Proceedings of the 26th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2021, Moscow, Russia

Predicting the speed of ships on the Northern Sea Route using ice concentration isolines

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ABSTRACT

The speed modes of movement for ships in continuous ice on the Northern Sea Route are poorly understood at present. The existing methods for predicting the speed of ships are based on its tactical and technical characteristics and aren't suitable for the Arctic conditions because they give large errors, which leads to economic uncertainty for many shipowners. The most objective and operational information about the speed of movement of ships in ice are AIS data, space and radar images. The processing of these data was carried out using the methods of mathematical statistics and using geographic information systems. Large-capacity ships with high ice class Arc7 and their routes in the Kara Sea during the winter navigation period were selected as objects of research. The main research method is the construction of lines of equal values for the speeds of ships in different parts of ice fields and in clear water. For ice fields, according to radiometric monitoring data, ice concentration fields with a grid of 1 square kilometer were determined, land areas were automatically removed, the separation line of clean water and ice edges was also recorded every day. Zones with the highest ice concentration were identified, which were also indicated using level isolines. The combination of lines of equal parameters of speed and ice concentration made it possible to measure the magnitude of the change (decrease) in the speed in comparison with the passport for clear water. Since several real AIS tracks can be collected for the water area of the Kara Sea during the day, quite adequate and related information about the change in speed in the ice is obtained. This work is rather the creation of a methodology for choosing a strategy and numerical methods for predicting the speed of movement of groups of vessels in the ice of the NSR, if it becomes possible to obtain satellite images several times a day, it can be used in practice. The processed data showed good convergence for the same areas of ice fields. In the future, this technique can be used to find the most optimal routes along the Northern Sea Route.

KEY WORDS: Northern Sea Route; Geoinformation modeling; Ice concentration; Ships speed; Level isolines.

INTRODUCTION

The movement of ships in ice fields is the most important problem for shipping in the Arctic. The transport system of the Northern Sea Route (NSR) has been actively developing in the past few years, a long experience of year-round navigation has appeared in the Kara Sea, the Ob Bay and the Yenisei Gulf, the problem of choosing the optimal route in the ice remains urgent. The traditional approach is based on the analysis of historical ice thickness data and is good in terms of using actual data, but still insufficient in geographic scope. Erikstad (2012) proposed the use of models with undefined input parameters, but known boundary conditions for navigation along the NSR, which depend on the ice class of the vessel and the extent of the ice. Such a model is good for qualitative analysis, but gives large deviations for quantitative predictions of vessel speed. Jeong (2018) presents a system for planning voyages in the Arctic, taking into account ice resistance, the model used remote sensing data from satellites, which provided data on the concentration of sea ice. Cheaitou (2019) provides data on the average thickness of sea ice and standard deviation in the Arctic for the period 2006-2016 at a cell of 12.5 km along the entire length of the NSR. In the studies of Kim (2020), to predict the speed of ships in the Kara Sea, it is proposed to use machine learning technology based on the use of historical data (tracks) obtained using a space-based automatic identification system (AIS). Pastusiak (2020) examines the impact of hazardous ice phenomena on the movement of ships, of particular interest is the section on the model of a long-term and operational decision support system for planning and scheduling ship voyages in the Arctic. The statement of the problem in this work is the existing methods for predicting the speed of ships on the NSR, based on its tactical and technical characteristics, are not suitable for Arctic conditions, since they give significant errors over long periods, which leads to economic uncertainty for many shipowners. The study by Aksenov (2017) proposes route optimization algorithms with an estimate of the sailing time, considers the development of route optimization tools to assess the fastest transarctic route, taking into account ice conditions for a particular season (navigation) of the year and the ice class of the vessel, all models are based on data analysis from satellite sounding, mainly by ice concentration. In the study by Ol'khovik (2019), we gave an overview of the actual duration of the movement of YamaMax vessels of the ice class Arc7 in the Kara Sea in 2018 along the route of the Kara Gates Strait - Ob Bay for summer-autumn navigation (September) and winter-spring navigation (March), which showed that the time of the sea passage significantly depends on the lateral deviation relative to the recommended route. Various climatic scenarios for Arctic shipping (for example, SSP5-8.5 according to the results of the study by Chen, et al., 2021) predict an extension of the ice-free navigation period by a month, until October-November after 2030, however, as we see most anthropogenic influences, it has ten-year cyclicity, which repeats with wide variations in the parameters of ice conditions. Thus, it can be noted that at present there are no objective and scientifically substantiated methods for laying routes for ships in the ice of the NSR, in most cases everything depends on the experience and information support of the ship's captain, who chooses one or another ice navigation tactic. This work is rather the creation of a methodology for choosing a strategy and numerical methods for predicting the speed of movement of groups of vessels in the ice of the NSR and choosing the most optimal route for navigation, if it becomes possible to obtain satellite and radar images several times a day, it can be used on real practice.

