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Comparative analysis of uncertainty factors in the problem of optimal ice routing

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ABSTRACT

This paper presents the methods and results of comparative analysis of uncertainty factors affecting the precision and efficiency of the automatic ship routing in ice. We tried to highlight and consider a set of interacting components of an overall ice routing procedure, each of which contributes to the uncertainty of a final result. They are (a) obtaining and primary processing of operational monitoring data on ice, such as satellite images; (b) recognition of satellite imagery and creation of diagnostic vector ice charts; (c) simulation of future ice dynamics and obtaining of ice forecasts; (d) accounting for auxiliary and difficult-to-observe ice features, such as ice leads, local breaks, hummocks, ice compressions; (e) accuracy of the model to predict resistance and other parameters of ship movement in ice; (f) restrictions of mathematical algorithms of optimal ice routing; (g) unformalized factors of navigator behavior that influence the choice of ice route and mode of movement. Multiple data sources were used to investigate the uncertainty of each of the components. We used ice charts and forecasts from several alternative providers, raw satellite imagery, historical AIS tracks of ship voyages, records from on-board expedition logs, and other data sources. The obtained results made it possible to estimate the relative contribution of each component to the overall accuracy of the complex algorithm of automatic ice routing.

KEY WORDS Ice routing; Remote sensing; Ice chart; Pathfinding algorithms; Ship transit model

INTRODUCTION

Ship navigation in ice-covered Arctic waters has a number of specific features in contrast to open water operation. Optimization of ship route under significant spatial and temporal variability of ice conditions is of major importance for efficient high latitude navigation. Recently, an ambitious idea to implement automatic ice routing services as built-in decision support tools in modern digital systems of fleet management becomes more and more popular. However, some shipmasters experienced in Arctic navigation are skeptical about the prospects of such an approach (Lehtola et al., 2020). This is mainly due to the number of uncertainties and significant inaccuracy in input data on ice parameters that do not allow obtaining sustainable results in every practical case. Therefore, there is a need for research that would allow us to better understand the constraints, peculiarities, and various issues in the practical implementation of ice routing services.

Most publications related to the problem of the automatic ship routing in ice pay main attention to one specific component of the general problem. E.g., Volkov et al. (2012) investigated the issues of ice monitoring and forecasting. Modeling of ship performance in ice using probabilistic approach and semi-empirical methods is described in (Montewka et al., 2015) and (Valkonen & Riska, 2014) respectively. Formal mathematics and numerical algorithms to find the optimal path in ice-covered waters were studied by Guinness et al. (2014), Lin et al. (2013), Wang et al. (2019), and Topaj et al. (2019). At the same time, there are only several publications where all these problems are considered simultaneously (Kotovirta et all., 2009; Schütz, 2014). In this study, we tried to continue such a comprehensive approach and reveal various uncertainty factors that influence the task of optimal ship routing in ice.

Fig. 1 shows a diagram of the main components and stages of the ice routing process. Such a process aims to find the optimal ship path in continuous and non-stationary media. However, the routing itself is a specific numerical optimization (NO) method that uses the spatio-temporal distribution of ship performance parameters (attainable speed or travel costs) as input data. Such data could be provided by a ship transit model (STM). The latter one uses the following input data: (a) ship informational model (SIM), i.e., the static description of a ship; (b) vector of environmental variables. Environmental parameters are represented mainly by ice data and could be divided into diagnostic ice charts (DIC) obtained from remote sensing (RS), and forecasted ice charts (IFC) provided by the models of the global circulation of the atmosphere, ocean, and ice. At the same time, some important local ice features, such as leads and cracks, are often either unknown or not considered in the ship transit model. Such features, as well as any other unknown ice parameters, are shown in Fig. 1 as supplementary ice factors (SIF). Finally, the choice of a path by shipmaster is often determined by subjective factors (SF) that cannot be involved in any formal model. In Fig.1 we considered the fact that experienced shipmasters prefer to use satellite imagery as the main source of ice data and rarely use predictive models and diagnostic charts. This conclusion is based on the results of our personal communications with Arctic shipmasters.

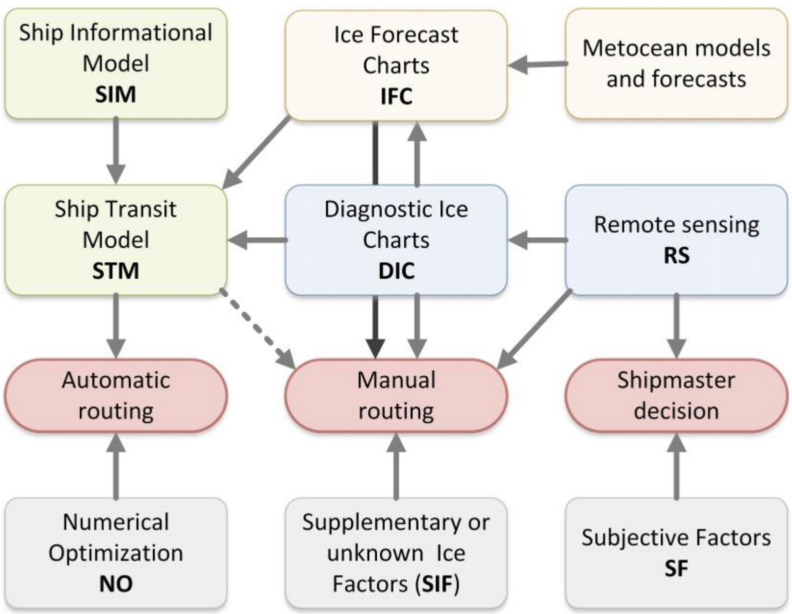

Figure 1. Interaction of uncertainty components in the ship routing problem

According to the classification in Fig. 1, the chain of sequential accumulation of inaccuracies and uncertainties ε during automatic routing procedure can be described by the following equation:

$$\varepsilon_{ROUTING} = F_{NO}(F_{STM}(F_{DIC}(\varepsilon_{RS}) + \varepsilon_{DIC} + \varepsilon_{IFC} + \varepsilon_{SIM}) + \varepsilon_{SIF} + \varepsilon_{STM}) + \varepsilon_{NO} + \varepsilon_{SF}, \qquad (1)$$

where lower index indicates the component of routing procedure according to Fig. 1; the capital letter F indicates a functional dependence of the procedure from some parameter.

