice Network (BaSMIN). Data analyzed in this paper provides novel insight into how ridge keel depths relate to level ice drafts in the Barents Sea and how these parameters may evolve seasonally.

Ice ridges are formed from pressure and shear stresses inside an ice cover, which may break level ice into ice blocks and pack it together. The ridge sail, that is the part above water, is small in comparison to the ridge keel, which is below the water. In the following we will focus on the ridge keel that is detected by the instrumentation applied in this study. The depth of the ridge keel depends on the thickness of the level ice that formed the ridge keel. For design purposes, it is therefore meaningful to relate keel depths to level ice draft and for probabilistic design, the parametric distribution of keel depths conditional on level ice draft is of great interest. Keel depth distributions as well as maximum values related to level ice draft will be the focus of this paper.

DATA AND METHODS

Data

Five moored Ice Profiling Sonars (IPS, also referred to as upward looking sonars, ULS) coupled with Acoustic Doppler Current Profilers (ADCP) have been deployed in the Barents Sea since 2013 as part of the Barents Sea Metocean and Ice Network (BaSMIN). The instrument locations are shown in Figure 1 and listed in Table 1. The IPS instruments measure ice draft, while the ADCPs measure ice drift. When combined, they provide a spatial series of draft of 1 m resolution.

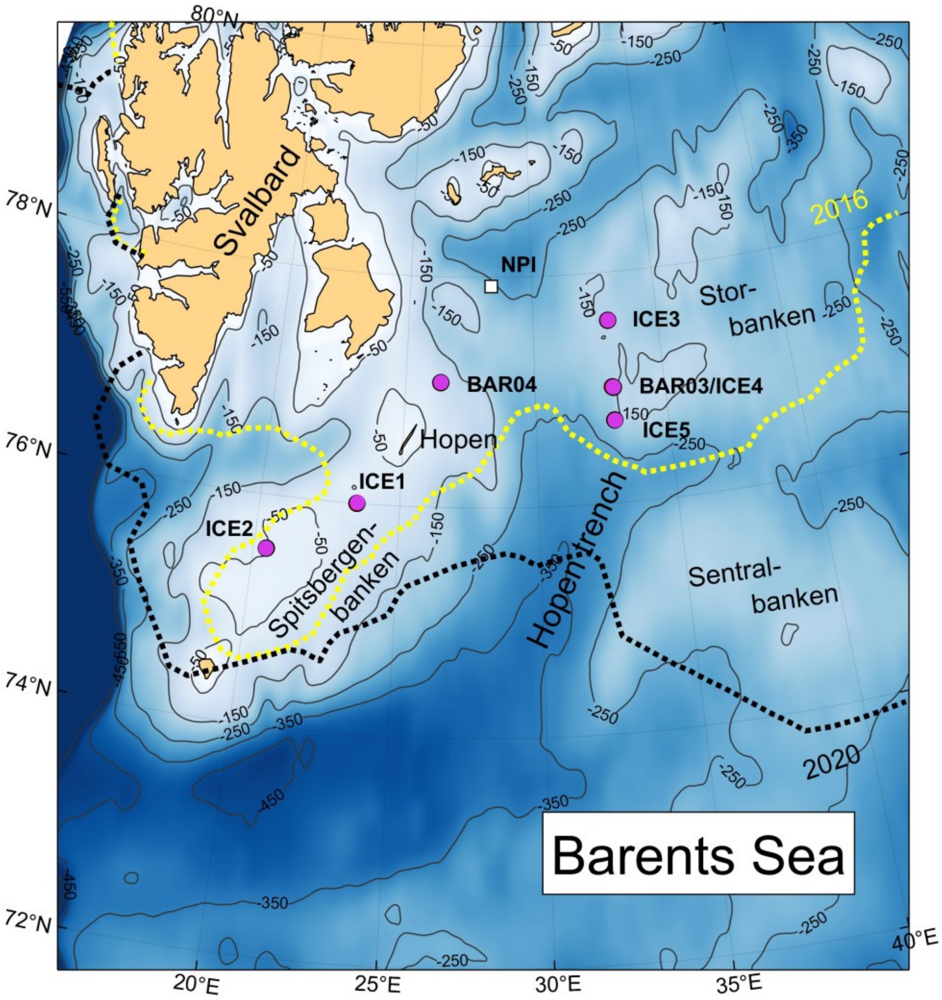

Figure 1. The location of the ice profiling sensors shown with pink dots. The dashed lines display the maximum ice extent in 2016 (yellow) and in 2020 (black).

