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

Statistical analysis of IPS-data in Fram Strait 2006 – 2011

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ABSTRACT

An empirical ridge statistic that correlates weekly level ice thickness with keel depth and weekly number of ridges was investigated using ice profiling sonar (IPS) data from 2006 to 2011 in the Fram Strait. The applied methodology was similar to the studies for the Beaufort Sea (Samardžija and Høyland, 2023) for IPS data from 2003 to 2017. The data were divided into weekly segments. For each of them, the number of ridges based on the Rayleigh criterion with a threshold of 2.5 m and a minimum keel draft of 5 m, average and deepest keel depth, and level ice thickness were calculated. A correlation between the level ice thickness and the keel depth was established. The broader idea is to compare regions with different ice regimes, see how the ridge statistics change, and how well the model can handle these differences. In this paper, we compared the Beaufort Sea and the Fram Strait. Both have a positive correlation between level ice thickness (h_i) and weekly mean ridge keel draft ($\langle h_k \rangle$), weekly deepest ridge keel draft (h_{k_deep}) and ridge frequency. Linear regressions $\langle h_k \rangle = 5.60 + 0.82 h_i$ and $h_{k\_deep} = 8.15 + 6.60 h_i$ with Pearson correlation coefficients $R = 0.49$ and $R = 0.35$, respectively, were established in this work, which are both lower in comparison with Beaufort Sea results.

KEY WORDS: Sea ice; Ridge keel; Ice draft; Level ice thickness

NOMENCLATURE:
IPS - Ice Profiling Sonar
ULS – Upward Looking Sonars
ADCP – Acoustic Doppler Current Profiler

NPI – Norwegian Polar Institute

INTRODUCTION

The Fram Strait is a unique region due to the Arctic outflow, which brings ice from remote places such as the Central Arctic Ocean and Russian Arctic. Hansen et al. (2013) back-calculated trajectories of sea ice from the Transpolar Drift in the Fram Strait during 1990 - 2011 and identified whether this ice originated from one, two or three years earlier, tracking the lifespan of the sea ice. Since the 1990s, it has been noticed that the ice thickness, ice age and summer ice extent have substantially declined. A smaller fraction of old ice (sea ice which has survived at least one summer melt) was recorded over the years. Ice conditions are changing rapidly, and it is essential to be aware of them for an accurate estimation of risks from sea ice in various areas of human activity. The decrease in sea ice extent and thickness provides more opportunities for the development of the northern regions, but it is also a strong indicator of global changes. There is a range of ice types in Fram Strait, from newly formed ice to old ice, both level and deformed. Arctic outflow is very dynamic, and a lot of interaction and ice deformation occur. Some of them arrived with older ice from different areas, but some originated locally. This made the sea ice study in the Fram Strait more complicated in comparison with other regions where ice is predominantly of local origin and is thermodynamically grown along the season. There was an idea to use a statistical approach for describing sea ice ridges and assessing ridge loads based on level ice thickness, which was implemented for the Beaufort Sea by Samardžija (2023, 2024). The ice draft from remote locations allows us to study sea ice with its different features and estimate the sea ice-associated risks in various areas such as industry, shipping, tourism, and fisheries. The model presented a probabilistic assessment of global ice ridge actions on offshore vertical structures. The model applies level ice thickness, number of ridges, ridge keel draft and consolidated layer thickness as its major random variables. A sea ice ridge is a result of the interaction of two ice sheets/floes at their edges (ISO19906:2019). Part of the ridge above water is called the sail, and beneath is the keel. The ridge keel consists of the upper refrozen layer, the consolidated layer, which grows during the ridge's lifetime, and the lower unconsolidated layer. In this paper, we continue to develop this model, focusing on the other regions, on the correlation between level ice thickness and keel draft in the Fram Strait.

DATA SOURCE

This work was based on data from the ice profiling sonars installed by the Norwegian Polar Institute (NPI) during 2006 and 2011 in the western Fram Strait region (Figure 1). They have installed upward looking sonars (ULS) (1990 - 2006) and then ice profiling sonars (since 2006) annually in the late summer/early autumn by installing anchors with mooring equipped with ULS/IPS together with other sensors (salinity, temperature, ADCP, current meters) for one-two years (Hansen, et al., 2013). IPS provides data on ice draft in time with a sampling interval of around 2 seconds. It sends an ultrasonic beam upward, scattering from the ice surface under the water and returning to the transducer at a specific depth (Fissel, et al., 2008). The stations were located along the 78.8°N - 79.2°N latitude and around 3°W (F11), 4°W (F12), 5°W (F13), 6.5 / 7.0°W (F14) longitude. This location was determined by the Eastern Greenland Current (EGC), where a substantial part of the sea ice transport occurs, with moorings positioned across it and above the shelf slope. The water depth of the mooring locations was growing from F14 (approximately 400 m) to F11 (approximately 2000 m) (Hansen, et al., 2013). A list of available data can be seen in Table 1.

