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A method to find intervals with probability of harsh ice induced vibrations

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ABSTRACT

A method is proposed to estimate when harsh ice induced vibrations could be expected at an offshore site in an ice-infested region. The method aims to come up with specific estimates based on input parameters that are easily accessible. Therefore, the proposed method uses measured air temperatures, wind speeds, wind directions and ice concentrations, where some other relevant parameters such as ice thickness and ice drift speed could be calculated from these measured parameters. Test runs have been performed from a database with 60years of environmental data. However, because global sea ice concentration climate data record was only available between the years of 1979 and 2015 in EUMETSAT OSI SAF[1], database of input parameters were adjusted covering this period. Further comparisons with historical observations as well as the full-scale data sets from the LOLEIF and STRICE projects have been utilized. The early results of this model show that including ice thickness, air temperature, ice drift speed, wind direction and ice concentration, time periods of the year with high probability of ice induced vibrations could be hindcasted. These findings have been proved against three seasons of registered vibration events at the Norströmsgrund lighthouse.

KEY WORDS: Ice; Lock-in; Dynamics; Environment.

INTRODUCTION

Ice induced vibrations (IIV) of offshore structures in ice infested waters have been addressed since the early 1960s. The first observations of the phenomenon, later named as frequency locked-in (FLI) ice load, were performed in Cook Inlet, Alaska (Peyton, 1968). Later, similar events with coupled ice crushing and large amplitude dynamic responses were reported from structure sizes ranging from small channel markers and lighthouses (Määttänen, 1987) in the

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[1] EUMETSAT stands for European Organization for the Exploitation of Meteorological Satellites and OSI SAF stands for Satellite Application Facility on Ocean and Sea Ice

Gulf of Bothnia (GoB) to the large Molikpaq caisson in the Beaufort Sea (Jefferies and Wright, 1988). A great deal of research has been conducted to describe the two most important aspects of the problem such as identifying maximum amplitude responses and understanding why and when these vibrations occur (Sodhi, 1988). In addition, some attempts have been made on the estimation of the expected number of cycles caused by FLI during a winter season (Bjerkås et al., 2014). However, results of the study in Bjerkås et al. (2014) show large discrepancy between the expected and observed number of cycles for a given structure, which causes unrealistically low fatigue life estimations. In this paper, we present an alternative methodology aiming a more realistic estimate of the days with high probability of harsh IIV. Further, the method has been tested for the Norströmsgrund lighthouse (NSG) located in the northern Gulf of Bothnia (GoB).

Figure 1 shows a typical one-hour data sample, where environmental conditions and structural characteristics together make the NSG vulnerable to harsh IIV (these vibrations also include some FLI as illustrated in Fig.1). The criterion to describe the IIV as harsh has been accelerations higher than 0.5 m/s^2 based on the work by Nord et al. (2018). On this structure, some events have been observed to last up to 80 sec, while most events were shorter. In addition, maximum number of cycles in one day due to FLI was 1850 during the period of 2001-2003 at NSG (see Nord et al., 2018).

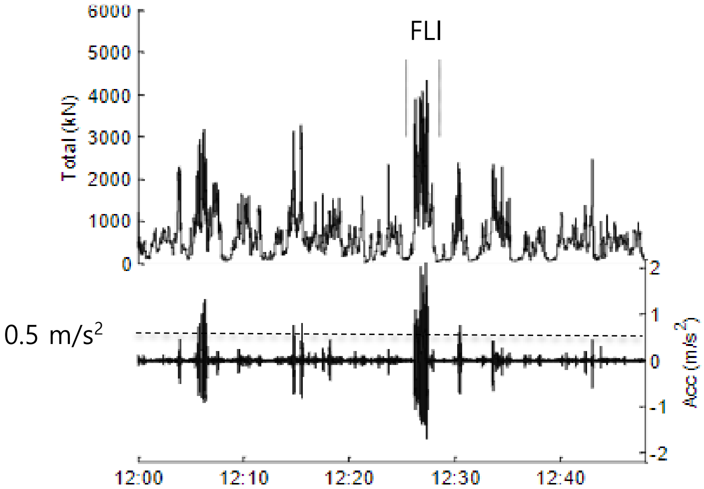

Figure 1. Typical one-hour interval with harsh IIV including FLI for Norströmsgrund lighthouse, 30 March 2003 (Bjerkås et al., 2013b).