Table 1. List of location name and position of sea ice draft and drift observations in the Barents Sea operating in the period 2013-2020.

Year	Name	Latitude	Longitude	Water depth (m)	Location
2013-2014	BAR03	77° 00'N	33° 01'E	155	Storbanken
2013-2014	BAR04	77° 05'N	26° 21'E	110	Spitsbergenbanken
2015-2020	ICE1	76° 00'N	23° 28'E	54	Spitsbergenbanken
2015-2020	ICE2	75° 32'N	20° 27'E	68	Spitsbergenbanken
2015-2020	ICE3	77° 35'N	33° 01'E	158	Storbanken
2015-2020	ICE4	77° 03'N	32° 59'E	142	Storbanken

Method for obtaining level ice draft and keel depth

Level ice was identified from the spatial series of ice drafts by application of a classification criterion (Melling and Riedel, 1995; Wadhams and Horne, 1980). Looping over all the points in the spatial series of each instrument, a point is identified as level ice if no point within 10 m in either direction differs in draft by more than 25 cm. For a given day, the level ice draft would vary in thickness owing to different origins and age of ice floes drifting past the measurement sites. Some of the floes consist of refrozen leads of various thicknesses others of thicker longer lived first year floes as well as ice transported from the north. Therefore, for each day of ice a distribution of level ice draft was established.

Individual ice ridge keels were detected using an ice draft threshold technique to identify thick ice, and a Rayleigh criterion in combination with a minimum threshold value to categorize the associated width (Fissel et al., 2010). The level ice seldom reaches drafts above ~1.8 m and therefore a ridge threshold of 2.5 m was used, along with a Rayleigh criterion value of 0.5 and a start and end threshold of 2.0 m. This approach ensures that most of the ridges are accounted for.

Further, we seek a relationship between ridge keel depth and level ice draft which is practical to apply for engineering purposes. Initially it appears meaningful to relate ridge keel depth to level ice adjacent to the ridge, expecting that the ridge originated from the nearby level ice. Due to variations in level ice draft explained previously in this section, we attempted averaging 10 to 100 m of level ice surrounding the ridge. However, this approach proved difficult due to consecutive ridges of varying depths being separated by only a few meters of level ice. Additionally, some of the ridges probably originated from refrozen leads being pressed between thicker level ice and in those cases the level ice that the ridge originated from would not be detected. Another approach was selected where a representative daily level ice draft was related to daily keel depths. For engineering purposes, the level ice draft should reflect the draft of the longest-surviving and thickest floes in the ice pack. At the same time, we should avoid including the largest values that may result from misidentifications. Using the daily 90th percentile level ice draft appears to represent a trade-off between the value of draft, conservatism, and rejection of outliers. Furthermore, daily ridge keels were related to the weekly average of the daily 90th percentile level ice draft, in order to smooth out large variations from one day to the other.

RESULTS

In total 130 708 ice ridges were detected with a keel deeper than the threshold of 2.5 m, where the deepest keel was 19.9 m. All keel depths were fitted to a Weibull distribution with scale and shape parameters of 1.297 and 0.9195, respectively. This produces mean keel depth of 3.8 m, median of 3.4 m, 99th percentile of 9.4 m.

Only focusing on keels in the winter months Feb-Mar-Apr reduces the data set to 85 215 ridge keels. The distribution of keel depth during these months is indistinguishable from the full data set, both are displayed in Figure 2. The following sections start by presenting results of maximum daily keel depths and follow with presenting the entire range of keels for each day.

