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Vessel movement velocity as the integral parameter of ice navigation conditions

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Abstract. The publication is considered methodology and preliminary results of computer processing of vector ice charts and simulation of ice navigation by empirical statistical model, which was designed in the AARI. The model is result of generalization of multi-year special ship ice observations, produced by the AARI scientists. The Institute has unique archive of ice charts, which were made by recognition of satellite images, their composition and vectorization. The archive covers the period since 1997. Average navigation velocity and total time expenditure for sailing along a route can be used as the objective indexes of the ice navigation conditions. In the article is presented detailed description of the technique for preparing data for numerical experiments with the empirical statistical model by applying the ice charts from the archive. The data preparing is processed in ArcGIS by means of specially designed computer programs. The numerical experiments simulate ice navigation of "Arctica" nuclear icebreaker. The comparison between the average navigation velocity and time expenditure for sailing along the route "Sabetta Port – Kara Gate Strait" at simulation of ice conditions in the first ten-day interval of May 1998 and the same temporal interval of 2019 indicates significant improve of the ice navigation conditions.

1. Introduction

Expected increase of the Arctic region usage in extraction of mineral resources, including ocean mining within the Arctic shelf, and cargo traffic along routes of the Northern Sea Route, including through traffic, is evident. A number of the Russian State programs, such as "Social-Economic Development of the Arctic Zone of the Russian Federation up to 2020" with additions till 2030, "Support of the National Plan of Actions for the Arctic Marine Environment protection", "Transport infrastructure development" define the Arctic region as "territories of advanced economic development" [1, 2]. Of course, this definition can be spread over the Russian exclusive economic zone in the Arctic Ocean. One of the territories is the Yamal Peninsula with the plant of natural gas liquefaction in the Sabetta City and numerous fossil fuels deposits [3, 4]. Next territory of the advanced economic development is the Taimyr-Turukhansk Region producing copper, nickel, platinum, and palladium. Exportation of the extractable resources from the both territories is mainly carried out by shipping. The development demands improving of the marine transport systems of the Northern Sea Route [5, 6, 7]. The Arctic is one of the main subjects of the Russian strategic interests



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[8]. With no doubt, the development proposes assessment and designing of the ecological safety and navigation conditions [9, 10, 11].

Therefore, it is necessary monitoring of ice navigation conditions along the standard paths of the Northern Sea Route. The average sailing velocity throughout a standard route and total time expenditure for the sailing can be used as the objective indicators of the degree of the sailing difficulty caused by ice conditions. The values can be calculated by means of the empirical statistical model [12]. Of course, we must make all the numerical experiments with the model for the same ship.

2. Materials and methods

In the Arctic and Antarctic Research Institute there has been processed the empiric statistical model of a ship movement at sea ice presence. The model parameters are: a) lengths of navigation route legs with homogeneous set of the ice cover characteristics in nautical miles; b) numbers of the ice cover age gradations (We can use no more than 4 gradations for a route leg); c) partial concentrations of the ice age gradations; d) the ice forms (the floes dimensions) separately for the ice age gradations; e) the ice thickness separately for the age gradations; f) average hummock degree for the route leg as a whole; g) average degree of the ice degradation for the leg as a whole. The model parameters are written in the text file with special structure. The ice characteristics of each leg of the route are written in separate string.

In the AARI, there has been processed methodology of the Institute archive of vector ice charts usage for the empiric statistical model initial data preparing. The processing of the ice charts in form of shapefiles is realized in ArcGIS by means of specially processed computer Python programs. The processing includes:

Reprojecting of the initial layers with ice information from geographical coordinate system in rectangular coordinate system;

Deleting of empty fields in attribute tables of the reprojected layers of the ice information;

Merging of the reprojected layers relating to separate Arctic seas;

Overlay operation of intersection between the merged layer of ice information and layer of buffer zone around a navigation route. The buffer zone has width in 20 km that is 10 km in each direction. The overlay operation produces new layer of homogeneous ice areas within the buffer zone;

Deleting of all probable spatial duplicates of the intersection result layer;

Dissolving of spatial objects of the layer with all identical ice characteristics;