The spatial distribution of ice can be described by a set of parameters grouped in DIC, IFC, and SIF blocks in Fig.1. These parameters influence the performance of a ship most of all. At the same time, some of ice parameters can be rather easily estimated from remote sensing images by explicit methods, while others can be assessed indirectly or sometimes can be completely inaccessible.

Ice concentration, i.e. the percentage of ice-covered areas in the region, determines the ability to choose the path through water openings by maneuvering. It can be explicitly estimated from the analysis of satellite imagery. ***Ice thickness*** is the main factor affecting ship resistance in ice. The radar images allow obtaining its absolute value with required accuracy. Another approach is based on strong coherence between ice thickness and ice age. The latter can be assessed by a qualified ice expert based on the colorimetric characteristics of satellite imagery at a specific point. The ***form of ice***, i.e. the typical size of ice floes, also significantly impacts ship performance. ***Concentration***, ***age,*** and ***form*** are the main and mandatory data in SIGRID-3 format, which is the conventional sea ice reporting standard. Moreover, the mentioned variables are presented in SIGRID-3 separately for the first, second, and third stages of ice development. It allows a more detailed and realistic description of the ice state in the current location. So, these principal characteristics of ice topography are the part of ε_{DIC} uncertainty component.

There are several additional characteristics of sea ice that strongly affect ship performance. ***Ice compression*** significantly influences both ship propulsion and navigation safety. Moreover, not only the compression pressure is important, but also its direction. From ice navigation practice it is known that lateral compression is much more dangerous than frontal one. ***Hummocks and ridges*** also significantly increase the ice-related ship resistance, as well as a thick layer of ***snow***. The physical and mechanical properties of ice affect ship performance as well and depend on the season and area of navigation. E.g., it is much easier to pass ***melting*** ice in summer than the ice of the same thickness in winter. Thus, such additional ice parameters as ***snow depth***, ***hummocks***, ***compression,*** and ***melting stage*** are the variables that also should be considered in the ship transit model, while they are optional in SIGRID. We would note here that SIGRID was historically developed as a geographically oriented standard, which is intended for the visual human-based (subjective) classification. All SIGRID parameters are represented by conditional codes, not by physical dimensional values. The latter fact is an additional source of uncertainty. E.g., age code 86 (First Year Ice) corresponds to ice thickness from 30 to 200 cm. It is clear that it is impossible to use such inaccurate values as input data for the ship transit model. Anyway, the only method today to obtain mentioned additional parameters of ice in a wide geographic area is the model-based forecasts, therefore the corresponding uncertainties should be included in ε_{IFC}.

Finally, there are supplementary ice factors (SIF), which are not included in SIGRID specification, but fairly influence the optimal path. It is the spatial distribution of leads, cracks, and other local discontinuities in ice cover. These small features have a width of a few hundred meters and can be observed on satellite images as a mesh of hardly recognizable thin lines. As a rule, such features are not taken into account when elaborating ice charts of integral ice parameters, while navigators always try to use favorable leads to facilitate the voyage. Similarly, local discontinuities are rarely considered in automatic vessel routing algorithms despite that it is quite important. The reason is the complexity of their presentation and formal description. The most precise approach here is to consider every crack as an independent linear object (polyline) in geographical space (May et al., 2020). However, so detailed ice charts are very hard to obtain. Also, the allocation of local breaks is very dynamic and can change significantly in a very short time due to ice drift. A generalized statistical description of the spatial distribution of leads seems to be a more sustainable approach (Losev et al., 2017). However, the use of such data as an input of the ship transit model requires the development of a solid methodological ground that will allow considering the impact of small discontinuities in ice cover on ship performance. The uncertainty caused by supplementary characteristics of ice is classified as ε_{SIF}.

If one of the parameters from the DIC or IFC group is unknown due to any reason it will also correspond to the ε_{SIF} uncertainty. Therefore, this uncertainty source reflects all ice parameters, which are unknown but influence the ice performance of a ship.

All ice data forms an input of the ship transit model (STM) that predicts vessel performance. In this study, we used a specially developed model that allows us to consider the influence of all ice parameters from DIC and IFC groups, while the model is unable to take into account discontinuities in ice cover. This model is based on a semi-empirical approach to calculate ice resistance and a static representation of forces interaction. The latter assumes the equality of thrust and resistance in a steady motion mode, the same as in (Kotovirta et all., 2009). The detailed description of this model goes beyond the scope of the current paper. However, we should note that there are various sources of uncertainty inside the model due to different assumptions and simplifications adopted under its development. Therefore, we could generalize that any STM-model will not guarantee an absolute accuracy in the prediction of vessel movement parameters. All corresponding uncertainties could be classified as ε_{STM}.

We used also an original algorithm for numerical optimization (NO) of ship route in non-stationary ice conditions, which is a modified combination of two well-known mathematical methods. They are the graph-based A* algorithm and cell-free or wave-based approach that extends the isochron technique. The program tool, developed based on this algorithm, takes into account the following aspects: 1) versatile cost function incorporating such factors as total voyage time, fuel consumption, icebreaker freight, and navigation risks; 2) identification of areas where the icebreaker assistance is economically proven; 3) optimization of sailing mode (stern- or bow forward) on route segments; 4) original algorithm to reduce the number of points in a wavefront based on the Concave Hull method; 5) consideration of the predefined fairways and restricted areas. Mathematical aspects of this algorithm can be found in (Topaj et al., 2019). The uncertainties related to the ice routing algorithm itself are mentioned as ε_{NO}.

