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Iceberg areal density in the Barents Sea

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ABSTRACT

Glacial ice drifting in the Barents Sea due to forcing from winds, waves and currents can potentially pose a threat to offshore installations and vessels. On the Norwegian continental shelf, installations are required to be designed robust against environmental loads with a return period of 10 000 years. To verify that offshore structures are designed in accordance with requirements, both frequency of impacts and impact characteristics must be known.

Within recent years, Equinor has engaged several companies with expertise in oceanography, meteorology and ice engineering to quantify the frequency of glacial ice occurrence at sites relevant for field developments in the Barents Sea. Results of analyses are scattered but still provide an important basis for safe design of offshore structures. The results also identify regions in the Barents Sea where glacial ice needs to be considered in relation to offshore activities.

Iceberg areal density (IAD), defined as number of icebergs per unit area at any time, is the most important parameter when calculating impact frequencies. IAD can be estimated from observations but also from hindcast-based iceberg drift simulations. This paper presents principles of both approaches, discusses advantages, limitations and assumptions. Maps with IAD estimates from different sources for the Barents Sea are presented and recommendations for use of results are included.

KEY WORDS: Icebergs; impact frequency; areal density; Barents Sea

INTRODUCTION

On request from Equinor and as part of a technology development initiative, C-Core and StormGeo analyzed iceberg areal densities (IADs) for the Barents Sea based on observations and iceberg trajectory simulations, respectively. C-Core presented seven maps all showing IAD estimates based on different underlying assumptions. StormGeo prepared a single IAD map, where results could be scaled as a function of iceberg calving rates.

As part of the Wisting field development in the Barents Sea, Multiconsult was engaged for a similar study with the objective to prepare an ice design basis for Floating Production Storage and Offloading concepts (FPSOs). Multiconsult also based their IAD estimates on simulations but used observations to calibrate the results. Furthermore, ArcISo was engaged to verify the work done by Multiconsult and prepared a probabilistic simulation model similar to what was used by StormGeo and Multiconsult.

The project reports delivered by StormGeo, C-Core, Multiconsult and ArcISo are not available in the public domain and therefore not referred to in this paper. However, since results from the four reports are considered relevant for activities in the Barents Sea, key information is extracted and presented here. The objective of this paper is to give a high-level description of the methodologies, discuss assumptions and results, and give some recommendations related to iceberg risks and for prioritization of future work.

ICEBERG AREAL DENSITY

In this paper, the term "Iceberg" is used on all drifting bodies consisting of ice of glacial origin, including growlers and bergy bits (waterline length less than 5 m and 15 m respectively).

To estimate characteristic loads from structure-iceberg interactions, the frequency of impacts must be known (exposure). An established methodology to quantify the exposure is the "swept area approach" presented by Fuglem et al. (1996). This is a geometrical approach which simply compares the ocean surface not swept by icebergs against the surface swept by icebergs (Figure 1). The total annual expected number of iceberg encounters (η_e) is expressed by Fuglem et al. (1996) as:

$$\eta_e = \rho_a \cdot (w_s + \overline{w_\iota}) \cdot \overline{v_\iota} \cdot T \qquad \text{(Eq. 1)}$$

where ρ_a is the average areal density of icebergs per year (number of icebergs per unit area), w_s is the width of the structure in consideration, $\overline{w_\iota}$ is the mean iceberg length, $\overline{v_\iota}$ is the mean iceberg drift speed, and T is the number of seconds per year.

In the case where regular surveys are available over time, e.g. from satellites, the areal density can be found by counting the number of icebergs in each image, divide by the area covered by the images and average the number of icebergs per unit area over all images. If such images are not available, a probabilistic approach combined with use of an iceberg drift simulation model can be applied. Such an approach was demonstrated be Eik et al. (2013). It requires access to good quality hindcast models for winds, waves, currents, and temperatures in addition to distribution of iceberg production from glaciers (frequency of icebergs produced and size distribution as minimum). A large number of icebergs are drawn from the calved size distribution within the time period covered by the hindcasts and seeded randomly in waters outside the glacier fronts. Each individual iceberg is exposed to forces from the metocean parameters and by use of Newton's second law, iceberg drift is simulated. During simulations, iceberg deterioration is also calculated so all icebergs are reduced in size over time. An area of interest (AOI) around the structure with uniform metocean conditions and water depths is defined and the number of simulated icebergs entering the AOI is counted.