MATERIALS AND METHOD

In this work, as the initial data on ice concentration in the Arctic, we used data provided by the research group of the University of Bremen "Remote sensing of polar regions", which are calculated daily, in near real time, from satellites AMSR-E and AMSR2, using the techniques and models proposed by Spreen (2008), Melsheimer et al. (2019) and Ludwig et al. (2020). The data from the archives of the Automatic Identification System (AIS) were used to analyze the routes of movement of vessels. We limited ourselves to the region of the Kara Sea and the Gulf of Ob, in which year-round shipping has been organized for several years. We used geoinformation modeling technologies as tools for data processing; their advantages for the analysis of shipping are presented in the works of Tezikov (2021) and Ol'khovik (2018). Figure 1 shows the routes for the movement of oil shuttle tankers of crude oil (42K) in March-April 2018 along the route "Kara Gate - the entrance to the Gulf of Ob Bay" in both directions, when ice conditions are most difficult. The green stripe lines indicate the recommended routes in the form of straight lines, which relate to the summer-autumn navigation during the ice-free period. The boundaries of the entrance and exit are shown with dashed lines, the route with thin colored lines. We found that vessels deviated significantly from the recommended routes eastward by more than 100 nautical miles, due to bypassing areas of dense ice, the thickness of which was constantly increasing. In the coastal area, ice was destroyed, its separation from the fast ice and constant movement associated with sea currents. It should be noted that routes without the use of icebreaker escort were selected for the analysis, since nuclear icebreakers are of great power and can overcome ice in the center of the Kara Sea during this period of the year. All routes of vessels are crossing ice with different concentration and areas with clear water, where the maximum speed corresponded to the technical data of the vessel's passport. Arctic sea ice concentration maps are presented in several graphics formats, these are *.PNG and *.NIC images, which have different color scales, the former is similar to the National Ice Center, and the visual color scale uses white and grayscale. Additionally, sea ice concentration data is available as HDF4 files, each file contains one 2D sea ice concentration array in a polar stereographic grid. In this work, we used *.GEOTIFF images with the NIC color scale, which is adapted to work in the QGIS GIS. Ice concentrations are scaled from 0 to 100, land and missing values are set to 120. To rank the concentration, we additionally ranked the data as follows: clear water: 0-39; land: 201-255; ice edge: 40-159; thin ice: 160-179; solid ice: 180-200. The scale of the coordinate grid corresponds to the size of 6, 3 and 1 km, which is quite enough for assessing the impact on navigation, given that the linear size of Arc7 ice class vessels is from 250 to 300 meters, i.e. one cell is for 5-7 ship lengths.