In this article, we applied various methods to assess the contribution of each term to the overall uncertainty. The methods and data are described in the next section. Analysis of various uncertainty factors is presented in the section “Results and discussion”, while the resulting diagram of the contribution of different components is given in conclusions.

MATERIALS AND METHODS

To obtain the rough estimates of the value of each term in Eq. (1) we applied different methods and used various data sources.

Analysis of the uncertainty from diagnostic ice charts (DIC) was done by comparing the spatio-temporal datasets obtained from different sources for the same dates and geographic areas. Since diagnostic ice charts are developed using remote sensing images (RS), corresponding uncertainty could be written as $F_{DIC}(\varepsilon_{RS}) + \varepsilon_{DIC}$. Table 1 contains the principal details of the used data sources. The advantageous features of each data provider are highlighted in bold. Horizontal arrows show the operations we done during the pairwise comparison of the same data from various sources.

The uncertainty of forecasted ice parameters for the current or future time step (ε_{IFC}) was estimated by comparing the diagnostic and forecasted ice charts (or the pairs of diagnostic ice charts prepared at different time) obtained from the same provider, the same time point, region, and ice parameter. Vertical arrows in Table 1 represent the procedure of comparison of various ice parameters from one particular data provider. The data sources considered under ε_{DIC} and ε_{IFC} uncertainty analysis were the following:

- Archive ice charts provided by the World Data Center of Russian Arctic Antarctic Research Institute (AARI, http://www.aari.ru/).
- Selected set of ice charts provided by Weathernews Inc. (WNI, https://global.weathernews.com/) from Japan.
- Demo raster charts of ice classification, provided by Nansen International Environmental and Remote Sensing Centre (Nansen Center, http://ru.niersc.spb.ru/)
- OSI product databases developed by the Norwegian and Danish Meteorological Institutes in a frame of European Organization for the Exploitation of Meteorological Satellites – EUMETSAT (ftp://osisaf.met.no).
- Dispatcher reports and expedition logs that contain the results of onboard observations of ice conditions for several voyages of transport arctic ships (see Table 2).

The degree of conformity of any pair of vector ice charts was assessed numerically by calculating the formal statistical correspondence of two datasets. Each dataset consists of the values of the studied parameter at the points of a predefined regular grid superimposed on both charts (see Fig. 2 as a demo).

Accuracy of ship transit model (STM) and its sensitivity to the uncertainty of input data ($F_{STM}(\dots) + \varepsilon_{STM}$) were studied by comparing the calculated values of ship performance parameters under ice conditions from expedition logs and factual performance parameters from onboard observations. See Table 2 for the details of this study.

The degree of influence of unknown ice factors (ε_{SIF}) were investigated in the following manner. We excluded some ice parameters of the DIC or IFC groups from the available datasets and run the ship transit model with a limited set of input data. The results obtained for the complete and limited datasets were compared with each other. This allowed us to reveal the sensitivity of the ship transit model to the lack of information on some ice parameters.

The overall uncertainty of the algorithms of ship routing in nonstationary ice conditions ($F_{NO}(\dots) + \varepsilon_{NO} + \varepsilon_{SF}$) was assessed through comparison of model and factual results for several historical ship voyages. The basic layout of each real route was recommended by a qualified ice expert, while the factual ship tracks could differ in some details due to the decisions of shipmaster. Corresponding factual tracks could be found from AIS records. In addition, we used high-resolution satellite images and expedition logs to explain the obtained discrepancies and identify the influence of various subjective factors for every case.

Table 1. Ice parameters and data providers in the analysis of ε_{DIC} and ε_{IFC} uncertainties.

Parameter	AARI	WNI	Nansen Center	OSISAF	Onboard reports
Concentration (Diagnostics)	Open access (Diagnostics), Limited access (Forecast) **Data for 3 development stages** SIGRID format (codes) Vector charts	Commercial access Single value for the point **Dimensional values (%, m)** Vector charts	Can be estimated from high-resolution charts of ice age	Open access Single value for the point **Dimensional values, %** **Raster data**	Limited access Local data in 4-6 hr temporal resolution SIGRID format (codes)
Concentration (Forecast)			Absent	Absent	Absent
Age, Thickness (Diagnostics)			Commercial access Single value for the point Ice age classification **High-resolution raster data**	Open access Single value for the point Binary classification Raster data	Limited access Local data in 4-6 hr temporal resolution SIGRID format (codes)
Age, Thickness (Forecast)			Absent	Absent	Absent
Form (Diagnostics)		Absent	Can be estimated from high-resolution charts of ice age	Absent	Limited access Local data in 4-6 hr temporal resolution SIGRID format (codes)
Form (Forecast)			Absent		Absent
Hummocks	Limited access Forecast only SIGRID format (codes) Vector charts	Absent	Absent	Absent	Actual data Limited access Local data in 4-6 hr temporal resolution SIGRID format (codes)
Compression	Limited access Forecast only No direction SIGRID format (codes) Vector charts	Commercial access No direction **Dimensional values (kPa)** Vector charts	Absent	Absent	

