Outlet Glaciers as Iceberg Factories: Case Study for the Kara Sea

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ABSTRACT

This article presents the results of comprehensive research carried out in 2012-2017 by Rosneft Oil Company in cooperation with the Russian Arctic and Antarctic Research Institute, Institute of Geography (Russian Academy of Science), with the participation of Arctic Research Centre.
Calving glaciers of Novaya Zemlya, Franz Josef Land and Severnaya Zemlya were examined with airborne radar that allowed to measure their thickness and to build 3D models.
Satellite remote sensing data were used to derive glacier fronts position, ice surface flow velocity, changes of glacier margins, and parameters of iceberg distribution. The data on the flow rates of the main glaciers were compared with the satellite beacons equipped with GPS (ARGOS) installed on several glaciers.
Systematic differences in the volume of the underwater part for icebergs observed in the winter-spring period and the autumn-summer period are demonstrated. These differences should be taken into account when interpreting satellite remote sensing data or estimating iceberg underwater part.
The size distribution of produced icebergs is related to the structure of glaciers. The glacier areas close to flotation, zones of intensive icebergs production, present and potential intensity of icebergs production were assessed.
The obtained data can be applied for simulating iceberg production in the Russian Arctic, assessing iceberg risk for offshore oil and gas facilities and ensuring safety of operations in iceberg infested waters as part of geological exploration ice management system.

KEY WORDS: iceberg; glacier; Kara sea; Laptev sea, ice management.

INTRODUCTION

Risk of offshore structure interaction with an iceberg is among the most important considerations during the exploration of hydrocarbons and the subsequent development of license areas located in the iceberg-infested waters.

The formation of icebergs occurs as a result of calving off blocks of ice from the outlet part of glaciers. Glacier geometry is crucial for iceberg production

In the Arctic waters, where license blocks are located close to glaciers.
In the Russian Arctic, icebergs are widely spread throughout Barents, Kara and Laptev seas. The distribution of icebergs in the central part of Barents Sea is better described, taking into account a large amount of accumulated data (Abramov 1992; Løset 1996, Zubakin et al., 2006, Buzin 2008). Icebergs of Kara and Laptev seas are less studied, whereas several license blocks are located in close proximity to calving glaciers (Dowdeswell et al., 2002, Sochnev et al., 2018).

Knowledge of glacier parameters is useful for estimating the number and geometry of produced icebergs at present and during the exploration period. To estimate the probability and scenario of iceberg encounter at a given site, the data could be used as input into iceberg drift numerical models jointly with metocean reanalysis results.

In the long term, knowledge of the structure and dynamics of the glacier makes it possible to estimate the quantitative risks posed by icebergs for the development of a given area.

Over the period 2012-2017 the Rosneft conducted a number of research expeditions in Russian Arctic during the cold (April-May) and warm (July-September) seasons (Pavlov et al., 2018). The main focus of this work was the study of calving glaciers and associated icebergs of the archipelagoes Novaya Zemlya (mostly the eastern coast), the Severnaya Zemlya and Franz Josef Land. The next section outlines the field methods and preliminary results.

The methodology for characterizing a glacier as a marine terminating iceberg producer is presented for the eastern coast of North Island of the Novaya Zemlya archipelago.

METHODS

The field campaigns activity included:
• Installation of automatic meteorological stations (4 - in Kara sea, 2 of them - near the glaciers);

• Glaciers studies by ground-penetrating radar (GPR) in 2014-2016;
• Installation of GPS satellite beacons on the glaciers in 2015-2016;
• Aerial photography of icebergs in 2012-2017.

In addition to field studies, satellite monitoring capabilities were extensively used to analyze the dynamics of changes of the glacier fronts, speed of movement of its surface and the size of icebergs produced in the glacial zone.
As compared with the previous studies, where iceberg discharge of Arctic archipelagoes is a component of glacier mass balance (e.g., Sánches-Gámez and Navarro, 2018), this study is focused on an assessment of iceberg production as part of ice management system.

A detailed description of the methods used is given below.

Glaciers study by ground-penetrating radar

To measure the thickness of glaciers in 2014-2016 a helicopter-based radar with a central frequency of 20 MHz was used (Vasilenko E. et al 2011). All equipment was mounted on a specially designed framework, suspended on a synthetic cable 30 m long under the helicopter.

Measurements were carried out in August-early September 2014, in May 2015, in late September – early October 2016.

To get the most complete information about the thickness of the ice, the flight routes over calving glaciers were chosen either along the glacier fronts (transverse profiles) or with their intersection (longitudinal profiles).

The altitude of the flight relative to the physical surface of the glacier, depending on its geometry and weather conditions, was 100–400 m, the flight speed was about 100 km/h. The georeferencing of flight routes was carried out using a GPS receiver. Ice thickness data were combined with available high-precision digital elevation model created for the Arctic regions based on high-resolution space images (ArcticDEM 2017), to construct the ice thickness and subglacial bedrock elevation maps, and to identify hydrostatic flotation zones.