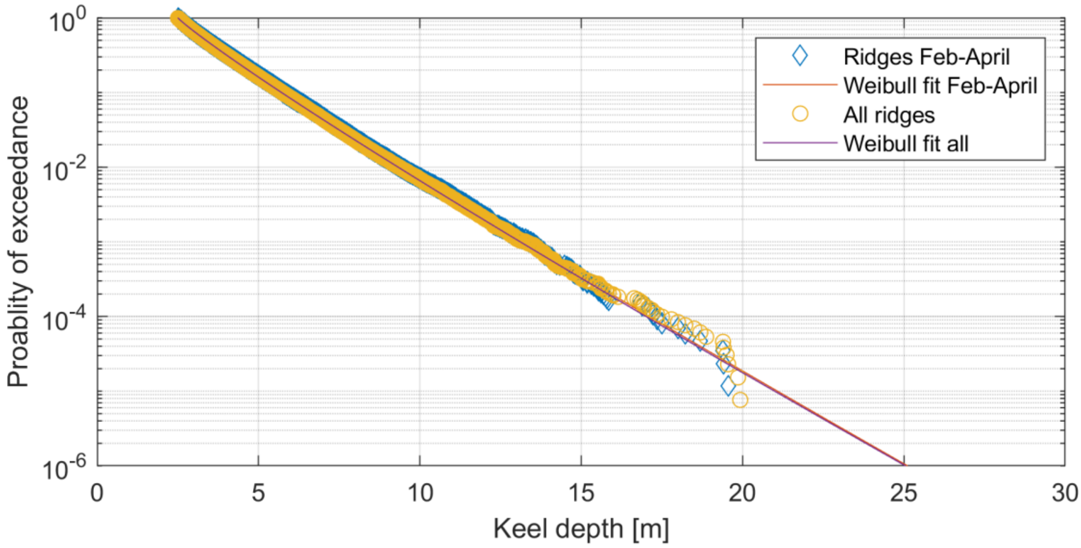

Figure 2. Probability of exceedance of keel depth for all ridges and for ridges in Feb-Mar-Apr. Fitted to Weibull distributions. The two Weibull distributions are indistinguishable and therefore it looks like only one line is displayed.

Maximum daily keel depths

For each ice day and each instrument, the maximum keel depth was found. The time series is displayed in Figure 3.

The smallest ice extent and shortest duration of ice was observed in 2016, whereas the largest ice extent and longest duration of ice was observed in 2020. These trends follow closely interannual variations in sea water temperatures below freezing. For details on sea water temperatures reference is made to Hansen et al. (2023). Data in Figure 3 display interannual and annual variability in maximum daily keel depth, as well as geographical differences between the observation sites. The variability is also seen in the number of ridges. In 2016 few and shallow ice ridges were measured, whereas in 2020 ice ridges were measured almost continuously from January to July. In 2020 a clear seasonal cycle in maximum keel depth is observed, where the values increase from February to March, followed by a stable level before a decrease in values is observed from May until July. Spatial differences between measurement sites are also apparent, where most of ridges extending deeper than 15 m occur at Spitsbergenbanken (BAR04, ICE1 and ICE 2).