Calculation of the layer spatial objects areas;

Calculation of ratios between areas of the spatial objects with various ice conditions within the buffer zone and total area of the buffer zone;

Production of the route length by the ratios. The results are average total lengths of the route legs within ice cover with unique ice cover characteristics;

Calculation of partial concentrations of various age categories of sea ice;

Identification of ice forms (floes dimensions) for each age category of the ice;

Adding of new textual field into the layer attribute table and its filling by sequences of partial concentrations of the ice age gradations. The field cannot comprise greater than four values of the partial ice concentrations. The numeral values of the concentrations are converted into textual ones and are separated by space symbol. Order of the values are from the oldest ice category with the biggest thickness up to the youngest ice. When number of the age gradations exceeds four, there are written partial concentrations of three oldest ice categories, and concentrations of all the rest ice gradations are summarized;

Creating the lists of the ice form codes. Each ice age category is characterized by one ice form code. However, values of the ice form codes in textual files of initial data for the empirical statistical model are different from the ice form codes in the attribute tables of vector layers of the ice charts. Therefore, we have to transform the codes by the Python program. When an ice age category has few ice forms there is written the form with maximal floes dimensions. In case of presence both floes and

medium floes there is written the special symbol. Forms of nilas and new ice are taken as medium floes and small floes;

Creation of new textual field and its filling by the ice form sequences also from the oldest ice category up to the ice of minimal thickness. When there are more than four ice age categories the form codes of three oldest age gradations are written. As fourth ice form, we use the form with maximal floes dimensions among the ice forms of the rest ice age categories;

Determination of the ice thickness in centimeters for the ice age gradations. If we do not consider the oldest ice age category in some homogeneous ice area within the buffer zone, we take center of the thickness diapason of the ice gradation as the value. For example, in case of the thin first-year ice the lower limit of the diapason is 30 centimeters, upper limits is 70 cm. Therefore, the ice thickness is 30 cm: $h = 30 + (70-30)/2$. We propose that the statistical distribution of the ice thickness of the all ice age gradations is equally probable one. In the case of the oldest ice age gradation, we have to determine the maximum possible ice thickness on the assumption of the thickness growth from the beginning of ice formation. For the determination, we have to interpolate values of the fast ice thickness according to figures provided by meteorological stations. Under otherwise equal conditions, there is some lag of drift ice growth in comparison of fast ice growth. The lag equals to two ten-days intervals in the case of cold winter, three ten-days intervals in the case of temperate winter, and four ones for mild winter. Definition of the winter type is carried out by calculation of sum of freezing degree-days after beginning of stable negative air temperature at meteorological stations of "Amderma", "Belyj Isle", and "Dixon". The number of meteorological stations making monitoring of the fast ice thickness is insignificant. Therefore, the interpolation is carried out by the IDW method only within the buffer zone of the route. The scheme of the monitoring stations in April 2019 is presented in the figure 1.