From the simulations, the sizes of all icebergs entering the AOI must be stored together with the duration of drift within the AOI and the average drift speed. The methodology can be demonstrated by an example:

An AOI with dimensions 100 km by 100 km with the structure located in the center is considered. Additionally, it is assumed that 3000 icebergs of various sizes and shapes are produced in the Barents Sea per year. If the simulations show that 1% of all produced icebergs enter the AOI and the icebergs stay in average 3 days within the AOI before they leave or have melted completely, the average areal density becomes:

$$\rho_a = \frac{30\ icebergs\ pr\ year}{100 \cdot 100 \cdot 10^6 m^2} \cdot \frac{3\ day\ residence\ time}{365\ days\ in\ a\ year} = 2.4658 \cdot 10^{-11}$$ icebergs per m^2 at any time within the AOI

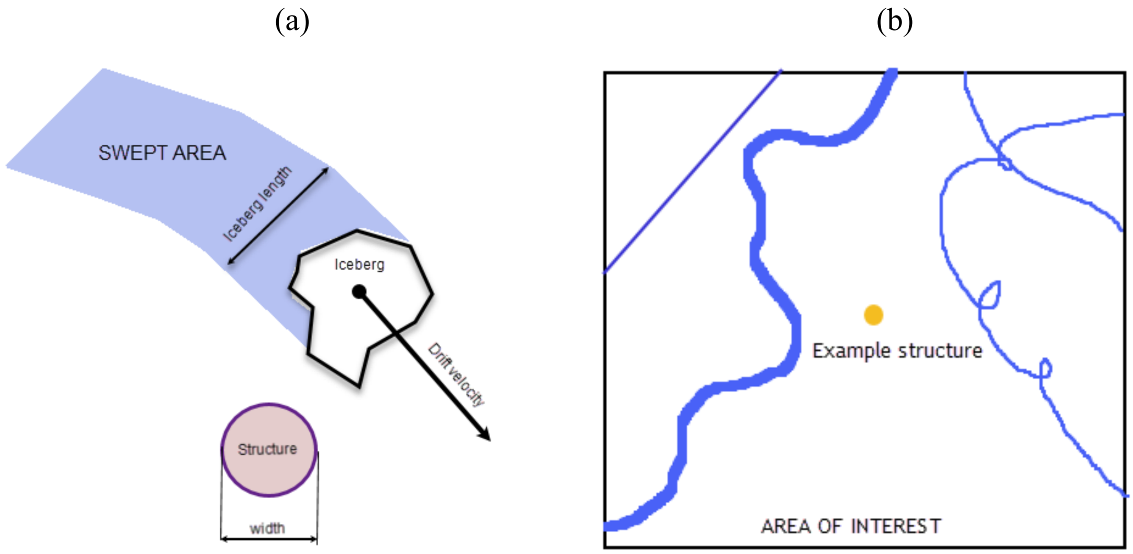

Figure 1. Illustration of the "swept area approach". a) Illustrates how the swept area from one single iceberg is a function of size and drift pattern, b) Illustrates how the number of icebergs, their sizes and drift patterns contribute to the total impact probability. Large icebergs are represented by wide blue trajectories as they swipe over larger surfaces than smaller (represented by thin lines)

INDUSTRY STUDIES

C-Core

The scope for C-Core was to search for and evaluate sources of iceberg observations in the Barents Sea. The most relevant observations were analysed and formed the basis for iceberg areal density maps for the Norwegian part of the Barents Sea.

C-Core concluded that the best source for systematic iceberg observations are the observations between 1881 and 1989 presented in the Abramov Atlas of Arctic Icebergs (Abramov, 1996). The observations, mainly from fixed wing flights, were extended with more recent satellite observations. 933 satellite images within the period 2003-2016 acquired from five different satellite sources were used. The satellite sources varied from wide-swath, low-resolution SAR images (Envisat) to narrow-swath, high-resolution optical images (Landsat). To compensate for the difficulty to detect smaller icebergs in wide-swath and low-resolution images, non-detection factors were included in the methodology.

Initially, C-Core used monthly contours from the iceberg atlas (Abramov, 1996) for the following parameters:

- Mean number of icebergs in a cell
- Maximum number of icebergs in a cell
- Probability of iceberg occurrence in a cell

The cells in the iceberg atlas refer to 100 km x 100 km areas covering the entire Barents Sea. In addition, C-Core included "abnormal" observations, which are observations made outside all the contour lines in the atlas, to estimate a "floor areal density estimate". These abnormal observations were mainly made close to the Norwegian coastline in 1881, 1929 and 1933.

