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Ice condition parameters of the Gulf of Bothnia with relation to offshore wind turbine design

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ABSTRACT

VTT has developed a web-based ice load portal for the Baltic Sea for use in offshore wind turbine design. In the portal, map-based environmental parameters, load calculation methods and structures are combined in order to shorten the planning phase of offshore wind turbines. In this paper, the ice condition data used in the ice load portal is presented for the Gulf of Bothnia. The data is based on the series of 37 years of the Finnish Ice Service's ice charts for navigational purposes. The earlier ice charts from the winters 1980/1981 to 2005/2006 were first digitized for the statistical analysis. The later ice charts from the winters 2006/2007 to 2016/2017 were already available in digital form. From these charts, parameters such as ice thickness, ice type, concentration and degree of ridging were analyzed to achieve design parameters for the offshore wind turbine design. In this paper, the main findings from the analysis are presented.

KEY WORDS Ice conditions, Baltic Sea, Offshore wind turbines

INTRODUCTION

Climate change challenges societies to reduce greenhouse gas emissions. One solution is renewable energy such as wind energy. Over sea areas, wind speeds are often higher and more stable compared to land areas. This and possible conflicts regarding land use make offshore wind farming an attractive concept. In the Baltic Sea, there has been an increasing number of offshore wind farm designs and installations, especially in the southern region. This paper concentrates on the Gulf of Bothnia, located in the northern part of the Baltic Sea. In that area, the Tahkoluoto offshore wind farm, close to Pori, Finland, is currently operational and other farms are in planning phase. Finland is also carrying out marine spatial planning for its marine areas, including Finnish parts of the Gulf of Bothnia.

To speed up the early design phase of offshore wind turbines, VTT has developed a web-based ice load design load portal for the Baltic Sea. The portal combines environmental parameters of the Baltic Sea with offshore wind turbine structures and their load calculation methods. The portal includes calculation methods for ice, wind, and wave loads.

When designing offshore wind turbines for seasonally ice-covered waters such as the Baltic Sea, knowledge of the local ice conditions is important for the ice load design of support structures. A realistic estimation of ice loads has a crucial role when developing a functioning and economically feasible design. This paper provides an introduction to the ice load design portal focusing on the ice condition data produced for the portal. The data is based on the Finnish Meteorological Institute's ice charts from the winters 1980/1981 to 2016/2017. A statistical analysis is performed to generate ice condition parameters relevant for the design of the structures, such as the maximum ice thickness occurring once in 50 years. The area governed in this paper is the Gulf of Bothnia, shown in Figure *1*.

In general, first-year sea ice exists every year in the northern part of the Gulf of Bothnia. The southern part does not freeze over completely every year, but ice does form close to the shores every winter. Close to the shore and in the archipelago, the ice is so-called fast ice, which remains immobile apart from the early and late parts of the ice season. Fast ice is a solid and smooth ice sheet which in the Gulf of Bothnia can reach thicknesses up to 1.2 meters. Drift ice in the middle parts of the Gulf of Bothnia is thinner than fast ice close to the shore. The drift ice field in the Baltic Sea is mostly driven by winds, and it is a mixture of floes and leads and may contain ridges and other deformed ice types. (Leppäranta & Myrberg, 2009).

Ice conditions of the Baltic Sea have earlier been presented comprehensively for example in the Climatological Ice Atlas (SMHI, 1982). The scope of the ice atlas is focused mainly on climatological ice features. This study is based on more recent ice charts and has its scope in the ice condition parameters relevant for offshore wind turbine design. Earlier, Tikanmäki et al. (2012) produced a first version of the study with a much more limited set of ice charts.

In this paper, a brief introduction to the ice load portal is given and the ice charts as source material are presented. Then, the analysis methods and results are presented and discussed.

Figure 1. The Baltic Sea, located in northern Europe. The black box shows the Gulf of Bothnia, the area concerned in the ice condition analyses of this paper. The Gulf of Bothnia is located between Sweden and Finland.

