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Ice Risk Analysis for Floating Wind Turbines, Offshore Newfoundland and Labrador

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Abstract

The move to reduce greenhouse gas emissions in the offshore hydrocarbons production industry has resulted in a growing interest in the possibility of using offshore wind to reduce on-platform power generation. While some offshore areas are progressing towards or planning for the use of offshore wind to electrify hydrocarbon producing platforms, they do not have the challenges associated with Newfoundland & Labrador's offshore environment.This region is prone to incursions by icebergs and pack ice, which would present a risk to offshore wind turbines. Analysis approachesto assess these risks, along with preliminary results, are presented herefor floating offshore wind turbines (FOWT).

An area of interest (AOI), covering 45°N to 51°N and 45°W to 51°W, was defined covering all development licenses on the Grand Banks, Flemish Pass and Orphan Basin. Iceberg and pack ice contact rates and loads were calculated using data from the Nalcor NESS Metocean database, Canadian Ice Service (CIS) ice charts and satellite imagery. Ice loads corresponding to 50-year return periods levels were assessed, with and without ice management, giving a basis for determining whether ice management and/or disconnection capabilities are required. The frequency and severity of atmospheric icing of turbines was also modelled using available data and models.

Introduction

Energy Research & Innovation Newfoundland & Labrador is managing and administering the offshore research, development, and demonstration (RD&D) component of Natural Resources Canada's Emissions Reduction Fund (ERF). ERF applied research and innovation projects are looking at ways to reduce greenhouse gas (GHG) emissions in Newfoundland and Labrador's offshore oil and gas industry. The Intecsea study is looking at the use of offshore floating wind-turbines to provide power to offshore oil and gas production facilities. The Governments of Canada and Newfoundland and Labrador are also supporting projects through the NL Offshore Oil and Gas Industry Recovery Assistance Fund (OGIRA), where projects provide direct and indirect employment within the province and offshore sector, generate positive environmental benefits or co-benefits, and support the existing oil and gas installations and infrastructure linked to existing installations. OGIRA funds, which the Government of NL is managing, is augmenting the offshore floating wind-turbines study.

One component of the Intecsea-led study, executed by C-CORE,is an assessment of iceberg, sea ice and icing risk to offshore wind turbines in the region. An overview of the Intecsea work is given in Paulin et al. (2022). Incremental costs associated with ice risk mitigation may influence the viability of floating offshore wind turbines (FOWT) for emissions reductions. For the ice risk analysis, the AOI (covering 45°N to 51°N and 45°W to 51°W, see Figure 1), was broken down into 72 grid cells covering 1 degree longitude and 0.5 degrees latitude. For each grid cell, iceberg, pack ice and Metocean characteristics were extracted from various sources including the Nalcor Exploration Strategy System (NESS), Canadian Ice Service (CIS) ice charts and satellite imagery. Iceberg and sea ice loads corresponding to a 50-year return period were calculated using proprietary software (ILS™, DynIIS™ and SILS™) andicing of turbines was assessed using available spray and atmospheric icing models and site-specific Metocean parameters. Five distinct floating offshore wind turbine configurations were considered: a spar, a barge, a semisubmersible and a tension-leg platform. (Figure 2). These structures were scaled to sizes appropriate for generating 8MW output, for consistency with the Intecsea study scope.

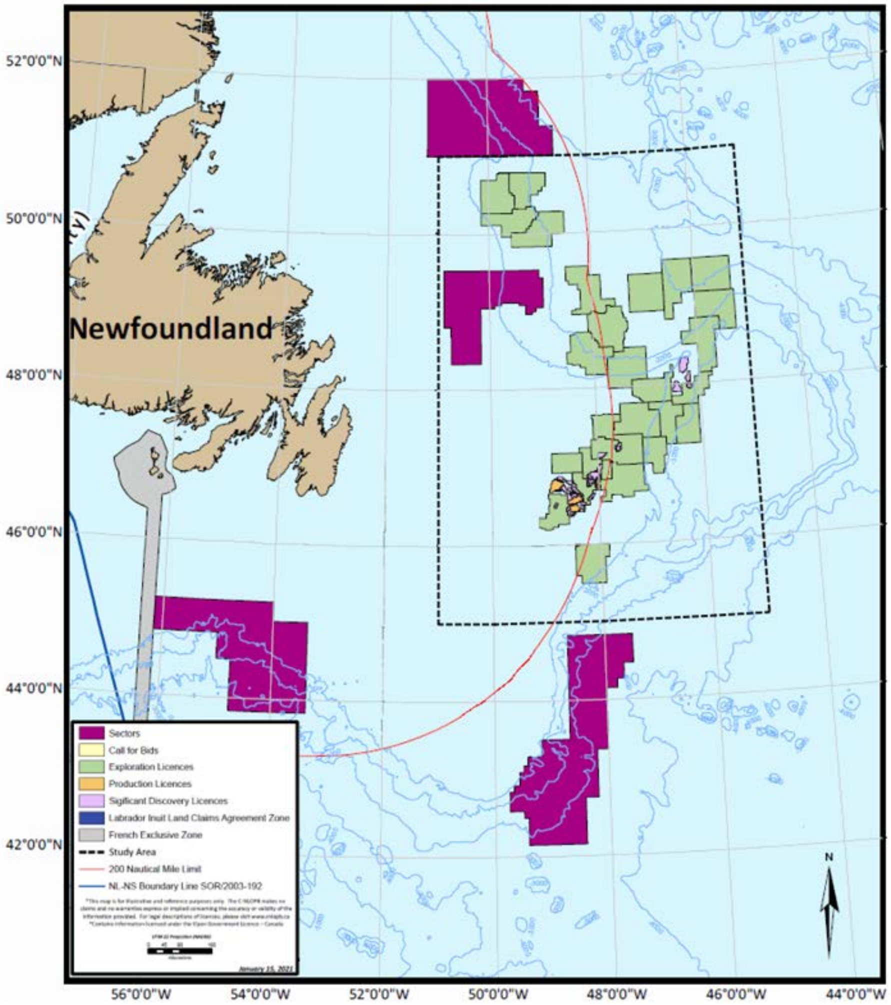


Figure 1—Study area considered for ice risk analysis (modified, from https://www.cnlopb.ca)