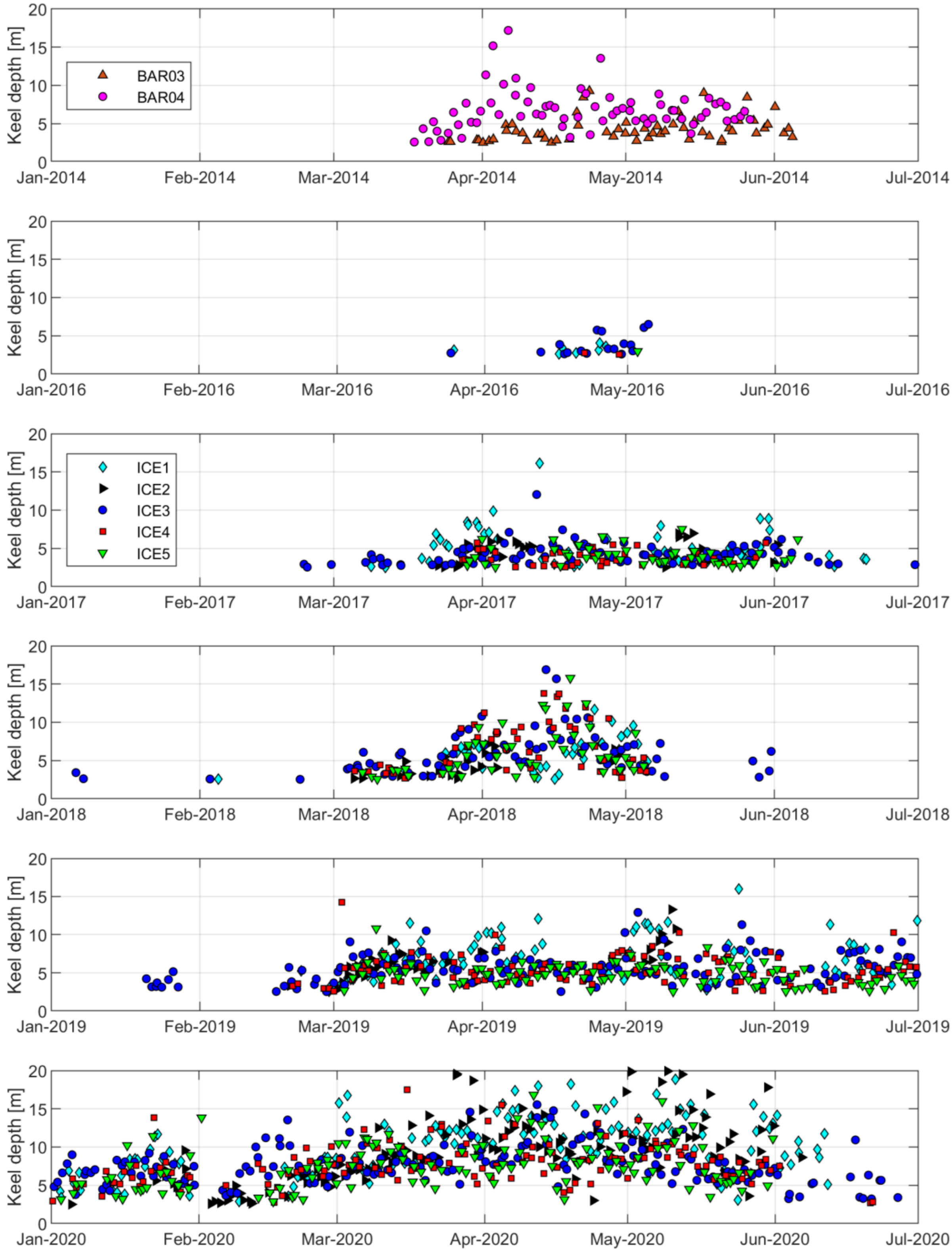

Figure 3. Time series of daily maximum keel depth for each instrument.

Time series of the ratio between maximum daily keel depths and level ice draft is displayed in Figure 4. For all datapoints the mean ratio was 11.8. In March and April, the keel depth varies less than for the summer months of May-June-July.