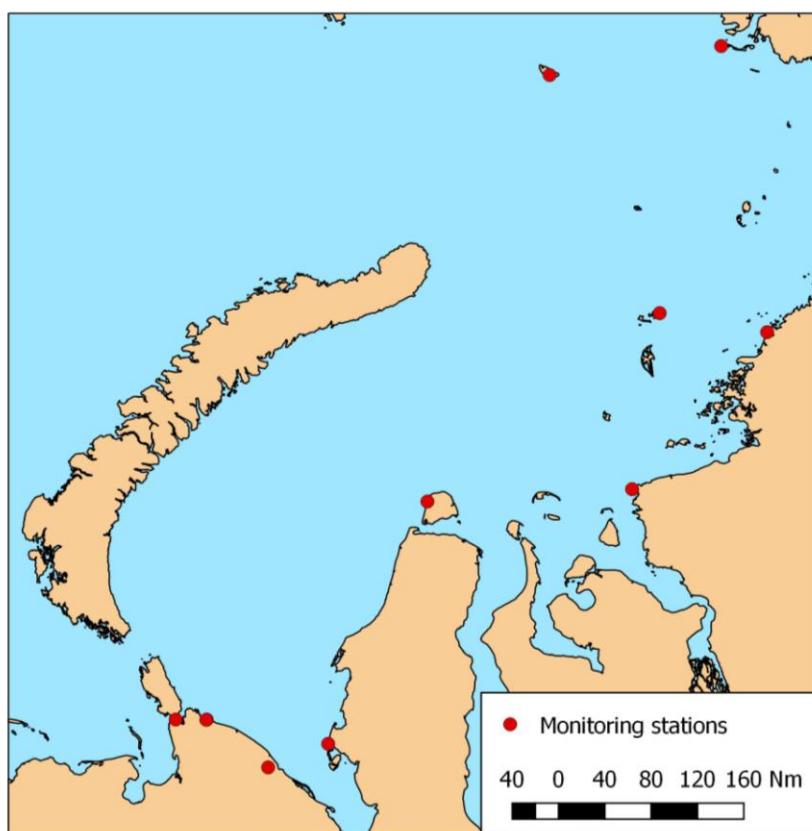


Figure 1. Scheme of the monitoring stations in April 2019

The figure 2 demonstrates result of the fast ice thickness interpolation on the basis of the monitoring in the first ten-day interval of April 2019.

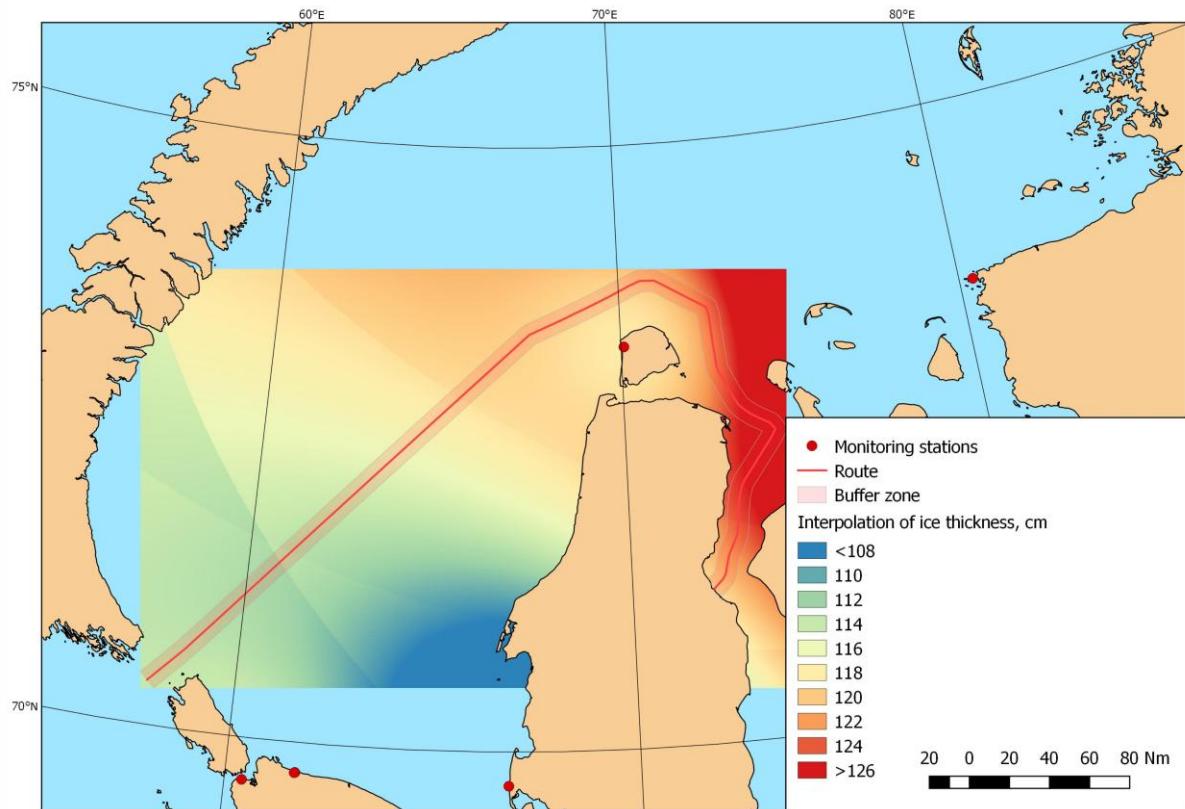


Figure 2. Result of the fast ice thickness interpolation on the basis of the monitoring in the first ten-day interval of April 2019

The ice chart of the first ten-day interval of May 2019 is presented in the figure 3.