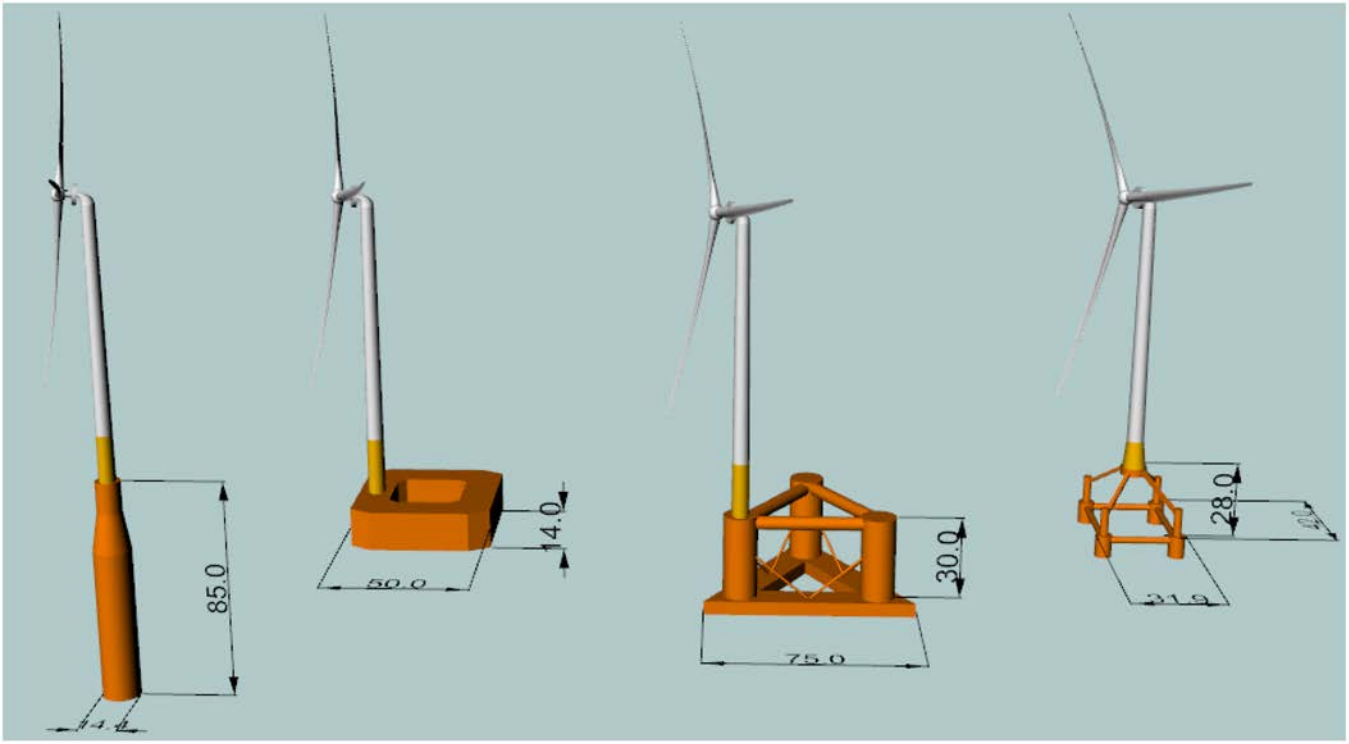


Figure 2—Floating offshore wind turbine configurations considered (left to right): spar, barge, semisubmersible, and a tension-leg platform (no moorings or cables shown)

Iceberg Loads Analysis

Probabilistic Analysis

Iceberg impact loads on the wind turbines were modelled using the Iceberg Load Software (ILS™)which was first developed during the CODIE projects at Memorial University of Newfoundland and Labrador (CODIE 1995; CODIE II 2003). Since then there have been numerous additions, updates and enhancements (Stuckey et al., 2008; 2009; 2016; 2021). The software is fully probabilistic, considering a large number of loading events based on the expected range of iceberg and environmental conditions that a structure would likely encounter as a function of its location. The algorithms employ a Monte-Carlo simulation approach to obtain global design loads. This approach was adopted since it provides an accurate representation of the iceberg loading regime, following the provisions of ISO 19906, without introducing unnecessary conservatism in the design load. An overview of the ILS™ is shown in Figure 3. The ILS™ was originally developed for use in the design of the Hebron gravity based structure (Widianto et al., 2013), but has since been used to determine iceberg design loads for a number of fixed and floating structures. The ILS™accounts for the influence of mooring compliance of floating structures, which allows part the kinetic energy of the iceberg to be dissipated by accelerating the structure and also by developing tension in the mooring lines, reducing the loads on the structure (Jordaan et al., 2014; Fuglem et al., 2020). The result of this process were curves giving the annual probability of exceedance for iceberg loads, with the y-intercept (zero load) corresponding to the iceberg contact frequency with the structure. Exceedance curves were generated for each structure type in each of the cells in the AOI, with loads interpolated for a exceedance level of 0.02 yr^{-1} (a 50-year return period), typically used for environmental loads on wind turbines (i.e. IEC, 2009). Additional details on the iceberg loads analysis for floating wind turbines may be found in Stuckey et al. (2022).Figure 4 shows the distribution of iceberg contact loads over the study area for the spar structure, with and without the influence of mooring compliance included. Mooring compliance significantly reduces iceberg impact loads. Cells with zero loads are cases where the annual iceberg interaction rate was less than 0.02 yr^{-1} (1 in 50 years).Results in Figure 4 do not include the effect of ice management, which would further reduce 50-year loads by reducing the frequency of impacts.Figure 5 shows estimated mooring loads for the spar and semi-submersible structures. The spar structure has the lowest loads primarily due to the fact it presents the smallest target to approaching icebergs, while the larger semi-submersible structure has the highest loads. Darkened cells in Figure 5 indicate where mooring loads during iceberg interaction are likely result in the structure excursion to exceed 10% of the water depth.