ICE LOAD PORTAL

The ice load design portal is designed to simplify and speed up the design process of offshore wind farms. The portal is a modular script-based design tool that will be freely available via an internet browser. The portal brings together principles of maritime spatial planning (MSP) by using Geographic Information System (GIS) data and structural design of offshore wind turbines. Simplified load and structural models are applied to integrate all the necessary information (site-specific environmental data, common structural design concepts, and environmental loads) into a single tool. The main goal is to streamline the preliminary design process for offshore wind farms, including the siting and structural design.

The following computational procedures (modules) are described in the design load portal:

In the first module, the user selects the location of the wind turbine by using a map-based interface of the portal. This brings together GIS tools in the northern Baltic Sea related to physical, geological and climatological marine conditions. The portal has an interface that easily receives site-specific data on environmental conditions regarding ice, wind, waves, water depth, and seabed substrate.

In the second module, the user pre-selects the size of the turbine and the support structures as well as the type of the sub-structure. The user can decide whether to supplement the monopile with an ice-breaking cone or not. Next, a model generator script produces a structural model for dynamic analyses based on the selected dimensions, components, and materials.

The third module describes the design loads based on the site-specific environmental conditions (e.g. ice thickness and wind speed) and the main parameters from the structure (shape and size). The user can create one or several load cases by applying various load combinations. The design portal includes several options for each load source: the ice load, the wind load, and the wave load. The load models are based on various references, in-house codes, and standards such as IEC 61400 and ISO 19906.

Based on these three modules, structural performance studies can be carried out with dynamic simulations. As an output, the user receives the simulated vibration response of a wind turbine to the given load excitation for each load case. Post-processing is performed in a result module, in which the user can analyze e.g. structural forces, displacements, and stresses and compare them to critical or recommended limits. More information from the ice load design portal was presented by Heinonen et al. (2018).

In the following, the ice condition data produced for the ice load portal’s first module is presented.

ICE CHART DATA

The best source of information about past ice conditions in the Gulf of Bothnia are the ice charts produced by the Finnish Ice Service. They have been produced regularly during the ice season, mainly for navigational purposes. In an ice chart, all available data about ice conditions of a given date is analyzed and presented in a chart format. The ice chart tells the existence of ice, its horizontal concentration, type, thickness and deformation degree.

Several different data sources are utilized when drawing ice charts. Local observers in the coastal area make visual observations as far as they can see and measure the ice thickness by drilling a hole through the ice. In addition, some ships report ice observations to the ice service. Until the 1990s, airborne observations were a relevant source of ice information. Since 1967, when satellite image acquisitions started to be available, the ever-increasing number and constantly improving quality of satellite images has increased their role among the observations. When drawing the ice chart, an ice expert combines all the available information and compiles a general view of the current ice conditions.

In this study, ice charts since the winter of 1980/1981 were combined to a database in order to make statistical calculations for the whole 37-year data series. In order to make statistical calculation of ice features possible, the earlier charts from 1980-2006 were digitized from paper charts. This was accomplished by re-drawing them with a program currently used for ice charting. From this period, one ice chart per week was digitized.

ANALYSIS METHODS

The ice chart data from the winters 1980/1981 to 2005/2006 was digitized to the netcdf format. The ice charts from the winters 2015/2016 and 2016/2017 were also available in the same format. The charts from the winters 2006/2007 to 2014/2015 were in a specific IceMap format. Data in both formats was imported to the MATLAB software for further analysis. Both formats are grid type file formats, but the grid size of the data differs. Thus, netcdf-type ice charts were converted to the same grid as the IceMap ice charts. The grid size of the IceMap charts and of the maps presented in this study is around 1 km × 1 km.

The amount of data was so large that individual ice charts could not be used directly in the analysis. Each ice chart was loaded to MATLAB, converted to the above-mentioned grid format and then the data was recorded into the histogram grids. These grids included for example the number of days each ice feature occurred in each grid cell during the study period. For example, in a certain grid cell a record was made of how many days of ice of thickness 10-20 cm and how many days of a certain degree of ridging or a certain ice type occurred.

