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RESEARCH ARTICLE

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Estimating extreme level ice and ridge thickness for offshore wind turbine design: Case study Kriegers Flak

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Abstract

When designing offshore wind turbines in ice-covered seas, site-specific ice conditions present crucial input for the structural design. In this study, methods of estimating the maximum level ice thickness occurring once in 50 years and parameters of a design ice ridge in an area where no direct ice thickness measurements exists are presented. The site of Kriegers Flak at the Southern Baltic Sea is taken as a case study. Rather than just applying basic equations found from the standards, the method gives more detailed estimates by utilizing available ice chart information, ice reports and atlases together with measured air temperature data to estimate the starting and ending date of ice growth. The maximum level ice thickness occurring once in 50 years at the site of Kriegers Flak wind farm was estimated to be between 0.26 and 0.44 m depending on the assumptions. The effect of the studied history length, the utilized weather station and the use of snow thicknesses to the 50-year ice thickness estimates are compared and discussed. Interaction with ice ridges was found to be a relevant but infrequent, load scenario for the site of Kriegers Flak. For this reason, a representative ridge for determining ice ridge loads is presented. The most important parameter in a ridge, the thickness of the consolidated layer, was found based on scenario analyses to be in a range between 0.43 and 0.67 m can be used to calculate ice loads against the wind turbine substructures.

KEYWORDS
extreme ice thickness, ice ridge parameters, Kriegers Flak, offshore wind power, the Baltic Sea

1 | INTRODUCTION

In this paper, we concentrate on estimating ice conditions for offshore wind turbine design in areas where no direct ice thickness measurements on site exists. Methods to estimate both the maximum level ice thickness occurring once in 50 years at the wind farm site and the ice ridge parameters, especially the thickness of the consolidated layer, are presented. We take the Kriegers Flak wind farm in the Southern Baltic Sea as a case study. Kriegers Flak is an offshore wind farm site at the Arkona Basin in Danish waters of the Southern Baltic Sea. The central point of Kriegers Flak is located in 55.0270°N and 12.9390°E. The location of the Kriegers Flak is shown in Figure 1.

The number of offshore wind farms are rising as the demand for renewable energy is increasing. The transition to the offshore wind farms in the freezing sea areas is ongoing. In the Southern Baltic Sea, that is an occasionally freezing sea area, there exists already running offshore wind farm installations, and many plans exist. For example, the vision of Wind Europe is to have 83 GW of offshore wind in the Baltic Sea by 2050.[1] To

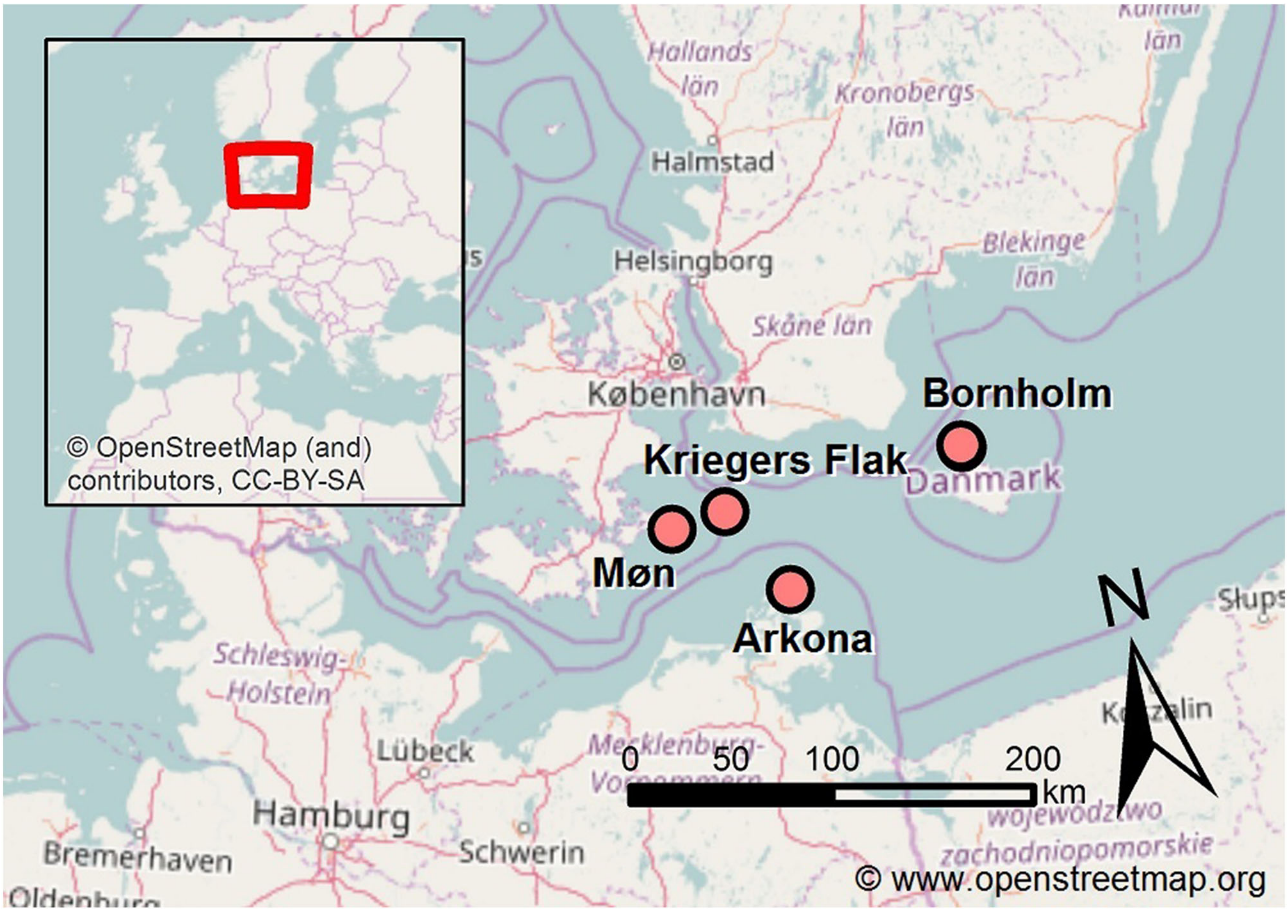

FIGURE 1 The location of the offshore wind farm Kriegers Flak and the utilized weather stations on islands of Møn, Rügen (denoted 'Arkona') and Bornholm [Colour figure can be viewed at wileyonlinelibrary.com]

achieve this, site-specific ice conditions and the principles of ice-structure interaction need to be known. Too harsh estimated ice conditions lead to expensive structural design and might thus prevent the construction of the wind farms. On the contrary, too mild estimates can cause structural damage and financial loss during the lifetime of the wind turbine.

Ice in the Baltic Sea has been studied extensively on a geophysical point of view,[2] but studies related to specific ice condition parameters needed in offshore wind turbine design are lacking. Gravesen and Kärnä[3] estimated ice thicknesses to be used in the Southern Baltic in the offshore wind turbine design. They presented their results briefly, and their approach has been to estimate ice thickness based on the temperature histories and compare it to the values found from the ice charts similarly as in this study. In this paper, we take this approach further and do more detailed analysis. Tikanmäki et al.[4,5] have estimated ice condition parameters to be used in the offshore wind turbine design for the Gulf of Bothnia in the Northern Baltic Sea based on the historical ice charts.

Ice conditions can be estimated based on the historical ice occurrences. Due to the climate change, ice conditions in the Baltic Sea are changing, and the trend is towards milder ice conditions.[6,7] The use of the historical ice occurrences then might lead to an overestimation of ice thicknesses. However, it is often the best estimate that can be derived if no credible prediction model results exist for the site. In ice conditions at the Baltic Sea, interannual variabilities are large.[2] In areas where ice occurs regularly, shorter time periods can be used in order to obtain the statistical variability between years. For places such as the Southern Baltic Sea where sea ice occurs more rarely, longer time histories are needed. By using long data series, the past climate change plays a role in the estimates.

In the Southern Baltic Sea, ice forms first close to the shores and forms a narrow landfast ice zone where ice stays immobile. Further away in the sea, ice is so-called drift ice, and it moves driven by wind and sea currents. Since ice is drifting, sometimes leads and polynyas open between ice floes. Depending on temperature conditions, new thinner ice might form between ice floes. Thus, the thickness of drifting sea ice varies over the region, and the drifting ice is a mixture of different ice types.[7] These include ridges and rafted ice.

The 50-year maximum level ice thickness and ice ridge properties are required for the structural design of offshore wind turbines (IEC, 2019).[8] Thus, in this paper, the emphasis is on maximum level ice thickness and ice ridges.

First-year ice ridges are elongated accumulations of broken ice floes. Ridges form when sea ice is deforming and fracturing due to driving forces from winds and sea currents. In that process, large sea ice flows are compressed or sheared against each other causing the ice to fail into smaller pieces forming a ridge. Ice rubble is a result of crushing and flexural failure or ice during the ridge formation process. A compression ridge is often highly irregular, both in direction and in vertical height. A shear ridge is normally very straight, because separate ice fields move laterally in opposite directions. A ridge contains a large number of ice pieces of varying sizes and shapes that are piled arbitrarily and they are floating in the seawater; see Figure 2. The ice ridge is categorically composed of three geometrical sections: a sail composed of ice rubble above the waterline, a keel composed of ice rubble underneath the waterline and refrozen ice layer, i.e., consolidated layer at the waterline. Rafting is a process during the ridge building in which an ice plate overrides or underrides another ice plate. Rafted ice layers are very common in the ridges or in the vicinity of ridges.