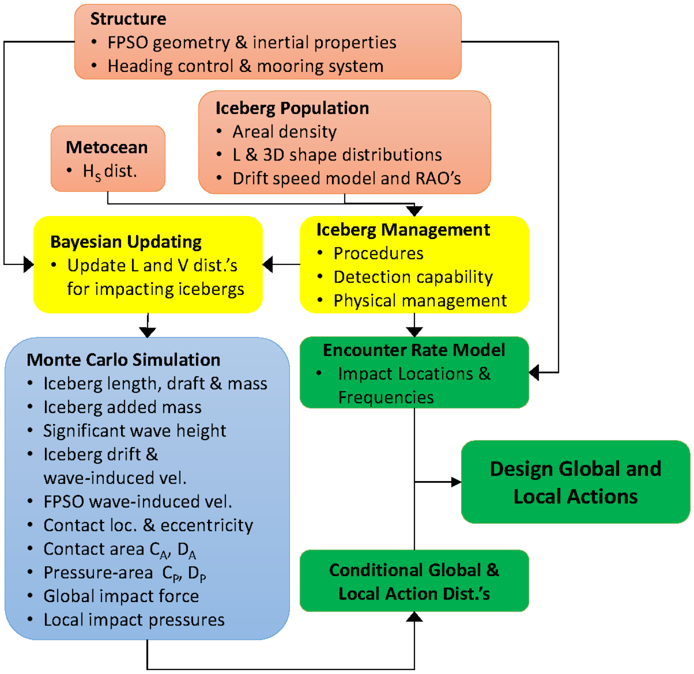


Figure 3—Schematic of the ILS™ components and models

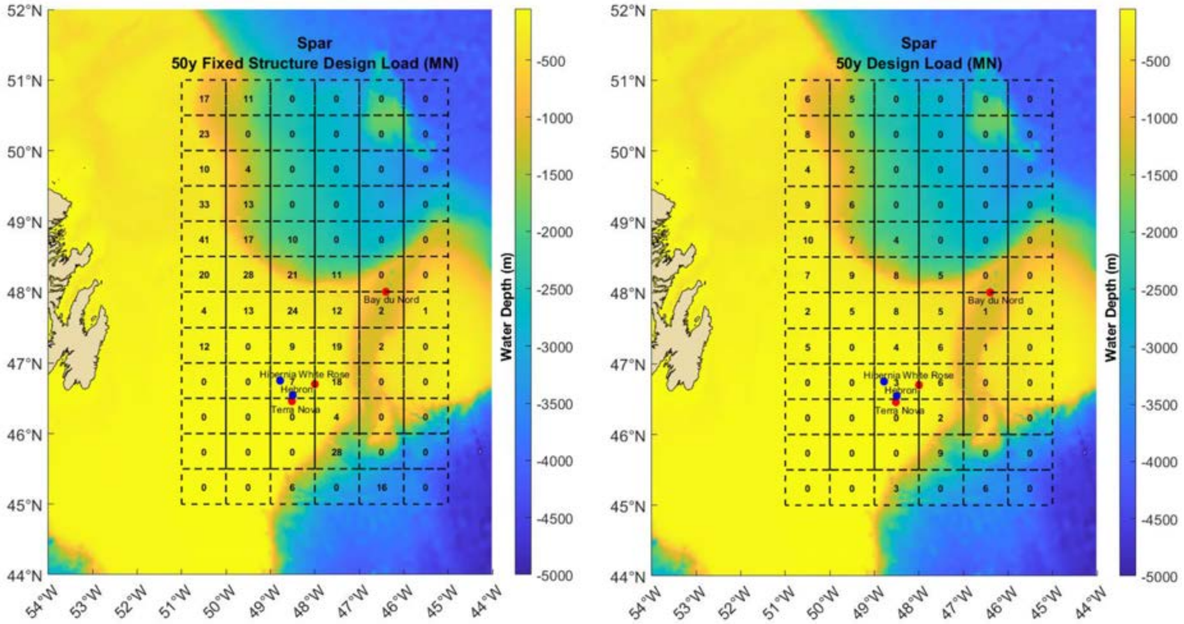


Figure 4—50-year loads on spar structure, (left) no mooring compliance and (right) mooring compliance included

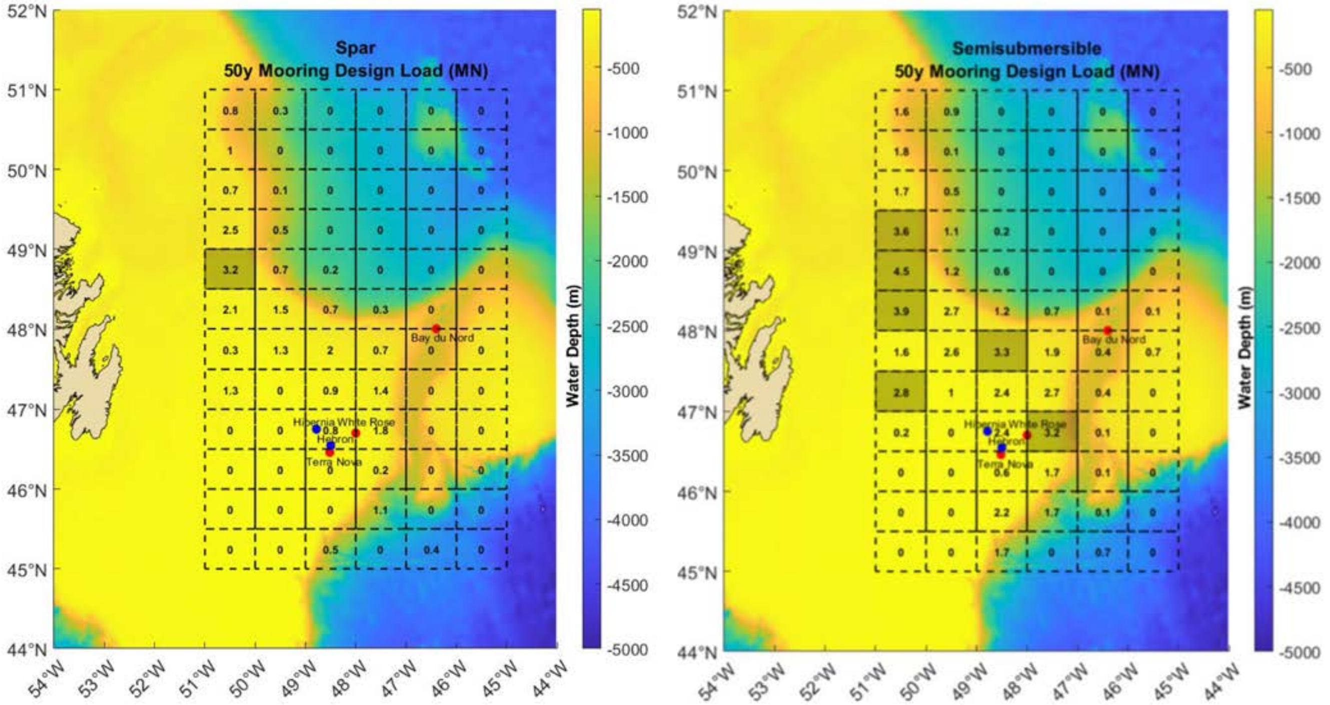


Figure 5—50-year iceberg mooring design loads on spar (left) and semi-submersible (right) structures

Dynamic Modeling

C-CORE's Dynamic Iceberg Impact Simulator (DynIIS™) software package models the full interaction of iceberg impacts with floating offshore platforms in 12 degrees of freedom (Fuglem and Younan, 2016). The model allows treatment of ice strength using pressure-area curves as outlined in ISO 19906, and considers removal of crushed ice. While the hull of the offshore structure is treated as a rigid body, the model determines hydrostatic forces on the iceberg and platform given their heave, pitch and roll. Hydrodynamic coefficients were determined using Computational Fluid Dynamics (CFD) simulations, as noted below. The model does not consider wave effects.

DynIIS™was used to estimate maximum 50-year platform roll/pitch and hub accelerations in addition to the iceberg impact loads and maximum mooring offsets determined using the ILS™ software. It should be noted that DynIIS™was used to determine the values associated solely with the iceberg impact, and does not directly include additional wave and wind gust effects (i.e. load effect combinations).Though DynIIS™ does not explicitly model wave effects, the iceberg impact velocities considered are based on estimates of full impact velocities including mean drift velocity given wind drag, current drag and wave-drift forces plus a random wave-induced surge velocity component, as determined using the ILS™ software.

An evaluation of ILS™ cases and parameters contributing to 50-year loads was conducted to determine the critical combinations of iceberg mass and impact velocity as well as ice strength and local iceberg shape.Appropriate representative iceberg shapes, based on 3D iceberg profiles collected offshore Newfoundland and Labrador (Bruce et al., 2021), were selected for the impact simulations (see Figure 6).A global ice crushing strength of 1 MPa was used. Iceberg interactions with the mooring lines were not considered in the analyses. It was observed that the impact dynamics depended significantly on the shapes and sizes of the iceberg and structure, the initial impact velocity and the positions of the structure centers of gravity (CGs) and mooring attachment points. The loads and accelerations varied significantly depending which face of the iceberg was impacted. In some cases a recommended maximum turbine hub acceleration of approximately 2 m/s^2 (Leimeister et al., 2020) was exceeded, and differences in the overall stability of the various structure types were noted. Additional documentation of the dynamic modelling of iceberg interactions with floating wind turbines can be found in Fuglem et al. (2022).