To estimate the maximum ice thickness occurring on average once in 50 years, the maximum thickness of each year was recorded for all the grid cells. Then the method presented by Makkonen and Tikanmäki (2019) was used to estimate the 50-year value of ice thickness. First, the annual maximum ice thicknesses h_m of each grid cell were sorted from the smallest to the highest value $h_1 \leq h_2 \leq ... \leq h_m \leq ... \leq h_{37}$, where m is the rank and 37 is the number of the annual maxima in this study. The probabilities P of each observation were used as plotting positions

$$P = m/(N+1) \,. \tag{1}$$

Then, the inverse of the generalized extreme value (GEV) distribution function was fitted, i.e.

$$\xi = \mu + \sigma/\gamma \, [- 1 - (- \ln P)^{-\gamma}], \tag{2}$$

where μ, σ and γ are parameters of the distribution. The fitting was made with the weighted least squares method as

$$\min \sum_{m=1}^{37} w_m \, (x_m - \xi_m)^2 \,, \tag{3}$$

where w_m are the weights determined iteratively so that they are proportional to the inverse of the variance σ_m^2 of the observation, i.e.

$$w_m \sim 1/\, \sigma_m^2. \tag{4}$$

The maximum ice thickness occurring once in 50 years was calculated from the fitted function (2) by inserting $P = 0.98$. The details of the method can be found from Makkonen and Tikanmäki (2019).

RESULTS

Figure 2 shows the maximum level ice thickness occurring once in 50 years in the Gulf of Bothnia; it varies between 40 and 120 cm. It can be seen that the maximum ice thickness in the fast-ice zone close to the shore is thicker than in the drift-ice zone in the central parts of the Gulf of Bothnia. The highest 50-year level ice thickness values are reached in the northern part of the Gulf of Bothnia. It should be noted that the thickness of deformed ice features such as ridged and rafted ice can be higher.

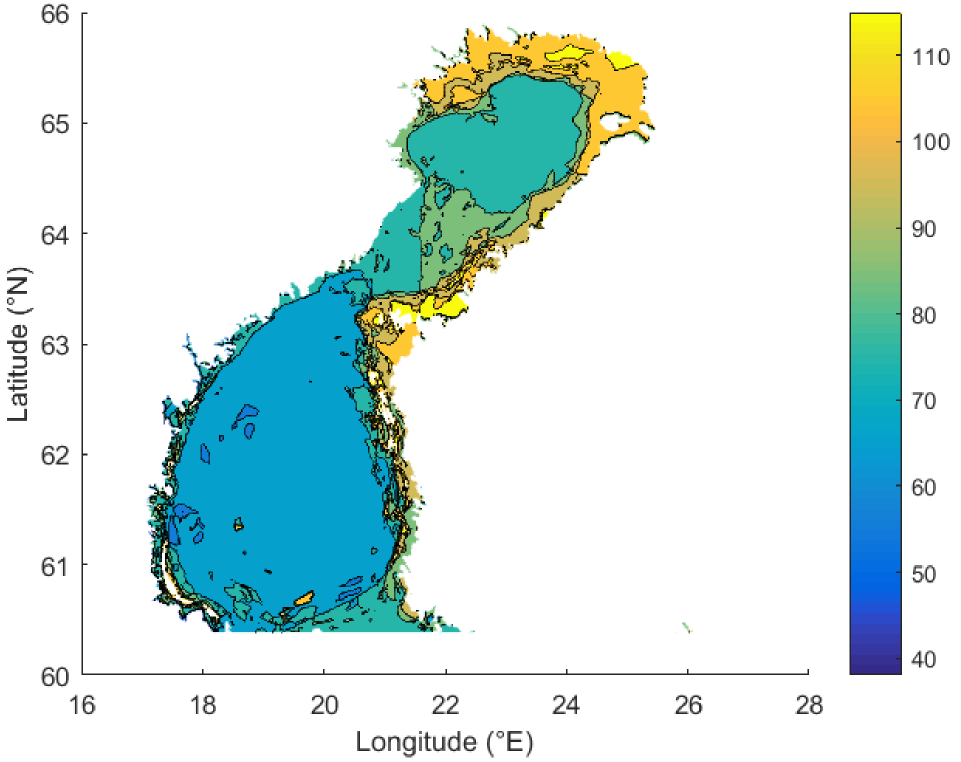

Figure 2. Maximum ice thickness occurring once in 50 years in the Gulf of Bothnia. The analysis is based on the ice charts of the Finnish Ice Service from the winters of 1980/1981 to 2016/2017.