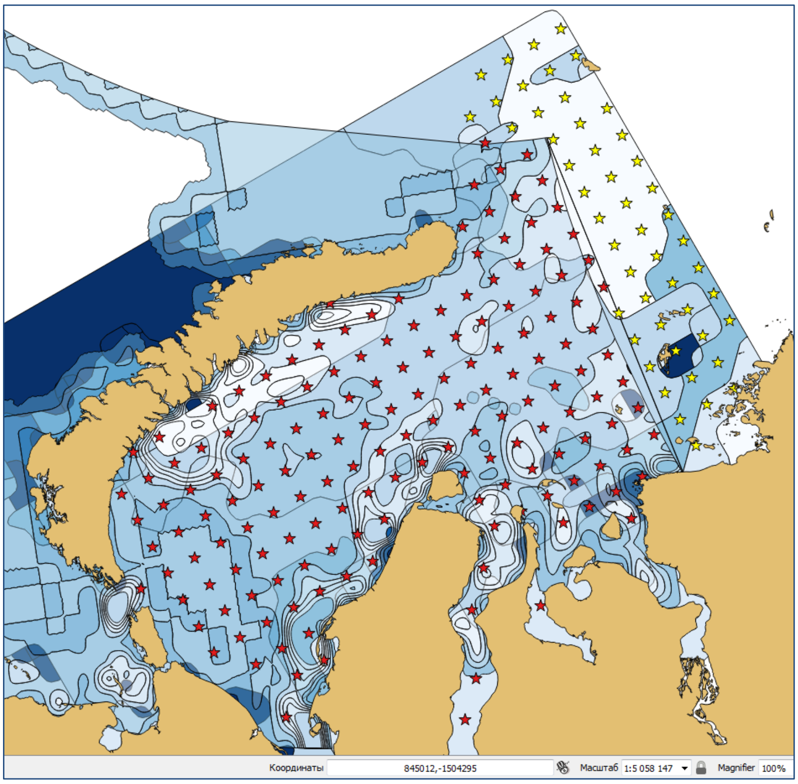

Figure 2. Assessment of the correspondence of two vector ice charts on a regular grid of compared points

Table 2. Case study of arctic ship voyages

Ship (IMO, Project)	Voyage Dates	Data type	Notes
ENISEY 9079169 Aker ACS 650	01–07.02.2018	AIS records, Ship onboard report summaries, recommended routes	Observations of actual ice state, parameters of vessel movement regime
NORILSKIY NICKEL 9330836 Aker ACS 650	19–24.03.2018		
	30.04–02.05.2008	AIS records, Detailed data on expedition logs	Detailed data on outboard and nearest ice conditions, shaft power and speed, etc.
ZAPOLYARNYY 9404027 Aker ACS 650	27–31.03.2018 02–09.05.2018	AIS records, Ship onboard report summaries (ice parameters, movement regime), recommended routes	Observations of actual ice state, parameters of vessel movement regime
MONCHEGORSK 8013039 Aker ACS 650	03–11.04.2018		
NADEZHDA 9404041 Aker ACS 650	24–29.04.2018 19–25.05.2018		
	30.04–04.05.2009 17-23.05.2009	AIS records, Detailed data of expedition logs	Detailed data on outboard and nearest ice conditions, shaft power and speed, etc.
CHRISTOPHE DE MARGERIE 9737187 Yamalmax	19–24.05.2020	AIS records, Ship onboard report summaries (ice, movement regime)	Voyages were partially assisted by the nuclear icebreaker "50 Let Pobedy"
	15-18.02.2021		
	07-15.12.2021		

RESULTS AND DISCUSSION

Table 3 contains a brief summary of the results of statistical analysis of the conformity between ice parameters obtained from diagnostic ice charts of different providers as well as the correspondence between diagnostic and earlier forecasted values from the same provider. This relates to ε_{DIC} and ε_{IFC} uncertainties. To compare data on the ice age, we used the effective thickness as a comparison value. Such thickness was calculated as a weighted average of the thicknesses specified for the three stages of development, where the weight of each stage was equal to its concentration. The analyzed lead time for the forecasts is 3 days.

Table 3. Statistical analysis of ε_{REC} and ε_{FRC} uncertainty components

Datasets of pairwise comparison	Number of points	Correlation	Standard Error	Uncert. comp.
Current total concentration (AARI vs. WNI)	316	0.17	9.3 %	ε_{DIC}
Current effective thickness (AARI vs. WNI)	316	0.09	0.38 m	ε_{DIC}
Estimated current compression (AARI vs. WNI)	316	0.23	0.66 pts	ε_{DIC}
Current total concentration (AARI vs. OSISAF)	1200	0.54	12.1 %	ε_{DIC}
Current total concentration (AARI vs. Onboard records)	432	0.19	26.6 %	ε_{DIC}
Current effective thickness (AARI vs. Onboard records)	432	0.47	0.4 m	ε_{DIC}
Forecasted vs. diagnostic thickness (AARI)	4080	0.78	0.24 m	ε_{IFC}
Forecasted vs. current compression (AARI)	4080	0.48	0.68 pts	ε_{IFC}
Forecasted vs. diagnostic thickness (WNI)	1104	0.89	0.14 m	ε_{IFC}
Forecasted vs. current compression (WNI)	1104	0.35	0.52 pts	ε_{IFC}

The main conclusion that could be drawn from Table 3 is that there is a very low agreement between the data from various providers on the current distribution of ice in a region. It is even worse than the estimated inaccuracies in ice forecasts of each provider.

Fig. 2 shows the selective results of a study on different types of ε_{SIF} uncertainty. Firstly, we investigated the sensitivity of the used ship transit model to the lack of data on the distribution of ice by the stages of development. We compared the results of attainable speed calculations for a full dataset (three gradations of ice development stage) and for the reduced dataset, where a single effective ice thickness was used as model input. To estimate the effective ice thickness in this task we used two alternative methods: simple weighted average (as it was done above) and the Sergeev's (1978) method. The latter one implicitly considers the ability of the navigator to choose the easiest path in a heterogeneous environment. Fig. 3A presents the results of such a comparison and the corresponding values of standard square errors (SSE). It is easy to see that the use of the weighted average ice thickness leads to a systematic underestimation of the attainable speed. The use of a more sophisticated method of effective thickness calculation eliminates systematic error but still leads to the coarsening of results.