Some uncertainty lies into the reported "mean number of icebergs in a cell" and whether this relates to "the average number of icebergs in the cell at any time" or " the mean number of icebergs conditional one or several icebergs actually are present". By investigating a map of observations published by Abramov, 1992 (Figure 2) the latter was found to be most likely. The map showing IAD values for the Barents Sea produced by C-Core based on the abovementioned data and assumptions is shown in Figure 3.

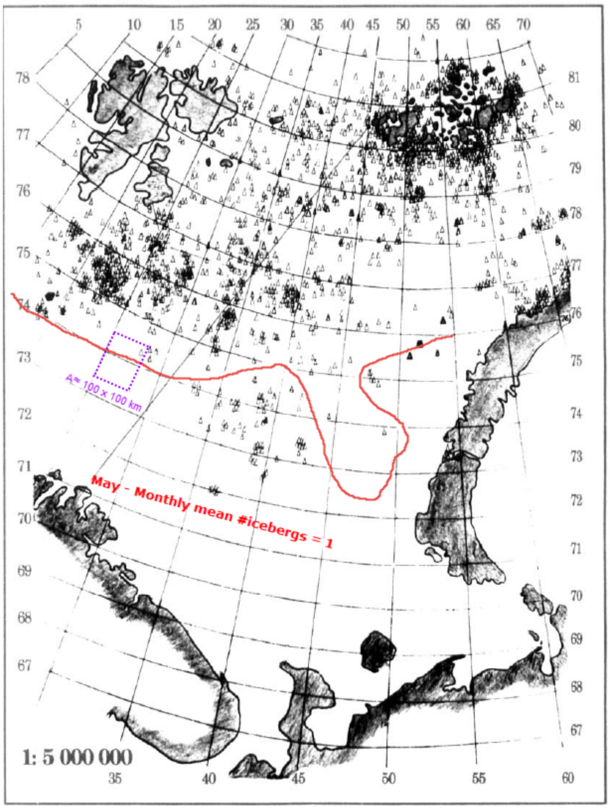

Figure 2. Iceberg observations made by the Arctic and Antarctic Research Institute 1933-1990. Approximate location of contour for one iceberg in average in May from the Abramov atlas is drawn by hand as a red contour line. Approximate extent of one 100 km x 100 km cell is indicated in purple.

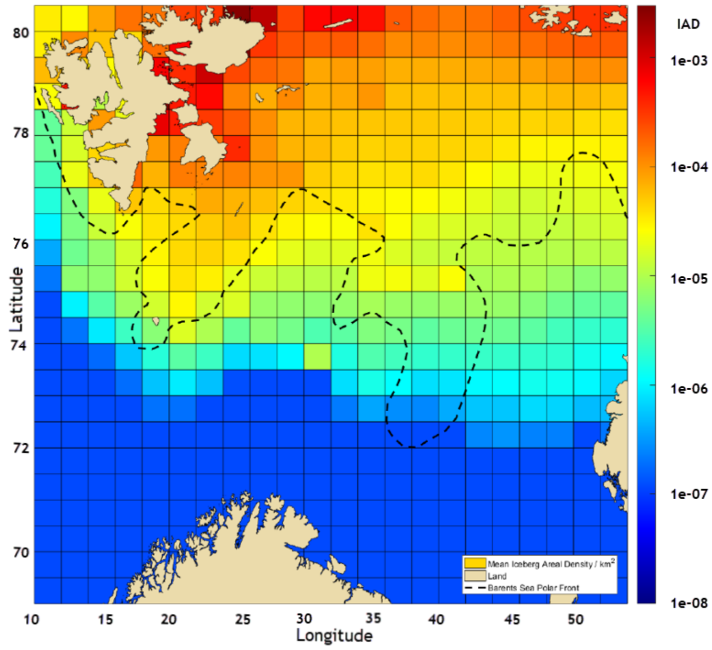

Figure 3. IAD reported by C-Core based on the combination of satellite observations and the Abramov Atlas of Arctic Icebergs (Abramov, 1996). The IAD values represent mean iceberg areal density per km^2 for cells with spacing 2° longitude and 0.5° latitude.

StormGeo

StormGeo was requested to perform a probabilistic study including iceberg drift modelling. The NORA10 hindcast provided by the Norwegian Meteorological Institute (NMI) was used to provide forcing from winds and waves in addition to sea and air temperatures. An oceanographic hindcast called BaSIC, also prepared by NMI, was used to provide time series of currents and sea ice occurrence. NORA10 provides time series with 3 h resolution in time in a 10 by10 km grid while BaSIC provides currents at 33 depth levels in a grid with 4 km horizontal resolution and 1 h resolution in time. In general, data from NORA10 is documented to be of good quality through comparisons with recordings from European offshore installations and met-masts while BaSIC (and oceanographic models in general) struggle to reproduce correct local currents at correct time but is expected to statistically reproduce general circulation and current patterns well. The BaSIC hindcast period from 1985-2012 was used in the probabilistic study.