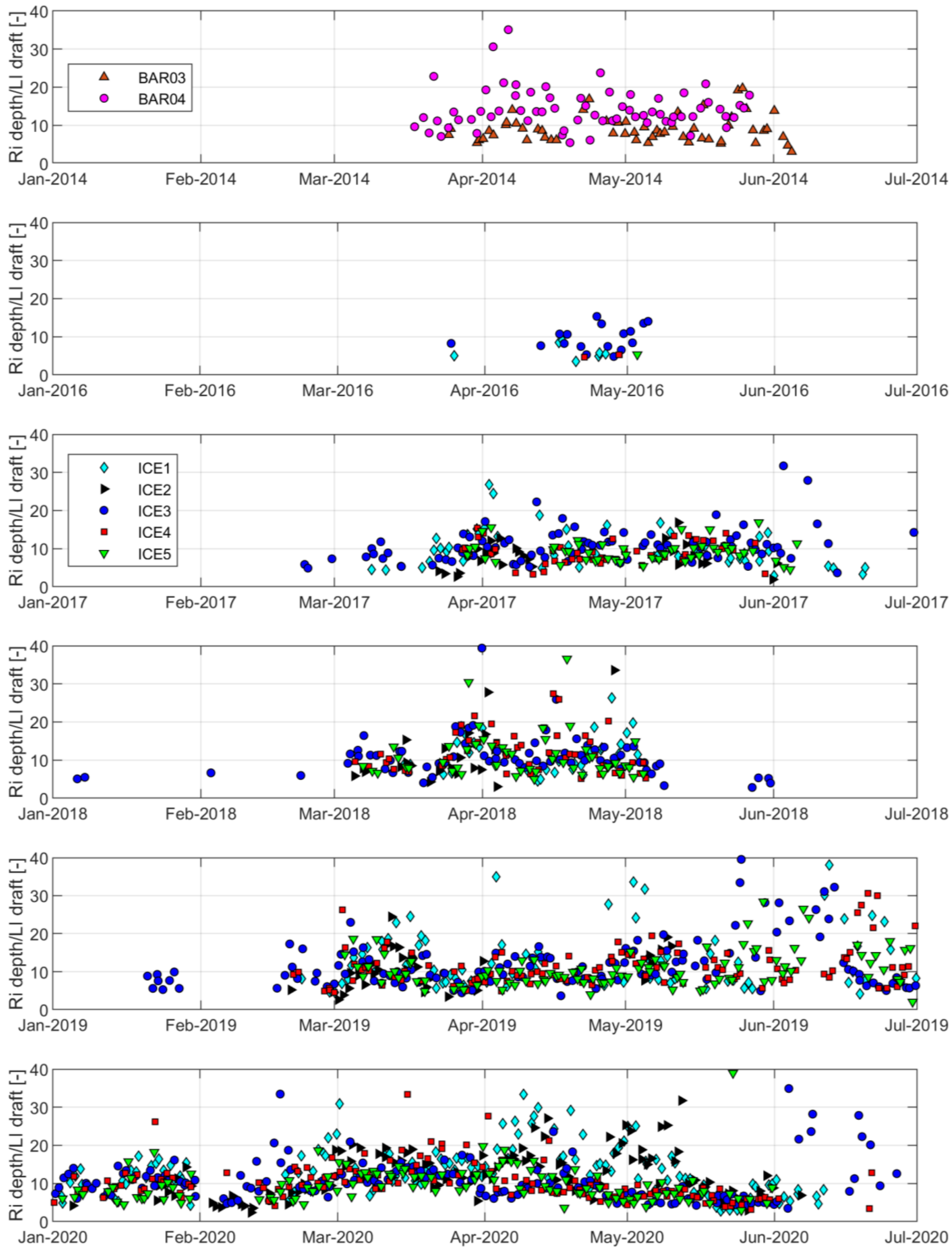

Figure 4. Ratio between daily maximum keel depth and level ice draft.

The relation between maximum daily keel depth and level ice draft is displayed in Figure 5. An upper bound relationship between maximum keel depth and level ice draft (Amundrud et al., 2004) from data in the Beaufort Sea is included for comparison.

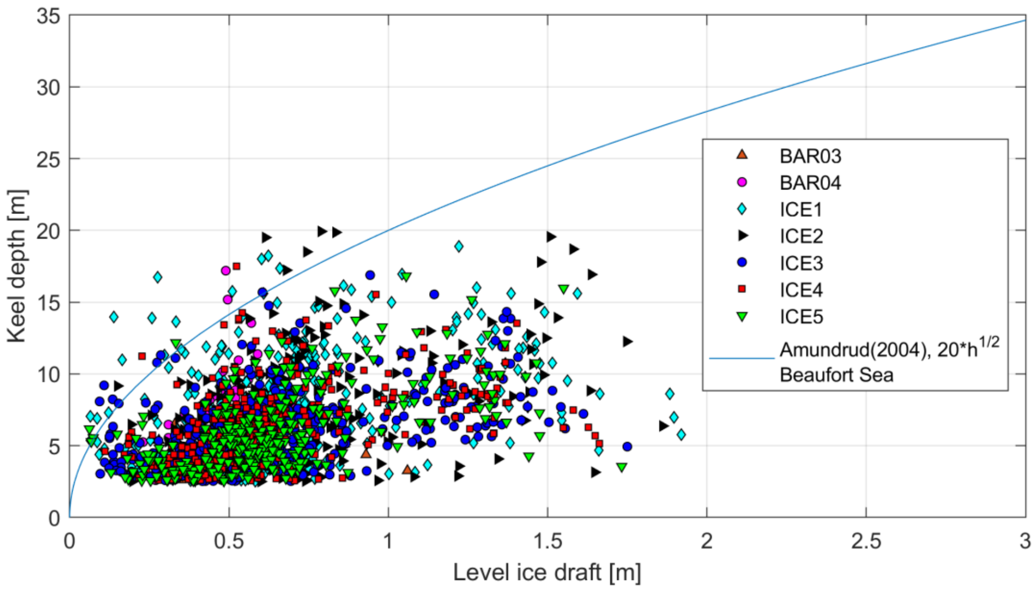

Figure 5. Maximum daily keel depth in function of level ice draft. The upper bound relationship Amundrud et al. (2004) was derived for data in the Beaufort Sea and is included here for comparison.

Distribution of daily keel depths in relation to level ice draft

In addition to comparing daily values of maximum keel depth to level ice draft, the daily distributions of keel depths were related to level ice draft. We chose to use data only from the winter months Feb-Mar-Apr, such that effects of melting and ice transported in from the north are avoided. This means that the results presented here are representing locally grown ice.