Figure 1 shows a map of glaciers covered by the studies. They are located at the Novaya Zemlya, Franz Josef Land and Severnaya Zemlya (Kotlyakov et al. 1997) in the area of the Company's licensed areas. Only the glaciers that make a significant contribution to the production of icebergs were considered (indicated as «studied»/«planned» on Fig. 1). As a result of the work carried out, radar sounding covered the main part of the outlet glaciers. The contribution of the iceberg-producing glaciers studied by radio sounding to date is about 70% of the discharge of continental ice into the sea for a given area.

Installation GPS buoys on the glaciers

In order to quantify ice discharge of the outlet glaciers, in addition to knowledge of the thickness of glacier front, information about the surface velocity of the glacier is needed.

For this purpose, autonomous satellite beacons equipped with GPS receivers and transmitters of the ARGOS satellite data acquisition system were installed on several main glaciers.

The criterion for choosing the location of the satellite beacon on the glacier was the presence of maximum depth of the glacier bed relative to sea level - the place with expected highest ice flow rates (the thalweg of the subglacial valley). An additional control beacon was installed on the rock at the Vershinsky glacier to assess the quality of the data received.

Determination of the surface velocity of glacier from satellite imagery

To determine the velocities of the glaciers high-resolution radar satellite images of spacecraft with synthetic aperture radar (SAR) of the following satellite groups were used: TerraSAR-X and COSMO-SkyMed.

Monitoring of horizontal displacements of the glacier surface was performed using the algorithms of the mutual correlation of fragments of multi-temporal satellite images. To map the displacements of the surface of the glacier from high-resolution radar satellite imagery data, so-called RMT (Rapid Motion Tracking) method was utilized (Iannacone et. al. 2016).

The resulted maps of the velocities of the glacier surface showed a good agreement with the point data from the satellite beacons.

Satellite monitoring of glacier front dynamics

The cartographic materials and space images were used to determine the change in the location and area of the frontal parts of glaciers terminating at sea.

The change was determined by the digitization of cartographic materials and space images. The main source for building maps of changes in the position of the front of the outlet glaciers for the period since 2001 were space images in the visible range Landsat TM, ETM, OLI8.

For the glaciers of the Novaya Zemlya archipelago, the data obtained were also supplemented with a series of high-resolution radar images TerraSAR-X. Based on the processed information, maps of changes in glacier fronts from the mid-20th century to 2018 were constructed. The average retreat or advance of the front over different periods was calculated.

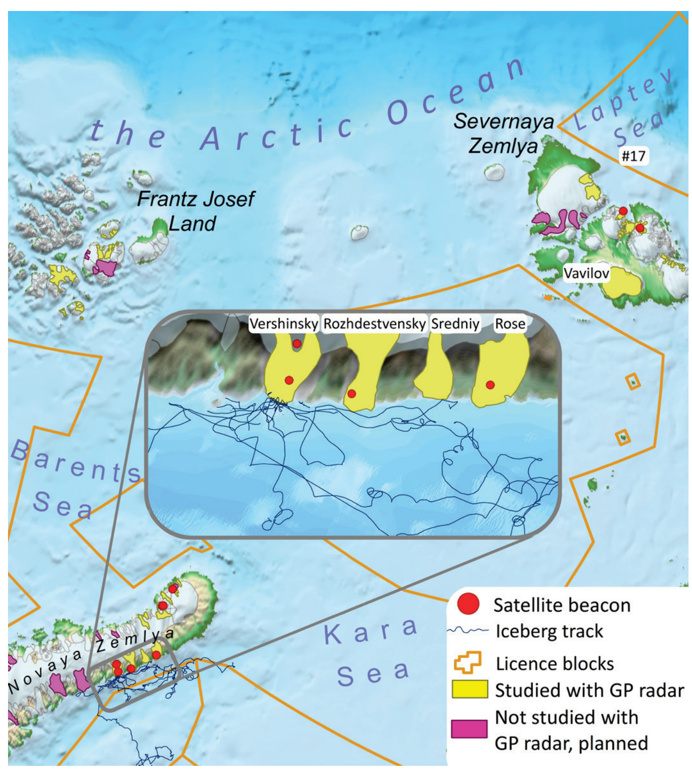

Fig. 1. Coverage of glaciers studied in 2014-2016. Drift trajectories from data of satellite beacons are shown only for icebergs originated from Vershinsky glacier.

The vast majority (90%) of outlet glaciers of Novaya Zemlya have been retreating during last decades. A post-2000 acceleration in marine-terminating glacier retreat, is reported to be connected with changes in sea-ice concentrations (Carr et.al. 2014).