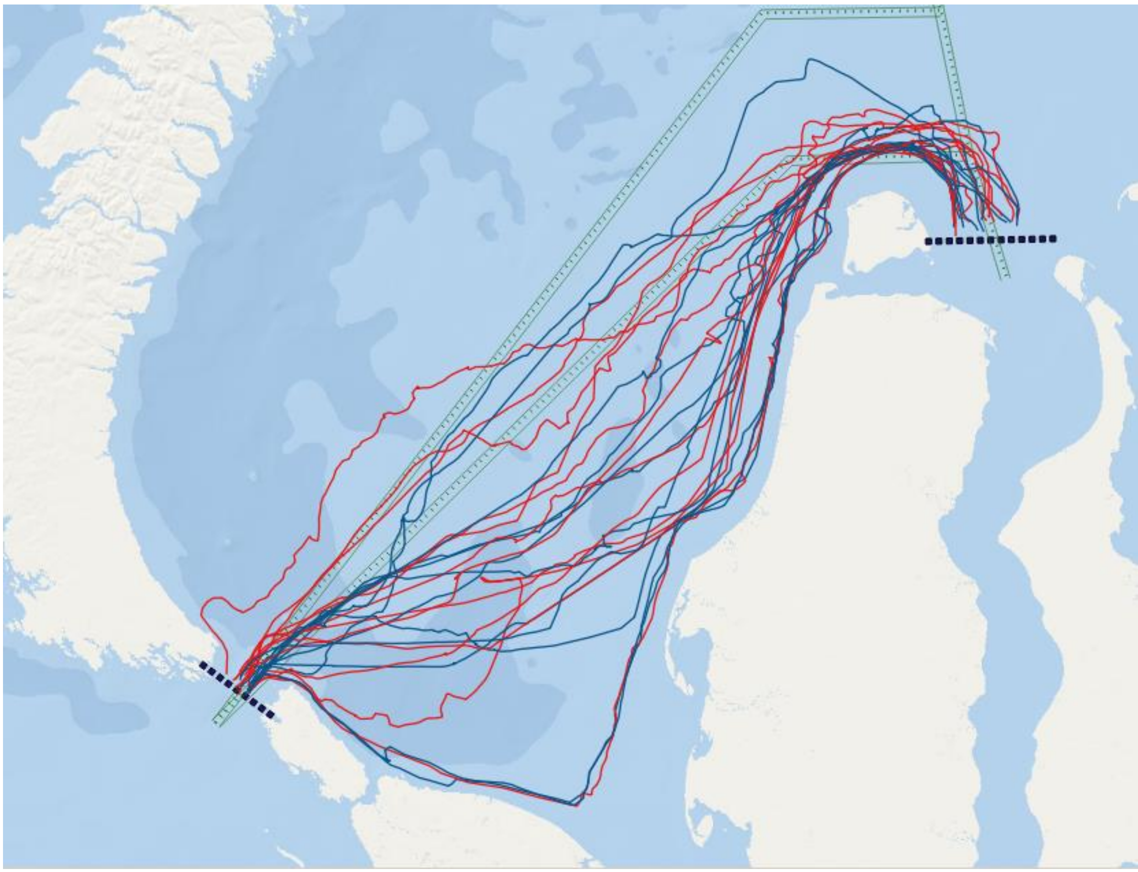

Figure 1. Crude oil shuttle tankers (42K) routes in March-April 2018

RESULTS

We carried out a detailed numerical study of the speeds of movement of oil shuttle tankers of the K42 type of ice class Arc7 from the Barents Sea through the Kara Gates to the Gulf of Ob, the results are shown in Figure 2. The vertical axis shows the speeds in nautical miles, on the horizontal axis, the sea crossing time in hours, in addition, the graph provides explanations of geographic features and sea ice. Movement speed graphs were built according to AIS messages. Despite all the variety of routes shown in Figure 1, we chose the routes that most closely coincided with the recommended routes on clear water in Kara sea, this approach is justified by the fact that on these routes it is possible to collect a large amount of data on the speed of movement with reference to geographic coordinates. As can be seen from the graph in Figure 2, the vessel's speed changes stepwise, this is clearly related and explained by the ice resistance. The ice concentration in digital values is taken according to the Sea Ice Remote Sensing Group's data once a day, then it is possible to combine the archives of vessel speeds on the route with the ice concentration.

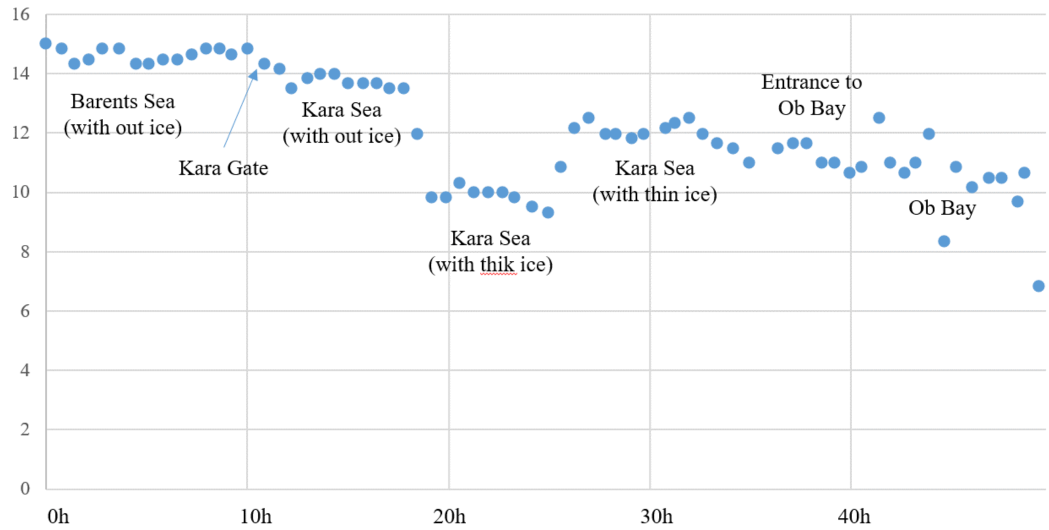

Figure 2. Speeds driving modes of crude oil shuttle tankers (42K) in March-April 2018