Figure 3 presents the maximum degree of ridging occurred between the winters of 2006/2007 and 2014/2015. Numbers 1-3 present slightly, moderately and heavily ridged areas, respectively. Number 0 indicates that no ridging was registered at the grid cell during the entire period. Rafted ice and brash ice barriers are excluded from the figure. It can be seen that areas where heavy ridging occurs are dominating, and that ridging of ice has been present almost everywhere in the Gulf of Bothnia during the winters of 2006/2007 to 2014/2015. This means that ice ridges must be taken into account as a design load case for offshore wind turbines in the Gulf of Bothnia. Only some areas close to the shore and in the archipelago are sites with no ridging, because there the ice remains immobile throughout every winter. This can be seen by comparing Figure 4 and Figure 5.

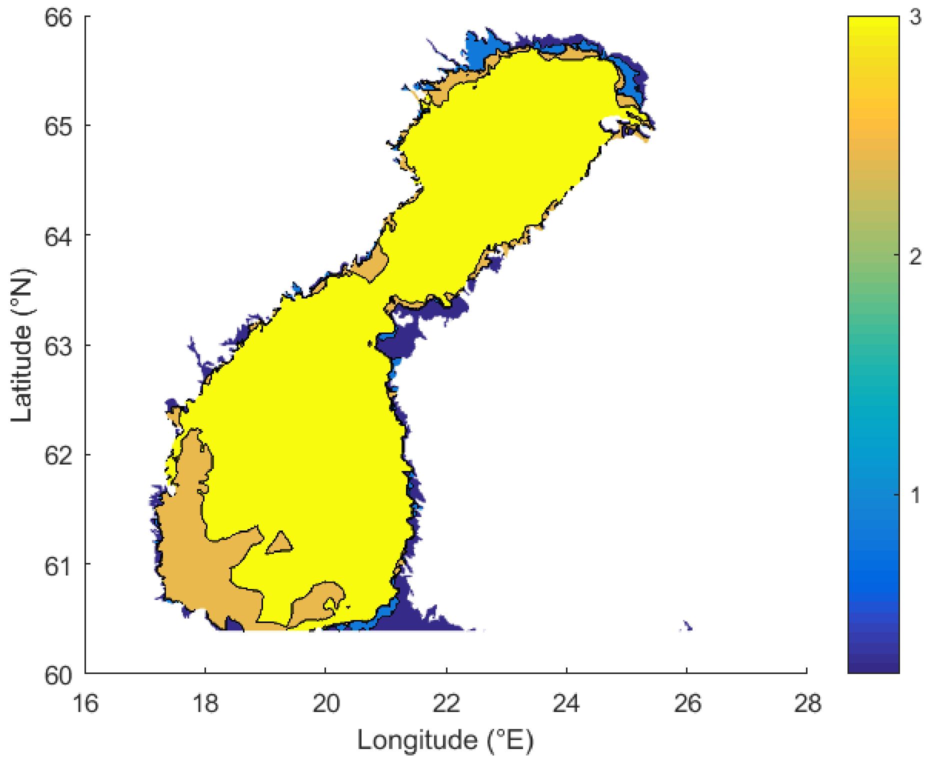

Figure 3. Maximum degree of ridging in the Gulf of Bothnia during the winters of 1980/1981 to 2016/2017.

Figure 4 shows the annual average number of days with any type of ice, and Figure 5 presents the annual average number of days with fast ice. The annual average number of days with ice in the Gulf of Bothnia varies between 15 and 180 days, and with fast ice between 0 and 160 days. The maximum number of days with ice of any type and with fast ice is located in the northernmost part of the Gulf of Bothnia. Fast ice occurs close to the shores and sheltered areas in the archipelago. Other types of ice occur in the more open sea.