Cavities in the rubble of the keel are filled with water and slush, but in the sail, they contain snow and air. Hence, the ridge is a porous feature. Immediately after the formation, if the air temperature is well below the freezing point of water, the water between the blocks starts to freeze creating a strong layer called consolidated layer. The freezing zone expands downwards and ice blocks freeze together with the level ice layer or rafted layers, creating the consolidated layer, which also is porous. Porosity of ice rubble defines the volume fraction of non-ice material (voids) is usually around 30%, but its variation can be large.

Ridges are usually present in all ice-covered sea areas, if the ice concentration is high enough.[9] Ice ridges are very common ice features in the Baltic Sea.[10,11] After ridges have been formed, they drift due to wind and sea current. When a ridge collides with an offshore structure, it introduces a significant load scenario for offshore structures.

Ice ridges have been important research topic in freezing sea areas for a long time, mostly because they hamper winter navigation and drifting ridges induce major loads on offshore structures. So far, the research has been focused to annually freezing sea areas. Leppäranta et al.[12] studied the internal structure and temperature of one sea ice ridge in the northern Baltic Sea in the winter of 1991. Within 3.5 months, they monitored how the ridge consolidated in comparison to the level ice near the site and at the shore. Leppäranta and Hakala[10] studied ridge topology and mechanical properties for selected areas in the Gulf of Bothnia. Kankaanpää[11] made thorough study about ridge geometries and internal structure in the same area. She developed statistical relationships between geometrical quantities in the ridge based on large number of experimentally studied ridges. Høyland has made research on the ridge consolidation in various seas like the Gulf of Bothnia[13] and the north-western Barents Sea around Svalbard.[14] He characterized experimentally the geometry and morphology of ridges. He also published measured and collected earlier measurements of uniaxial compression tests on ice from first-year ice ridges. Heinonen[15] published experiments of ridge mechanical properties in the Gulf of Bothnia carried out in 1999–2003. During these measurement campaigns, several ridges were first characterized (geometry and porosity) and thereafter loaded by punch shear tests.

Strub-Klein and Sudom[9] made a comprehensive review about the morphology of first-year sea ice ridges in many ice-infested waters like the Bering and Chukchi Seas, Beaufort Sea, Svalbard waters, Barents Sea, Russian Arctic Ocean, East Coasts of Canada, Baltic Sea, Sea of Azov, Caspian Sea and Offshore Sakhalin. In addition to determine typical geometrical quantities, like the sail height and keel depth, they observed that

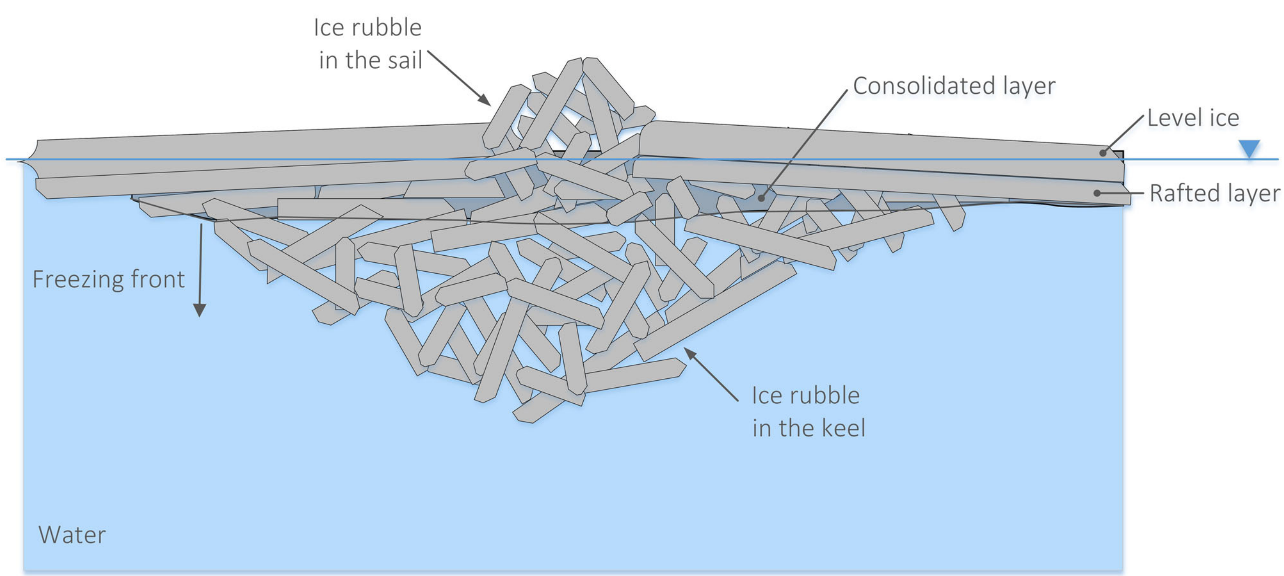

FIGURE 2 Schematic illustration of the cross section of a ridge. During the consolidation the water between the blocks freezes to form a solid refrozen layer with the initial ice rubble. The freezing front progresses downwards [Colour figure can be viewed at wileyonlinelibrary.com]

ridge cross-sectional geometry varies greatly along the length of a ridge within in a short distance and the sail heights for individual ridges variate more than the keel depths. They also collected ice block thicknesses in the rubble from various seas and showed the majority of the blocks being 0.2–0.3 m thick.

Bonath et al.[16] studied ridge morphology and internal structure in the sea around Svalbard. One of their main conclusions was that the ridge cross-sectional areas including the sail, the keel and the consolidated layer are often poorly determined. They also highlighted that the macroporosity in the ridge keel varies significantly along the depth. Salganik[17] studied ridge consolidation in different scales and characterized the freezing process of deformed ice. He compared numerical models with laboratory and full-scale tests of ridge consolidation and observed overestimation of the consolidated layer thickness from the measured temperatures both in small- and large-scale experiments. Recently, Girjatowicz and Łabuz[18] reported various forms of piled ice observed at the southern coast of the Baltic Sea. Their study focused on the characterization of deformed ice features in shallow water close to German and Polish shore, where piled ice features, like ridges, are often bottom-grounded.

For the ice load design purposes c.f. ISO 19906, the sail height and keel depth are usually defined with maximum values. Due to the complicated internal structure of ice rubble and challenges to determine the boundary of the consolidated layer, the definition of individual ridge geometry is not unambiguous. The consolidated layer is in high interest because it creates major load components during the ridge-structure interaction. Due to natural irregularities in the consolidated layer, observed thickness variations are often significant.[9,14] When the thickness of the consolidated layer in a ridge is determined by a single value, one must understand that to be a representative value.

In this paper, the ways to estimate ice conditions for an offshore wind turbine design in the Southern Baltic Sea are presented. Because no direct measurements of ice thickness and ice ridges exists from the site, the expected ice thickness and ice ridge geometries must be determined based on temperature histories and other observations. As a case study, ice conditions for the Kriegers Flak wind farm are estimated including the maximum level ice thickness occurring once in 50 years and the existence of ice ridges. These ice parameters are important in estimating ultimate ice loads against offshore structures.[8]

The use of historical ice occurrences are studied based on the Danish ice and navigation year books,[19,20] available atlases and reports[21–23] and ice charts.[24] The past temperature and weather measurements from nearby weather stations are also utilized to be able to estimate the actual ice thickness. The effect of the record length, the utilized weather station and the use of snow thicknesses to the ice thickness estimates are compared.

First, in this paper, we present the utilized methods, sources and data. Then, we present the results and ice conditions for the Kriegers Flak site. Then at the end, we discuss the findings and conclude.

2 | METHODS

The ice conditions are determined by combining knowledge from various sources. Ice services have been producing ice charts for the navigational purposes. These charts are exploited together with temperature histories, ice atlases, ice and navigation reports and other available information. In this chapter, the calculation method for the thermal growth of ice, the utilized extreme value method, utilized temperature and snow thickness histories, utilized ice charts and reports, the process to determine extreme level ice thickness and the ridge geometry and consolidation are explained.

2.1 | Thermal growth of ice

Based on a thermal growth mechanism, an estimate of the maximum level ice thickness h can be calculated from the Stefan's ice growth rule

$$\frac{dh}{dt}=\frac{a(T_f-T_s)}{h}, \tag{1}$$

where is $a=\frac{k_i}{\rho L_f}$ (where $k_i=2.2$ W/mK is the thermal conductivity of ice, $\rho=917\,\mathrm{kg/m^3}$ is the density of ice, and $L_f=333.4$ kJ/kg is latent heat of freezing), T_s is the temperature of the top surface of ice, and T_f is the freezing temperature.[25] Water in the Southern Baltic is brackish and thus the freezing temperature is lower than 0°C. In this study, the freezing temperature for the area is taken as -0.4°C.[21]

The assumptions for Equation (1) are as follows: (i) Thermal inertia is ignored, (ii) penetration of solar radiation into the ice is ignored, (iii) there is no heat flux from water to ice, and (iv) the surface temperature is a known function of time $T_s=T_s(t)$.[25] Here, it is assumed that the surface temperature of ice equals temperature of air $T_s=T_a$. When using the thermal growth mechanism of ice, it is assumed that there is no upwelling of warm water or that ice is not drifting away from the area or from the other areas. The assumptions behind this method mean that the values have to be taken as an upper limit for the thermal growth of ice.