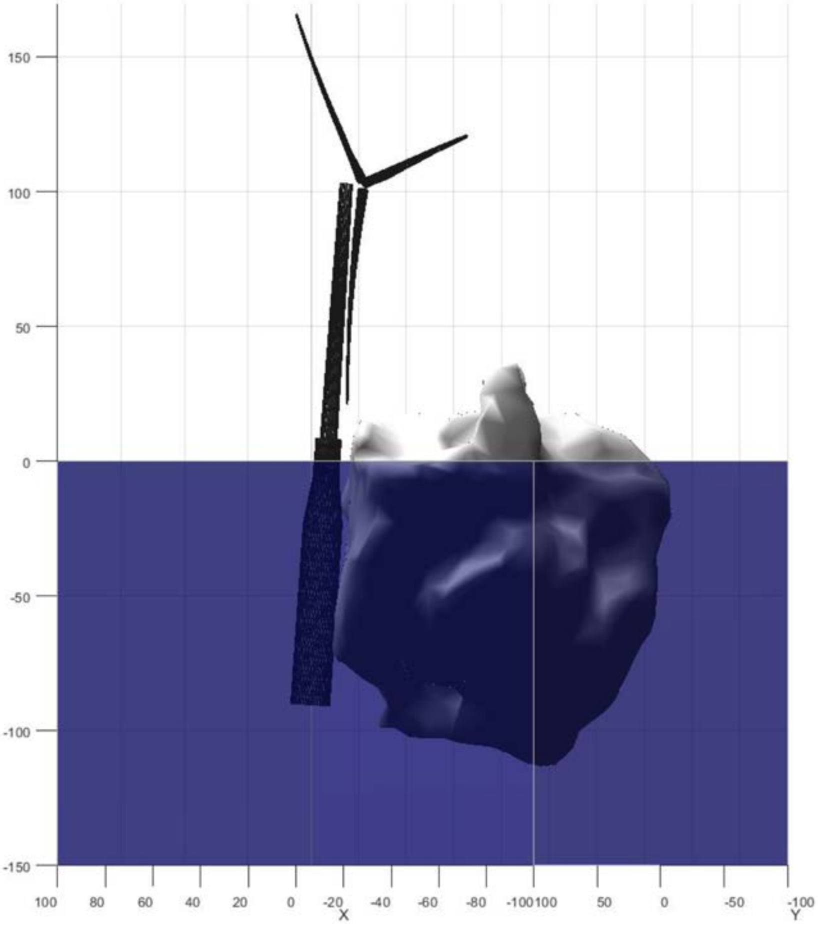


Figure 6—Iceberg interaction with spar floating wind turbine modelled using DynIIS™

CFD Modeling

A CFD model was used to study the dynamic response of floating wind turbines and icebergsto the wave, wind and current environment during the structure-iceberg collision process, and support the DynIIS™ analysis by providing hydrodynamic parameters of iceberg.Analyses were conducted using commercial CFD software (Star-CCM+). Parameters investigated for use in the DynIIS™ analysis included coefficients for hydrodynamic added mass and moment effects, translational and rotational drag coefficients and damping coefficients for heave, pitch and roll. Results of previous investigations of iceberg hydrodynamics (Talimi et al., 2016) were also incorporated. CFD modelling was also used to assess the effects of platform-induced hydrodynamics on the motions of icebergs as they approacheda platform in varying current, wind and wave conditions (Figure 7).

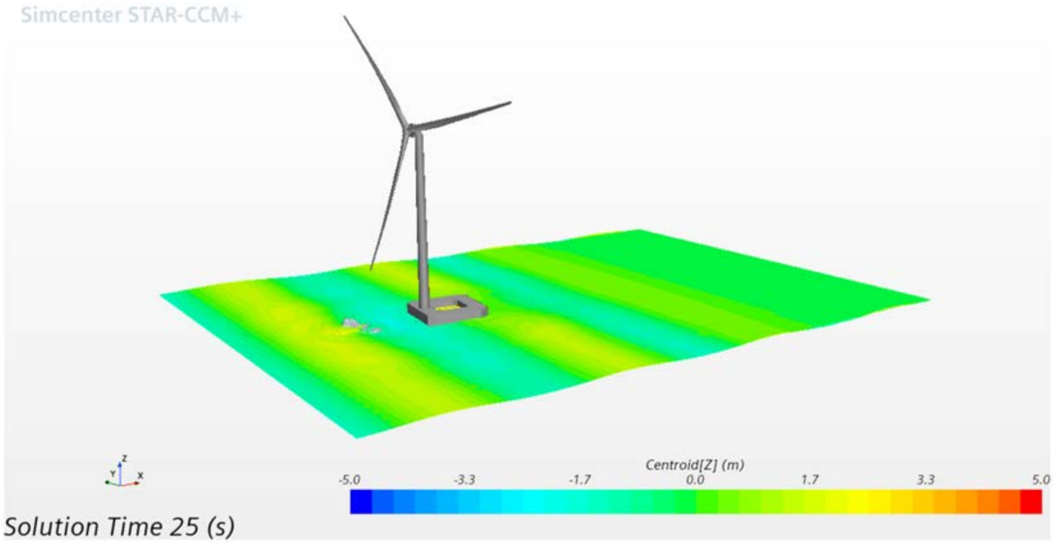


Figure 7—CFD simulation of iceberg approaching barge type floating wind turbine

Iceberg Contacts with Mooring Lines

A first-order 2D model was developed to assess iceberg interaction frequency with the floating wind turbine mooring lines as shown in Figure 8 (red lines). The probability of impacting a mooring line will depend on the mooring spread, mooring attachment points, the mooring offset due to environmental loads (which can change the relative vertical and horizontal angles of the lines), the shape and size of the iceberg, the direction of movement and offset of the iceberg, and wave-induced motions of the iceberg and platform. If the iceberg contacts a mooring line, it could potentially snap the line or pull on the platform, resulting in platform impact. Depending on the size distribution of icebergs and the position and angle of the mooring attachment points, the probability of impacting mooring lines could even be greater than the probability of impacting the platform (for example, if the mooring lines are attached near the surface).

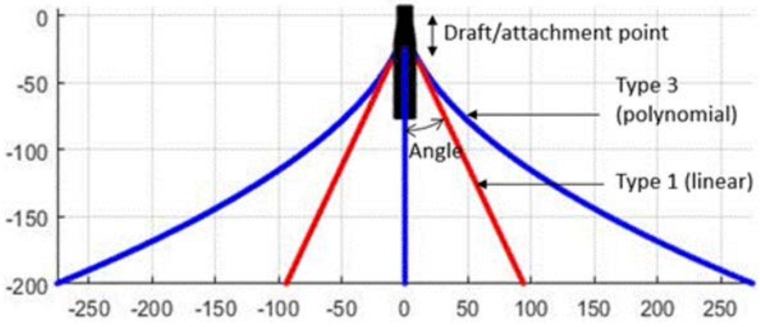


Figure 8—Scenario considered for mooring line contacts

Mooring line impact rates were assessed using actual iceberg profiles. It was observed that contact rates increased with attachment angle and decreased with attachment depth.In particular, structures with mooring lines near or on the surface (i.e. barge) had notably higher interaction rates with icebergs and pack ice than other configurations such as spar or TLP.

Sea Ice Loads

Analysis Approach

Sea ice loads were determined for 50-year return periods using approaches in ISO 19906 (2019) incorporated into the Sea Ice Loads Software Suite (SILS+™).SILS+™includes: a Monte Carlo simulator for sea ice forces (Thijssen et al., 2014, 2015a, 2016a; Fuglem 2014a, 2014b); a DEM simulator to simulate specific flexural ice failure modes and broken ice clearing (Richard and McKenna, 2013); a station keeping tool for estimating mooring loads for floaters operating in pack ice (Thijssen et al., 2018, 2019); a probabilistic tool for obtaining design ice loads (crushing) directly using the ice conditions from ice charts as inputs (Thijssen et al., 2015a, 2015b); and a probabilistic tool to account for wave companion loads to the principal sea ice load (Fuglem et al., 2018). The AOI is in a marginal ice zone where ice conditions can vary widely depending on the distance to the ice edge, wave actions breaks up ice into smaller pieces, and many other factors come into play, such as reduced wave actions in the presence of sea ice. For large floes the ice failure mode will be flexure or crushing as the floe drifts past the structure, while loads from small floes are more limited by how well they clear around the structure.