Aerial photography of icebergs

To obtain information on the morphometry of the part of icebergs above sea level, their aerial photography was carried out. Aerial photography work was performed by following means:

• by installing on the helicopter an automatic aerial photography system for manned aircraft developed by Geoskan LLC, Russia;
• using a camera with a GPS receiver during a flight around the investigated iceberg at a low flight altitude;
• with remotely-piloted copter.

Based on the results of the stereo processing of filming materials, a 3D model of the sail of the iceberg was compiled. The following parameters were computed:

• the linear dimensions;
• the volume of the sail of the iceberg;
• the surface area of the sail of the iceberg (of 2D projection).

Assuming iceberg being in hydrostatic equilibrium, the total iceberg mass was calculated.

Surface area-to-volume correlations from 3D models data were analyzed for summer and winter periods.

Most of icebergs captured by aerial photography, to study their drift trajectories, were also marked by satellite beacons similar to those used on glaciers (not discussed in this paper).

Estimation of the size distribution of icebergs from satellite imagery

Radarsat-2 high-resolution radar images with a resolution of 8 m were used to search for icebergs and assess iceberg conditions at glaciers as information support of the 2012-2017 expeditions.

High resolution radar satellite images obtained for remote monitoring of glacier flow were also used to identify icebergs located close to outlet glaciers. The identified iceberg was outlined as a polygon. Its characteristic dimensions were determined including length (maximum size) and width (size in the orthogonal direction), surface area.

According to surface area-to-volume correlations obtained from the aerial photography data in the summer period, the iceberg mass was estimated.

The field methods described are schematically presented on Fig.2.

RESULTS: SEASONAL VARIATIONS OF THE ICE DISCHARGE OF OUTLET GLACIERS

Calculation of the ice discharge of glaciers, going to the formation of icebergs, in general, consists of two components.

First, with the glacier front is stable, all the ice flux approaching this front should later discharge to the sea. This ice flux can be estimated knowing ice surface velocities at the transverse gate near the glacier front. Since the surface velocities of the glacier differ from the depth-averaged velocity, a correction factor ~0.9 was applied (IASC –CWG NAG workshop summary report 2016).

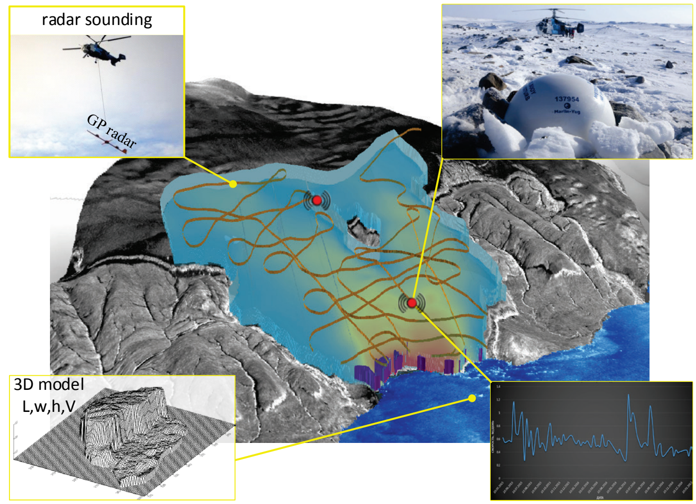

Fig. 2. 3D model of the Vershinsky glacier from GPR data. Brown color indicates the track of helicopter with GPR. Areas close to flotation marked by magenta color. Inset boxes illustrate the field works carried out: radar sounding, aerial photography of icebergs, the installation of a satellite beacon.

The position of glacier front also is not stable. If the front of the glacier retreats, the glacier additionally loses ice and the ice flowing to the front does not compensate it (and vice versa).

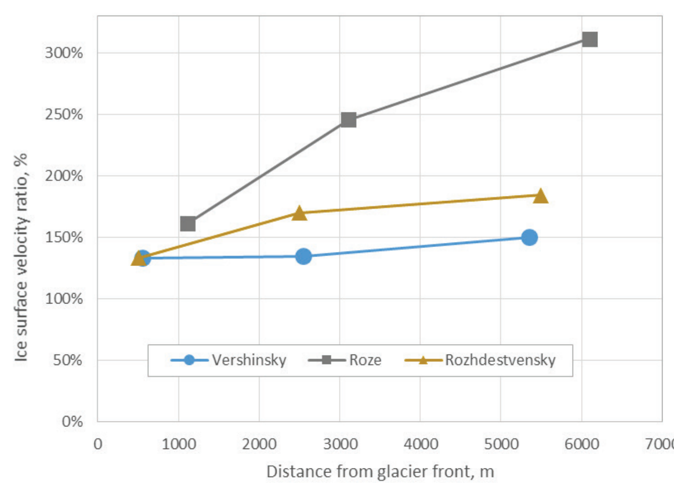

Fig. 3. Observed ratio (seasonal increase) of ice surface velocity in warm (July-August) and cold (October-January) seasons to distance from the glacier front.