The solution for Equation (1) is

$$h = \sqrt{h_1^2 + 2aS_F}, \tag{2}$$

where h_1 is the initial ice thickness and S_F is cumulative freezing degree-days (CFDD) defined by

$$S_F = \int_0^t (T_f - T_s)dt, \tag{3}$$

where $T_s < T_f$. When integrating over the time when ice is present, the estimate for the maximum level ice thickness can be determined by temperature data. Melting was not taken into account since the air temperature stayed below the freezing temperature after the freezing started until the maximum level ice thickness was reached.

Equation (1) is presented in similar form in the ISO 19906 standard,[26] but the coefficient a is given in a form of $\omega\frac{k}{\rho L_f}$, where ω is an empirical coefficient varying between 0.2 and 1 depending on the local conditions. In this study, a value $\omega = 1$ is taken according to Equation (1) since in the ISO standard, the value of ω should be based on the local measurements that do not exists from the site. In the ISO 19906 standard,[26] it is stated that the starting date of calculating the CFDD has to be some way decided. In this study, this is done by reviewing simultaneously existing ice charts, reports and temperature histories.

For this analysis, the effect of snow thickness is shown as an example and estimated from the nearby onshore weather station since no direct observations from the site are available, and thus no better estimate on the thickness of snow on the ice cover can be made. This is done by inserting heat conduction through snow into Equation (1)

$$\frac{dh}{dt} = \frac{T_f - T_s}{\rho_i L_f \left(\frac{h}{k_i} + \frac{h_s}{k_s}\right)}, \tag{4}$$

where h_s is thickness of snow cover and k_s is thermal conductivity of snow. More detailed derivation can be found from Leppäranta,[25] and here, it is used with similar assumptions as Equation (1). Most importantly, it is assumed that the surface temperature equals the air temperature. The thermal conductivity of snow varies over time and is dependent for example on the density of snow. Leppäranta[25] estimates that the thermal conductivity of snow is roughly tenth of the thermal conductivity of ice. Thus, a constant value $k_s = 0.2$ W/mK is adopted here. In this study, it is assumed that the snow thickness on top of the ice at the Kriegers Flak site is small enough not to cause any snow ice formation. This assumption is reasonable given the modest thickness of snow cover measured at the Arkona station. On average, the snow thickness is less than 2 cm and mostly less than 10 cm new snow after the formation of ice.

2.2 | Extreme value analysis method

The level ice thickness exceeded once in 50 years is calculated by an extreme value analysis method which is suitable for small sample sizes.[27] First, the annual maximum values of level ice thickness x_m are sorted from the smallest to the largest as $x_1 \le \ldots \le x_m \le \ldots \le x_N$, where m is the rank and N is the number of years in the data series. The probability P_m of each observation was used as plotting positions

$$P_m = \frac{m}{N+1}. \tag{5}$$

The return period R of the observation in years is

$$R_m = \frac{1}{1 - P_m} \tag{6}$$

Then, the generalized extreme value distribution (GEV-distribution) function is fitted through a weighted minimum least squares method in the direction of the ice thickness. Thereby, the fitted function is the inverse of the distribution function, i.e.,

$$x = \mu + \frac{\sigma}{\gamma}\left[-1 - (\ln P)^{-\gamma}\right], \tag{7}$$

where μ, σ and γ are parameters of the distribution and P is the non-exceedance probability. The calculation method weights the observations according to their theoretical variance σ_m^2 as

$$w_m = \frac{1}{\sigma_m^2}, \tag{8}$$

and normalized as

$$\sum_{m=k}^{N} w_m = 1, \tag{9}$$

where k is the index of the first non-zero ice thickness. The years with the maximum ice thickness of 0 cm have been left out from the analysis by setting their weight to zero.

The method is iterative so that the calculation is repeated with new weights determined from the variance σ_m^2 achieved in each iteration loop. This procedure is repeated as long as the variance does not change any more between the iteration rounds. This method has been shown to be more effective compared to other methods especially when the number of observations is low. For more details of the method and complete set of equations, see Makkonen and Tikanmäki.[27] This method has also earlier been used to estimate the 50-year maximum ice thickness.[5]

2.3 | Temperature histories

The applied air temperature histories are from four different measurement stations: Arkona, Møn Lighthouse, Hammer Odde Lighthouse, and Sandvig. The measurement station Arkona is located at the Northern part of the German island of Rügen. The data are from Deutscher Wetterdienst.[28] Møn Lighthouse is located at the Danish island of Møn. This station is closest to the site of Kriegers Flak, and thus it would have been the best source of the temperature histories. Unfortunately, it only started to measure temperature from 1977 onwards. The Møn data are from Danish Meteorological Institute.[29] The Hammer Odde Lighthouse and Sandvig are located at the Northern part of the Danish Bornholm Island. Their data are combined together, and it is called the Bornholm data in this report. The Bornholm data were available as daily maximum and minimum temperatures instead of daily mean temperature.[30] Thus, the daily mean temperature was estimated to be a mean of the daily maximum and minimum temperature. Detailed information of the weather stations and applied weather data are presented in Table 1. The places of the weather stations can be found from Figure 1.

2.4 | Ice condition reports and ice charts

In the climatological ice atlas for the western and southern Baltic Sea,[21] climatological ice conditions are summarized. In the atlas, they also show ice charts for the winters 1962/63, 1986/87 and 2010/11. These winters are classified in the atlas as extremely strong, very strong and moderate.

Lundqvist and Omstedt[22] report ice conditions in the southern and western waters of Sweden in years 1936–1986. They give short description of each of the winters and show an ice chart from the date of the maximum ice extent in each winter. This report is utilized when estimating the ice conditions for those winters.

TABLE 1 Location and elevation of the weather stations and the applied variables

Station	Location	Coordinates	Elevation (mMSL)	Applied measurement period	Measured variables
Arkona (DWD station 183)	Rügen, Germany	54.6792°N, 13.4343°E	42	1947–2016	Daily mean temperature, snow depth
Møn Lighthouse (DMI station 06179)	Møn, Denmark	54.9500°N, 12.5333°E	14	1979–1996	Daily mean temperature
Hammer Odde lighthouse (DMI station 6193)	Bornholm, Denmark	55.2997°N, 14.7749°E	11	1984–2015	Daily minimum and maximum temperature
Hammer Odde lighthouse (DMI station 32020)	Bornholm, Denmark	55.2997°N, 14.7749°E	11	1971–1987	Daily minimum and maximum temperature
Sandvig (DMI station 32030)	Bornholm, Denmark	55.2901°N, 14.7817°E (1953–1966) 55.2893°N, 14.7770°E (1966–1972)	13 (1906–1966)12 (1966–1970)	1906–1970	Daily minimum and maximum temperature

Danish authorities have been producing annual reports of ice conditions and winter navigation over one hundred years.[19,20] In these reports, the amount of data and how the data are presented varies. Mainly, they report verbally the course of the winter and coastal observations as tables. For some years, ice charts are also presented. The coastal observations do not present the ice conditions at the site, but they are valuable in estimating the differences between each winter. Also, it can be estimated that if coastal ice has been absent the whole winter, then it is probable that there has not been ice at the site either. The Danish ice reports from the winters 1934, 1944, 1945 and 1946 were not available.

For some years and dates, the ice charts from the Finnish Ice Service where also available for that area.[24] These charts were utilized when possible.

The information available in the ice charts from different sources and years varied. In general, one can find the existence of ice at the site on the given day from the charts. In addition, there are notions about ice thickness and type if known. Areas of ridged and rafted ice are also marked. However, especially from the early years, the information is limited, and possibly only the spatial distribution of ice is shown with scarce resolution. During the 20th century, the ice surveillance methods have been improved, and charts from the late 20th century include much more precise information of ice conditions compared to those from the early 20th century.

2.5 | Process to estimate extreme level ice thickness

The process to estimate the maximum level ice thickness goes as follows:

1. Investigation of existing reports and charts. The following are studied for each year: existence of ice at the site, freezing date, ice break-up date, ice thickness and type, existence of deformed ice types and any other relevant information related to annual ice conditions.
2. Simulation of ice thickness based on the temperature histories using freezing and break-up dates from the Step 1.
3. Comparison of simulated ice thicknesses to the ice thicknesses found from the charts in each date in Step 1. This step is only for verification purposes.
4. Generalized extreme value distribution is fitted to the annual maxima and 50-year value is defined.

2.6 | Ridge geometry

To determine ridge loads on the wind turbine substructure, one needs to know the geometry of the ridge. For the structural design, the main geometrical parameters are the keel depth, sail height, keel width, keel shape and possibly ice block thickness. However, the simplified load models, i.e., from ISO 19906,[26] usually consider only the keel depth and the thickness of the consolidated layer. The sail is usually ignored in the load calculations, because its load contribution is relatively small.