The analysis approach is illustrated in Figure 9. Using data from Canadian Ice Service (CIS) ice charts, upward-looking sonar (ULS), and satellite imagery,the appropriate 50-year design cases are determined (ice thickness, drift speed, concentration, environmental driving forces, ice strength, etc.). For small floe scenarios, an isolated floe impact is simulated, as well as floe clearing loads. The maximum load will govern the design loads. Isolated impact loads are also calculated for large floe scenarios, considering also the pack ice driving forces behind the larger floe pushing the floe further into the structure. It is possible that the driving force behind the large floe is greater than the direct interaction forces from the floe on the structure.

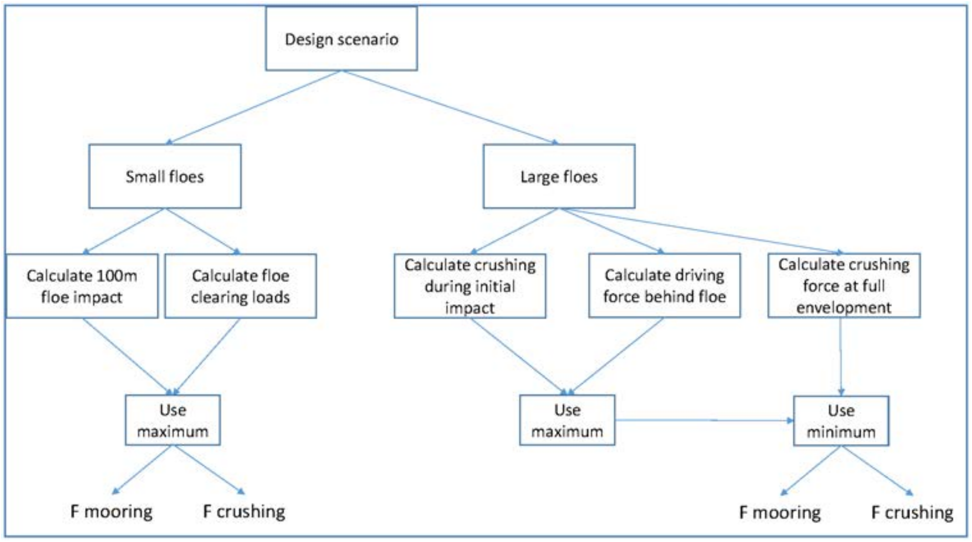


Figure 9—Procedure for assessing pack ice loads

The isolated floe impact model is based on formulations in DNV-RP-C204 Section 3.3.1, where a momentum-based approach is provided accounting for the compliance of the structure. The most important aspect in these calculations is to distinguish the mooring load from the impact load. The initial kinetic energy of the floe is dissipated partly by ice crushing and partly into the mooring. The more compliant the structure, the more energy it will absorb, and in effect the less the impact loads will be. The ratio of structure mass to floe mass may also have a major effect. While light compliant structures will benefit as they take less energy to start moving with the floe, a downside is thatthey may be susceptible to very large offsets. An offset limit of 10% of the water depth is typical. Further information on the sea ice loads analysis can be found in Thijssen et al. (2022).

Ice Chart Analysis

The Canadian Ice Service (CIS) publishes daily products where they map ice conditions derived from vessel observations, reconnaissance flights and satellite imagery. The products contain polygons with attributes encoded with SIGRID-3, a vector archive format for sea ice charts developed by World Meteorological Organization. The CIS provided access to its historical ice charts archive coveringdaily ice conditions offshore Newfoundland between 2006 and 2021. The polygons include various ice attributes, including total ice concentration and partial concentrations, stage of development and floe sizes for the various ice types detected. Figure 10 shows sample results from the analysis carried out. Pack ice presence and floe sizes are greatest in the northwest corner of the study area, with floe size increasing towards the northwest. The overall distribution of ice in the AOIis consistent with the trajectory of the Labrador Current.

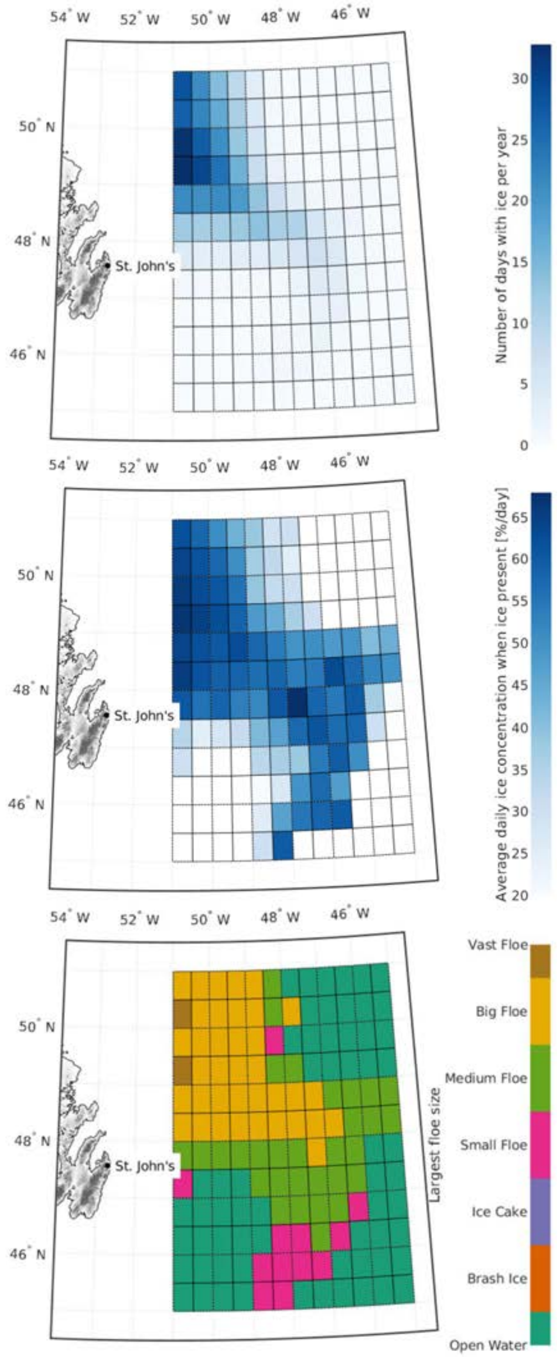


Figure 10—Sample results of CIS ice charts analysis showing (top) average number of days per year with pack ice (middle) average pack ice concentration when present, and (bottom) largest floe size

Satellite Imagery Analysis

Satellite imagery analysis was conducted over the AOI to verify the accuracy of the sea ice floe size characterization reported in the CIS charts. Satellite data through 2016-2021 were analyzed and compared with corresponding CIS sea ice charts. The digital CIS sea ice charts were compiled within the satellite frame extents, ensuring that less than a 24 hour difference occurred between images and charts. An example comparison is shown in Figure 11. The analysis was repeated for 186 cases. While the CIS charts indicated floes > 100 m within the AOI (i.e. vast floes are 2-10 km, see Figure 10, bottom) no ice floes larger than 100m were detected.