Both components are subject to seasonal variations. As it is illustrated in Fig. 3 the surface velocity of glacier acquired from satellite imagery of the glaciers of the eastern part of Novaya Zemlya increases in warm season (data for July-August) by 30%-300% with respect to cold season (data for October-January). Seasonal variation in flow velocity is more pronounced with the distance increase from the glacier front.

Apparently, the seasonal variation of the flow velocity of the glacier is induced by seasonal changes in the upper part of the snout of the glacier (>5 km from the front).

While, the condition of glacier at its front is probably only responsible for dynamics of ice discharge to the sea, including calving of icebergs.

Here again, the overwhelming mass loss of the glacier occurs in a warm season. Sea temperature is reported to be the major driver of glacier retreat, also it can adequately explain the seasonal variation in calving behavior of glacier (Luckman et al., 2015).

The records of terminus positions of glaciers of Svalbard also contain interannual variability, which coincides with the temperature of the sea in those years (Blaszczyk et al., 2013).

Waves are reported as a secondary factor of stimulating turbulence at the sea−ice interface and facilitate heat transfer to the ice wall (Carr et al., 2014). No evidence for a change in air temperatures that coincided with glacier retreat in Novaya Zemlya is found, suggesting that they are not a primary driver of marine-terminating glacier retreat on Novaya Zemlya (Carr et al., 2014).

RESULTS: SEASONAL VARIATIONS IN SIZE PARAMETERS OF ICEBERGS

3D models from aerial photography allowed to estimate volume of iceberg sail and projection area (analog to area value that can be estimated from satellite imagery). Total mass of iceberg was estimated assuming the iceberg is in a state close to hydrostatic equilibrium.

To analyze aerial photographs, most of the captured icebergs were associated with producing glaciers on the basis of proximity to glacier. Then icebergs were separated into two groups: measured in April-May (cold season) and in July-September (warm season).

It appeared that for the same projection area the mass of iceberg is systematically less in the warm season than in the cold season:

• ~4 times less for the icebergs of the Novaya Zemlya archipelago in Kara Sea (Fig.4)
• ~1.5 times less for the icebergs of the Laptev Sea (Fig.5)

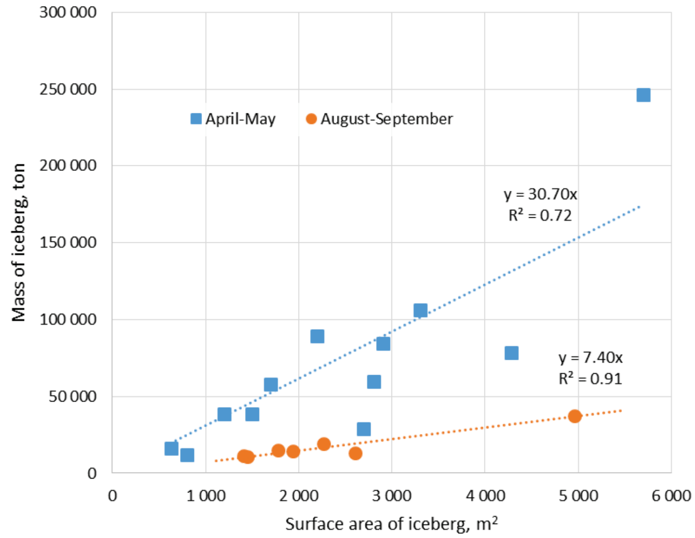

Fig. 4. The area-mass ratio for icebergs near the Vershinsky glacier. Seasonal differences are pronounced.

A probable cause of the seasonal difference in icebergs area-mass ratio in the Kara Sea is at different melting rates. To verify that hypothesis temperature profiles of seawater were extracted from CTD (conductivity, temperature, depth) measures performed during expeditions near outlet glaciers of the Novaya Zemlya for cold season – (between 16-22 of May) and warm season (between 17-19 of August). Fig. 6 illustrates positions of CTD sampling sites in 2012-2015 taken for analysis.