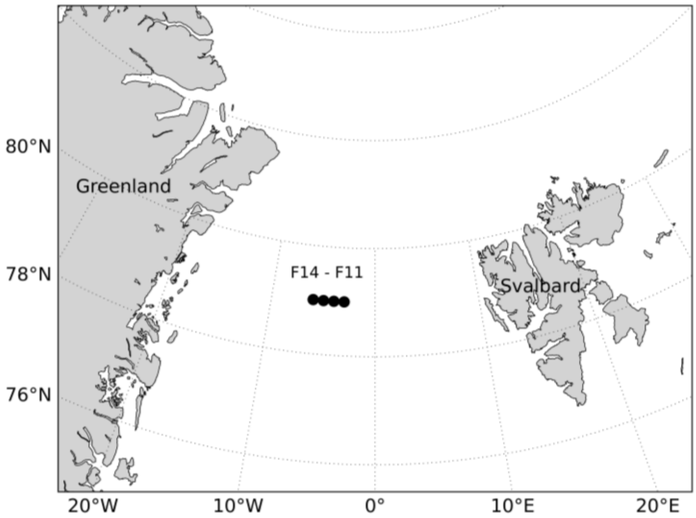

Figure 1. Locations of the ice profiling sonars in the Fram Strait

Table 1. Data availability by stations and years

Year	F11	F12	F13	F14
2006 - 2008			V	V
2008 - 2009	V	V	V	V
2009 - 2010		V		V
2010 - 2011	V	V		

DATA PROCESSING

The IPS data was divided into weekly segments, where week one was from September 1st to 7th, week two was from September 8th—14th, and so on. The approach to divide data into time intervals rather than space intervals was chosen because it resembles the scenario of drifted ice ridges interacting with a fixed offshore structure (Samardžija, 2019). Data was divided with a threshold of 2.5 m. Ice draft below this threshold was associated with level ice. Different types of deformed ice were close to the 2.5 m. Starting from the 3m, there were most likely ice ridges. The ridges were identified using the Rayleigh criterion. For each weekly segment, the level ice draft, number of ridges and mean ridge keel were identified, and the deepest keel draft was recorded, Figure 2:

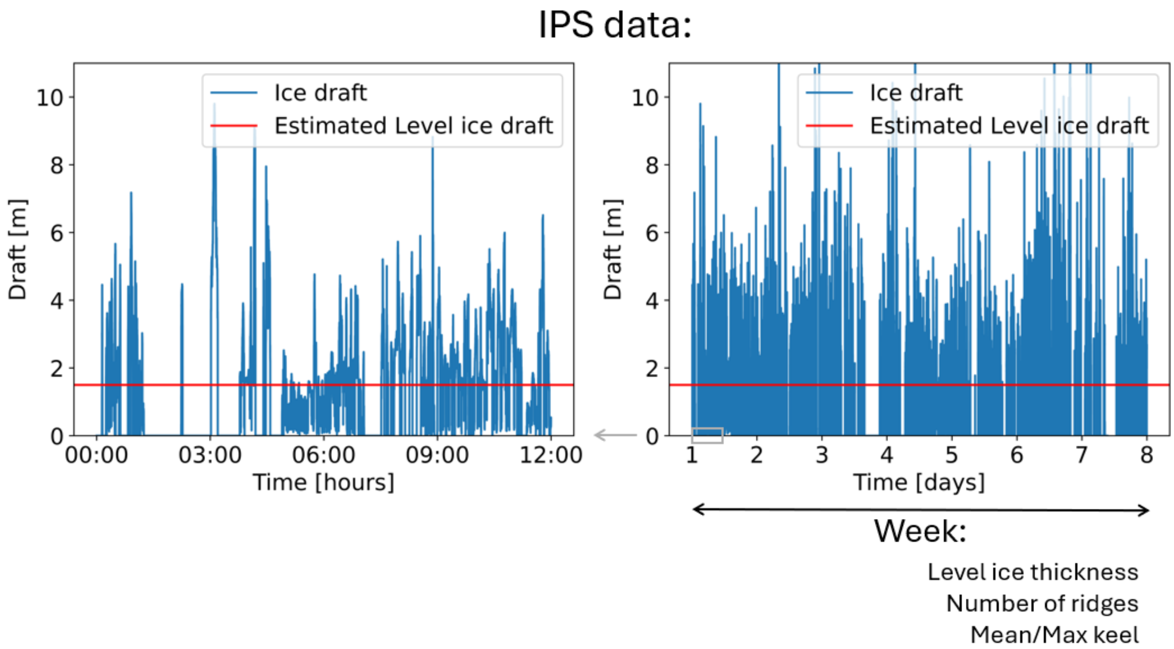

Figure 2. Example of weekly segment of ice draft data. Level ice draft was estimated using histogram analysis

Ridge identification, the Rayleigh criterion

The Rayleigh criterion helps to identify if two neighbouring peaks are related to one ridge or should be counted as two separate ridges. This method is well described in Ekeberg et al. (2012). The Rayleigh criterion is based on a threshold value h_{thres}, which reflects the level ice thickness in the investigated area and three main parameters, which are collected from the data: α is the difference between the threshold value and maximum observed draft, β is the difference between current and maximum observed drafts, and δ is the maximum observed draft after local minimum (second peak). If:

$$\beta > 0.5\alpha, \quad (1)$$

then this is likely to be the end of the ridge after the first peak. If also:

$$\delta > 2(\alpha - \beta) + h_{thres}, \quad (2)$$

then the two peaks are two separate ridges. In addition, there is a condition on a minimum keel draft. In this way, moving step by step and applying the Rayleigh criterion, we identify ice ridges.

The Rayleigh method with a threshold of 2.5 m and a minimum keel draft of 5 m was used on IPS data as the most widely used method, according to Ekeberg et al. (2012, 2015), and gives the opportunity to compare results with other research. The Rayleigh criterion is less sensitive to the threshold value, which helps to identify more ridges near the threshold. At the same time, this increases false identification of large ridges (deeper than 15 m) if there are multiple ridges in a row. In the Fram Strait, the presence of the large ridges is not that frequent, which makes it more important to focus on other ridges and provides an opportunity to use the Rayleigh method.

Level ice thickness

The identification of level ice thickness was more complicated. In the Fram Strait, there is ice of local origin, formed thermodynamically from zero, together with ice of non-local origin, advected from the Central Arctic or Russian Arctic and which can be very old. Moreover, there are also dynamic processes, that influence ice growth during the lifespan, such as rafting (pressure processes whereby one piece of ice overrides another. Most common in new and young ice), ridging (the pressure process by which sea ice is forced into ridges), lead opening and refreezing (Samardžija, 2019; World Meteorological Organization, 2014). Some are making already existing ice thicker; some are starting new ice growth. New ice could start to form in the open water or refreeze water in the lead (a large fracture in the sea ice). All these provide variability in ice type in the region and distribution of level ice thickness with several modes, Figure 3. Each mode provides information about the type of ice. According to the World Meteorological Organization Sea ice nomenclature (World Meteorological Organization (2014), 0.1 – 0.3 m thickness represents the young ice (ice in the transition stage between newly formed ice and first-year ice); 0.3 – 2 m thickness corresponds to first-year ice (sea ice of not more than one winter's growth); while 2 m thickness and more (typically up to 3 m and more) is old ice (sea ice which has survived at least one summer melt) or very thick first-year ice. Old ice modal peak (right mode, if old ice is present), downward concave points grow and then decrease in the fraction of thermodynamic level ice growth, while an upward concave curve to the right from the old ice modal reflects an increase in the fraction of deformed ice (Hansen, et al., 2013).