Therefore, a design ridge for the site is defined based on ISO 19906[26] and experimental studies in the northern part of the Gulf of Bothnia.[11,15] An idealized first-year ridge based on ISO 19906 is shown in Figure 3.

According to Kankaanpää[11] in the Baltic Sea, the main dimensions of the ridge can be estimated based on the level ice thickness h_i as

$$H_s = 2.8\sqrt{h_i}, \tag{10}$$

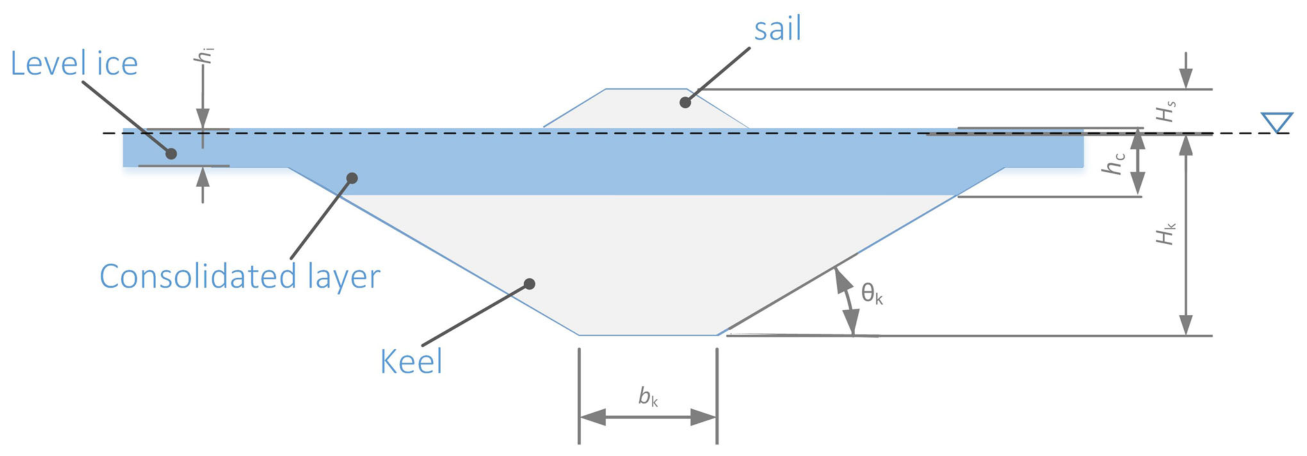

FIGURE 3 Idealized geometry of a first-year ridge. Schematic drawing redrawn based on the ISO 19906.[26] h_i is the level ice thickness H_s is the sail height, H_k is the keel depth, h_c is the thickness of the consolidated layer, b_k is the width of the keel bottom and θ_k is the keel angle [Colour figure can be viewed at wileyonlinelibrary.com]

$$H_k = 6.35H_s - 0.02\,\mathrm{m},$$

where H_s in the height of sail and H_k the depth of keel, both of them measured from the water level (Figure 3). For the comparison, similar empirically determined correlation between the level ice thickness and the ridge keel was found by Amundrud et al.[31] Based on their observations of seasonal pack ice in the Beaufort Sea during the1990s, they found out that the keel thickness $H_k = 20\sqrt{h_i}$. By combining the two expression in Equation (8), we find $H_k = 17.8\sqrt{h_i}$.

2.7 | Consolidation

A major contribution of the ridge load on a structure comes from the consolidated part. Therefore, it is important to predict the thickness of the consolidated layer as accurate as possible. Since there do not exist any experimental full-scale measurements from the site or near the site in the southern Baltic Sea, one needs to rely only on theoretical models. Firstly, we need to estimate the initial conditions: from which situation the ridge starts to re-freeze. Secondly, we need an estimate of the CFDD to calculate how the thickness of the consolidated layer increases corresponding to the selected recurrence period. 50-year value of CFDD (S_{F50}) is determined based on the temperature data and the extreme value analysis method as described above. This value is then reduced by the initial state of CFDD (S_{F0}) corresponding the initial ice thickness when the ridge was formed. The analysis is based on situation without snow on the ice.

$$S_{FR} = S_{F\,50} - S_{F0}, \tag{11}$$

where S_{FR} is the value of CFDD consolidating the ridge and calculated based on the temperature measurements in Arkona and Bornholm.

When a ridge consolidates, only part of the rubble volume changes phase. The freezing process takes place in the cavities between the ice blocks, as visualized in Figure 2. Because there is less water to be frozen, the rubble thickens faster than corresponding level ice. Equation (2) needs to be modified to include the porosity of the rubble (η) as described by Høyland and Løset[32]; see Equation (12). Additional empirical coefficient (ω) is introduced to modify the thermal conductivity of ice, because Stefan's law ignores snow, oceanic heat flux, solar radiation and thermal inertia. In addition, the sail gives extra thermal insulation to the ridge compared to level ice, which delays the consolidation.

$$h = \sqrt{h_1^2 + \omega \frac{2k}{\eta \rho L_f} S_F}. \tag{12}$$

For the Gulf of Bothnia, Høyland and Liferov[33] evaluated ω equal to 0.9. The porosity is 31%.[11]

3 | RESULTS

The ice conditions in the southern Baltic Sea are summarized in the Climatological Ice Atlas.[21] According the atlas, the site of Kriegers Flak has had ice cover in 11%–20% of the winters between 1961 and 2010 and the maximum ice thickness of 30–50 cm. However, when designing, a wind farm more detailed information is needed. Values from the atlas are taken as a reference for this study.

Based on the utilized sources,[21,22] ice occurring at the Kriegers Flak area is so-called drift ice. It means that ice is moving against the structures and the existence of ice ridges needs to be investigated. Rafted ice is not studied since it is assumed that the ice ridge causes higher ultimate loads against the structures.

Based on the ice charts,[24] reports[19,20,22] and the ice atlases,[21,23] ice does not form regularly in the Southern Baltic Sea, and year-to-year changes in ice conditions are large. Hence, sufficiently long data series need to be taken into account in order to catch the statistical variability. Nevertheless, the climate is changing and reducing the extent and thickness of ice in the Baltic Sea.[6,7] Also, recent ice charts are more reliable than the older ones because of the development of surveillance methods (e.g., satellite imaging).[34] This means that taking into account too long time periods does not give relevant information about the present ice conditions. Using very long data series would be advantageous if a structure that needs to withstand loads even in the most extreme occasions is designed, but for other structures, it leads to overestimated and expensive designs. Thus, choosing a proper time period for the analysis is essential. In this study, the effect of the time period is studied.

In the past 113 years (1907–2019), ice has been present at the site of Kriegers Flak in the first months of the years, 1996, 1987, 1986, 1985, 1979, 1970, 1966, 1963, 1956, 1954, 1947, 1942, 1941, 1940, 1929, 1924, 1922 and 1909 (18 years in total) based on the available information.[19,20,22,24] Based on this, the frequency of ice existence is 16%, which is consistent with the value given in the ice atlas.[21] In some of the years 1906–1937, there was no ice charts and existence of ice at the site needed to be estimated based on the cumulative freezing degree-days and reported navigational conditions and ice observations close to the shore.

3.1 | Year-to-year changes in ice conditions

The cumulative freezing degree-days for the period from 1906–1907 to 2014–2015 are presented in Appendix A. They are calculated from the Arkona, Bornholm and Møn data by Equation (3) for the whole winter. The results are shown only for the years where the temperature data were available. The amount of missing measurement days is shown in parenthesis. The years with ice are shaded in blue. As can be seen, there are only two missing measurement days in the Bornholm data from the winters with ice. These days did not occur at the same time with ice, and thus do not affect the ice thickness estimates but might reduce the CFDD by a couple of degree-days. The temperature histories from Arkona and Møn did not have any missing measurement days.

The CFDDs from the Bornholm data are shown in Figure 4. It can be seen that ice was present at the site only when CFDD was over 100 degree-days calculated from the Bornholm data. In some years, CFDD was over 100 degree-days, but the existence of ice was not probable based on the other available information. In general, it was noted that the higher the calculated CFDD value the more severe ice conditions were reported also in the other sources.

The Danish ice reports from the winters 1934, 1944, 1945 and 1946 were not available. According to the CFDDs reported in Appendix A and Figure 4, these were relatively mild winters, and thus it is assumed that no ice existed at the site.

The maximum ice thickness was simulated with Equation (2) for the years when ice was found to be present at the site. These values are presented in Table 2. The maximum thickness was calculated from temperature histories from three different nearby weather stations. The one closest to site, Møn Lighthouse, was used for calculations for years 1979–1996, Arkona for 1947–1996, and Bornholm for all of the years 1909–1996. The estimated dates of freezing and disappearance of ice at the site were estimated based on the available reports, ice charts and temperature histories and are presented in Appendix B together with a short description of the most serious ice conditions of each winter based on the ice charts and reports. The maximum ice thickness values from the annual Danish ice condition reports were given as a certain number until 1979 and as an interval for 1985 onwards. If these values were not available for the station of Møn Lighthouse, closest possible values were listed.

The effect of snow was illustrated by calculating the thickness of thermally grown ice by Equation (4) using the snow thickness measurements from the Arkona station. These daily values were used for the Kriegers Flak since no direct measurements from the site are available. Only snowfall after the formation of ice was taken into account. It was noted that the estimated ice thickness under snow cover was highly dependent on the chosen thermal conductivity of snow as well as the thickness of the snow cover.