METHOD

The present approach aims to use publicly available data to estimate when harsh IIV could be expected at an offshore site in an ice-infested region. Calibration of the model is performed against the STRICE data at NSG between the years of 2001-2003. Therefore, at this point, we limit the application of the model simple by being structure specific, where the selected structure is Norströmsgrund lighthouse.

Data Source

Data sources used for the hindcast calculations are:

- Metocean data are obtained from the Swedish Meteorological and Hydrological Institute (SMHI) for Rödkallen lighthouse and Luleå airport for the time interval of 1952-2015 (62 years). Data include daily average values of:
    - Air temperature (T_a)
    - Wind speed (U_{10}) and wind direction (θ_w)
    - Ice concentration

Wind speed is scaled down to point 0.1 meters above the ground level using logarithmic wind profile as:

$$U_g = U_{10} \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \tag{1}$$

where U_{10} is the measured wind speed at height h_1. U_g represents the wind speed at height h_2 and z_0 is the roughness length. The roughness length of Arctic sea ice is kept constant at average of 0.02 cm for the upper surface as in Untersteiner and Badgley (1965) for brevity. Further the ice drift speed is estimated based on the equation of motion with the steady state solution (Weiss, 2013):

$$U_i = U_g \sqrt{\frac{\rho_a C_a}{\rho_w C_w}} \tag{2}$$

where ρ_a and ρ_w are the air and water densities, respectively. The drag factor C_a describes the drag resistance between air and ice top surface and C_w describes the drag resistance between water and ice sub surface. Based on studies in GoB by Leppäranta (2011) the following numerical values were taken: $\rho_a = 1.23$ kg/m^3, $\rho_w = 1025$ kg/m^3, $C_a \approx 1.5 \times 10^{-3}$ and $C_w \approx 5 \times 10^{-3}$. The square root term in Eq. (2) is often named "Nansen number" and tends to be slightly lower than 0.02.

Due to lack of data at Rödkallen, simple correlation functions have been applied to scale SMHI-data from Luleå airport to Rödkallen because of their location as illustrated in Fig. 2. The distance between NSG and Rödkallen is about 15km while the distance between Rödkallen and Luleå airport is about 27 km (see Fig. 2).

A number of different ice drift models exist (Leppäranta, 2011, Omstedt et al., 1994). Other projects may therefore have more accurate ice drift data than we have. However, the proposed method presents a new methodology and more advanced ice drift models can be implemented later.

Figure 2. Location of meteorological stations. Top left image shows the magnified view of the area of interest that is highlighted in right bottom image.

Decreasing air temperature during the fall season is the primary driving force of ice growth. A level-ice thickness growth can be estimated using air temperature with different models; however, in this study we use the empirical Zubov (1945) model to estimate the ice thickness.

Field observations from NSG shows that FLI tends to be more frequent when the air temperatures are high (Bjerkås et al., 2013a). Increasing air temperatures may slow down or stop the ice growth and change the material characteristics of ice. Cold ice tends to crush in a brittle behavior while warmer ice fails more ductile. In addition, increasing air temperature and solar influx tend to open lead between larger ice floes, slow down or stop consolidation of rubble fields. Calibration results of the model shows the effect of air temperatures and solar influx. Using Eq. (3), we define an air temperature criterion where we formulate an empirical function that connects the day length D_a to the required air temperature T_a:

$$T_a = -0.625 \cdot D_a + 5.25 \tag{3}$$

It should be remembered that a short day in January usually requires higher air temperatures than a longer day in April to meet the criteria for probability of harsh IIV.

The ice drift in the northern Gulf of Bothnia (GoB) is mainly driven by wind. Therefore, in this study we use the wind speed (U_{10}) and estimate the wind speed at the surface level. Then, using Eq. (2), we estimate the ice drift speeds and formulate an ice drift speed criteria of 0.02 – 0.08 m/s to observe harsh IIV following the arguments in Bjerkås and Skiple (2005). Although, we use constant drag coefficients (see Table 1 in Omstedt, 1994 for the parameters in the model) during the interaction to convert wind speeds (2-day average) to ice drift speeds (U_i), a more advanced method including varying drag coefficients will be adopted later.