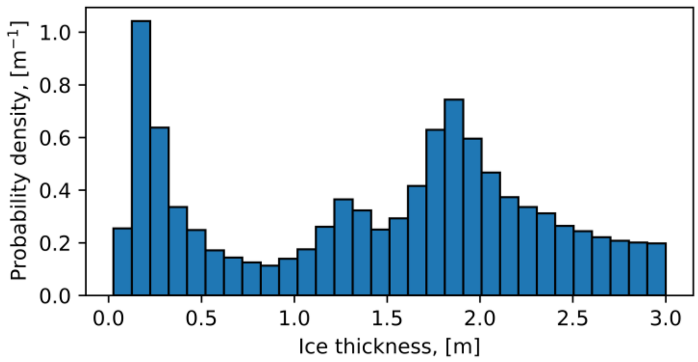

Figure 3. Example of multimodal ice thickness distribution for an extended period with a limit of 3 meters

Weekly level ice thickness was analysed using the histogram method with a 0.1 m bin. This bin corresponds to the accuracy of the IPS measurements (Hansen 2013). The correct bin selection was important for accurately identifying the position of the modes. There is a question, which mode to choose for describing the weekly mean and deepest keel draft. This work was similar to a statistical model by Samardžija and Høyland (2023), which used the relationship between level ice thickness and keel draft for the probabilistic assessment of ridge loads (Samardžija, 2019). Therefore, the rightmost mode was chosen as the thicker ice, which can cause a higher force.

RESULTS AND DISCUSSIONS

The seasonal development of a weekly number of ridges is presented in Figure 4. Weeks with less than 15 ridges were not considered because statistics with a low number of ridges were unreliable (Samardžija and Høyland, 2023). There were six discarded weeks in total. The timing of all six was between the middle of August and the middle of September, which typically corresponds to sea ice minimum in the region. The number of ridges varied throughout the season with a broad maximum during winter. Median monthly values were up to 1000 ridges/week, and the maximum monthly number of ridges was up to 3500 ridges/week. In contrast, the Beaufort Sea experienced a more monotonic increase, with a peak in May. Median monthly values were significantly lower, up to 200 ridges/week. The maximum monthly number of ridges was up to 1200 ridges/week, which is almost one-third of the maximum for Fram Strait (Samardžija and Høyland, 2023).

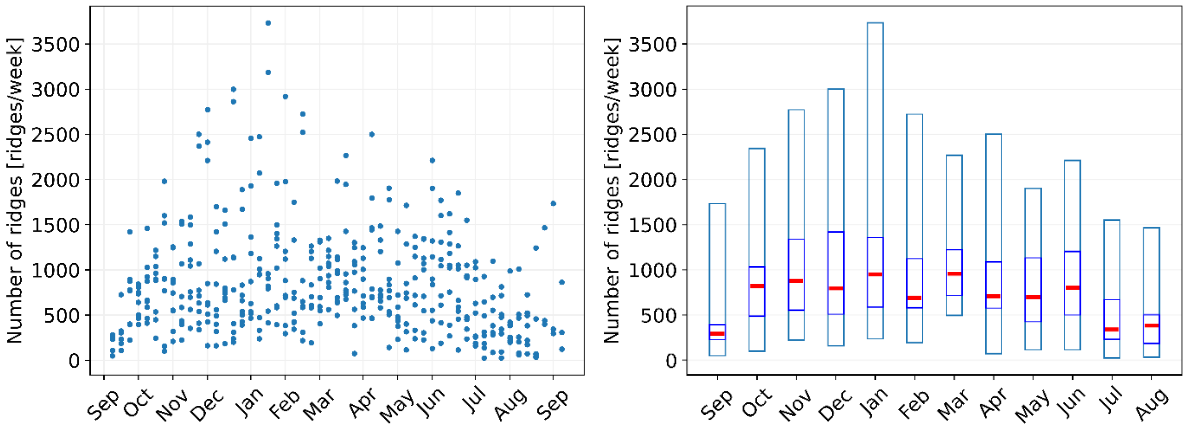

Figure 4. Seasonal development of the weekly number of ridges. On the left plot, each point represents a weekly number of ridges. On the right plot, the red line is the median value for the weekly number of ridges for each month; dark blue represents the 25th and 75th percentiles, and light blue indicates the minimum and maximum weekly number of ridges for each month

Minor fluctuations throughout the season were observed for the mean keel draft (Figure 5) and the deepest keel draft (Figure 6). The timing of the peak was around May-June. 25^{th}, 75^{th} percentiles and minimum, maximum values are presented on the plots. The 25^{th} (75^{th}) percentile is a data point below which 25^{th} (75^{th}) % of all data values exist. The percentile frame allows to exclude extreme values, focusing on the main part of the data. In contrast, the minimum-maximum frame highlights the limit values, which can be helpful for the future calculation of limit loads. Median values for weekly mean keel distributed from 6.5 m to 7.5 m, while for the Beaufort Sea, it ranged from 6 m to 7 m (Samardžija and Høyland, 2023). The deepest keel draft fluctuated near 20 m with a maximum ice draft up to 50 m, while in the Beaufort Sea, the limit was 30 m.