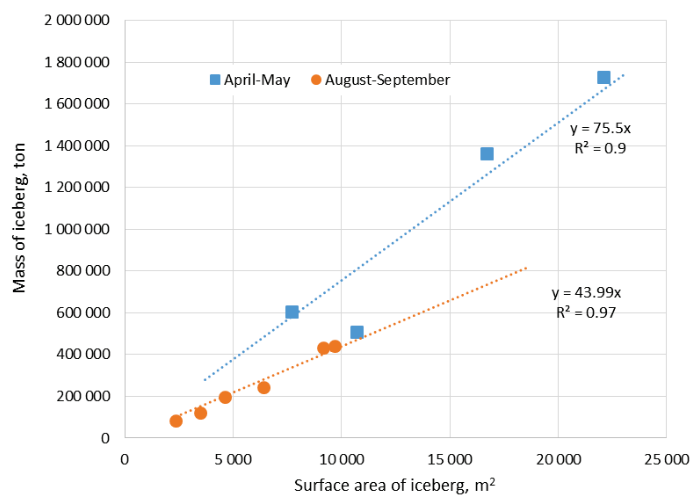

Fig. 5. The area-mass ratio for icebergs near the outlet glacier #17 Academy of Sciences Ice Cap. There are some seasonal differences.

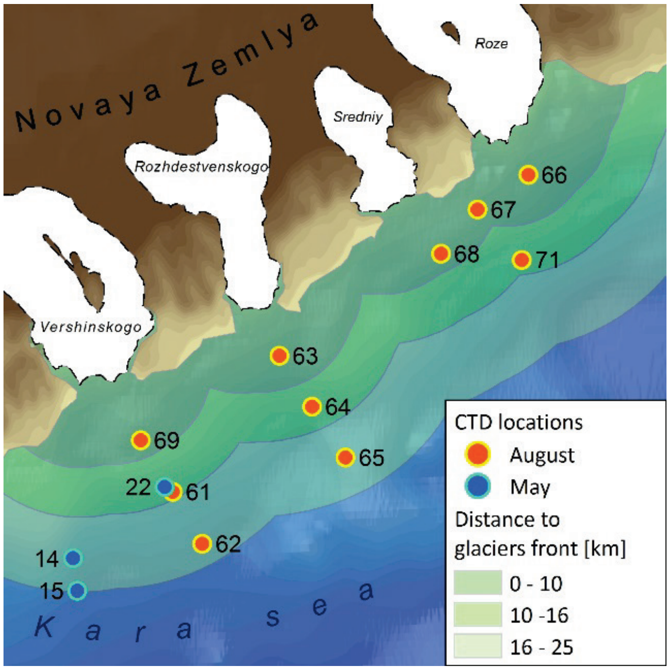

Fig. 6. Locations of CTD sampling sites near outlet glaciers of Novaya Zemlya.

The observed vertical distribution of seawater temperature is shown in Fig. 7. During cold season, water temperature is below zero Celsius and close to the freezing point. In summer water temperature is above ~+4 degrees Celsius from surface down to 25 m depth. The thermocline becomes more pronounced with distance from the glacier front. These results are also consistent with the long-term observations in this area.

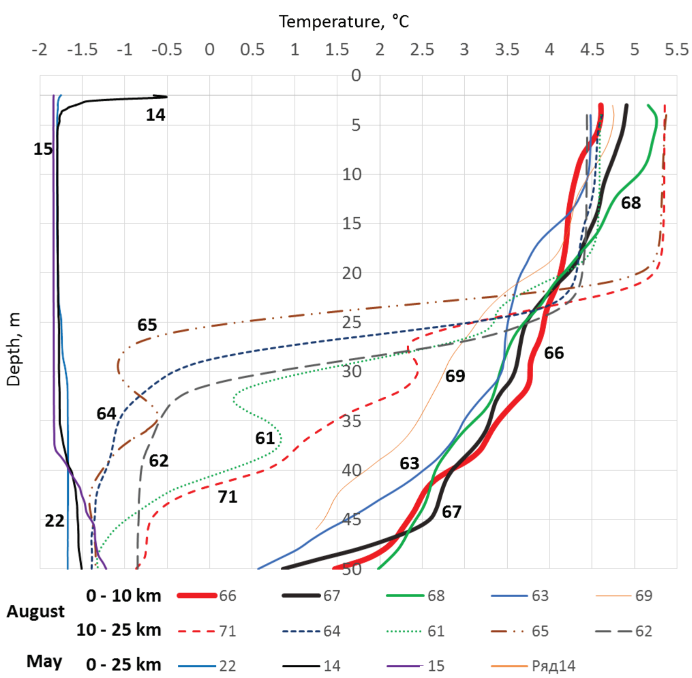

Fig. 7. Vertical distribution of sea water temperature near outlet glaciers of Novaya Zemlya.

Seasonal differences of mass/area ratio are not observed for icebergs produced by Vavilov Glacier (Fig.8.). In this case the glacier front advanced into the sea during its surge in 2010-2018 (Willis et al., 2018) and it had partially disintegrated in shallow waters before 2014-2015 observations presented in Fig. 8.

The observed differences in sea water temperature in cold season and summer indicate that it can be one of the main causes of accelerated melting of icebergs observed in the warm (August-September) period in the Kara Sea.