Winters 1940, 1942 and 1947 were severe ice winters. In Appendix B, the measured maximum values from the shore are presented from the available locations close to the shore. Some of the measured values are around 90–100 cm in these severe ice winters. These values can present thermally grown thickness of landfast ice at a sheltered coastal area for such a severe winter but are unrealistically large values for the drifting ice at the site. Even at the Bothnian Bay at the northern part of the Baltic Sea, the average annual maximum thickness of drift ice was less than 60 cm in 1994 and 1996–2011.[4] Close to the drifting ice area at the Marjaniemi in Hailuoto island, the cumulative freezing degree-days in 1999–

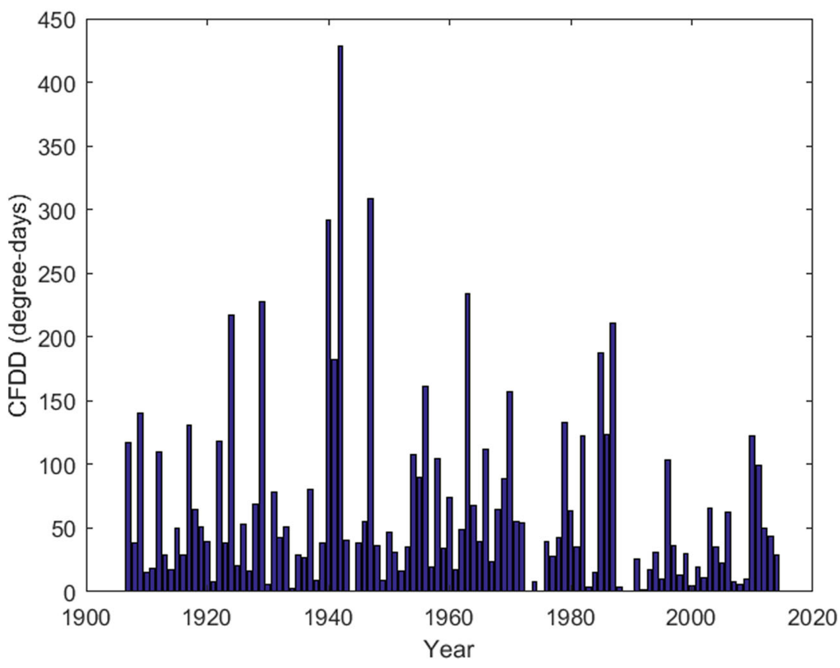

FIGURE 4 Cumulative freezing degree-days from the Bornholm data [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 The estimated annual maximum level ice thicknesses from the Kriegers Flak site. The values are calculated with and without taking snow cover into account

	Maximum ice thickness (m)					
	Arkona		Bornholm		Møn	
Year	Without snow	With snow	Without snow	With snow	Without snow	With snow
1996	0.14	0.08	0.12	0.06	0.15	0.10
1987	0.27	0.21	0.30	0.24	0.26	0.20
1986	0.23	0.23	0.20	0.20	0.22	0.22
1985	0.31	0.28	0.31	0.28	0.29	0.26
1979	0.29	0.23	0.24	0.19	0.26	0.20
1970	0.23	0.23	0.23	0.23	-	-
1966	0.13	0.13	0.13	0.13	-	-
1963	0.38	0.32	0.34	0.28	-	-
1956	0.25	-	0.25	-	-	-
1954	0.16	-	0.14	-	-	-
1947	0.50	-	0.50	-	-	-
1942	-	-	0.53	-	-	-
1941	-	-	0.26	-	-	-
1940	-	-	0.36	-	-	-
1929	-	-	0.32	-	-	-
1924	-	-	0.29	-	-	-
1922	-	-	0.17	-	-	-
1909	-	-	0.13	-	-	-

2004 was 730–1290 degree-days[35] which is 2–3 times more than the largest CFDD values calculated from the Bornholm data. This means that the thicknesses of drift ice even in the most severe ice winters of 1940, 1942 and 1947 must have been lower.

3.2 | 50-year ice thickness

In Figure 5, the result of the extreme value analysis of the thermally grown ice thickness from the Arkona station from years 1963–2019 is shown. The dots show the annual maxima and the line corresponds to maximum level ice thickness estimate with snow. Similar analysis was carried out by varying the time period, the place of the temperature history and the existence of snow on the ice. The maximum ice thicknesses occurring once in 50 years for each analysis are shown in Table 3.

Taking snow into account reduces the estimate of the 50-year ice thickness 0.02–0.07 m. Also, the effect of the use of temperature histories from different weather stations has an effect up to 0.04 m. Use of the more recent data leads mostly to smaller estimates than using longer periods with older data. The smallest estimate without snow is 0.28 m estimated from temperature histories from 1979–2019 from Møn Lighthouse. The largest estimate is 0.44 m achieved from temperature histories from 1907–2019 from Bornholm. The difference is 0.16 m, which demonstrates the challenge of choosing proper time period. The effect of individual severe ice winter is demonstrated by calculating the estimates for both 1963–2019 and 1964–2019. The winter 1962/63 was a severe ice winter and thus the 50-year ice thickness estimates 0.01–0.06 m larger if that winter is taken into calculations.

3.3 | Ice ridges

The possibility of ice ridges occurring in the Kriegers Flak site has been analysed based on the available sources[19–22,24] describing the ice conditions at the Southern Baltic Sea. During the study period, ice ridges and rafted ice have been observed close to the Kriegers Flak site. In addition, Climatological ice atlas,[23] based on ice charts from 1963 to 1979, indicate occurrence of several ice ridges in the week around 21st of February in

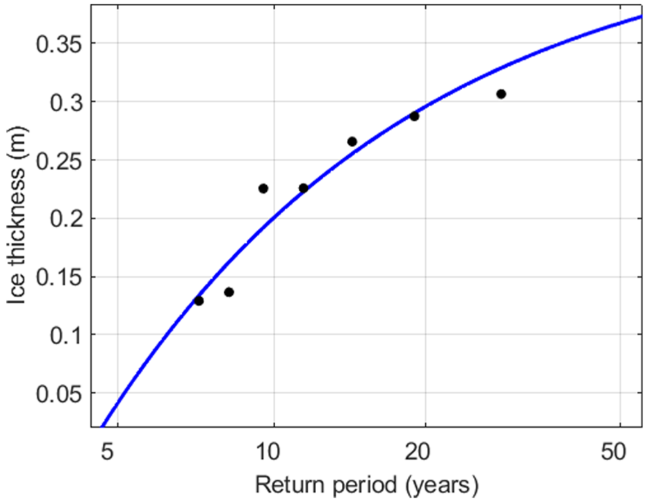

FIGURE 5 Return period of the maximum ice thickness in the site of Kriegers Flak based on the thermal growth of ice without snow cover. The growth is calculated from the temperature history measured from the Arkona station, and the covered time period is years 1963–2019 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 The maximum ice thickness occurring once in 50 years estimated on time periods 1979–2019, 1964–2019, 1963–2019, 1947–2019, and 1907–2019 using temperature measurements from different weather stations

	Møn		Arkona		Bornholm	
	Without snow	With snow	Without snow	With snow	Without snow	With snow
1979–2019	0.28	0.26	0.31	0.28	0.32	0.28
1964–2019	-	-	0.31	0.26	0.31	0.26
1963–2019	-	-	0.37	0.31	0.34	0.27
1947–2019	-	-	0.43	-	0.42	-
1907–2019	-	-	-	-	0.44	-

Note. The maximum ice thickness estimates with snow are indicative since no direct snow thickness measurements from the site exists.

winters with sea ice, with a probability of 10% on the condition that ice occurs. However, it has to be noted that ice ridges and their existence have not been extensively studied at the study area.

Ice ridges were mentioned a couple of times in the Danish annual ice reports. Also, the ice charts have symbols for ice ridges. At the beginning of the 20th century, the ice charts of the Danish ice reports did not include these symbols. All the found mentions of the occurrences of ice ridges, and their references are listed in the last column in Appendix B.

As a summary, there was 18 years with ice during the period of 113 years. Out of these 18 years, there were:

- Two years, 1942 and 1947, where ice ridges were marked on the site at the ice charts.
- Eight years, where there were ice ridges near the study area.
- Six years, where we could not find any notion of ice ridges near the study area from the ice charts or reports.
- Two years, 1909 and 1924, where we did not have enough information about the ice conditions.

Ice ridges tend to form close to the shore where drifting ice presses against the thicker landfast ice. If the wind turns so that these ice ridges start to move, it is possible that they drift towards the Kriegers Flak site. It has to be noted that if the ice season in the site is short, as it is when the estimated maximum level ice thickness is less than about 0.25 m, ice ridges do not have time to fully consolidate and thus they do not cause as large loads against the structure as they do in more severe ice winters. Based on this investigation, it can be concluded that the encounter of ice ridges is not a frequent event. But since ice is drifting in, and near, the area the possibility of ridges drifting to the site needs to be considered. Based on these historical ice ridge occurrences, ice ridges are important to be taken into account in ultimate load design in 50-year return period.