Fig. 3B shows the results of a study on the necessity to specify ice form (horizontal size of ice floes) as an input of the ship transit model. This value is not available for most data providers. We compared the results of calculations that were done using the actual horizontal ice size at each point and the virtual conventional constant values (they are shown in Fig. 2A as row names.). It can be stated that the inaccuracy in speed calculation is most evident when the constant floe size corresponds to the brash ice (especially in the case of thick ice). At the same time, if the constant value corresponds to the medium ice floes (100-500 m), then the calculation results best suit the real picture. The input dataset for both abovementioned studies is the record set of expeditionary logs of NADEZHDA voyage in April 2008.

Figures 3C and 3D illustrate the sensitivity of the ship transit model to the direction of ice compression. They present the polar diagrams of model-based attainable speeds (in knots) depending on the difference between the compression direction and ship course. Figures contain different gradations of ice compression and ice thickness. Test speed calculations performed for Yamalmax ship (fig. 3C) and «50 Let Pobedy» icebreaker (fig. 3D) shows, that neglecting the direction of ice compression can lead to significant errors in determining the attainable speed, especially for transport ships in severe ice conditions.

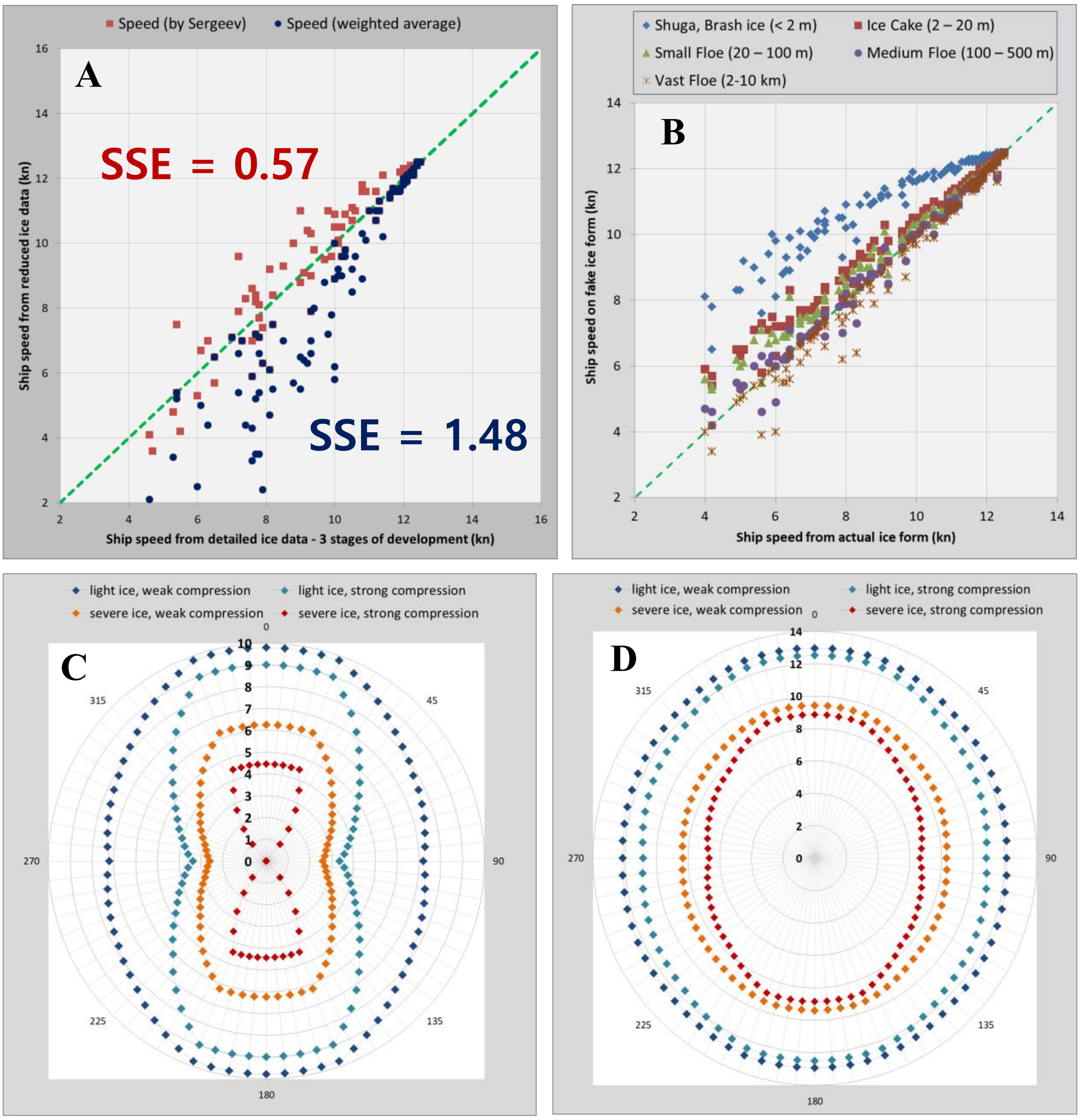

Figure 3. Estimation of ε_{SIF} uncertainty components.