An iceberg waterline length distribution based on several sources of observations and proposed by C-Core in industry projects was applied by StormGeo ((Eq. 2). Accompanying formulations for iceberg width and height based on observations were also applied ((Eq. 3 and (Eq. 4). All icebergs were assumed to be tabular with constant length, width and height. Since the distributions were based on observations in the Barents Sea, it was assumed that icebergs closer to their origin are larger so a crude constant value of 30 m was added to the iceberg waterline length when generated in the probabilistic study. With respect to iceberg calving masses, locations and fluxes based on studies by Kegouche et al. (2010) and Blaszczyk et al. (2009) were applied (Figure 4). From the calving volumes and size distributions, StormGeo based their IAD map (Figure 5b) on an annual production of approximately 160 000 icebergs per year (all with length greater than 45 m). Since a substantial proportion of the volume flux consists of smaller ice pieces and liquid water, this estimate is likely too high, but the map is scalable and can easily be corrected if more realistic estimates on iceberg production becomes available.

The iceberg model applied was based on models used by Kegouche et al. (2009), Kubat et al. (2005) and Kubat et al. (2007). The model consisted of a dynamical model calculating the movement of an iceberg given forcing from wind, ocean, sea ice and waves and a deterioration model that includes melting of the iceberg. In total, 442 217 icebergs were simulated within the period 1985-2012. One tenth of these trajectories are plotted in Figure 5a and illustrates where icebergs typically drift and how far south they may drift.

$$F_L(L) = 0.67\frac{1}{5.55}exp^{-\frac{(l-15)}{5.55}} + 0.33\frac{1}{100}exp^{-\frac{(l-15)}{100}} \text{ where } l > 15 \qquad (Eq.\ 2)$$