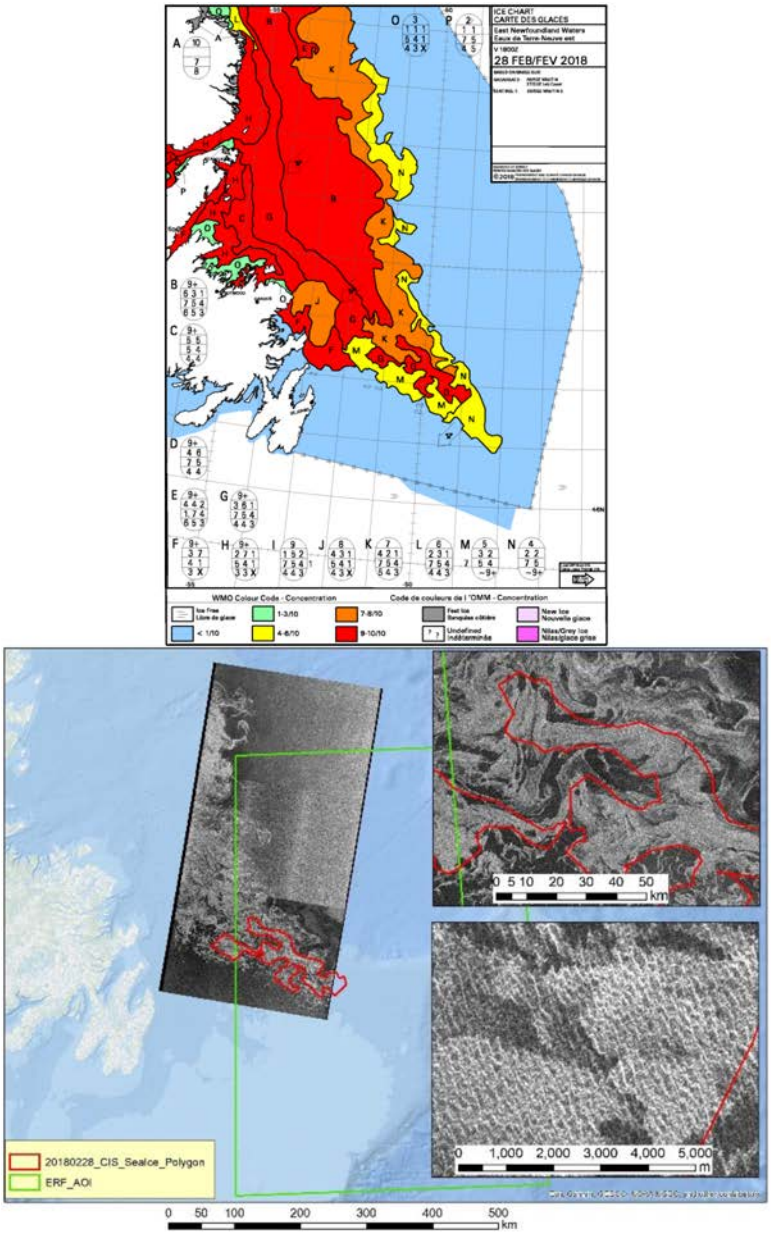


Figure 11—Ice chart (top) and satellite image (bottom) comparison - red polygon within AOI is from CIS sea ice shapefile and recorded to have a floe sizes of 100m -500m (February 28, 2018)

These results are consistent with observations by Wright (1998) of the presence of small ice floes on the Grand Banks. The inconsistency of floe sizes between CIS charts and satellite imagery analysis warrants further investigations as there are potential implications for shipping, vessel and facility design, and required ice class of vessels for operation in the region. Similar results may be seen in other regions, or this discrepancy may be more characteristic of a marginal ice zone.

Upward-Looking Sonar Analysis

Upward-looking sonar (ULS) data were analyzed for comparison with CIS chart data. ASL Environmental deployed ULS units at the three locations shown in Figure 12 for the winter of 2015-2016 on behalf of Equinor (Mudge et al., 2016). While outside the AOI, the proximity of these units make them useful indicators of ice conditions inside the AOI. Previous analysis of the data (Mudge et al., 2016) focused on ridge keel drafts and distributions.For this floating wind turbine study, level ice thickness data were analyzed for comparison with corresponding CIS charts.

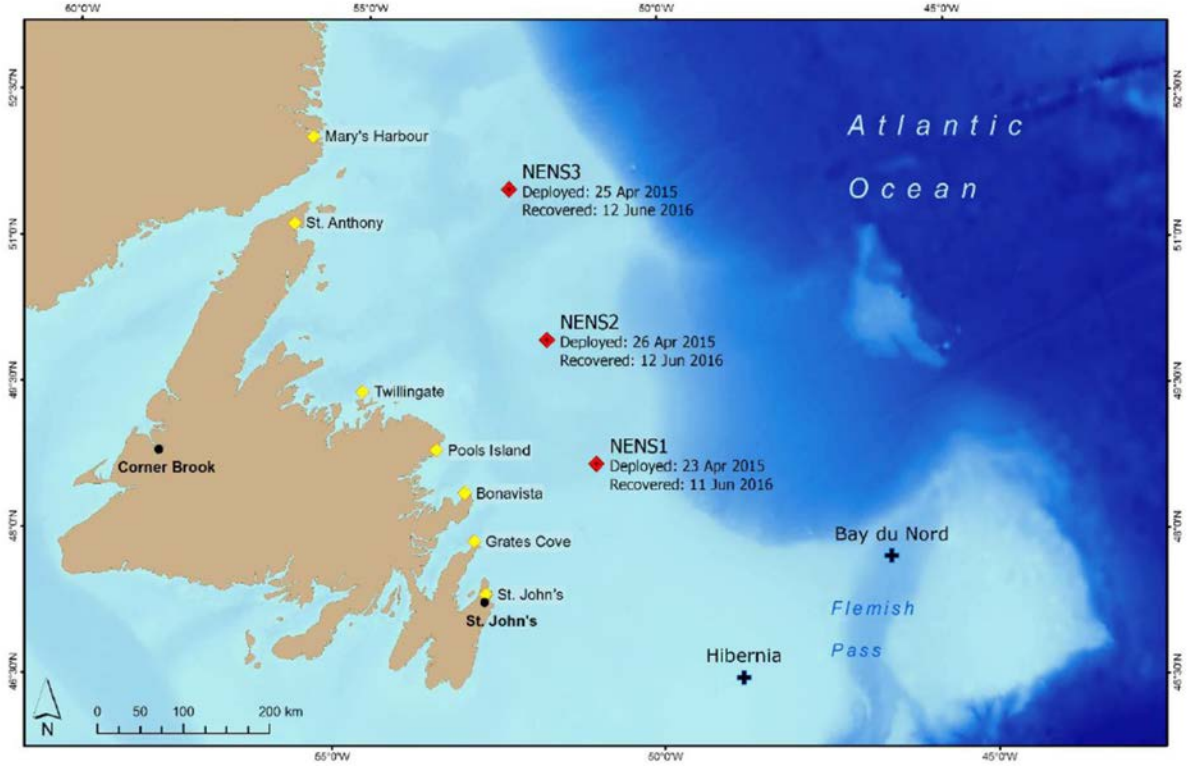
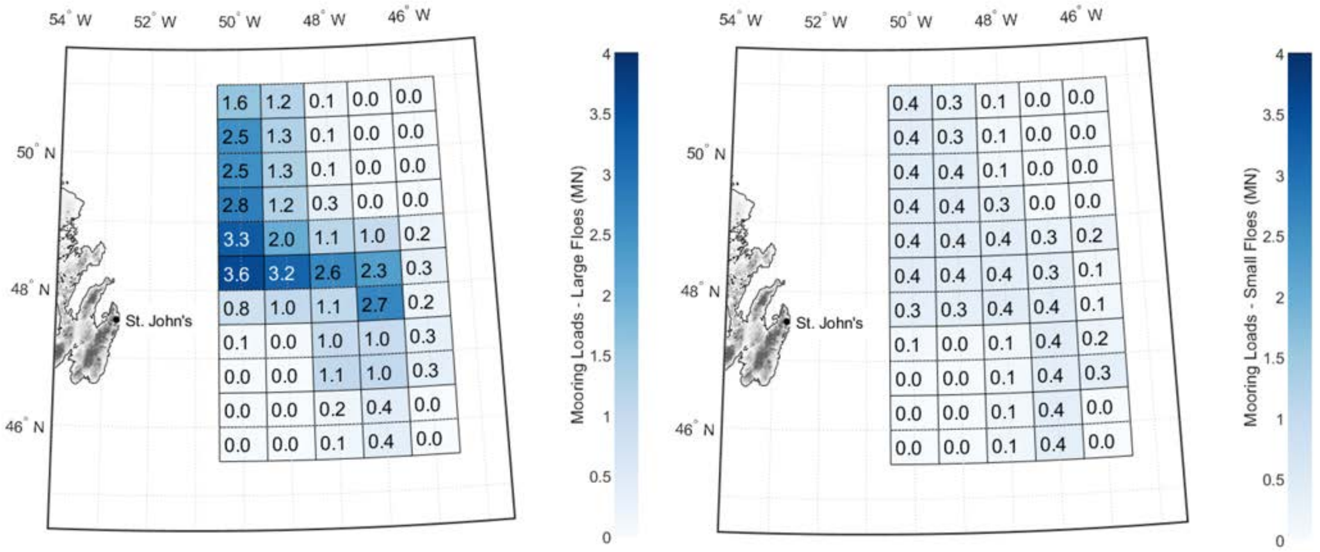