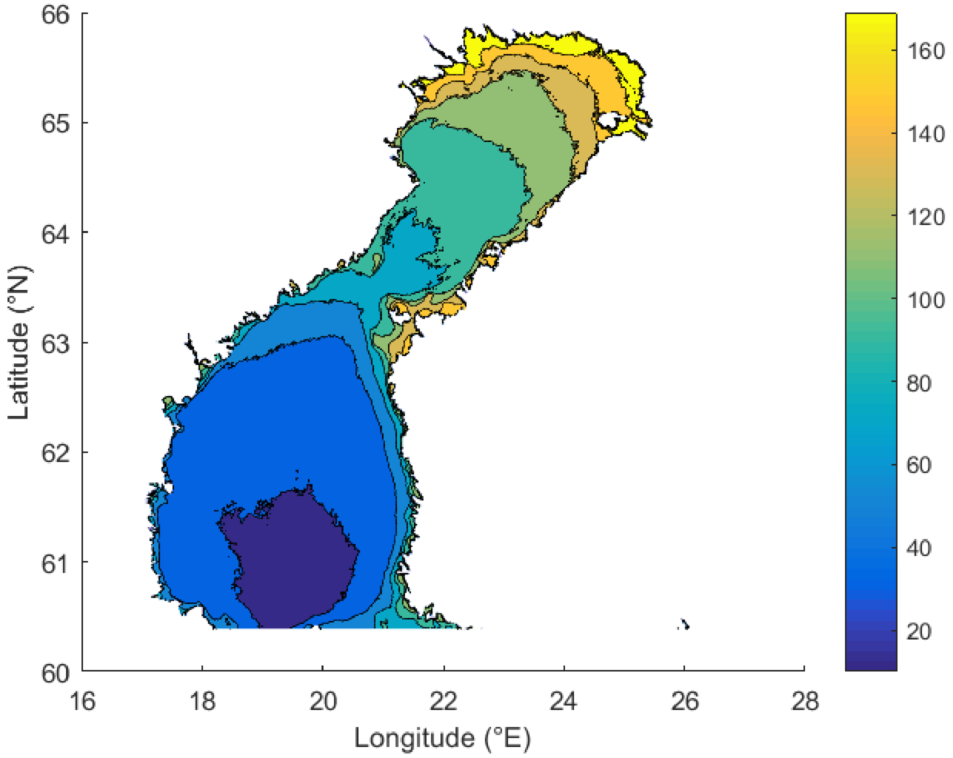

Figure 4. The annual average number of days when ice was present in the area.