We also performed a set of test calculations to assess the uncertainty due to the ship transit model, i.e. to estimate of $F_{STM}(\dots) + \varepsilon_{STM}$ uncertainty component according to Eq. (1). For this, we compared the calculated movement parameters (attainable and exploitation speed, fuel consumption, etc.) with the actual values from expedition logs. These calculations were carried out for several expeditionary voyages of "Norilskiy Nickel" type vessels in 2008-2009 and commercial voyages of Yamalmax LNG carriers in 2018-2021 (see Table 2). The selected results of verification are presented in Table 4, Fig. 4, and Fig. 5. It should be noted here that the main difficulty of STM verification is the lack of information on the current shaft power. This information is frequently missing or specified much more rarely than ice parameters. This does not allow making unambiguous conclusions about the reasons for the discrepancy between the model and actual values of ship speed. Therefore, it is difficult to accurately predict ship speed at each local track point. However, the analysis of historical records shows (see Fig. 4) that it is always possible to distinguish sections of ship movement along relatively homogeneous ice zones. Due to the mentioned uncertainties, it is better to calculate the average speeds for these zones rather than speeds at single points. This results in a much better agreement between actual and calculated data and allows an adequate assessment of the most important characteristics of the voyage, e.g, for the expected time of arrival (ETA). According to the conducted calculations, the relative error in the estimation of ETA does not exceed 10%.

Table 4. Selected results of ship transit model verification

Dataset (the sample of track points)	Track details	Sample size	Correla-tion	Standard Error (kn)
NORILSKIY NICKEL, 2008	The Kara Sea, from the exit from the Gulf of Ob to Cape Zhelaniya	176	0.47	2.11
NADEZHDA, April 2009		157	0.81	3.06
NADEZHDA, May 2009	The Kara Sea, from the exit from the Gulf of Ob to Kara Gate	156	0.80	4.16
CHRISTOPHE DE MARGERIE, May 2020	Eastern part of the Kara Sea - from the Yenisei Gulf to the Vilkitsky Strait	281	0.85	2.05
CHRISTOPHE DE MARGERIE, February 2021	Voyage from the Laptev Sea to the Kara Sea through the Vilkitsky Strait	377	0.78	2.3

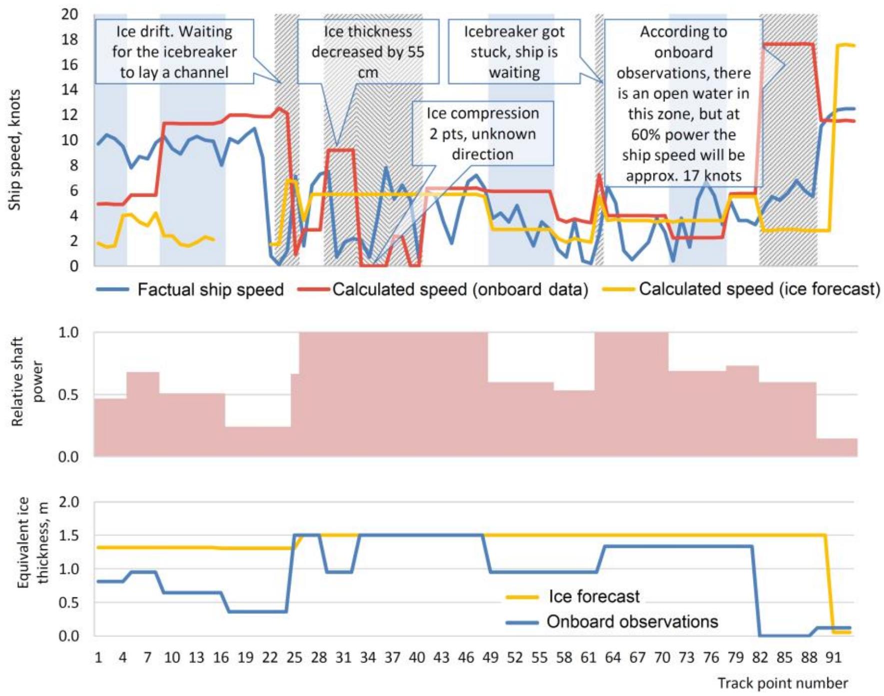

Figure 4. Actual and calculated voyage parameters in different ice zones for the voyage segment of CHRISTOPHE DE MARGERIE on 21-22.05.2020.

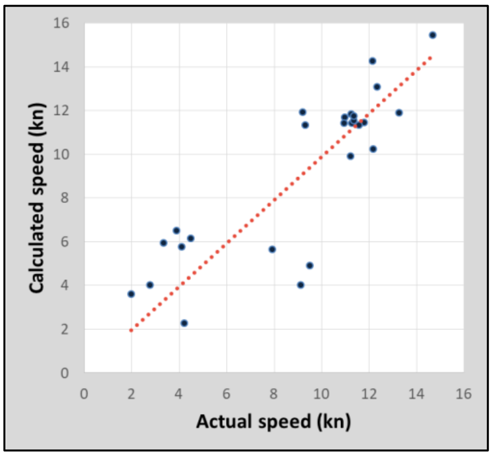

Figure 5. Correspondence of the actual and calculated values of the average ship speed in characteristic ice zones

Finally, verification of the whole automatic routing procedure was carried out by comparing the model routes obtained during the optimization procedure with actual routes, as well as the routes recommended by AARI ice experts. This allowed us to evaluate the components of uncertainty $(F_{NO}(\ldots) + \varepsilon_{NO} + \varepsilon_{SF})$. To carry out this research we used a software tool «Boreas» developed in LLC Bureau Hyperborea. In the frame of this study, we compared both the trajectories and the integral parameters of the route (voyage duration, traveled distance, etc.). The results of comparison for several historical voyages are presented in Table 5, while the spatial deviations in cartographic representation for two cases is shown in Fig. 6.

Table 5. Results of overall verification of optimal routing routine; A – actual route recorded; R – route recommended by ice expert, OR – optimized route; AM – calculation of voyage time for the track of actual route using the ship transit model.