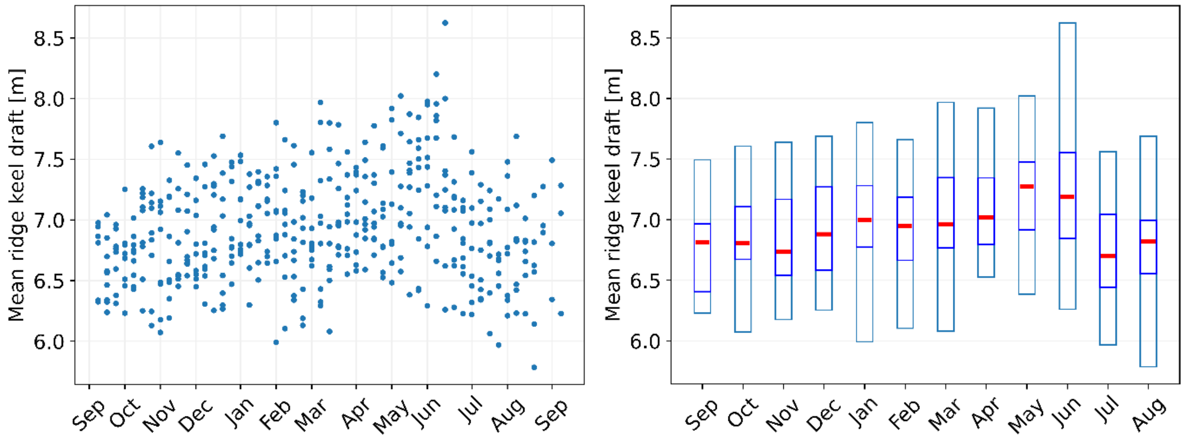

Figure 5. Seasonal development of a weekly mean keel draft. On the left plot, each point represents a weekly mean keel draft. On the right plot, the red line is the median value for the weekly mean keel draft for each month; dark blue represents the 25th and 75th percentiles, and light blue indicates the minimum and maximum weekly mean keel draft for each month

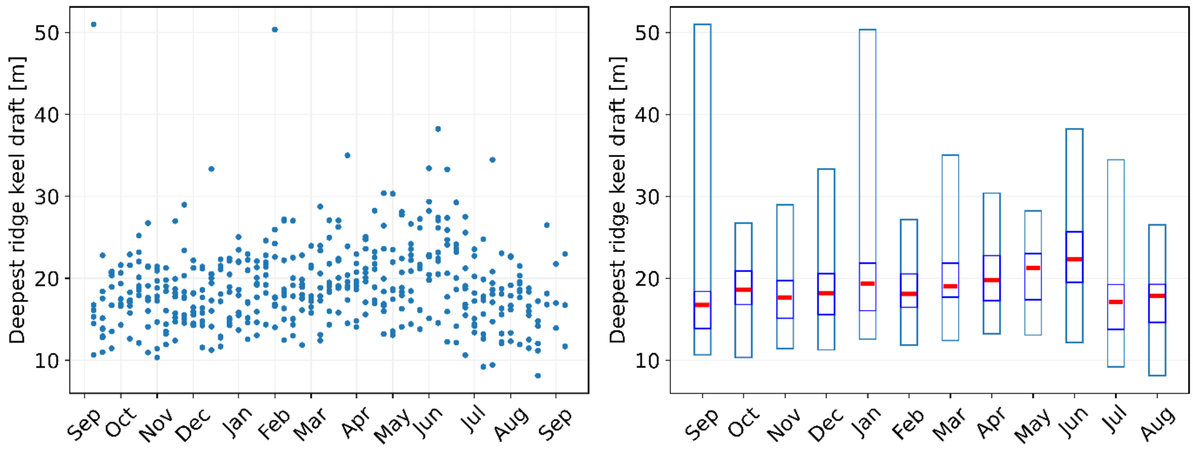

Figure 6. Seasonal development of a weekly deepest keel draft. On the left plot, each point represents a weekly deepest keel draft. On the right plot, the red line is the median value for the weekly deepest keel draft for each month; dark blue represents the 25th and 75th percentiles, and light blue indicates the minimum and maximum weekly deepest keel draft for each month