In the design of the model, it is first thought that ice drift direction should be from North due to the free ice edge that forms in the South part of GoB. This assumption was partly confirmed by the experimental setup at NSG with load panels pointing towards North and East. However, measured data including events with harsh IIV shows an almost opposite trend. Most events occur with wind from South-West to South-East. From detailed studies of satellite photos, it is found that an area with open water often was present North-West of NSG. A similar trend has been also reported in Omstedt et al. (1994).

The link between wind direction and ice direction is covered by advanced numerical models (Leppäranta, 2011). As a first attempt, wind direction (θ_w) criteria is defined as:

$$270 < \theta_w < 110 \qquad (4)$$

Further work with this model will include a more physical representation of the relation between wind direction and ice drift direction.

Global sea ice concentration climate data for the region was obtained from EUMETSAT OSI SAF covering the period from January 1979 to December 2015 (OSI-SAF, 2017). OSI SAF produces a range of air-sea interface products on an operational basis. These products include not only sea ice characteristics (i.e., sea ice concentration, sea ice edge, sea ice type, sea ice drift and sea ice surface temperature), but also, information on wind, sea surface temperatures, surface solar irradiance and downward longwave irradiance. Readers of this work are also encouraged to read the product user manual provided by Ocean & Sea Ice SAF (OSI-SAF, 2017) for more detailed information regarding the ice concentration data used in this study.

Since the occurrence of ice induced vibrations requires the presence of ice, a certain drift speed and knowledge on the direction of the ice floes, we define five criteria as follows:

1) Ice thickness should be greater than 0.2 m (Bjerkås and Skiple, 2005)
2) Ice drift speed should be within 0.02 – 0.08 m/s (2 day average)
3) A wind direction is pointing to a free ice edge (-90 to +110 from North with 2 day average)
4) Air temperature T_a should be large enough to make the ice edge ductile or leads to open
5) Ice concentration should be greater than 60%

If all five criteria are met in one day, the structure is expected to be vulnerable to harsh IIV.

RESULTS

In this section, we first present the results from calibration of the model against observed days with harsh IIV at NSG over three seasons from 2001 to 2003, and then the model is implemented on a set of data from 1979 to 2015 (36 years).

Table 1 shows the results from calibration tests against NSG data recorded during the STRICE project where it can be clearly seen that the model tends to overestimate the total number of days vulnerable to harsh IIV, which is good from the engineering perspective and can be considered to be on the safe side. On the other hand, total number of days in February 2002 is underestimated, which indicate that some additional parameters need to be implemented into the model to satisfy this particular month as well.

Table 1. Observed (OBS) and estimated (EST) number of days with harsh IIV at NSG 2001-2003

Year	Feb		Mar		Apr		Total	
	OBS	EST	OBS	EST	OBS	EST	OBS	EST
2001	0	1	1	1	3	24	4	26
2002	1	0	2	13	3	19	6	32
2003	0	6	6	22	0	28	6	56

Figures 3-5 illustrate the example model results for the years of 2001, 2002 and 2003. We have selected these years to compare with the NSG data that was part of the STRICE project. However, one important difference between the STRICE data and the model prediction is that the data in the STRICE project was limited from mid-February to mid-April (Li et al., 2016) while the model have been applied from 1. October to 29. May. In Figures 3-5, green color indicates that the specific criterion is met for the highlighted parameter; red color indicates that specific criterion fails for the same parameter and grey color indicates that there is no data available for that period. Bottom two rows show the estimated number of days with harsh IIV, in other words, estimated days (FLI-EST) and observed number of days (FLI-OBS) which are the STRICE measurements reporting harsh IIV including FLI as in Nord et al. (2018) where reported accelerations were above 0.5 m/s^2.

When compared with the STRICE measurements, results indicate that the model successfully detects the time intervals that may have high probability of harsh IIV. Moreover, the model tends to be on the safe side when the estimation of the number of days during a winter with high probability of vibrations is considered because it overestimates the number of days (see Figures 3-5).