Voyage	Actual voyage notes and features	Voyage distance (nm)				Voyage duration (hr)			
		A	R	OR	AM	A	R	OR	AM
ZAPOLYARNYY, 27–31.03.2018	The ship mainly moved along coastal polynyas, while had to ram in heavy ice	545	532	466	545	71.2	46.4	**41.3**	48.0
NADEZHDA, 24–29.04.2018	Movement along near-fast polynya. Overcoming the zone of strong compression by the perpendicular course	1090	542	941	1090	107	66.3	**81.1**	100.3
NORILSKIY NICKEL, 19-24.03.2018	Stern forward movement (mainly) in very hard ice	508	390	472	508	**80**	122	96.1	118.7

It can be noted that the formally calculated “optimal” route sometimes turns out to be worse, and sometimes better than the actual one. In each specific case, the obtained disagreement can be explained by the unique combination of specific factors of uncertainty, having both objective and subjective genesis.

CONCLUSIONS

The described studies and some supplementary results omitted in this paper allowed us to estimate the comparative contribution of various types of uncertainties to the overall uncertainty of the ice routing procedure. The pie chart in Fig. 7 represents our subjective estimation.

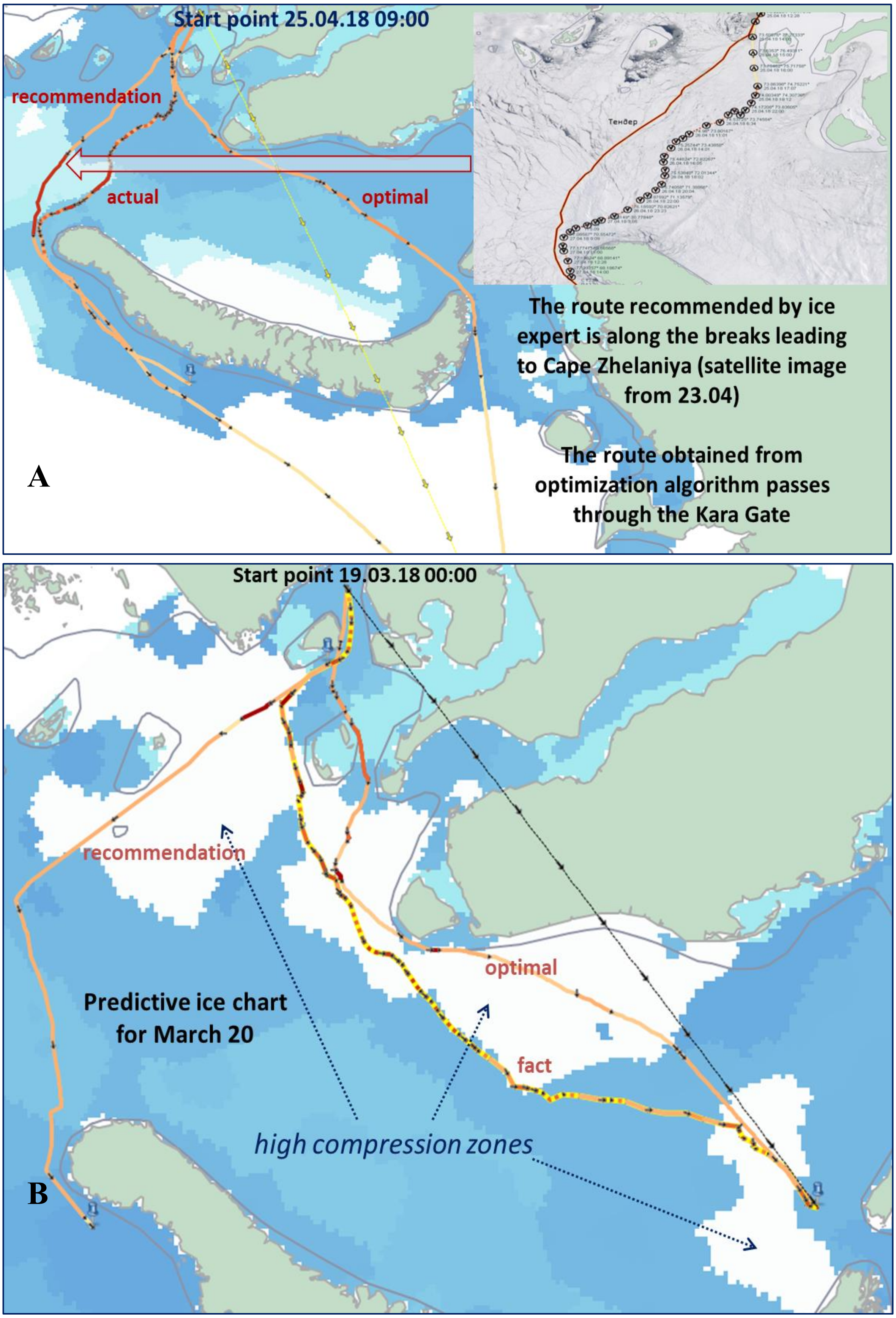

Figure 6. Actual, recommended, and optimized routes for the NADEZHDA (A) and NORILSKIY NICKEL (B) voyages in spring 2018

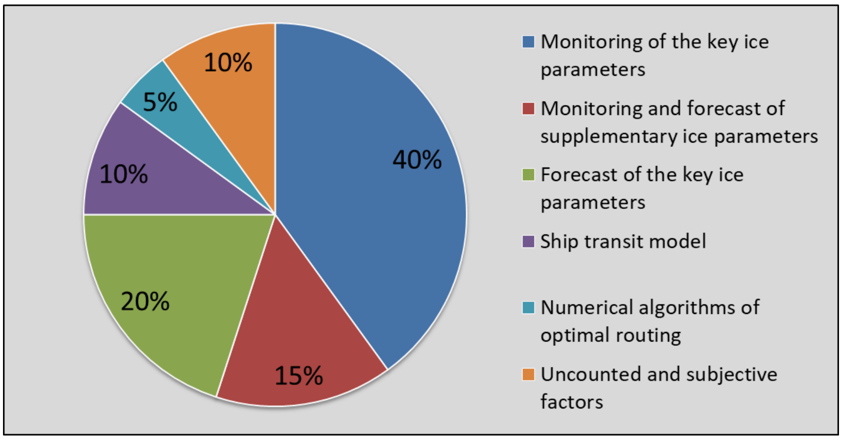

Figure 7. Contribution of different components to the overall uncertainty of ice routing