Examples of weekly level ice distributions during the season are shown in Figure 7. The top line represents the second-year-old ice, which survived the summer or sometimes it represents old ice. This "line" is most clearly observed on the plot for 2009. The diagonal line from the bottom left corner to the top right corner represents the present season's thermodynamically grown ice, which eventually merges with the "old" top line. They are reaching the same ice thickness values closer to the end of the season. This line is most visible on the plot for 2011. In both plots, we could see that later in the season, new horizontal lines started to occur in parallel with the first line. There are a lot of dynamic processes in the Fram Strait and, as a result, a lot of open water, which provided an opportunity for new ice growth. For some years, an additional domination of lead ice is noticed in the bottom line of the plot. In the Beaufort Sea, there is mainly new thermodynamically grown ice with rare old ice infusion and sometimes with ice from the previous season. However, the same approach was used in both regions for identifying weekly level ice.

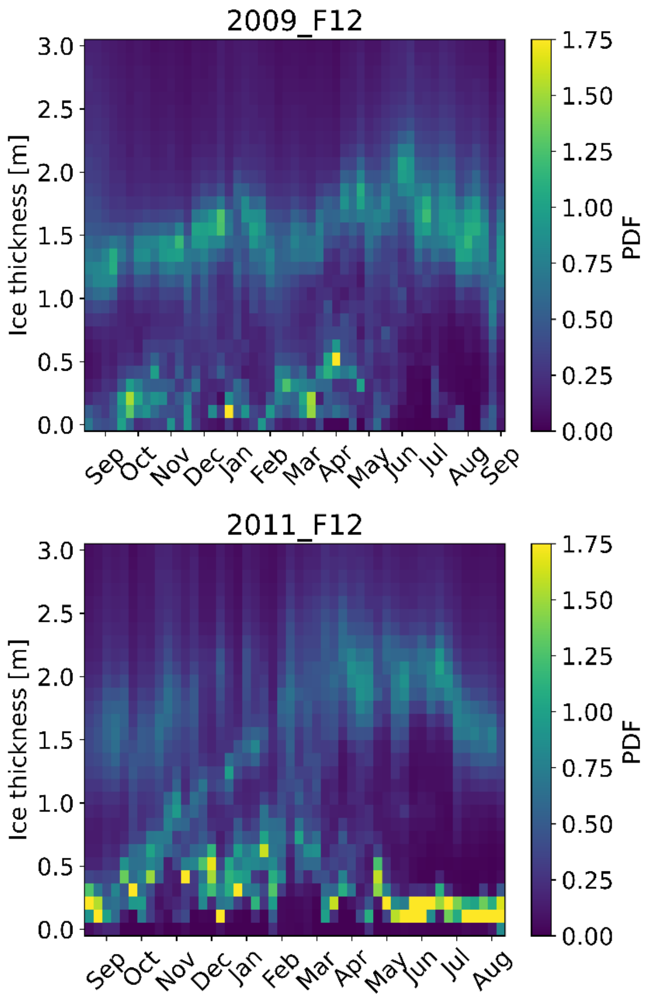

Figure 7. Weekly ice thickness probability density for 2009 and 2011, location F12.

The relationships between main parameters, level ice thickness, mean and deepest keel draft, and number of ridges are presented in Figure 8 and Figure 9. The dominant amount of values for level ice thickness is between 1 m and 2.25 m because of a significant amount of advected ice of non-local origin. There are not many level ice thickness values less than 1 m due to our approach of choosing level ice. There is no level ice of more than 2.25 m since the studied years in the Fram Strait are characterised by a lack of old ice. Moreover, level ice thickness up to 2.3 m fitted well to the chosen threshold of 2.5 m for the identification of ridges. A positive linear regression relationship (using least-squares approximation) is observed between level ice thickness and weekly mean keel draft $\langle h_k \rangle = 5.660 + 0.82h_i$, as well as between level ice thickness and weekly deepest keel draft $h_{k\_deep} = 8.15 + 6.60h_i$. The Pearson correlation coefficients are $R = 0.49$ and $R = 0.35$, respectively. For the Beaufort Sea, the results were

$R = 0.63$ and $R = 0.58$, respectively (Samardžija and Høyland, 2023). A power function $y = 260.40x^{2.28}$ describes the relationship between level ice thickness and the weekly number of ridges. As we can see, over time, the ice grows, and more events occur.