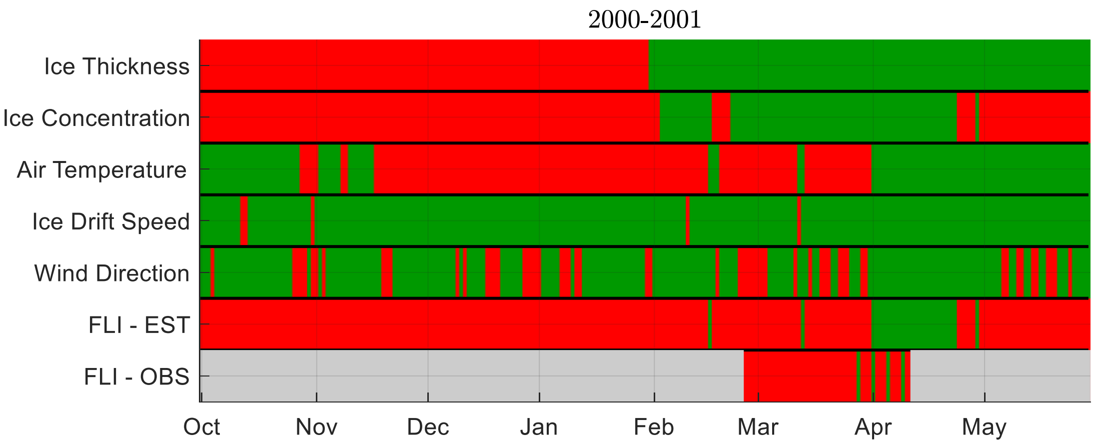

Figure 3. Example model results for 2000-2001

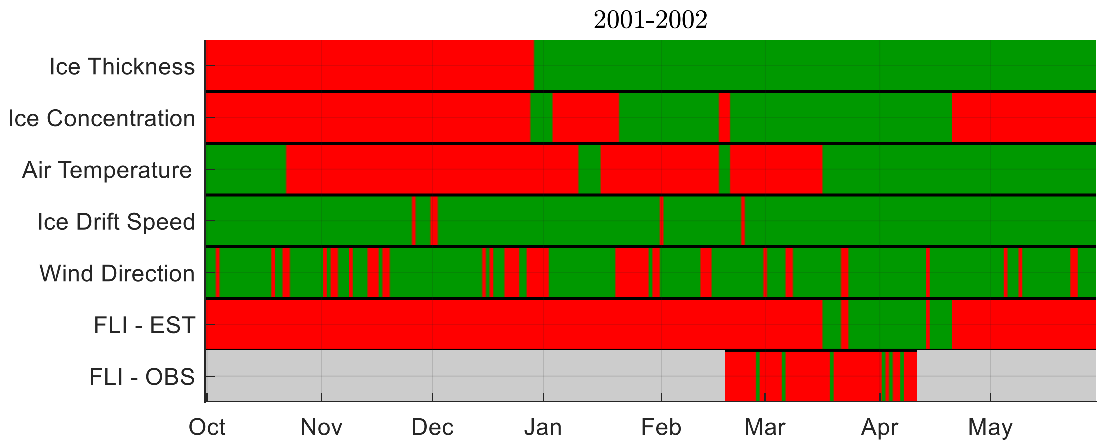

Figure 4. Example model results for 2001-2002.

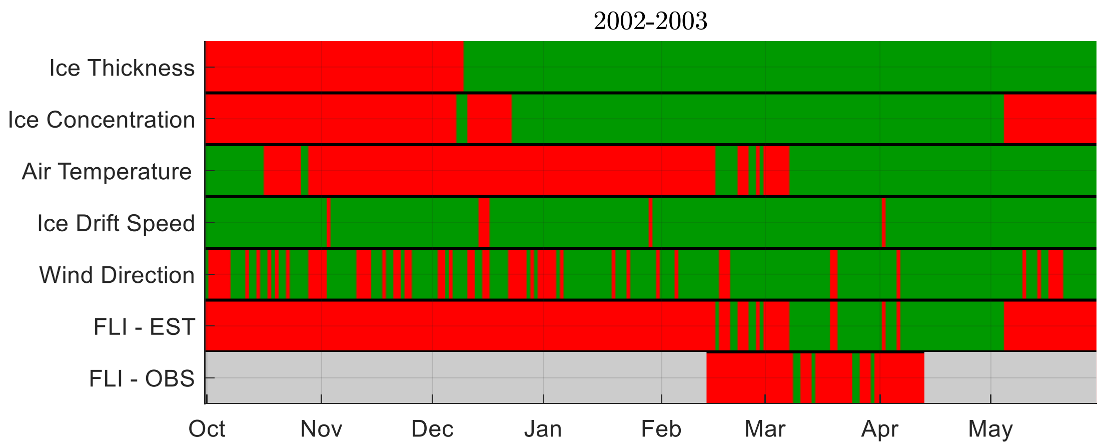

Figure 5. Example model results for 2002-2003.