The keel data is grouped according to the associated level ice draft, in level ice draft bins of 0.1 m. For each bin a Weibull distribution is fitted to the distribution of keel depths associated with that bin. In order to obtain a general expression for a distribution of the keel depth conditional on the level ice drafts, a polynomial curve is fitted through the parameters for the range of Weibull distributions associated to the level ice draft bins. The resulting conditional model for the Weibull probability density function of keel depth (kd), has scale and shape parameters depending on the level ice draft (h) given in Equation 1, displayed in Figure 6. Two of the level ice draft bins were omitted because of few ridge observations belonging to those bins and the results were considered outliers. Extra artificial data points were added beyond the observations, to improve the polynomial fit to the observed data. These extra values are highlighted in Figure 6.

$$F(kd) = \frac{\beta}{\alpha}\left(\frac{kd-2.5}{\alpha}\right)^{\beta-1} e^{-\left(\frac{kd-2.5}{\alpha}\right)^{\beta-1}} \text{ for kd>2.5, with } \alpha = \begin{cases} \sum_1^6 a_n h^n & \text{for } h \leq 1.5 \\ 1.53 \text{ for } h > 1.5 \end{cases}$$

$$\beta = \begin{cases} \sum_0^6 b_n h^n & \text{for } h \leq 1.5 \\ 0.936 \text{ for } h > 1.5 \end{cases} \quad (1)$$

with

$$a_1 = 2.519, a_2 = 0.292, a_3 = -2.959,\ a_4 = 2.183, a_5 = 0.602, a_6 = 0.053$$
$$b_0 = 1.657, b_1 = -3.041, b_2 = 4.852, b_3 = -3.767,\ b_4 = 1.51, b_5 = -0.294, b_6 = 0.021$$

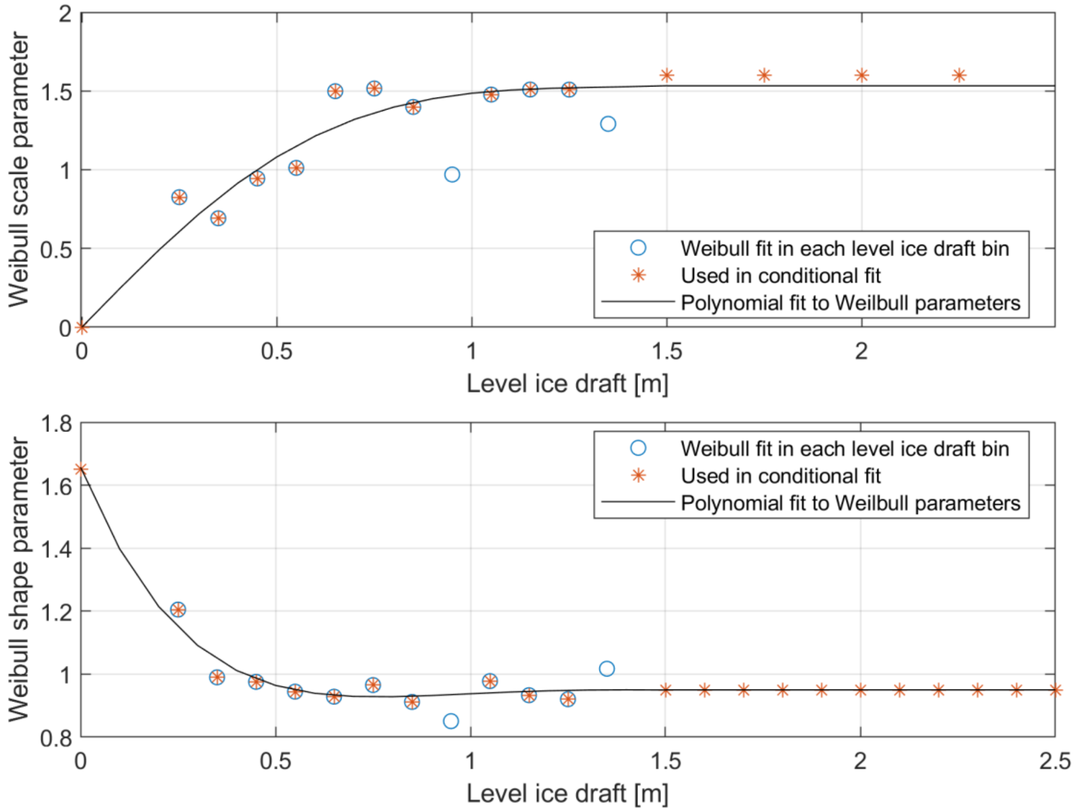

Figure 6. Curve fitted through parameters of the Weibull distributions. Two datapoints are omitted because of few ridge observations belonging to those level ice draft bins. Artificial data points added to improve the fit to the observed data are shown as red starts.