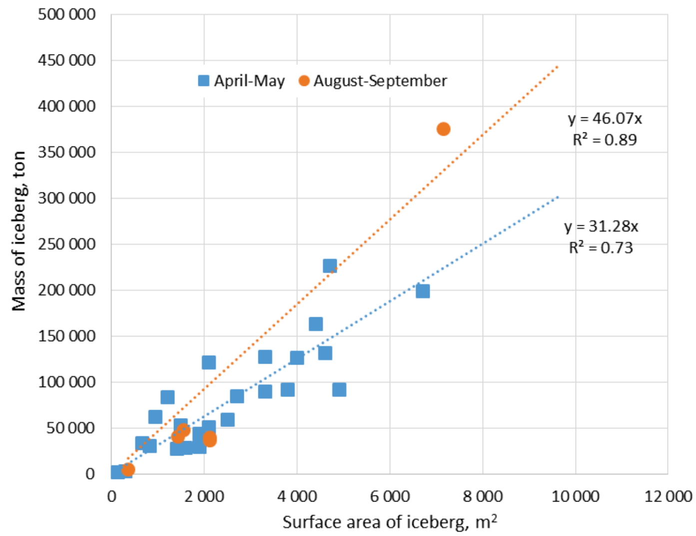

Fig. 8. The area-mass ratio for icebergs near the Vavilov glacier. Seasonal difference is not significant.

Similar observations were performed for large individual Greenland icebergs situated within fjords for several months using very high-resolution (2 m) stereo satellite images. Melt rate followed expected patterns based on hydrographic observations, including a decrease in melt rate with latitude, and observed 4-fold melt rate increase which was attributed to fiord seasonal circulation changes (Enderlin et al., 2018).

RESULTS: CASE STUDY OF VERSHINSKY OUTLET GLACIER

An example of close location of prospective geological structures and open hydrocarbon deposits relative to iceberg formation sites is the license areas in southwestern part of Kara Sea near the eastern coast of the Northern Island of the Novaya Zemlya archipelago (Fig. 1). The Vershinsky glacier, which is a typical example of the eastern coast of Novaya Zemlya, is presented below (Fig. 2).

Geometry of the glacier terminus

The area of the part of the Vershinsky glacier, studied using ground penetrating radar, is 250 km^2. The average thickness of ice in this part is 200 m, reaching 500 m (Fig. 10). The total volume of ice in this part is 50 km^3, with almost half of it located on the bed below sea level. The zone potentially capable to produce icebergs covers an area of 90 km^2 and extends for ~ 15 km upstream of the glacier in its western branch. The maximum bed depth in this part of the glacier reaches almost 180 m below sea level. In the eastern branch of the glacier, the length of the subglacial valley with a bed below sea level is about 10 km, and the depth of the bed does not exceed 120 m.

Ice discharge

For the Vershinsky glacier, the ice discharge estimated at the gate near the modern glacier front (Fig. 9 and Fig. 10.1), is on average 0.13 km^3 of ice per year. This ice flux rate of the glacier characterizes the overall intensity of the production of icebergs, without taking into account the size and shape of the ice blocks at their calving.

At present, the only small part of the terminus of the Vershinsky glacier is near to the state of hydrostatic flotation (Fig. 9). The largest icebergs are formed when large areas of ice are calved from the glacier, which is possible only in zones where the glacier is afloat or close to flotation. The size and characteristics of the current and the future flotation zones allow us to estimate the maximum size and the intensity of the formation of large icebergs.

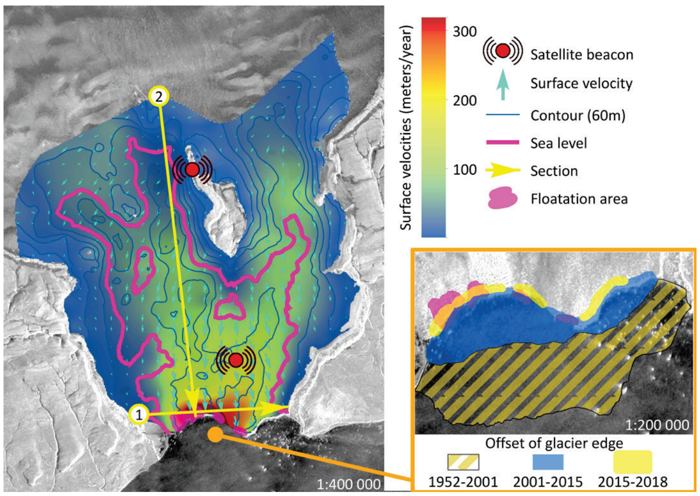

Fig. 9. Interpretation of data on the glacier geometry and ice flow rates. The position of the profile is plotted. The inset shows the dynamics of glacier front changes. The contour lines show the topography of the glacier bed.

The suggestion is that this part with some efficacy coefficient is responsible for production of large icebergs. The destruction of the rest of its frontal edge is carried out by crushing with the formation of debris, pieces of icebergs and other forms of ice with masses within 10 thousand tons.