3.4 | Design ridge geometry

Several studies conclude that ridges in the Gulf of Bothnia are formed from sheets of parent ice when the level ice thickness is around 0.2 m.[10,11,15] For thinner ice—under 0.1–0.15 m—the ice sheets do not normally form ridges, but the ice sheets may raft.[11]

Regarding the level ice thickness of 0.2 m, the sail height and keel depth are determined by Equation (8) resulting in 1.3 and 7.9 m, respectively. Even though keel depths exceeding 10 m are not unusual in the Northern Baltic Sea, this prediction is well in-line with local observations. There is no evidence to consider larger floating ridges in the southern Baltic Sea. For the comparison, the range of keel depths in the Danish Belts according to ISO 19906 is 5–15 m.

3.5 | Ridge consolidation

As described earlier, the ridge usually forms from sheets of parent ice when the level ice thickness was 0.20 m. This situation was taken as an initial state in the analysis of the ridge consolidation, when calculating the 50-year value of CFDD by Equation (3).

Table 4 shows CFDD's for different time periods in similar ways as in Table 3 with corresponding thicknesses of the consolidated layer. However, because of low number of ice winters with more than 0.2 m thick ice during 1979–2019, the ridge consolidation analysis is not accurate enough, and the values are not presented.

Three different ridge consolidation scenarios were analysed by varying the initial state after ridge formation:

1. After the ridge formation, rubble starts to freeze at the water level. There exists neither level ice nor rafted layers. The thickness of the consolidated layer is initially zero, i.e., $h_1 = 0.0$ m.
2. The rubble starts to consolidate from the situation that one layer of level ice is already at the water level, i.e., $h_1 = 0.2$ m.
3. The rubble starts to consolidate from the situation that two layers of level ice are located at the water level due to previous rafting processes, i.e., $h_1 = 0.4$ m.

Based on the analysis of CFDD in Arkona and Bornholm, the thickness of the consolidated layer for the above-described scenarios was calculated and summarized in Table 4.

Scenarios 1–3 are based on Stefan's model with some adjustments for the ridges as described above. In harsher sea areas, like more north in the Baltic Sea, rafting commonly takes place during the ridge building process and rafted layers are often found inside the ridge. Due to lack of experimental observations of the internal structure of ridges in the Southern Baltic Sea, we suggest these scenarios to represent a realistic range for the thickness of the consolidated layer.

4 | DISCUSSION

The estimated annual maximum level ice thicknesses in Table 2 are mostly in line with the maximum ice thicknesses found from the ice charts and other sources (presented in Appendix B). It has to be noted, that the maximum thickness values given from the observation stations close to the shore are larger than those from the site of Kriegers Flak since the ice forms earlier close to the shore and has thus more time to thicken. This is natural behaviour of sea ice. The maximum level ice thickness estimates for year 1979 are larger than observed values of the year. However, reducing the ice thickness estimate from the year 1979 to the observed value of 0.2 m does not have an effect on to the 50-year level ice thickness value. The estimated 50-year level ice thicknesses presented in Table 3 are in line with the maximum level ice thickness values given in the Climatological Ice Atlas for the western and southern Baltic Sea (1961–2010).[21]

TABLE 4 50-year CFDD and corresponding thickness of the consolidated layer based on various scenarios and temperature histories from Arkona and Bornholm

	Arkona				Bornholm			
	CFDD	Scenario 1	Scenario 2	Scenario 3	CFDD	Scenario 1	Scenario 2	Scenario 3
1964–2019	50	0.43	0.47	0.58	51	0.43	0.47	0.59
1963–2019	79	0.54	0.57	0.67	64	0.48	0.52	0.63
1947–2019	112	0.64	0.67	0.75	107	0.63	0.66	0.74
1907–2019	-	-	-	-	119	0.66	0.69	0.77

The weather station Møn Lighthouse is located closest to the site of Kriegers Flak, and for this reason, using its temperature history could have been the best choice. Unfortunately, its temperature history was available only from 1979 onwards. Between 1979 and 2019, there has been only five winters of ice at the site of Kriegers Flak. This means that this time period might be too short for making statistically valid analysis of the maximum ice thickness occurring once in 50 years at the site. However, these values are presented to show the effect of the time period and effect of the weather station.

All of the three weather stations are located onshore since no direct temperature measurements are available from the site from the years with ice. Temperature at the shore tends to be lower than that on the open sea leading to larger ice thicknesses than using direct measurements from the site. Bornholm is located close to the Bornholm Basin which freezes less frequently than the Arkona basin where Kriegers Flak is located. When ice has been present at the Kriegers Flak but not in the Bornholm Basin the heat flux from the open water close by the stations at Bornholm Island might have increased the air temperature there compared to the air temperature at Kriegers Flak. This might cause underestimation of the simulated ice thicknesses when using air temperatures from Bornholm.

However, the use of Stefan's ice growth rule as given in Equations (1–3) leads to estimates that can be considered as upper limits for the ice thicknesses. Also, neglecting the snow on top of ice leads to conservative estimates. Thus, it can be stated that values given in this study present rather an upper limits of level ice thickness.

However, the use of the Stefan's law is justified in this study by comparing the simulated ice thickness values to the ones found from the charts. As these values match well to each other, it is believed that the simplified model of ice thickness growth adopted here is reasonable even though there are several simplifying assumptions made. If one compares the 50-year maximum level ice thicknesses achieved by the presented study to the equation in IEC standard[8] for the Northern Europe

$$h = 0.032\sqrt{0.9 \times CFDD - 50},$$

we get 0.04–0.13 m less in 50-year value. This is due to the fact that IEC equation does not take into account the local conditions such as distance to shore and water depth affecting to ice formation, but it is same for all the locations. Thus, the use of the IEC equation leads to overestimation of design ice thickness compared to the present analysis.

The maximum level ice thickness was estimated using a model of thermal growth of ice. Snow cover on ice would insulate the ice from cold air and thus limit its growth. The effect of snow was illustrated based on the measurements from the coast since no direct observations from the site are available. At the site, the thickness of snow might differ from that of onshore because of the different place, wind-driven drift of snow, and that only snow which has fallen after formation of the ice cover has an effect to the ice thickness. However, the effect of snow was illustrated by calculating the ice growth with snow thickness measured at the Arkona station taking into account only snowfall after the ice has formed at the site of Kriegers Flak. In this analysis, the maximum level ice thickness was reduced by 0.02–0.07 m. However, it was noted that the estimated ice thickness under snow cover was highly dependent on the chosen thermal conductivity of snow as well as the thickness of the snow cover. Thus, it has to be noted that since no direct measurements of either snow thickness or its thermal conductivity from the site are available, the presented values are indicative only.

The estimated level ice thickness occurring once in 50 years is based on the assumption that ice is thermally grown. This means that no mechanical growth such as rafting is taken into account. Also, the effects of shipping channels are neglected. On one hand, they make the ice conditions less severe by breaking the ice. But on the other hand, due to brash ice accumulation, the edge of the channels might get thicker compared to the thermally grown level ice. However, brash ice or rafted ice interaction with a structure is not as severe as the ridge interaction, because the ridge is a much larger ice feature and the ultimate ridge loads are higher compared to brash ice or rafted ice loads. For this reason, it is believed that possible interactions with brash ice or rafted ice can be neglected when loads caused by the presented design ridge are taken into account.

Based on the past ice charts, ice ridges have represented a relevant load scenario for the wind farm. However, the frequency of ice ridge interactions is hard to estimate. From the past ice charts, it can be seen that ice ridges are marked on the site only in severe ice winters in 1942 and 1947. In other less severe ice winters, ice ridges are formed on the more coastal regions where landfast ice and drift ice are interacting. The possible ridge interaction at Kriegers Flak would demand the formed ice ridges to drift to the site due to change in the wind direction. Since ice ridges are not frequently marked on the ice charts and the ice conditions in the Baltic Sea has gotten milder during the past 100 years, it was concluded that ridge-structure interactions are infrequent. Because there is no information about the ridge geometries in the Southern Baltic, one needs to apply available information from the northern part of the Baltic Sea.

Only some occasional observations of ridges in the Southern Baltic Sea have been reported. Even though keel depths of more than 10 m are not unusual in the Northern Baltic Sea, such large ridges are not expected in the Southern Baltic Sea. Therefore, the typical ridge geometry described by Kankaanpää[11] for the Northern Baltic Sea was considered as a design ridge for the Kriegers Flak site. Also, the thickness of the consolidated layer is not well known. Our estimate was based on various scenarios based on the thermal ice growth model (Stefan's model) with some adjustments for the ridges. Three scenarios described different initial state of the ridge before it starts to refreeze. This resulted in a reasonable region for the thickness of the consolidated layer depending if the rafting during the ridge building takes place or not. Rafting with two layers was suggested to describe probable upper bound. Respectively, refreezing without initial rafted layers describes the lower bound. Reasonable region for the thickness of the consolidated layer was determined to be between 0.43 and 0.67 m corresponding to the 50-year return period. One may determine the ratio R by comparing the consolidated layer thickness with the level ice thickness being between 1.4 and 1.9, which is well in line for other observations, e.g., Høyland and Løset,[32] Høyland.[13]

Climate change will affect the ice conditions of the Baltic Sea. In this paper, we have made estimations based on the historical ice occurrences, and climate change has not been taken into account. Haapala et al.[7] reviewed the current understanding of the effects climate change has had to the sea ice conditions of the Baltic Sea. They state that, although all parameters related to sea ice have large interannual variability, a change towards milder winters has been observed over the past 100 years. They also state that occurrence of severe ice winters has decreased over the past 25 years. Their notion is supported by our results of 50-year ice thickness shown in Table 3 having also a decreasing trend when only more recent years are taken into account in calculations. Their notions also mean that using of long data series might lead overestimation of ice thicknesses and ice ridge existence.