Figure 12—Positions of ULS installations 2015-2016 (Mudge et al., 2016)

Similar to the floe size comparisons, the level ice thicknesses in the CIS charts were greater than thicknesses determined from the ULS data. The majority of ice in the ULS data was broken/rubbled ice and level ice was relatively infrequent. Also similar to the satellite imagery analysis, ice concentrations determined from the ULS data were lower than CIS charts. In cases where thick level ice was detected, these ice sections were relatively limited in extent (no large thick floes). As expected, ice conditions became less severe going from the northern ULS site to the southern ULS site.

Results

For the AOI, the environmental data is inconclusive on presence of large floes at a 50 year return period. It is believed that information from CIS ice charts tend to be on the conservative side, and large floes will be very rare. Since the ice is not grown locally, and travels from far north, it is very likely to encounter wave actions that further break up the floes into smaller pieces. Continuous level ice is rare as well, as ULS shows a vast majority of sea ice to consist of rubbled and broken ice. A consolidated layer may exist within the ridge of same strength as unbroken level ice, yet thicker than the surrounding ice. Given that the ice does not grow locally, it is assumed here that only small fragments of consolidated layers will be encountered, and will not dominate the design loads. Figure 13 shows 50-year mooring loads on the spar structure using floe sizes based on the CIS charts and the satellite imagery analysis. Loads exceeding 2.7 MN are considered sufficient to cause the structure to exceed an excursion of 10% of the water depth. Clearly, floe size has a profound effect on the mooring loads.



1.6	1.2	0.1	0.0	0.0
2.5	1.3	0.1	0.0	0.0
2.5	1.3	0.1	0.0	0.0
2.8	1.2	0.3	0.0	0.0
3.3	2.0	1.1	1.0	0.2
3.6	3.2	2.6	2.3	0.3
0.8	1.0	1.1	2.7	0.2
0.1	0.0	1.0	1.0	0.3
0.0	0.0	1.1	1.0	0.3
0.0	0.0	0.2	0.4	0.0
0.0	0.0	0.1	0.4	0.0

0.4	0.3	0.1	0.0	0.0
0.4	0.3	0.1	0.0	0.0
0.4	0.4	0.1	0.0	0.0
0.4	0.4	0.3	0.0	0.0
0.4	0.4	0.4	0.3	0.2
0.4	0.4	0.4	0.3	0.1
0.3	0.3	0.4	0.4	0.1
0.1	0.0	0.1	0.4	0.2
0.0	0.0	0.1	0.4	0.3
0.0	0.0	0.1	0.4	0.0
0.0	0.0	0.1	0.4	0.0

Figure 13—50-year sea ice mooring design loads on spar using floe sizes based on CIS chart analysis (left) and satellite imagery analysis (right)

Ice Management Requirements

One of the objectives of the work described here was to determine whether ice management (i.e. iceberg detection,iceberg towing, facility disconnection, or reducing large sea ice floes to smaller fragments using an ice breaker) would be required for floating wind turbines in the AOI. Costs associated with ice management (i.e.vessel costs or increased facility cost to enable disconnection)may have significant implications regarding the economic viability of floating wind turbines.The analyses described here gives loads, but in order todetermine whether ice management should be considered to prevent structural damage is was necessary to assess the typical load capacity of the various floating wind turbine structures. Should the 50-year loads exceed the load capacity of the structures, then ice management in some form may be required. It ultimately depends on the economics associated with increased capital costs to further strengthen the structures, or increased annual operating costs for ice management support. In the opinion of the authors, the floating wind turbine concepts considered are likely to be capable of withstanding the 50-year loadsor, if not, modified to become more robust. This will depend on the results of further analysis of satellite data to verify that floe sizes are considerably smaller than previously reported in CIS charts. While this statement refers to the load capacity or hull strength of the floating wind turbines, the capacity of the mooring and anchoring systems have yet to be considered, including: mooring configuration, attachment location, pre-tension, contact rates, platform stability should a mooring be contacted, or even severed. Understanding these will help discern whether ice management risk mitigation is required.

Structure Icing

Icing on offshore wind turbines can occur due to various mechanisms such as (1) spray icing due to wind and wave-generated sea spray,(2)precipitation icing due to the accretion of freezing rain or wet snow, and (3) frost icing due to water vapor freezing directly onto the turbine blades. Frost icing was not considered a significant concern and was not considered further. Wind turbine icing can impede power generation, damage turbine blades, present hazards to personnel, and for floating offshore wind turbines may additionally create balance issues. Super-cooled sea spray can freeze on contact with the turbines, with the accumulation rate a function of the air and sea surface temperatures, wind speed, and the saltwater freezing temperature. The rate of ice accretion on turbine blades due to precipitation icing is a function of wind speed, liquid water content of the precipitation, mean droplet size, fraction of the precipitation that freezes, and efficiency with which the turbine blades collect the freezing precipitation. Icing of offshore structures is a complex topic and additional information on the icing analysis performed as part of the ERF project may be found in Turnbull et al. (2022).

Metocean data for the AOI were obtained from the European Centre for Medium Range Weather Forecasting (ECMWF) ERA5 Reanalysis datasetand the Global Ocean Physics Reanalysis dataset. Data included air temperature at 2m elevation, sea surface temperature, wind speed at 10 m elevation, sea ice concentration and precipitation occurrence for freezing rain and wet snow and sea surface salinity. Sea spray icing was assessed using an empirical prediction model developed by Overland (1990) for sea spray icing of vessels as a function of air and sea surface temperature, wind speed, and the seawater freezing temperature.It was assumed that sea spray icing only occurred when sea ice concentrations were below 15% (Jones and Andreas, 2013). The output of the Overland (1990) equation is an icing predictor value which corresponds to a range of icing rates (light <0.7 cm/hr; moderate = 0.7-2 cm/hr, heavy = 1-4 cm/hr and extreme > 4 cm/hr). The analysis indicated limited potential for heavy or extreme spray icing conditions. Figure 14 (left) shows the occurrence of light to moderate icing conditions in the AOI during the winter months and Figure 14 (right) shows the average duration of icing events with icing rates light or greater. Spray icing potential and duration were both greatest in the northeast corner of the AOI.