If part of the buffer zone is situated within the fast ice, the interpolation is carried out twice: for determination of the maximal thickness of fast ice areas and drift ice areas. In the former case the initial data for the interpolation relate to the decade of Earth's remote sensing, which produced satellite images of the ice cover. In the latter case, we have to use as the initial data values of the fast ice thickness at the meteorological stations, which were measured at the lag interval earlier. The lag duration depends on the rigours of winter. At the interpolations, we have to use masks: in the former case, it is the fast ice areas within the buffer zone, in the latter case it is the drift ice areas. Then we carry out zonal statistics of the layer (layers) of the interpolation result. As the operation result, we get maximal and average ice thickness within each spatial object of the buffer zone. These values are the characteristics of the ice, which was produced at the beginning of ice formation, and it did not leave the zone. Of course, such approach does not take into account possible ice drift. We suppose equal probability of entering both thicker and thinner ice. The approach allows considering the ice thickness dynamics during the autumn and winter period. As the oldest ice thickness, we get the center of the diapason between the lowest value of the ice thickness and the maximal thickness according to the interpolation. If the upper limit of the oldest ice is less than the maximal ice thickness according to the interpolation, we get medium thickness of the ice category;

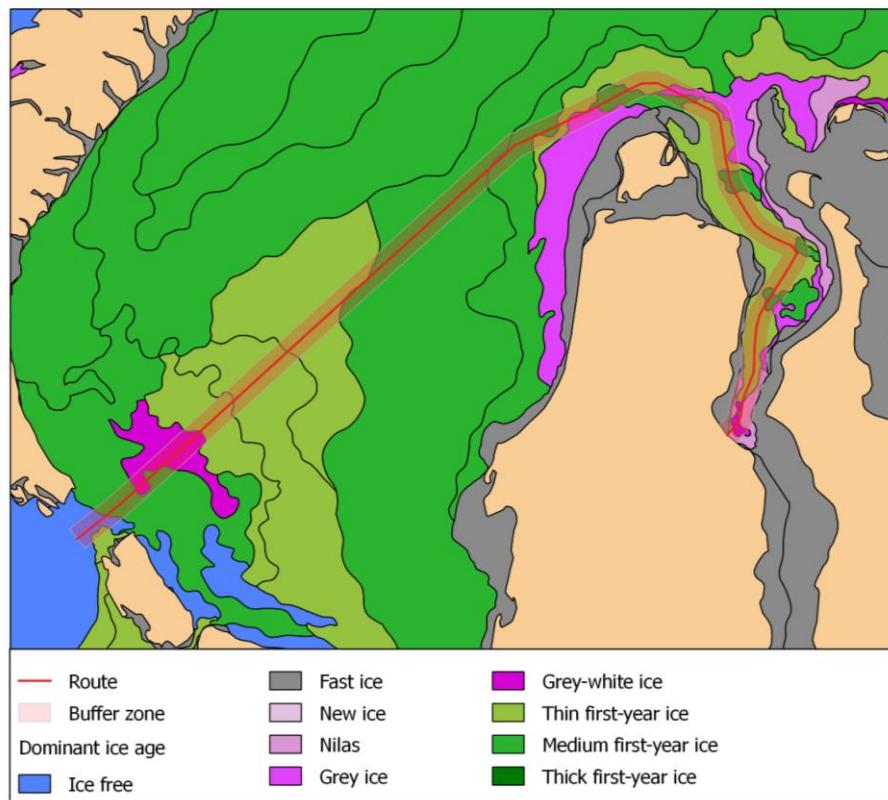


Figure 3. Ice chart of the first ten-day interval of May 2019

Creation of new textual field and its filling by sequences of the thickness of the ice age categories. If there are more than four age categories of ice, we determine thicknesses of three oldest age categories of the ice. Fourth element of the sequence that is the average thickness of the rest ice is calculated on the base of the medium values of the ice age categories with taking into account partial concentrations of the ice gradations;