The trend to milder winters has been seen also in future climate models. Luomaranta et al.[6] estimated changes in ice conditions of the Baltic Sea under different climate change scenarios in the future. They found out that the differences between separate scenarios were large, but all studied scenarios indicated that both the thickness of ice and the maximum ice extent in the Baltic Sea will have a decreasing trend in this century.

Modelling of the future climate is an active research question. After the effect of climate change on ice conditions of the Baltic Sea will be known more in detail, the estimates of ice conditions used in the offshore wind turbine design can also be estimated based on the present and future climate rather than the historical ice observations.

5 | CONCLUSIONS AND SUMMARY

In this study, the method of estimating ice conditions for offshore wind farm design was shown. As a case study, the maximum level ice thickness occurring once in 50 years and a design ice ridge at the site of Kriegers Flak were estimated. No direct measurements of ice from the site existed, and thus available ice chart information, ice reports and atlas together with air temperature data were utilized in estimation of the ice conditions. The estimation was based on the historical ice occurrences and air temperatures, and thus the effect of climate change is not taken into account.

The 50-year ice thickness was estimated to be between 0.26 and 0.44 m depending on the used assumptions. The use of temperature histories from different nearby weather stations had an effect up to 0.04 m to the 50-year value. Taking into account the snow thickness on top of the ice sheet decreased the 50-year value by 0.02–0.07 m. The effect of the snow cover has to be taken as indicative since no direct measurements from the site exists. The largest effect to the estimate of the 50-year value had the time period used. Since Haapala et al.[7] have stated that there has been a trend towards milder ice winters in the Baltic Sea over past 100 years and Luomaranta et al.[6] are expecting that to continue, it is estimated that taking into account the extremely severe ice winters in the 1940's might lead too conservative ice condition parameters in the design of offshore wind farms. But it has to be noted, that enough long data series are needed for catching the large interannual variability of ice conditions in the Baltic Sea. Based on these reasons, the range from 0.31 to 0.37 m is suggested to be reasonable. This range of maximum level ice thickness is achieved when time periods of 1963–2019 and 1964–2019 are used.

As ice ridges have been observed at and near the Kriegers Flak site and because the ice ridges drift due to the wind and sea current, interaction with ice ridges represent a relevant, but infrequent, load scenario for the wind farm. Therefore, a representative design ridge with the sail height of 1.3 m and the keel depth of 7.9 m was defined based on earlier measurements in the Baltic Sea. The consolidated layer at the waterline was determined based on the Stefan's model with some adjustments for the ridges and the 50-year return period of the CFDDs. For the CFDD, only the period after assumed ridge formation was considered. Based on scenario analyses, a reasonable range between 0.43 and 0.67 m for the thickness of the consolidated layer was found. Relying mostly to the time periods of 1964–2019 and 1963–2019, similarly as motivated earlier for the level ice thickness, the thickness of the consolidated layer varies between 0.43 and 0.67 m corresponding to the 50-year return period. Almost the same values were analysed in both location: Arkona and Bornholm. By considering the time periods 1947–2019 and 1907–2019, maximum thickness of the consolidated layer is respectively 0.75 and 0.77 m.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors

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APPENDIX A

TABLE A1 Cumulative freezing degree-days from the Bornholm, Arkona and Møn data

	CFDD		CFDD			CFDD		
Year	Bornholm	Year	Arkona	Bornholm	Year	Arkona	Bornholm	Møn
1907	117	1943		40	1979	227	133	183
1908	38	1944		0	1980	117	64	
1909	140	1945		39	1981	59	35	
1910	15	1946		55	1982	163	123	
1911	18 (19)	1947		309	1983	9	4	
1912	110	1948	50	36 (8)	1984	41	15 (1)	
1913	29	1949	29	9	1985	247	187	222
1914	17	1950	66	46	1986	167	123	162
1915	50	1951	65	31	1987	253	211 (1)	225
1916	29	1952	32	16	1988	11	3	
1917	131	1953	57	35	1989	10	0 (1)	
1918	65	1954	159	108	1990	7	1 (1)	
1919	51	1955	113	90	1991	43	26	
1920	40	1956	198	161	1992	22	2 (3)	
1921	8	1957	28	20	1993	47	18	
1922	118	1958	112	105	1994	62	31	
1923	38	1959	48	34	1995	28	10	
1924	218	1960	99	74	1996	205	104 (1)	166
1925	21	1961	31	17	1997	91	37 (7)	
1926	53	1962	99	49	1998	26	13	
1927	17	1963	320	234	1999	80	30	
1928	69	1964	102	67	2000	16	5	
1929	228	1965	55	39	2001	39	19	
1930	6	1966	137	112	2002	28	11	
1931	79	1967	25	24	2003	100	65	
1932	42	1968	81	64	2004	56	35	
1933	51	1969	157	89	2005	33	23 (2)	
1934	2	1970	266	157	2006	105	63	
1935	29	1971	88	56	2007	9	8	
1936	27	1972	90	54	2008	15	6	
1937	80	1973	21	1	2009	21	10	
1938	9	1974	25	8	2010	159	123	
1939	38	1975	4	1	2011	165	100	
1940	292	1976	71	39	2012	67	50	
1941	182	1977	54	28	2013		43	
1942	428	1978	63	42	2014		29	
					2015		1	

Note. The year-columns show the last year involved in the winter. For each winter, the number of missing measurement days is shown in parenthesis. The years with ice at the site are shaded in blue. The missing measurement days in the Bornholm data are mostly in years with no ice at the site.

APPENDIX B

TABLE B1 The estimated date of freezing and disappearance of ice, simulated maximum level ice thicknesses without snow, indicative maximum ice thicknesses with snow (in parenthesis), and a short description of most serious ice conditions based on the ice charts at the site of Kriegers Flak

			Maximum ice thickness (m) (indicative maximum ice thickness with snow (m))		
Year	Estimated date of freezing	Estimated date of ice disappearance	Arkona	Bornholm	Møn
1996	02/21	02/28	0.14 (0.08)	0.12 (0.06)	0.15 (0.10)
1987	01/27 and again 03/03	02/21 and again 03/25	0.27 (0.21)	0.30 (0.24)	0.26 (0.20)
1986	02/25	03/06	0.23 (0.23)	0.20 (0.20)	0.22 (0.22)
1985	02/12	12/03	0.31 (0.28)	0.31 (0.28)	0.29 (0.26)
1979	02/07	03/02	0.29 (0.23)	0.24 (0.19)	0.26 (0.20)
1970	02/11	02/20	0.23 (0.23)	0.23 (0.23)	-
1966	02/17	02/22	0.13 (0.13)	0.13 (0.13)	-
1963	02/01	03/11	0.38 (0.32)	0.34 (0.28)	-
1956	02/16	03/05	0.25	0.25	-
1954	02/22	02/25	0.16	0.14	-
1947	02/08	04/10	0.50	0.50	-
1942	02/09	04/12	-	0.53	-
1941	01/30	02/09	-	0.26	-
1940	02/09	01/03	-	0.36	-
1929	02/15	03/08	-	0.32	-
1924	02/13	03/15	-	0.29	-
1922	02/08	02/23	-	0.17	-
1909	03/04	03/10	-	0.13	-

[a]The ice thickness histogram shows 1 day with ice thickness 30–50 cm. Twenty-day ice was predominantly 15–30 cm thick with some ice thicker than 30 cm. For 13 days, there was no information, or they were unable to report a thickness value. This suggests that the maximum level ice thickness has been closer to 30 cm than 50 cm.

[b]The ice thickness histogram shows 2 days with ice thickness 30–50 cm. Twenty-six-day ice was predominantly 15–30 cm thick with some ice thicker than 30 cm. For 1 day, there was no information, or they were unable to report a thickness value. This suggests that the maximum level ice thickness has been closer to 30 cm than 50 cm.

[c]The ice thickness histogram shows 6 days with ice thickness 30–50 cm. For 18 days, there was no information or they were unable to report a thickness value. This suggests that the maximum level ice thickness has been closer to 30 cm than 50 cm.

[d]The measured ice thickness values of 90–100 cm represent most likely thermal growth of landfast ice close by the shore or deformed ice thickness. The thickness of the drift ice at the site has been smaller.