$$W = 0.7 \cdot L \cdot exp^{-0.00062 \cdot L} \qquad (Eq.\ 3)$$

$$H_{tot} = 0.3 \cdot L \cdot exp^{-0.00062 \cdot L} \qquad (Eq.\ 4)$$

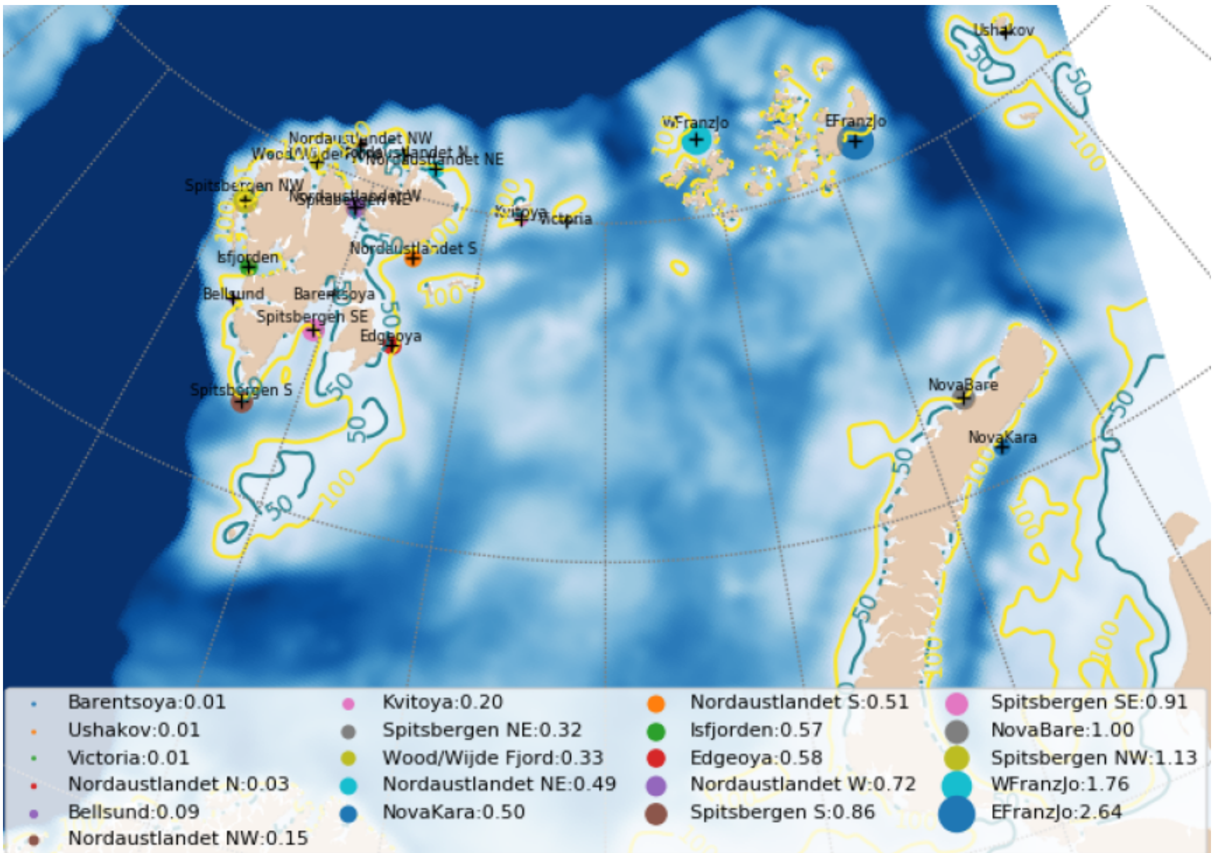

Figure 4. Iceberg calving sources in water equivalents used by StormGeo. Circle area indicates relative magnitude of the flux, contours indicate 50 m (green) and 100 m (yellow) isobaths. The map was prepared by StormGeo.

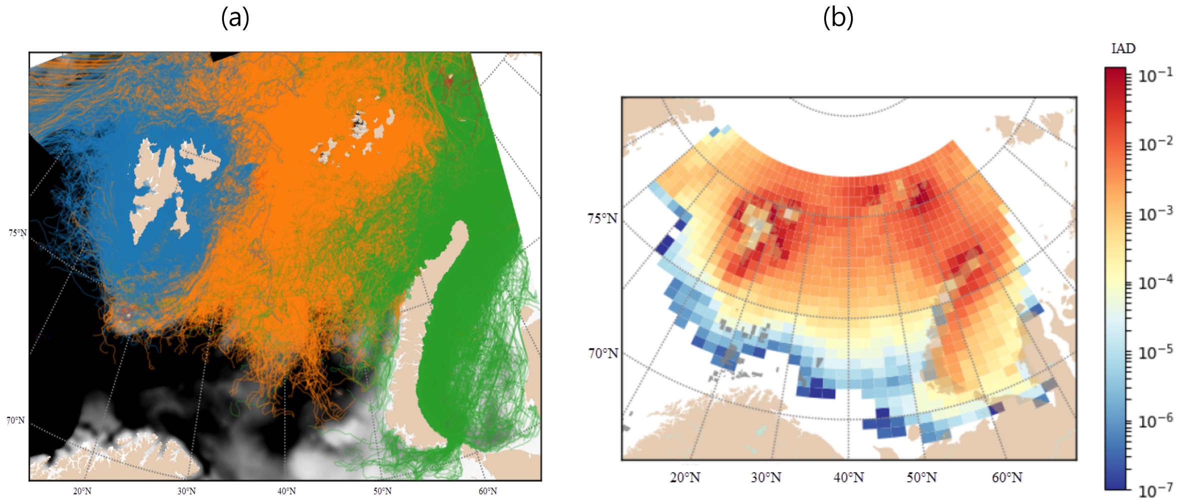

Figure 5. a) Iceberg drift trajectories from the StormGeo model, b) IAD map from Stor mGeo. Values represent number of icebergs per km^2 at any time.

Multiconsult

The approach used by Multiconsult was similar to the approach used by StormGeo. A more detailed description of the Multiconsult model for estimation of IAD values was presented by Hansen et al. (2019). Rather than using the direct volume flux from glaciers as a basis for the annual number of new icebergs fed into the Barents Sea, Multiconsult considered observations from Abramov (1996), Zubakin et al. (2007) and Zubakin et al. (1992). They identified a strong correlation between the number of surveillance flights and the number of iceberg observations and concluded there was underreporting of the real presence of icebergs in the Barents Sea. They suggested that the number of observations should be updated with a factor of 3 and indicated that the annual number of icebergs floating in the Barents Sea could be within the range 400-3000 each year. Their best estimate for annual number of icebergs present was 1600. Regarding iceberg sizes, Multiconsult applied the distribution reported by Zubakin et al. (2007). Initial distributions for iceberg drafts and widths where conditioned on iceberg length, similar to but not identical to conditional distributions used by StormGeo. Details are provided in Based on the assumed frequency of iceberg production and size distributions, Multiconsult simulated 44 186 icebergs. They used the information on iceberg volume flux from Blaszczyk et al. (2009) to spread the start positions for icebergs so the relative contributions from glaciers around the Barents Sea would be realistic. Multiconsult simulated drift of both tabular and cylindrical icebergs. The simulated trajectories (**Error! Reference source not found.**a) give an impression of relative iceberg occurrence. Estimated IAD values are shown in **Error! Reference source not found.**b.