Undoubtedly, the ice thickness has the maximum effect on the ship's speed, but this parameter is not available from radar images or is available in a limited sense up to 60 cm, and during the winter-spring navigation in the Kara Sea, the ice thickness reaches up to 1.5 meters. The process of ice formation takes a long time, while fast ice can break down forming areas with open water, and ice hummocks form in large areas during the passage of ships due to the overlapping of ice floes. Thus, it is clear that the thickness of ice on shipping routes is variable, both along the length of the route and during several days. Nevertheless, some parameters, such as - ice edge along the section with clear water or areas with thin ice, low concentration can be identified from space-based radar images from AMSR-E/AMSR2. We have developed algorithms that, using digitized radar images, based on ice concentration data, determine the position of the ice edge with a width of 5-20 nautical miles, which later determined the moment ships entered the ice fields. The next solution is to identify local areas with clear water or low ice concentration, the practical significance of such a task is to identify the possibility of bypassing ice fields and laying out optimal routes. And a new promising solution is the construction of lines of equal values (isolines) according to the data on the concentration of sea ice. Plotting lines of equal values is a rather laborious task in the presence of a large scatter of data, for global ice maps, such an experience exists, for example, in the works of Pohl (2020) and Xie et al. (2018). But the standard results of ice maps are always very large scale, which is associated with limited data and blurred geographic referencing, which makes them difficult for organizing navigation and laying routes. The second solution is to analyze high-resolution satellite images, but there is another problem - real-time photographs are very expensive and there may be sufficient time gaps due to low clouds. An example of plotting lines of equal magnitude based on data on sea ice concentration is shown in Figure 3, it was obtained using the developed algorithm and using software on Python and QGIS GIS.

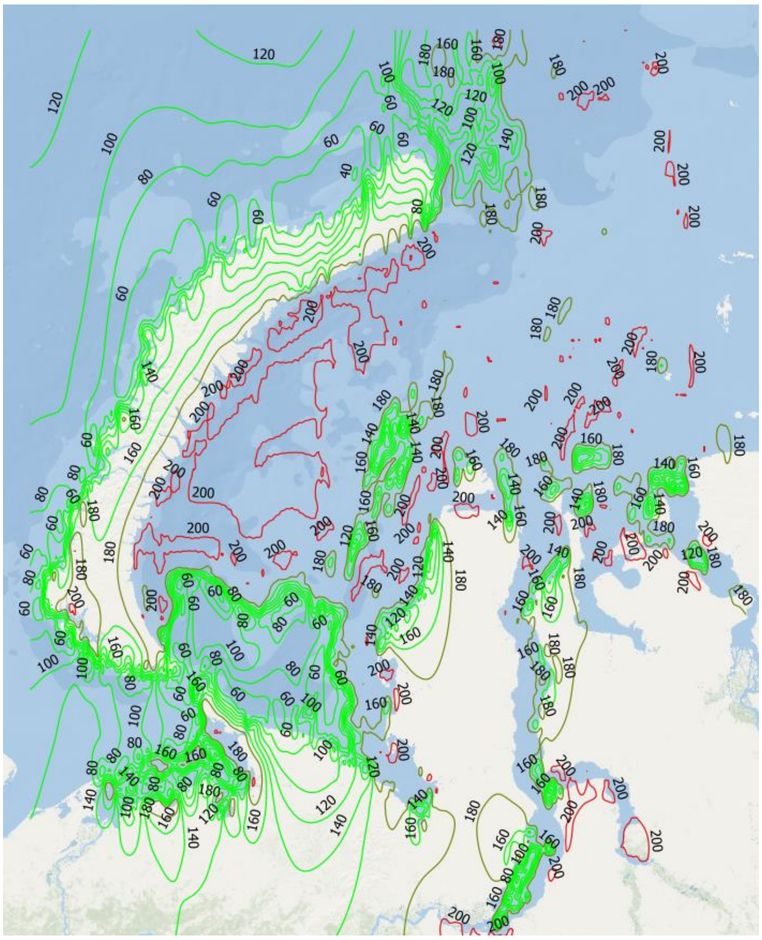

Figure 3. The result of plotting isolines (lines of equal size) based on the data on the concentration of sea ice in the Kara Sea

Green areas represent clear water, transition areas are thin ice or low concentration, and red areas are high concentration sea ice in which navigation is difficult. The numerical designations of the intensity of sea ice correspond to the purpose in the previous section. Space sensing data of sea ice in the Arctic is received and processed per day, and this is enough to identify routes with a width of 20-30 nautical miles for the passage of ships in light ice conditions. This, of course, is more related to the inter-navigation periods of time, but on the other hand, this range is 4-6 months in year. To check the adequacy of the results obtained, we superimposed the real tracks of the ships on this date, which is shown in Figure 4. The solid blue lines indicate the recommended routes for navigation, the colored triangles indicate the position of the vessel. It is clearly seen that vessels deviate from the recommended route lines to avoid ice obstacles. As can be seen from the figure, the real route is located with a lateral displacement to the east in the center of the Kara Sea.