TABLE B1 (Continued)

Year	Most serious ice conditions of the winter	Ice ridges
1996	Finnish ice chart from the day of the maximum ice extent: New ice[24] Measurements from the shore[20]: No thickness measurements from Møn Fyr Waters outside Stevns fyr: 10–15 cm Rødby Havn, Waters outside Rødby, Nysted Havn, Nysted bredningen, Waters outside Rødvig: 15–30 cm Rødvig Havn: 10–15 cm	Finnish ice chart from the day of the maximum ice extent: No ice ridges[24]
1987	Finnish ice charts from the whole winter: 10–30 cm, consolidated compact or very close pack ice, concentration 9–10/10[24] German ice charts from the whole winter: 10–30 cm, compact and rafted ice[21] Ice chart from 03/13 in the Danish ice description: 15–30 cm, consolidated compact or very close pack ice[20] Measurements from the shore[20]: Møn Fyr: 30–50 cm[a]	Finnish ice charts from the whole winter: Rafted ice at the site Ice ridges at the Faxe Bay and at the Southern coast of Sweden[24]
1986	Finnish ice charts from the whole winter: 10–20 cm, close pack ice, concentration 7–9/10[24] Ice chart from the day of the maximum ice extent (02/27): 10–20 cm[22] Ice chart from 03/03 in the Danish ice description: 30 cm[20] Measurements from the shore[20]: Møn Fyr: 30–50 cm[b]	Finnish ice charts from the whole winter: Ice ridges South of the island of Møn[24] Ice chart from the day of the maximum ice extent (02/27): No ice ridges[22]
1985	Finnish ice charts from the whole winter: 10–20 cm, level ice,[24] Ice chart from the day of the maximum ice extent 02/18: 10–20 cm[22] Ice chart from 02/20 and 03/15 in the Danish ice description: ca. 30 cm[20] Measurements from the shore[20]: Møn Fyr: 30–50 cm[c]	Finnish ice charts from the whole winter: Rafted ice at the site Ice ridges at the Faxe Bay, South from island of Møn and at the Southern coast of Sweden[24] Ice chart from the day of the maximum ice extent 02/18: No ice ridges[22]
1979	Finnish ice chart from the day of the maximum ice extent: Drift ice[24] Ice chart from the day of the maximum ice extent 02/23: 5–15 cm[22] Ice chart from 02/24 in the Danish ice description: Drift ice[20] Measurements from the shore[20]: No thickness measurements from Møn Fyr Rødvig Havn: 40 cm Waters outside Rødvig: 20 cm	Finnish ice chart from the day of the maximum ice extent: Ice ridges around the island of Møn[24] Ice chart from the day of the maximum ice extent 02/23: Ice ridges around the island of Møn[22]
1970	Ice chart from the day of the maximum ice extent 02/17: New ice[22] Ice chart from 02/18 in the Danish ice description: Drift ice[20] Measurements from the shore[20]: No thickness measurements from Møn Fyr Rødvig Havn: 25 cm Nysted Havn, Nysted bredningen: 32 cm	Ice chart from the day of the maximum ice extent 02/17: Ice ridges around Møn[22]
1966	Finnish ice charts from the whole winter: 10 cm[24] Measurements from the shore[20]: No thickness measurements from Møn Fyr Nysted Havn: 14 cm Nysted bredningen: 12 cm	Ice chart from the day of the maximum ice extent 02/18: No ice ridges[22]

TABLE B1 (Continued)

Year	Most serious ice conditions of the winter	Ice ridges
1963	German ice charts from the whole winter: Compact ice field with rafted ice[21] Measurements from the shore[20]: No thickness measurements from Møn Fyr Nysted Havn: 39 cm Nysted bredningen: 37 cm Kastrup Havn: 50 cm Køge Havn: 40 cm	Ice chart from the day of the maximum ice extent 02/22: No ice ridges[22]
1956	Ice chart from the day of the maximum ice extent 02/24: Very close drift ice at the site, very close drift ice near Bornholm 10–15 cm, consolidated drift ice 15–30 cm south of Fyn[22] Ice chart from 02/17 in the Danish ice description: Close drift ice[20] Measurements from the shore[20]: No thickness measurements from Møn Fyr or Stevns Fyr Drogdens fyr, northern part of Køge Bugt: 15 cm Nysted Havn: 30 cm Nysted bredningen: 25 cm	Ice chart from the day of the maximum ice extent 02/24: Ice ridges at the Faxe Bay[22]
1954	Ice chart from the day of the maximum ice extent 02/24: Open drift ice and new ice at the site, very close drift ice 5–15 cm south of Lolland[22] Ice chart from 02/22 in the Danish ice description: New ice[20] Measurements from the shore[20]: No thickness measurements from Møn Fyr or Stevns Fyr Køge Havn: 18 cm Nysted Havn: 35 cm Nysted bredningen: 36 cm	Ice chart from the day of the maximum ice extent 02/24: No ice ridges[22]
1947	Ice chart from the day of the maximum ice extent 02/18: Consolidated drift ice 15–40 cm with ice ridges[22] Ice chart from 02/22 in the Danish ice description: Drift ice[20] Measurements from the shore[20]: No thickness measurements from Møn Fyr or Stevns Fyr Køge Havn & bugten: 100 cm[d] Drogdens fyr, northern part of Køge Bugt: 50 cm Fakse Havn & bugten: 45 cm Nysted Havn: 100 cm[d] Nysted bredningen: 90 cm[d]	Ice chart from the day of the maximum ice extent 02/18: Ice ridges atthe site[22]
1942	Ice chart from the day of the maximum ice extent 02/18: Consolidated drift ice 15–30 cm with ice ridges[22] Ice chart from 02/14 in the Danish ice description: Drift ice[20] Measurements from the shore[20]: No thickness measurements from Møn Fyr or Stevns Fyr Køge Havn: 70 cm Køge bugten: 90 cm[d] Dragør, Drogden and fairways to the South: 50 cm Nysted Havn: 55 cm Nysted bredningen: 60 cm	Ice chart from the day of the maximum ice extent 02/11: Ice ridges at the site[22]

TABLE B1 (Continued)

Year	Most serious ice conditions of the winter	Ice ridges
1941	Ice chart from the day of the maximum ice extent 02/07: Very close drift ice 10–20 cm and new ice 5–15 cm[22] Ice chart from 02/14 in the Danish ice description: Ice[20] Measurements from the shore[20]: No thickness measurements from Møn Fyr or Stevns Fyr Køge havn: 30 cm Køge bugten: 40 cm Nysted Havn: 36 cm Nysted bredningen: 39 cm Gedser-Warnemünde: 30 cm	Ice chart from the day of the maximum ice extent 02/07: Ice ridges South from Falsterbo[22] 4–9 m ice ridges on the way from Gedser to Warnemünde[20]
1940	Ice chart from the day of the maximum ice extent 02/09: Very close drift ice (no thickness value) and new ice 5–15 cm[22] Ice chart from 02/20 in the Danish ice description: Ice[20] Measurements from the shore[20]: No thickness measurements from Stevns Fyr Møn Fyr: 60 cm Køge Havn: 50 cm Køge bugten: 100 cm[d] Nysted Havn & bredningen: 60 cm Gedser-Warnemünde: 50–80 cm Gedser Havn: 34 cm	Ice chart from the day of the maximum ice extent 02/09: No ice ridges[22]
1929	Ice chart from 02/28 in the Danish ice description: Thin or heavy fast-ice[19] Measurements from the shore[19]: No thickness measurements from Møn Fyr or Stevns Fyr Drogden: 30 cm Køge havn: 80 cm Køge bugten: 90 cm[d] Faxe Ladeplads Havn: 34 cm Faxe-Bugt inderste Del: 40 cm	Grounded ice ridges at the Faxe Bay[19]
1924	Ice chart from 03/10 in the Danish ice description: Drift ice[19] Measurements from the shore[19]: No thickness measurements from Stevns Fyr Møn Fyr: 70 cm Faxe-Bugt inderste Del: 40 cm	No information[19]

TABLE B1 (Continued)

Year	Most serious ice conditions of the winter	Ice ridges
1922	Ice chart from 03/10 in the Danish ice description: Fast ice[19] Measurements from the shore[19]: No thickness measurements from Møn Fyr or Stevns Fyr Faxe-Bugt inderste Del: 50 cm Nysted bredningen: 52 cm Køge Bugt: 30 cm	4–5 m ice ridges outside Rødby, no information about ridges closer to the site[19]
1909	Measurements from the shore:19 No thickness measurements from Møn Fyr Stevns Fyr: 25 cm Faxe-Bugt inderste Del: 14 cm Nysted bredningen: 50 cm Køge Bugt: 10 cm Fairways south from Drogden: 10 cm	No information[19]

[a]The ice thickness histogram shows 1 day with ice thickness 30–50 cm. Twenty-day ice was predominantly 15–30 cm thick with some ice thicker than 30 cm. For 13 days, there was no information, or they were unable to report a thickness value. This suggests that the maximum level ice thickness has been closer to 30 cm than 50 cm.
[b]The ice thickness histogram shows 2 days with ice thickness 30–50 cm. Twenty-six-day ice was predominantly 15–30 cm thick with some ice thicker than 30 cm. For 1 day, there was no information, or they were unable to report a thickness value. This suggests that the maximum level ice thickness has been closer to 30 cm than 50 cm.
[c]The ice thickness histogram shows 6 days with ice thickness 30–50 cm. For 18 days, there was no information or they were unable to report a thickness value. This suggests that the maximum level ice thickness has been closer to 30 cm than 50 cm.
[d]The measured ice thickness values of 90–100 cm represent most likely thermal growth of landfast ice close by the shore or deformed ice thickness. The thickness of the drift ice at the site has been smaller.