Table *1*. With respect to metocean conditions, Multiconsult used currents from the same BaSIC oceanographic hindcast as StormGeo. However, for winds and waves, Multiconsult used the ERA-Interim archive. This archive is based on a global model with coarser time and spatial resolution than NORA10.

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Table 1. Parameters used by Multiconsult when releasing icebergs into the probabilistic model

Parameter	Mean	Standard deviation	Distribution
Length[1]	110 m	80 m	Lognormal ($\mu = 4.3578;\ \sigma = 0.83$)
Length/Width ratio	1.578	0.086	Normal ($\mu = 1.578;\ \sigma = 0.086$)
Total height	$Draft + \frac{1}{5}Draft,$ where draft = 70% of width and sail is $\frac{1}{5}Draft$		

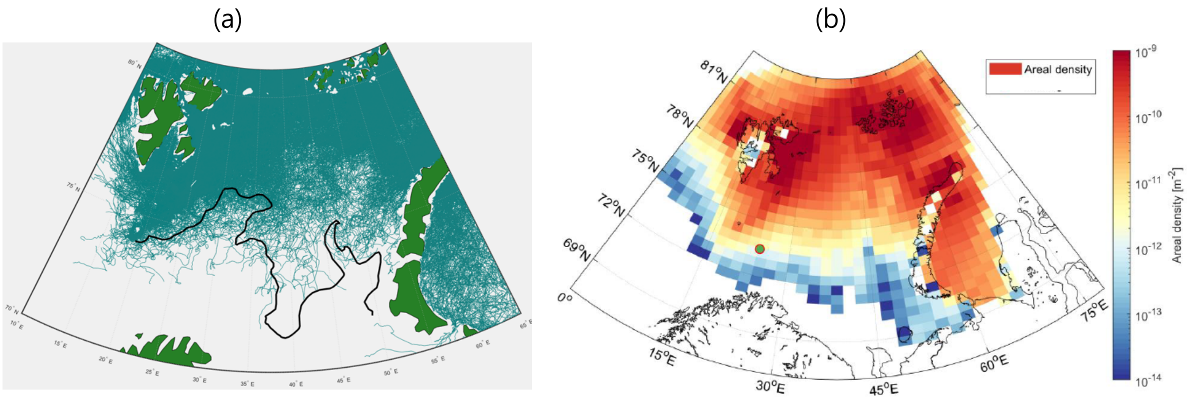

Figure 6. a) Iceberg drift trajectories from the Multiconsult model. Black line identifies the polar front b) Iceberg areal density map from Multiconsult. IAD values represent icebergs per m^2 at any time. The Wisting field is identified with a green circle.

ArcISo

ArcISo was engaged by Equinor to review previous IAD studies. As a benchmark, they made comparisons with the model and results presented by Monteban et al. (2020). The model presented by Monteban et al. (2020) was similar to the models used by StormGeo and Multiconsult but differed on the following sources:

- Estimates on annual iceberg production were based on satellite observations from Sentinel-1 and -2
- Wind and waves in the simulation model came from ERA5 with 0.25 degree spatial resolution an 2 h sampling rate
- Currents and sea ice drift were provided from TOPAZ hindcast (Bertino et al., 2008) with a 25 km spatial resolution and daily sampling rate

For details regarding the ArcISo modeling, reference is made to Monteban et al., (2020). Based on the Sentinel-1 and -2 images, ArcISo suggested that the number of smaller icebergs closer to their origin would be much higher than suggested by StormGeo and Multiconsult (Figure 7).

[1] Max lengths were set to 400 m for tabular icebergs and 200 m for non-tabular icebergs

With respect to suggested average number of produced icebergs, ArcISo suggested a somewhat higher rate than Multiconsult (Table 2). Similar to Multiconsult and StormGeo, icebergs in the ArcISO/Monteban model would sometimes drift far to the south (Figure 8a). A contour plot of iceberg probability of occurrence is shown in Figure 8b.