The main conclusions arising from our studies can be summarized as follows:

1) The main challenge in increasing the accuracy of operational ship routing in ice is the up-to-date information support with the actual and forecasted ice data. The following tasks should be solved within the frame of this problem:
   a) Diagnostic and forecasted ice charts should be obtained by combining multispectral images, radar images, and expert assessments from various providers and datasets;
   b) Multiple sources of in-situ correction of remote sensing data and satellite images should be applied to improve the accuracy of ice charts (e.g., shipboard recorder, etc.);
   c) Data on the main parameters of ice (concentration, thickness, floe size, compression, etc.) should be provided in physical dimensions, not in conditional codes;
   d) Compression direction should be included in ice charts along with compression pressure;
   e) Data on ice thickness, form, and concentration in a local area should be presented separately for several stages of development. An alternative solution is a transition from vector to gridded raster formats with high spatial resolution.
   f) Such local features of ice cover as hummocks and snow cover should be taken into account and considered in ice charts;
   g) Ice data should contain information on small discontinuities (leads and cracks). Possible solutions are the statistical description or the mesh representation of such features.
2) The principal issues in the development of ship transit models and numerical algorithms of ice routing are the following:
   a) Speed and efficiency of calculation algorithms are of great importance;
   b) The outputs of the ship transit model (attainable speed and fuel consumption) can be obtained in an interval or probabilistic form considering the inaccuracy in input data;
   c) The problem of joint optimization of the route and speed of a ship in continuous media should be formulated and solved. The requirements to arrive at a destination point no later than a specified date can be taken into consideration;
   d) The result of an automatic routing procedure can be not a single route, but a set of possible recommended routes. Their further selection and approval should be done by a qualified ice expert.

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REFERENCES

Guinness R.E., Saarimäki J., Ruotsalainen L., Kuusniemi H., Goerlandt F., Montewka J., Berlund R., Kotovirta V. A method for ice-aware maritime route optimization. *In: Proceedings of IEEE/ION PLANS*, 2014, pp. 1371-1378

Kotovirta V, Jalonen R, Axell L, Riska K, Berglund R. 2009. A system for route optimization for ice-covered waters. *Cold Regions Science and Technology*, 55(1), pp. 52-62. DOI: 10.1016/j.coldregions.2008.07.003

Lehtola V.V., Montewka J., Salokannel J. (2020) Sea Captains' Views on Automated Ship Route Optimization in Ice-covered Waters. The Journal of Navigation, 73(2). 2020. pp. 364 – 383 DOI: 10.1017/S0373463319000651

Lin Y.H, Fang M.C. The ship-routing optimization based on the three dimensional modified isochrone method. *In: Proceedings of the International Conference on Ocean, Offshore and Arctic Engineering – OMAE*, 2013, pp. 1-8

Losev S.M., Dyment L.N., Mironov Y.U. 2017. Length of large leads in drifting ice of the sub-Atlantic part of the Arctic Basin with the use of satellite images. *Ice and Snow*, 57(4), pp. 543-552. (In Russ.)

May R.I., Fedyakov V.E., Frolov S.V., Tarovik O.V., Topaj A.G. 2019. Method to optimize ship route in ice-covered waters based on vector polygons. In: *Proceedings of the International Offshore and Polar Engineering Conference ISOPE 2019*. pp. 878-885.

Montewka J., Goerlandt F., Kujala P., Lensu M. (2015) Towards probabilistic models for the prediction of a ship performance in dynamic ice. Cold Regions Science and Technology. No 112. 2015. pp. 14–28. DOI: 10.1016/j.coldregions.2014.12.009

Riska K., Patey M., Kishi S., Kamesaki K. (2001) Influence of ice conditions on ship transit times in ice. Proceedings of POAC-2001, Ottawa, Ontario, Canada. August 12-17, 2001. p. 17

Sergeev G.N. 1978. Using data on ice thickness to assess the passability of ice routes by ships. *Problems of Arctic and Antarctic*. (54), pp. 52-56. (In Russian: Ispolzovanie dannyh o tolshinakh l'da dlya ozenok prohodimosti ledovyh trass sudami. *Problemy Arktiki I Antarktiki*, tom 54, 52-56).

Schütz P. Dynamic routing through waters partially covered with sea ice. *In: proceedings of Society of Petroleum Engineers - Arctic Technology Conference*, 2014, pp. 929–936.

Topaj A.G, Tarovik O.V, Bakharev A.A, Kondratenko A.A. Optimal ice routing of a ship with icebreaker assistance. *Applied Ocean Research*, 2019, (86), pp. 177–187.

Valkonen J., Riska K. (2014) Assessment of the Feasibility of the Arctic Sea Transportation by using Ship Ice transit Simulation. Proceedings of OMAE-2014, San Francisco, USA, 8-13 Jun 2014. Paper No. 24188

Volkov V.A., Ivanov N.E., Demchev D.M. Application of a vectorial-algebraic method for investigation of spatial-temporal variability of sea ice drift and validation of model calculations in the Arctic Ocean. *Journal of Operational Oceanography*, 2012, (5)2, pp. 61-71.

Wang H, Mao W, Eriksson, L. A Three-Dimensional Dijkstra's algorithm for multi-objective ship voyage optimization. *Journal Ocean Engineering*, 2019. (186), pp. 106-131.