Creation of new textual field and its filling by data for import into the empirical statistical model of ice navigation. The model calculates ship velocity and time expenditure. The values are divided by the space symbol. Data related to each type of ice within the buffer zone of the route are written into a separate record of the attribute table. The data include the following successions: length of a route leg in nautical miles, number of the ice age categories (it must not be more than four!), partial concentrations of the ice categories starting on the oldest ice, the model codes of the ice categories forms, the ice thickness in centimeters for each ice gradation, the hummock degree and degree of the ice degradation for the spatial object as a whole. The hummock degree is set as homogeneous value for the whole route according to multi-year results of the ice researches. The ice degradation degree varies from zero only during summer.

The late stage of the processing in sphere of ArcGIS is export of the textual field of the attribute table into separate textual file. An example of the file structure is presented in the figure 4.

The next step of the research is the ice navigation simulation by means of the empirical statistical model.

3. Results

The research results show that ice charts from the AARI archive can serve as an objective source of data for researches of interannual dynamics of ice situation and ice navigation conditions in the Arctic Ocean and other freezing seas. The empirical statistical model can be used as instrument for

calculation of the most objective indices of the ice navigation conditions: average navigation velocity of a ship throughout a standard route and total time expenditure for the route navigation.

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23.2 4 1.667 3.333 4.0 1.0 2 4 4 4 95 50 23 8 1 0 6666
8.8 4 2.333 4.667 2.0 1.0 2 4 4 4 134 95 50 15 1 0 6666
66.0 4 7.5 1.5 0.333 0.667 3 4 4 4 146 95 23 8 1 0 6666
168.7 4 9.0 0.5 0.167 0.333 3 4 4 4 138 95 23 8 1 0 6666
46.1 4 1.5 3.0 3.0 2.0 2 4 4 4 134 95 50 15 1 0 6666
0.8 1 10.0 0 171 1 0 6666
166.1 1 10.0 0 172 1 0 6666
36.8 0 6666
7777

```

Figure 4. Structure of the textual file with data for the empirical statistical model