Table 2. Comparison of the number of icebergs seeded into simulation models per year

	Multiconsult	StormGeo	ArcISo/Monteban
Production rate [# icebergs per year]	1600	160 000	2600

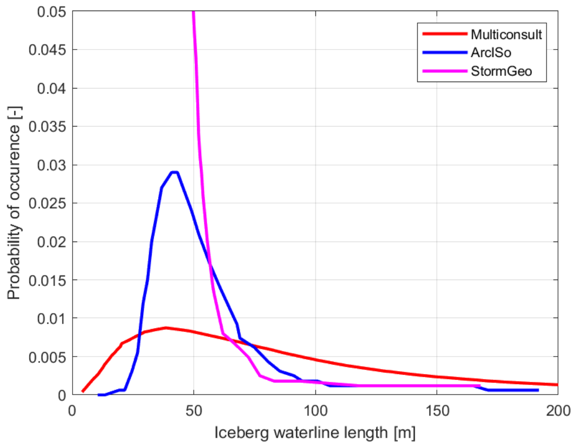

Figure 7. Iceberg waterline length distributions used as input to simulations by Multiconsult, ArcISO and StormGeo.

(a) (b)

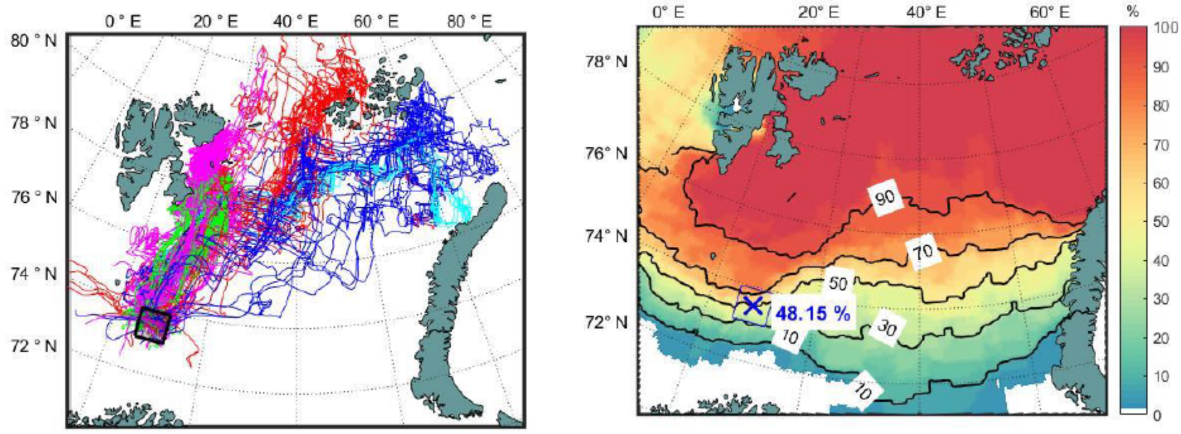

Figure 8. Iceberg drift trajectories prepared by ArcISo. Only trajectories that reached a 100 km x 100 km cell around the Wisting field are included, b) Annual probability of occurrence of one or several icebergs in 100 km x 100 km cells. Values are not directly comparable with IADs but can be used in combination with residence time data to calculate the areal density. The Wisting field development location is marked with an X.

DISCUSSIONS

All studies show that the iceberg occurrence is relatively high in waters close to the source glaciers, but gradually decays to the south. In the transition zone, where cold polar water meets the warmer water from the Atlantic ocean (the Polar Front), there is a very sharp gradient in the IAD values. This is supported both by observations and simulations. A practical implication of this is that offshore structures in the northernmost licenses on the Norwegian shelf will be in waters where iceberg occurrence is unlikely but the presence of icebergs in the near vicinity is still likely.

Using the IADs to estimate the impact frequencies for field developments such as Goliat, Johan Castberg and Wisting (Figure 9) reveals significant differences with a factor close to 10 in the number of impacts. Any characteristic iceberg impact load used as basis for design of offshore structures will suffer from this significant uncertainty in exposure. Using the most pessimistic source as a basis can lead to overly conservative design of offshore structures while the most optimistic source may lead to insufficient robustness in design. A viable solution can be to consider all sources and make a holistic (and subjective) assessment. If such an approach is used, the importance of including ice risk management, as required by NORSOK N-003 (2017), should be emphasized.