Keel depths in function of level ice draft is displayed in Figure 7, including all keels in Feb-Mar-Apr and 99th percentile of the Weibull distributions. To highlight how the data are distributed, the intensity is displayed by dividing the data into 20 bins where the colour of the bin represents the number of ridges. The intensity shows that most of the ridges were small, which is also reflected though the median (50th percentile) keel depth of 3.4 m. The 99th percentile line appears to have many ridges above it, but the use of coloured intensity plotting modifies this potential misunderstanding. An upper bound correlation Amundrud et al. (2004) found from data in the Beaufort Sea is also displayed.

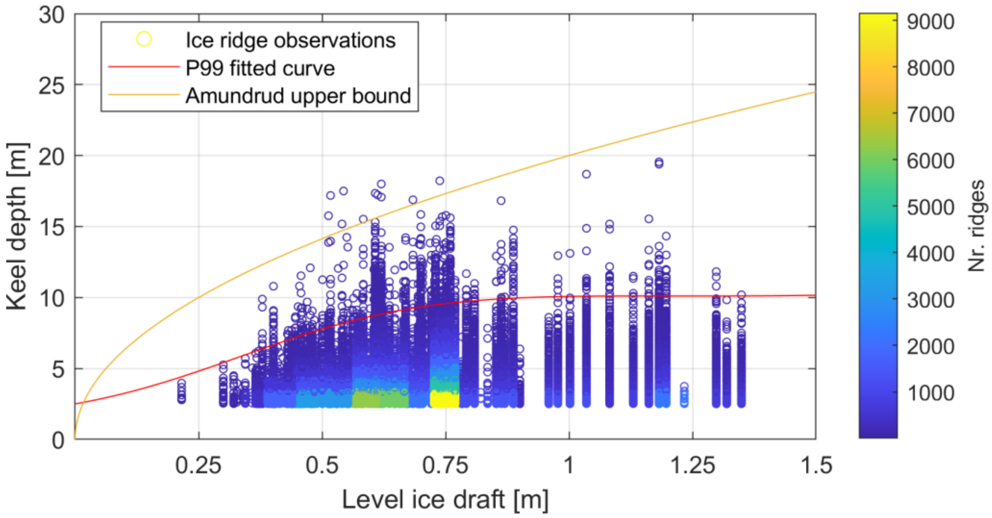

Figure 7. Keel depth in function of level ice draft. The 99th percentile of the conditional fit is displayed in this figure.

DISCUSSIONS

Maximum daily keel depth

Both the value of maximum daily keel depth and its ratio to level ice draft display seasonal variations, in Figure 3 and Figure 4. We expect a certain seasonality, owing to different ratios of formation of keels and level ice as well as different ratio of melt. The ridge formation process depends on both thermodynamic and dynamic processes, whereas ridge decay is mainly a thermodynamic process. We would expect deeper keels at Storbanken compared to Spitsbergenbanken due to earlier and longer duration of the period with sea temperatures at freezing. Seasonal variations in sea temperatures are shown in Hansen et al. (2023). Despite warmer temperatures at Spitsbergenbanken compared to Storbanken, ridge keels were deeper at Spitsbergenbanken. The deeper ridges may have been formed due to larger pack ice pressures from the islands of the Svalbard archipelago upstream from Spitsbergenbanken compared to Storbanken, which does not have islands immediately north of it. An alternative hypothesis is that the tidal currents at Spitsbergenbanken are stronger compared to Storbanken owing to shallower waters. An increased current may cause higher convergence and shear stresses in the ice cover resulting in more ice ridging.

Thermodynamics affect ridge and level ice decay differently, which is clearly observed in 2020, where the keel depth to level ice draft ratio clearly decreased from mid-April to June. Ice ridges extend deeper into the water column and ridge keels comprises porous rubble with pockets where water can circulate and melt ice rubble more efficiently than level ice. In the transition from winter to spring the ridges become shallower in depth relative to level ice. However, as long as there is rubble left in the ridge and some cold reserve it will continue to consolidate, this was shown in Shestov et al. (2018) and Ervik et al. (2018). The IPS data presented here cannot be used to quantify consolidated layer thickness.