Figure 6 shows the estimated total number of days with harsh IIV for each year covering all the days from 1979 to 2015. On the same figure, three seasons with STRICE measurements are also shown with a red dashed line. As a result, we see a significant variability in the number of days ranging from 1 day to 60 days of high probability of harsh IIV during a winter season. It is also seen that the winter of 2002/2003 is actually a winter with a relatively high number of days (60) with harsh IIV when the model is considered. Another observation is that a typical year may include between 25 to 35 days with high probability of harsh IIV when the proposed model is considered.

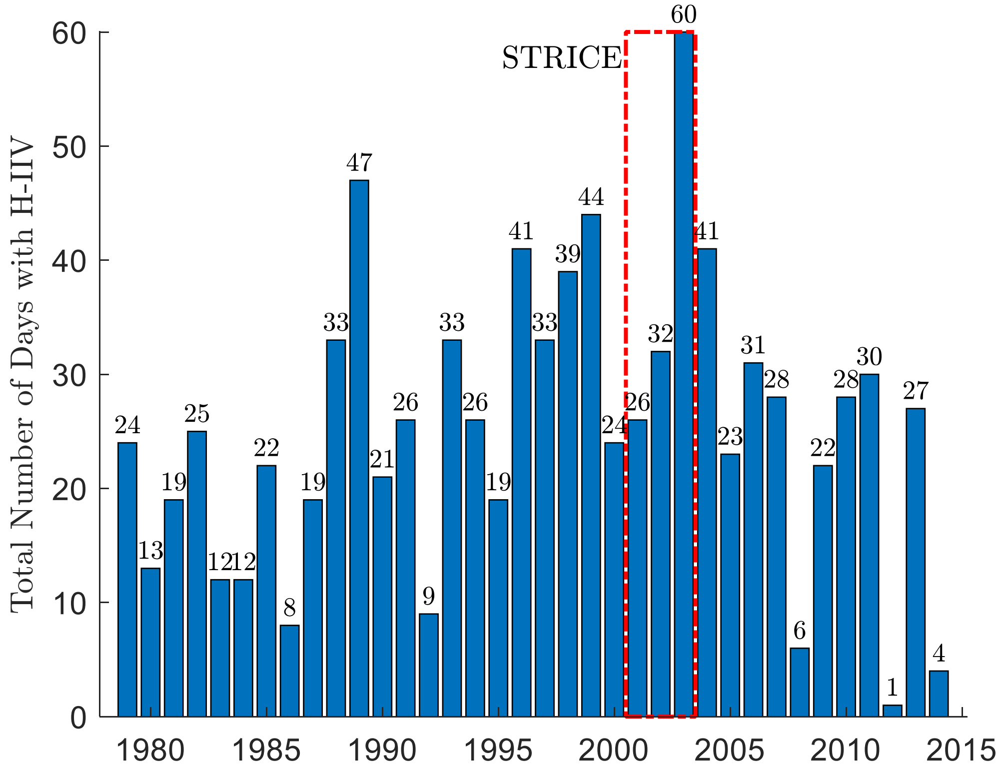

Figure 6. Total number of estimated days vulnerable to harsh IIV (H-IIV) between 1 October 1979 and 29 May 2015.

Table 2 summarizes the estimated number of days with high probability of harsh IIV between the years of 1979 and 2015. For example, total number of harsh IIV days seems to be in April with total of 532 days and the maximum number of days in a year is also found to be in April with 28 days. In February, the model detects 39 days of harsh IIV, whereas it does not detect any vibration prior to February in any of the analyzed years. Moreover, model detects 73 harsh IIV days in May; however, it is known that the ice crystal structure tends to be strongly degraded in May, an effect that the model is not capable of covering yet.

Table 2. Estimated total number of days with high probability of harsh IIV between 1979 and 2015.