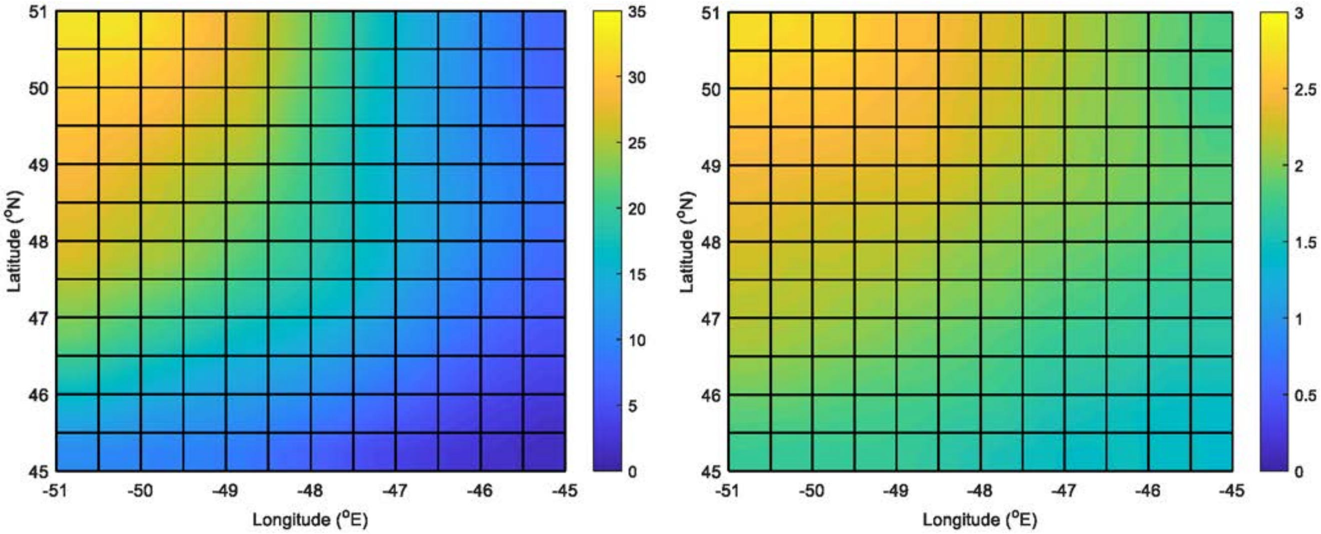


Figure 14—Percentage of days during winter (Dec.-Feb.) with light to moderate sea spray icing potential (left) and average duration of spray icing events in days (right)

Precipitation icing due to freezing rain or wet snow was calculated using the collection efficiency of the turbine blade, the liquid water content of the precipitation, the freezing fraction of rime ice and the density of the freshwater precipitation ice freezing onto the turbine blade from super-cooled water droplet (Laforte and Allaire, 1992). The analysis showed that precipitation icing was most frequent during the winter months (25-40% of days), but limited to light (≤0.7 cm/hr) accumulation rates (see Figure 15, left), reducing to 25-30% of days in the spring (March-May), and limited precipitation icing in the fall. Figure 15 (right) shows the average duration of precipitation icing events, generally about one day but closer to two days in the northeastern corner.

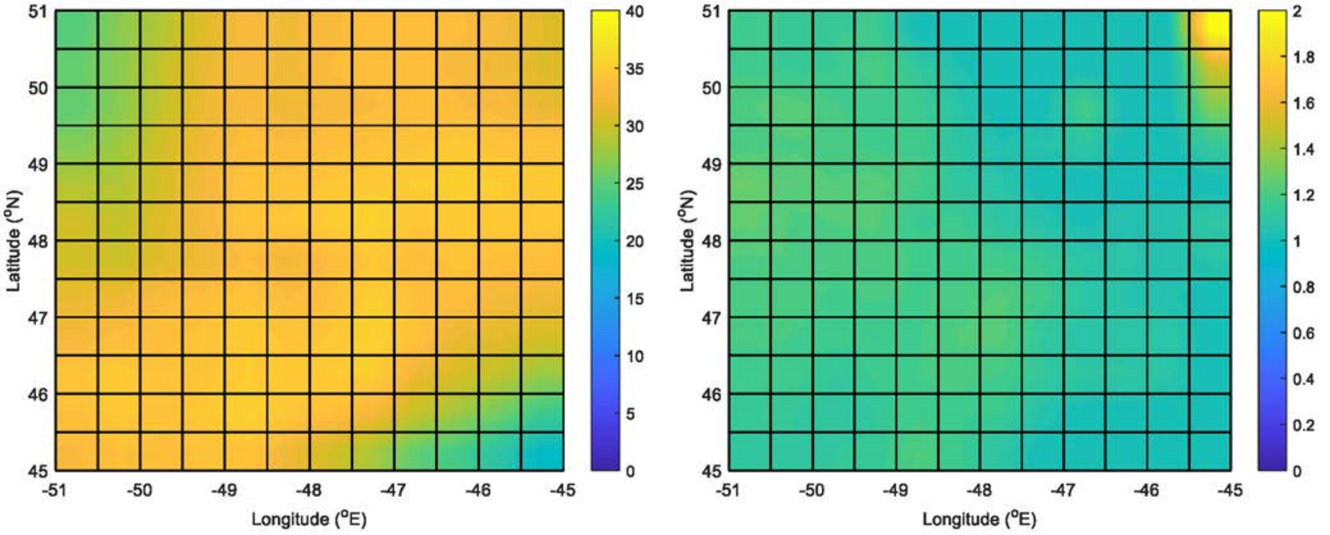


Figure 15—Percentage of days during winter (Dec.-Feb.) with light precipitation icing potential (left) and average duration of precipitation icing events in days (right)

Comparing the output of the two models, it can be seen that sea spray icing dominates over precipitation icing, however it is noted however that precipitation icing occurs over a greater proportion of the year. Overall, icing in the AOI is not severe when compared to more northern sub-Arctic and Arctic locations. Recommended icing mitigation measures included the use of hydrophobic paint and the heating of turbine blades.

Conclusions and Recommendations

The tools presented in this paper have been used to conduct a preliminary analysis to determine the key parameters influencing iceberg and sea ice loads.Iceberg global loads, mooring offsets, platform pitch motions and hub accelerations depend strongly on the areal density of icebergs, kinetic energy of the impacts, ice strength and the shape of the iceberg at the point of contact. Sea ice loads depend on the floe size, floe thickness, concentration and environmental driving forces. Ice loads also depend on the size and shape of the facility. Overall, iceberg loads dominate over sea ice loads, although this depends to some degree on the data source used to assess the floe size distribution. Icebergs are also more likely to interact with mooring lines which, except for cases where the attachment points are close to the sea surface, will not be contacted by sea ice. Overall, structure icing is not considered a significant threat to floating wind turbines in the AOI.

In order to minimize loads and risk of ice interaction it is recommended to limit size of facilities in the horizontal plane, and to keep mooring line attachment points as low as possible, and at as steep an angle as possible, to avoid contact with icebergs. Significant benefits can be realized by analysis of available satellite data, particularly since much of this data can now be accessed for free. Additional analysis, testing and model development to better understand the implications of iceberg contact with mooring lines is highly recommended.

Continued data collection and analysis is recommended. Recent work indicates that the current ice regime is less severe than that experienced in the 1980's (King, 2021) and this trend is considered likely to continue. This will reduce any barriers associated with the use of floating wind turbines offshore Newfoundland and Labrador.

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