With respect to variations in IAD estimates, two factors can explain the main differences in the probabilistic iceberg drift simulation studies:

1. The assumptions regarding annual iceberg production varies significantly spanning from 160 000 icebergs per year based on ice flux from glaciers to ±2000 based on observations
2. The iceberg deterioration varies significantly in similar models and could be explained by differences and uncertainties in applied oceanographic models

With respect to observations, the main concern relates to lack of systematic monitoring in recent years and uncertainties related to older observations. It may be questioned if events taking place 150 years ago, towards the end of the cold period termed “the Little Ice Age”, are relevant in current climate. Since icebergs passing the polar front are rare events, there could still be events not being documented in recent years. Satellite observations still do not provide sufficient coverage, temporal and spatial resolution to conclude clearly on iceberg presence.

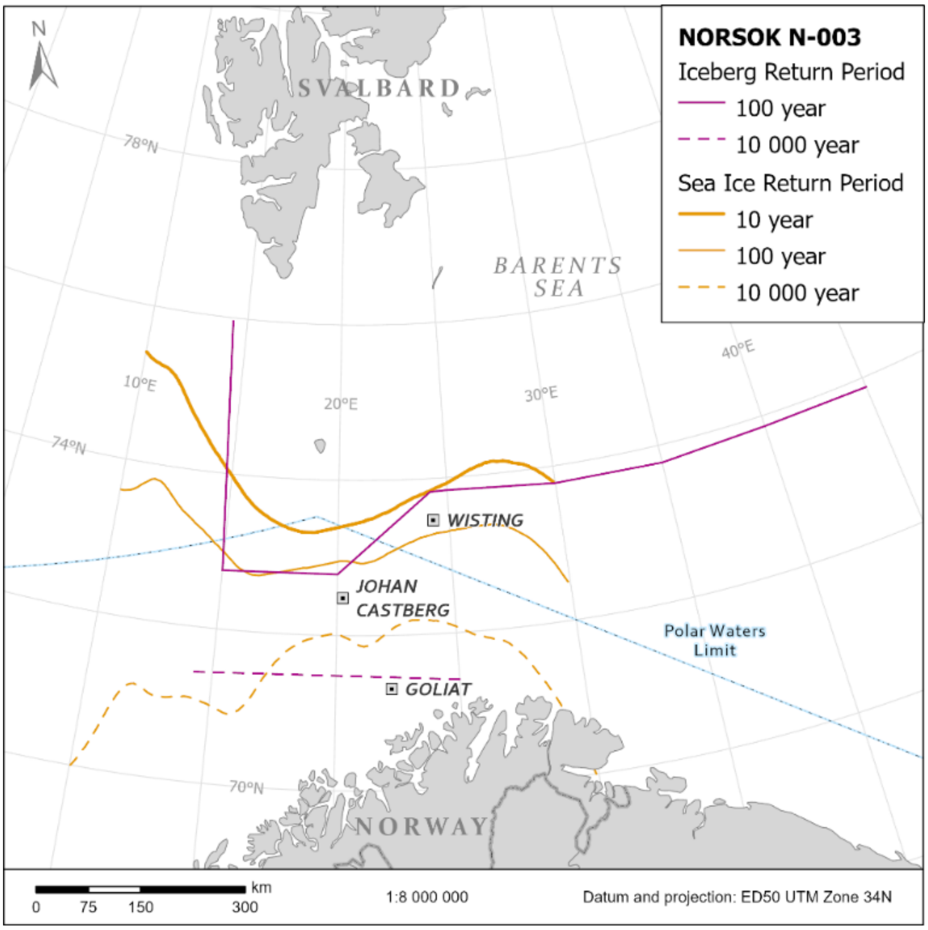

Figure 9. Limits for iceberg and sea ice presence (return period) in the Barents Sea from NORSOK N-003. Approximate locations of existing (Goliat), under construction (Johan Castberg) and future (Wisting) FPSOs are shown. In waters to the north of the 10 000 year lines, NORSOK N-003 requires use of ice management.

CONCLUSIONS

Four major initiatives have been made in recent years to quantify IADs in the Barents Sea. Results are scattered but all sources show that:

- Icebergs passing the oceanic polar front and venturing into waters open for oil & gas activities in the Norwegian part of the Barents Sea are very rare events
- Icebergs drifting far south in the Barents Sea is possible if large icebergs are calved at Svalbard or Frans Josef land before periods with persistent northerly winds in combination with reduced influx of warm Atlantic water.

Results from a single source should be avoided in relation with estimation of design loads on offshore structures while a holistic assessment of available observations, model results and meteorological and oceanographic conditions is recommended.

Use of iceberg drift simulation models in probabilistic analyses is efficient as a tool to quantif y iceberg exposure. However, both input and output from such modelling should be validated /calibrated against systematically collected observations of iceberg presence and characteristi cs.

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