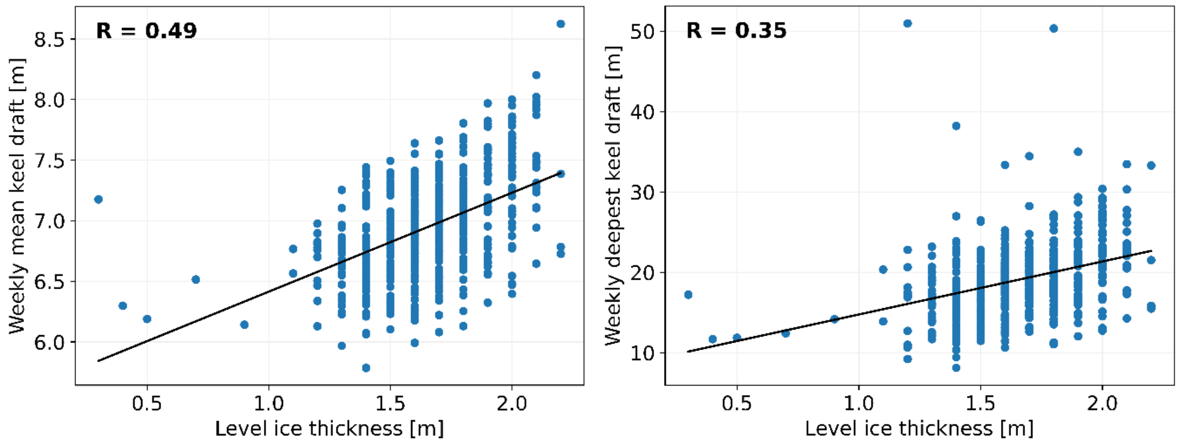

Figure 8. Relationship between level ice thickness and mean/deepest keel draft. The black line represents linear regression by least-squares approximation. For the mean keel draft, the intercept is 5.60; the slope is 0.82. For the deepest keel draft, the intercept is 8.15; the slope is 6.60. R is the Pearson correlation coefficient

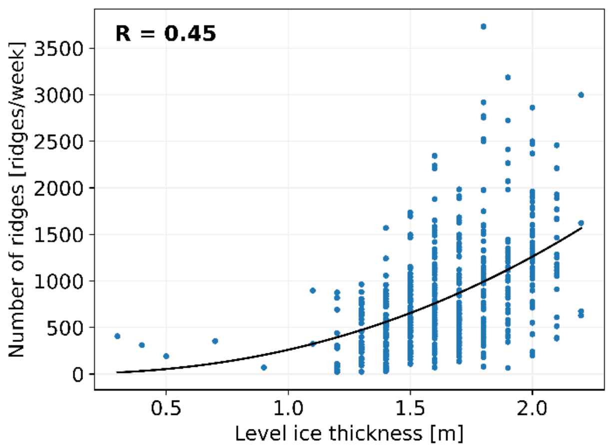

Figure 9. Relationship between level ice thickness and weekly number of ridges. The black line represents a fitted power function $y = 260.40x^{2.28}$. R is the Pearson correlation coefficient

CONCLUSIONS

We conducted a statistical analysis of ice ridges in the Fram Strait based on IPS data from 2006 to 2011. The results showed positive correlations between level ice thickness and keel draft. The Beaufort Sea and the Fram Strait have different ice regimes, which affect the ice presence and interpretation of IPS data. The number of ridges was significantly higher in the Fram Strait. Mean and deepest keel draft values were also higher. Ice distribution during the season was more complicated and almost always consisted of multiple modes, corresponding to lead ice, first-year and second-year old ice and ice of local and non-local origin. Such variability in ice affected the correlations and the considered level ice thickness range (1 m - 2.3 m). The focus shifted more towards ice of non-local origin and thermodynamically grown ice from the end of the season. The number of ridges grew as a power function of the level ice thickness. It is planned to continue this research by investigating the Barents Sea and, later, enhancing the statistical model for the physical processes of summer melting and consolidation.

ACKNOWLEDGEMENTS

The described work was produced as part of the RareIce project (326834) by the Research Council of Norway.

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