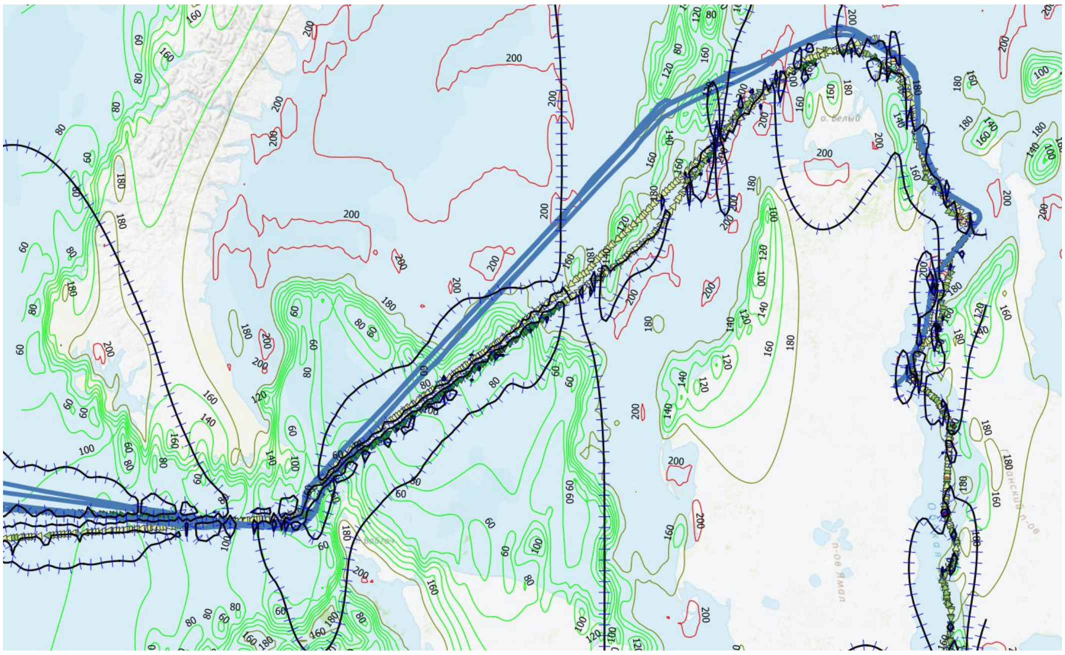

Figure 4. Combining the ice map with isolines of equal intensity and real tracks of ships in the Kara Sea

The speed modes of movement of vessels can also be identified, the speed in clear water was close to the technical capability, and when entering thin ice, it decreased. By analyzing the speeds of ships from the archives, it is additionally possible to construct such isolines only by the speed parameter, thus an areal mass will be formed according to the distribution of real velocities, which, when combined with ice concentration isolines, give a new result for optimizing routes in ice fields.

CONCLUSIONS

The proposed methods for processing digital data on the concentration of sea ice on the routes and in the water area of the Northern Sea Route make it possible to construct lines of equal equivalent values (isolines), which with high accuracy determine the following areas and boundaries necessary to ensure the safety of navigation, this is the interface of clean water and ice, local areas with thin ice and areas where ice is most concentrated. This approach is more accurate than traditional ice maps because it allows the identification of small areas rather than global areas. In the continuation of research, it is possible to combine real or archived tracks of ships with ice maps, then a new opportunity appears for analyzing the speed regimes of ship movement. This task is of high practical importance for laying routes and finding their optimal geographic forms. We performed an analysis on real data for high ice-class Arc7 crude oil shuttle tankers, which operate year-round in the Kara Sea and demonstrated the efficiency of the proposed methodology. The deviation from the recommended route took place in areas of clear water and thin ice, which were limited by consolidated ice on both sides. Nowadays, the difficulties are that the radar images are processed only once a day, and the next day, when the availability of data increases, the accuracy of forecasts will increase significantly. Taking into account the known ice drift velocities in the Kara Sea, it can be assumed that an objective forecast will require 4 radar satellite images per day. Research data was conducted at the Arctic

Faculty Admiral Makarov State University of Maritime and Inland Shipping and will be continued for other Arctic seas, especially for the eastern sector of the Northern Sea Route, where sea ice data and forecasts are still insufficient.

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