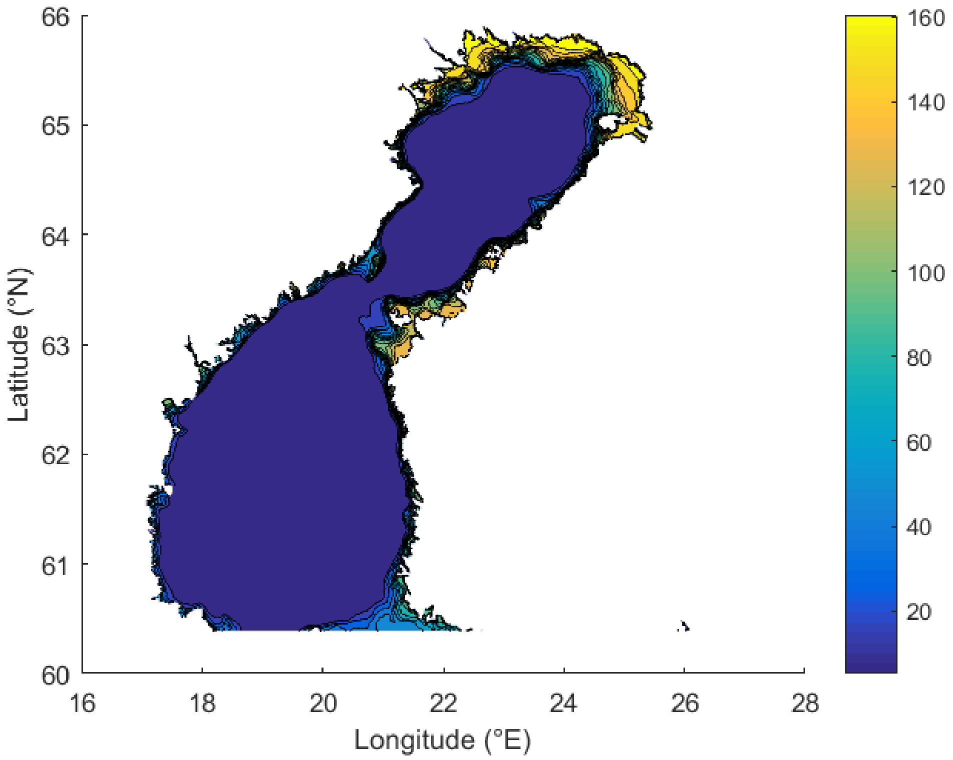

Figure 5. The annual average number of days when fast ice was present in the area.

DISCUSSION

This kind of database, in which historical ice charts were used to estimate the ice parameters to be used in offshore wind turbine design to this extent, is unique. In order to be able to establish such a database, a long history of ice charting in the Finnish Ice Service was essential.

Even though this database provides an excellent possibility to estimate the ice conditions for offshore wind turbine design, the nature of the ice charts as a source material must be understood. Each ice chart has been produced by an expert working in the Finnish Ice Service. The expert has combined the available knowledge of ice from e.g. satellite, airborne and on-site observations, as well as weather data, into a chart that is primarily intended to be used for navigational purposes. This means that the ice charts do not present only real observations from the whole area. When making the final assessment of ice conditions for the design, an expert's assessment of the local conditions is needed.

CONCLUSIONS

In this paper, the ice condition data produced for the web-based ice load design portal for offshore wind turbine design was presented for the Gulf of Bothnia. The data was based on the series of 37 years of the Finnish Ice Service's ice charts for navigational purposes from the winters of 1980/1981 to 2016/2017.

The main results, including 50-year level ice thickness, degree of ridging, the length of the winter season and existence of fast ice, were presented for the Gulf of Bothnia in the Baltic Sea. The maximum level ice thickness occurring once in 50 years varied between 40 and 120 cm. The annual average number of days with ice in the Gulf of Bothnia varied between 15 and 180 days, and with fast ice between 0 and 160 days. Ice ridges need to be taken into account in offshore wind turbine design in most of the Gulf of Bothnia except for some sheltered areas.

The ice condition data of the developed ice load design portal is a unique dataset. To the best of our knowledge, this kind of effort combining decades of ice charts for navigational purposes and their statistical analysis is not available for any other marine area. The presented ice condition dataset together with other environmental parameters implemented in the portal provides a large amount of information for spatial planning of wind parks. In addition, other ice parameters to support the offshore wind turbine design and other purposes can be estimated at a later date based on the digital ice chart data used in this study. However, in the final design of the offshore wind turbines, more detailed knowledge about local conditions might be needed.

This work will be continued and more detailed results for the whole Baltic Sea will be presented in a future work.

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REFERENCES

Heinonen, J., Tikanmäki, M., Kurkela, J., Klinge, P., Hekkala, T., Koskela, J., Montonen, A. & Eriksson, P.B., 2018. Ice load design portal for sub-structures in offshore wind turbines in ice-covered sea areas. In: Proceedings of the 28th International Ocean and Polar Engineering Conference, ISOPE 2018. vol. 2018-June, pp. 475-482, 28th International Ocean and Polar Engineering Conference, ISOPE 2018, Sapporo, Japan, 10/06/18

Leppäranta, M., & Myrberg, K., 2009. *Physical Oceanography of the Baltic Sea*. Springer.

Makkonen, L., & Tikanmäki, M., 2019. An improved method of extreme value analysis. *Journal of Hydrology X*, 2(2019), pp.100012.

SMHI, Swedish Meteorological and Hydrological Institute and Institute of Marine Research, Finland,1982. *Climatological Ice Atlas for the Baltic Sea, Kattegat, Skagerrak and Lake Vänern (1963–1979)*, Norrköping, Sweden.

Tikanmäki, M., Heinonen, J., and Makkonen, L., 2012. Estimation of Local Ice Conditions in the Baltic Sea for Offshore Wind Turbine Design. In: Zhijun Li and Peng Lu, eds. Proceedings of 21st IAHR International Symposium on Ice.