	Dec	Jan	Feb	Mar	Apr	May
Total	0	0	39	264	532	73
Max	0	0	12	27	28	12
Min	0	0	0	0	0	0

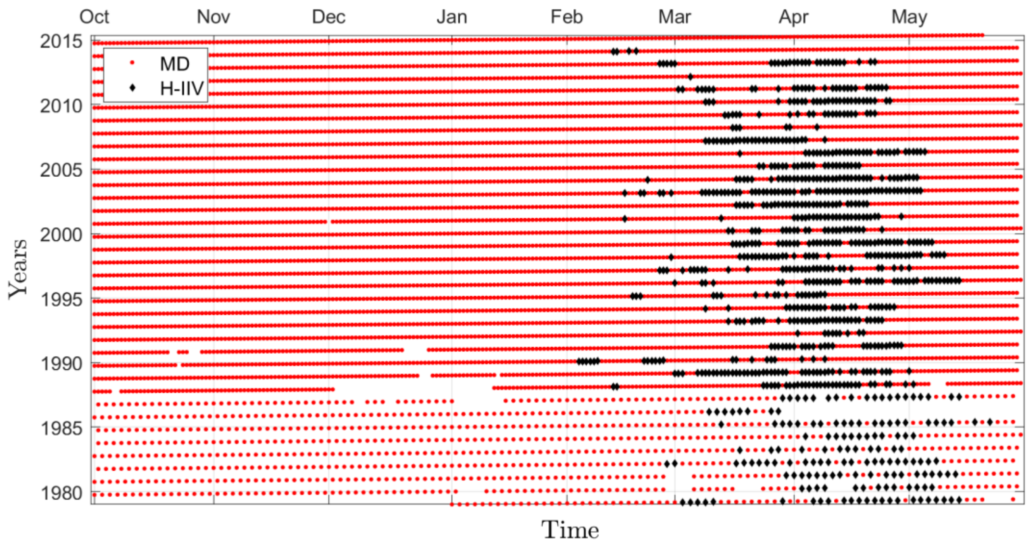

Figure 7. Distribution of estimated days vulnerable to harsh IIV between the years of 1979 and 2015. MD denotes measured days, and H-IIV denotes harsh IIV days.

Figure 7 illustrates the distribution of the estimated harsh IIV days between the year of 1979 and 2015. In this scatter plot, red dots indicate that the data is available for that particular day and black diamonds indicate the predicted harsh IIV. This figure also illustrates how the data is sampled. For example, the data is sampled every two days between the years of 1979 and 1987 due to sampling of ice concentration data. In addition, there are some data missing until the year of 1992.

Figure 7 shows one common behavior where harsh IIV are most likely to occur in March and/or April, although, the probability of harsh IIV occurrences increase for late February and early May as well in some years.

DISCUSSION

The goal of this study is to estimate the probability of occurrences of harsh IIV of a structure using Metocean data. This is important because it may help designers to estimate the fatigue lifetime of new offshore structures in ice infested waters in the decision period. Bjerkås et al. (2014) shows the large discrepancy between the available methods to estimate the number of vibration cycles due to FLI. Here, we propose a simple model to do a screening of air temperature, ice drift speed and wind direction to highlight the days with high probability of harsh IIV. Based on the published literature and experiences from the northern GoB, we define five distinct criteria to estimate the number of days with harsh IIV. All five criteria must be understood individually for the chosen structure (in this case NSG), and more detailed study is needed to generalize the current work to be able to use it for other structures.

The proposed model should be understood as a first step to establish a framework for further work. Most of the criteria have been parts of research topics for a long time, and the model must therefore be improved to include state-of-the-art knowledge within all topics. To author’s knowledge, there are very few models that aims to link the advanced geophysical models into the decision tools for structures in ice-infested waters. In that sense, the present work is much inspired by other fields in offshore engineering and especially the work performed on wave modelling.

CONCLUDING REMARKS

A new framework is presented in an aim to create a model that can support the estimate of fatigue life of offshore structures in ice infested waters. The first step has been taken to detect the days when the probability of harsh IIV are present. The model has been calibrated against data collected at Norströmsgrund lighthouse. Initial test runs show that estimated number of days with probability of harsh IIV is realistic compared to measured full-scale data. However, more work is needed for a better model, which should include:

- A physical ice-drift model
- Calibration against other data sets
- Generalization of the criteria applied

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