Let us estimate the frontal part of the glacier at flotation (marked by red lines in Fig. 10). The influx to the flotation zones determined in this way is of the order of 10%. Thus, in the case of the Vershinsky glacier, the formation of large icebergs, up to a table-like shape (or pyramidal, oblique), currently accounts for 10% of the total ice discharge into the sea or less.

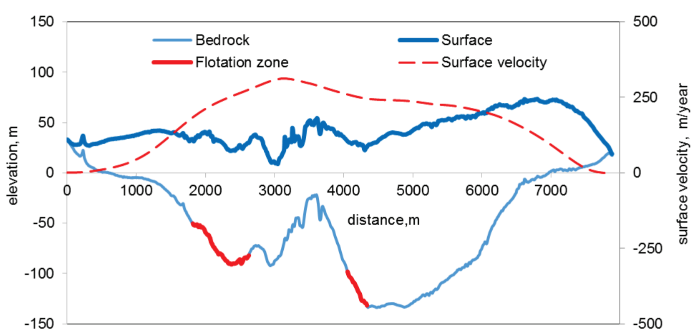

Fig. 10.1 The geometry of the glacier and the flow velocity profile at the front of Vershinsky glacier (cross-section 1 of Figure 9).

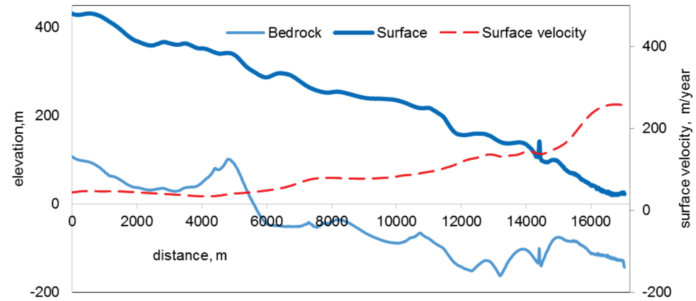

Fig. 10.2 The geometry of the glacier and the flow velocity profile along the snout of the Vershinsky glacier (cross section 2 of Figure 9).

Operational monitoring of the glacier flow rate and intensity of iceberg formation zones during the season

When ensuring iceberg security, an important issue is monitoring (satellite imagery, aerial reconnaissance) of iceberg formation zones which location can change during the year.

Real-time information on the displacement of the surface of the glacier is available when installing satellite beacons equipped with GPS receivers and with a system of satellite transmission. Relative changes in speed of the beacon correlate with the summer (warm)/winter (cold) season of the year, as determined by automatic weather stations (AWS) located near glaciers (Fig.11).

Beacon data is quite sensitive to both short-term glacier movements and long-period changes, such as the seasonal dependence of the flow velocity. The absolute values of the velocity of the surface motion are in good agreement with the velocity fields data constructed from satellite images (Fig.12).

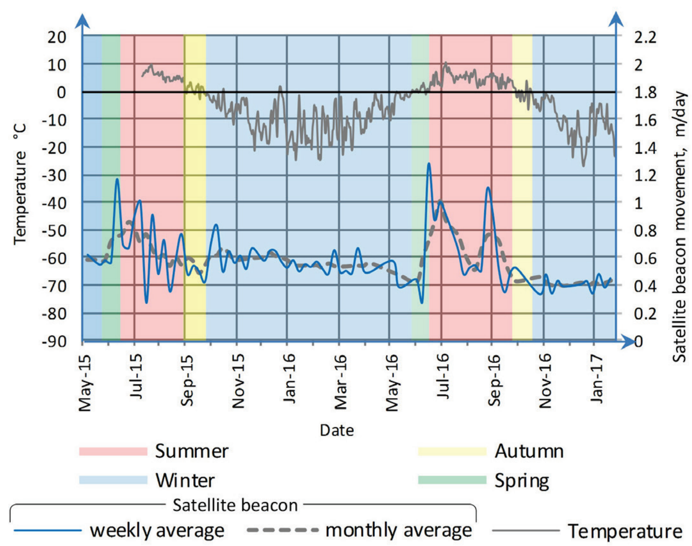

Fig. 11. Ice surface velocity of Vershinsky glacier by satellite beacon. Seasonal gates are based on AWS data near the glaciers.

For the Vershinsky glacier, the surface velocity value in winter obtained on its front is ~92% of the average annual value here. For example, the reported value of glacier flow in winter from observations of the glaciers of the Svalbard archipelago in the area of the Hornsund research station is at 90-95% of their annual average (IASC – CWG NAG workshop summary report 2016).