Data displayed in Figure 4, show scattered ratio between maximum keel depth and level ice draft with an increasing trend from May to July. Although the ratio increases, the keel depths do not increase c.f. Figure 3, which means level ice drafts have decreased in comparison. Ridges occurring in June and July have survived increasing water temperatures and are transforming to second-year ridges that probably originate from large first-year ridges. We expect ridges occurring in summer to be fully consolidated c.f. (Shestov et al., 2018). Fully consolidated ridges will have larger cold reserves compared to level ice and this may explain why the level ice has melted more rapidly than ridge keels in the summer months.

Distribution of keel depth

We have chosen to compare the distribution of ridge keel depth to the 90th percentile level ice draft (in Figure 7), where the level ice represents the thickest and longest-lived level ice out of the distribution of daily level ice draft. Due to this there are very few data points with level ice draft below 0.3 m. This, in turn, makes the 99th percentile curve for keel depth relatively flat for level ice drafts below 0.3 m. More observations of level ice drafts below 0.3 are likely to have modified the shape of the curve. Furthermore, the curve starts at 2.5 m keel depth coinciding with the ridge threshold. These two reasons at least partly explain the difference between the 99th percentile curve found for data presented here and the upper bound curve for ridges of the Beaufort Sea (Amundrud et al., 2004).

CONCLUSIONS

Results from consistent long-term observations of ice ridge keels by upward looking sonars at five sites in the southwestern part of the Barents Sea ice cover during the period 2014-2020 are presented, focusing on ice ridge keel depth and how it relates to level ice draft. In total, 130 708 ice ridges extending below 2.5 m were detected. These are the main conclusions:

- The mean keel depth of all keels observed at all sites during all years is 3.8 m, with a median of 3.4 m, a 99th percentile of 9.4 m, and a maximum of 19.9 m. The best fit to a Weibull distribution yields a scale and shape parameter of 1.297 and 0.9195, respectively.
- The seasonal maximum keel depths were measured in April and May.
- The ratio between maximum daily keel depth and level ice draft was quantified for each instrument and each winter. The overall mean ratio was 11.8.
- The daily distributions of keel depths were related to level ice draft. Ice ridge keel depths were grouped by level ice draft bins of 0.1 m width. For each bin a Weibull distribution was fitted to the distribution of keel depths. The resulting conditional model for the Weibull probability density function of keel depth, has scale and shape parameters depending on the level ice draft. In this way a distribution of keels can be obtained directly from a daily level ice draft.

Acknowledgements

The authors acknowledge the provision of data by Equinor and partners in the BaSMIN Joint Industry Project. This study was funded by Equinor.

REFERENCES

Amundrud T.L., Melling H., Ingram R.G., 2004. Geometrical constraints on the evolution of ridged sea ice, Journal of Geophysical Research, Vol. 109, doi:10.1029/2003JC002251

Ervik Å., Høyland K.V., Shestov A., Nors S. T., 2018. On the decay of first-year ice ridges: Measurements and evolution of rubble macroporosity, ridge drilling resistance and consolidated layer strength, Cold Regions Science and Technology, vol 151, https://doi.org/10.1016/j.coldregions.2018.03.024

Fissel, D., A. Kanwar, K. Borg, T. Mudge, J. Marko and A. Bard (2010), Automated Detection of Hazardous Sea Ice Features from Upward Looking Sonar Data, 10.5957/ICETECH-2010-150.

Hansen, E., Ervik, Å., Eik. K., Teigen., S., Long-term observations (2014-2020) of level ice draft, keel depth and ridge frequency in the Barents Sea (2023), Accepted for publication in Cold Regions Science and Technology

Melling, H., and D. A. Riedel (1995), The underside topography of sea ice over the continental shelf of the Beaufort Sea in the winter of 1990, J. Geophys. Res., 100 (C7),13641-13653, doi:10.1029/95JC00309.

Shestov A., Høyland K. V., Ervik Å., 2018. Decay phase thermodynamics of ice ridges in the Arctic Ocean, Cold Regions Science and Technology, vol. 152(2), https://doi.org/10.1016/j.coldregions.2018.04.005

Wadhams, P., and R. J. Horne (1980), An analysis of ice profiles obtained by submarine sonar in the Beaufort Sea, J. Glaciol., 25(93), 401-424.