The comparison between results of the numerical experiments with simulation of the nuclear icebreaker “Arctica” sailings throughout the route “Sabetta Port – Kara Gate Strait” in the first ten-day interval in May of 1998 and 2019 shows significant improving of the navigation conditions. Thus, the average velocity according to the results of the simulation of 1998 year ice conditions is equal to 6.9 knots (nautical miles per an hour), and the same characteristic of the 2019 simulation results is equal to 14.9 knot. Also there is the sizable decrease of the total time expenditure from 74.5 hours in 1998 down to 34.8 ones in 2019. Adding of the nipping condition (drift ice pressure on the ship hull) at the simulation does not change the ratios between the velocities and the time expenditures. Thus, in this case at nip in 1 unit of Russian three-grade scale the velocity in 1998 is equal to 6.7 knots, and in 2019 – 14.5 knots. The time expenditure decreases from 77.7 hours in 1998 down to 35.6 in 2019. The phenomenon may be explained by revealed significant change of spatial distribution of the ice age categories in the buffer zone of the route from 1998 to 2019. These distributions are presented in figures 5 and 6.

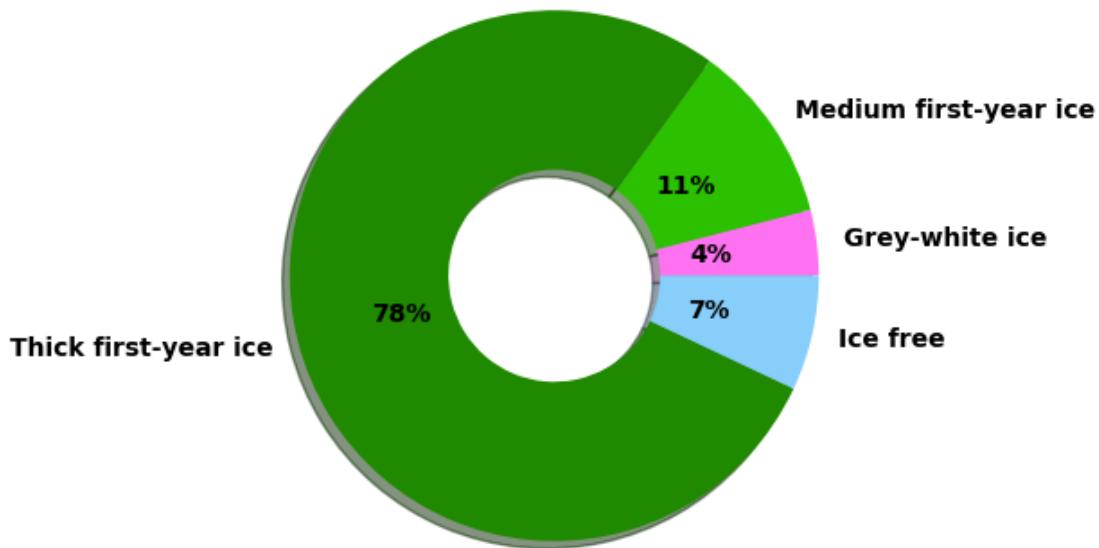


Figure 5. Total distribution of the ice age categories in the buffer zone in the first ten-day interval of May 1998

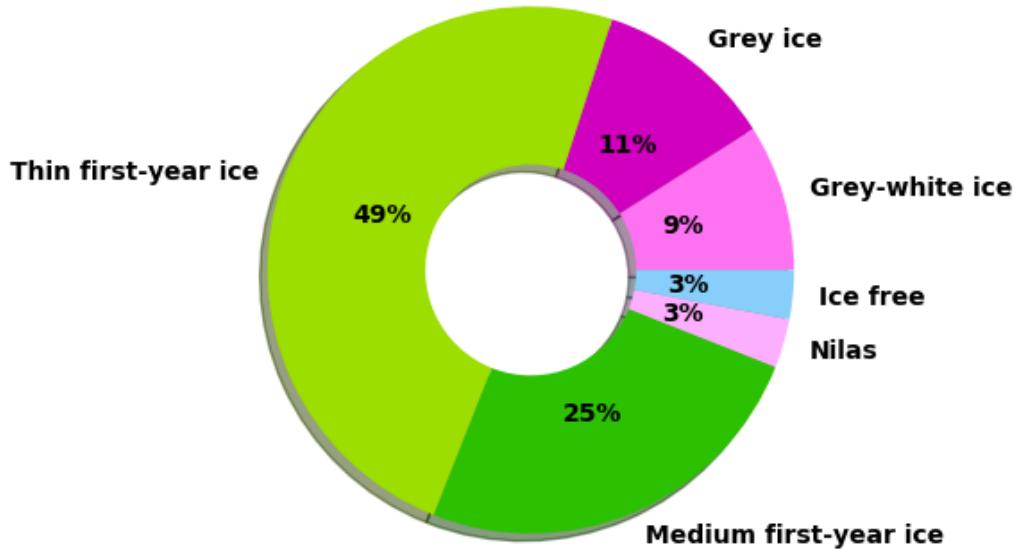


Figure 6. Total distribution of the ice age categories in the buffer zone in the first ten-day interval of May 2019

It is evident the thick first-year ice disappearance.

4. Discussion and conclusions

The research revealed significant possibilities of the empirical statistical model for climatic changes studying. The average velocities of sailings throughout the standard routes of the Northern Sea Route and the total time expenditures can be used as summarizing indicators of the climatic changes in the Arctic Ocean and freezing seas. Of course, the model does not take into account all factors which influence ice navigation. For example, it does not give consideration to cracks, fractures, and polynyas in ice cover. Nevertheless, numerical series of the normalized relative values can be examined for heterogeneity using various test for homogeneity.

5. Acknowledgements

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