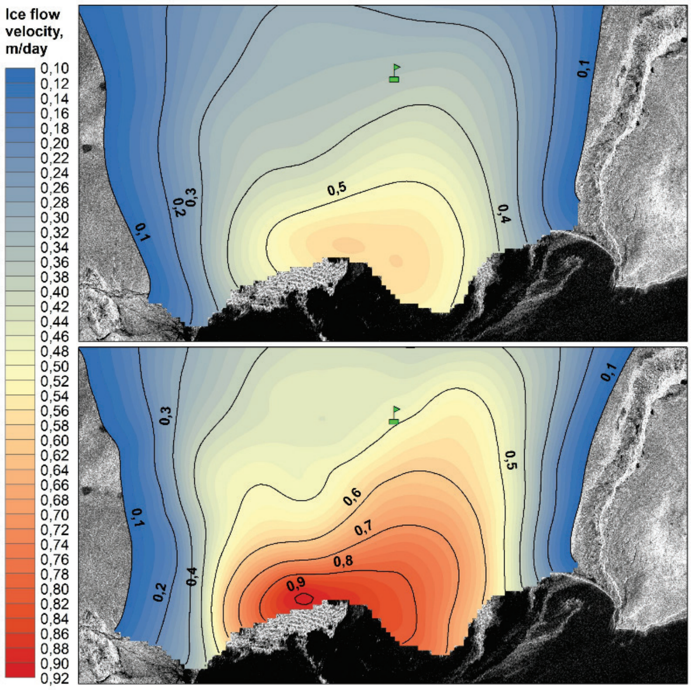

Fig. 12. The seasonal patterns (in m/day) of the surface flow velocity of the Vershinsky glacier. Top – October-January 2017, bottom – June-August 2018. Location of satellite beacon is marked by green flag. TerraSAR-X image is shown as a background.

Estimation of the size of icebergs

The mass spectrum of icebergs produced by the glacier was estimated based on the results of high-resolution radar images. Fig. 13 shows the mass distribution of icebergs near the Vershinsky glacier. This distribution can be used in a simulation of iceberg production from the given glacier with consequent propagation and occurrence in the area (Andersson et al., 2019).

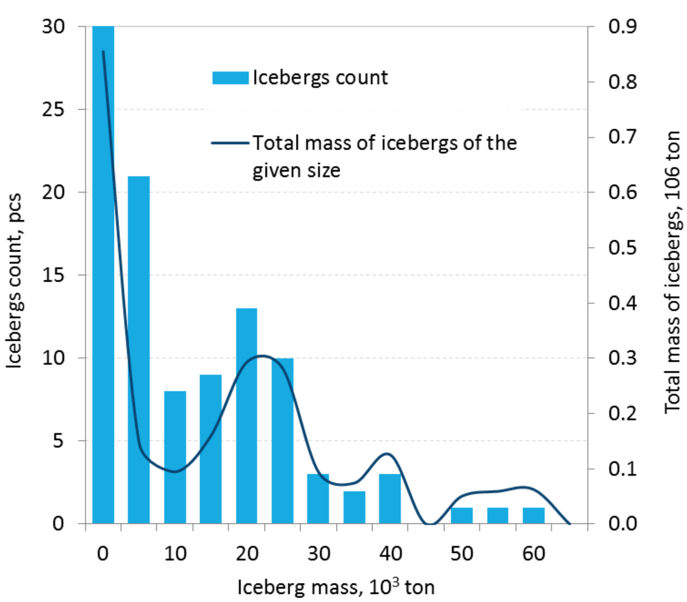

Fig. 13. The distribution of icebergs by mass produced by the Vershinsky glacier in 2017

Estimation of iceberg draft is of fundamental importance for evaluation of possible scouring and development of methods for protecting underwater facilities (subsea wellheads, pipelines) when operating in the Arctic waters. The possible draft of icebergs coincides with the thickness of the glacier on its front and is also limited to the bathymetry of the glacial zone. At present, for the Vershinsky glacier, an iceberg can be calved having a draft up to 100 m, and the typical draft of icebergs being produced of about 27 m.

Long-term prediction of iceberg characteristics

An important piece of a field development design is the assessment of size of ice bodies that can occur in the water area during the entire period of economic activity. In order to evaluate the capability of the glacier to produce icebergs in the nearest future, it is necessary to use a 3D model of a glacier.

If the current retreat rates maintained, the Vershinsky glacier will be capable of producing icebergs with similar intensity at least in the next 50 years. Iceberg size and draft may increase. The maximum size of icebergs that the Vershinsky glacier will be able to produce in the future, when its edge recedes 1-2 km from its current location, will be 300-500 m long with a draft of about 100 m.

For several neighboring glaciers of the eastern coast of Novaya Zemlya, estimated parameters include the dimensions of the outlet part of the glacier, ice speed, ice flow rate on icebergs, iceberg production parameters, and its duration (Table 1). Glacier Sredniy (also known as Novopashenny) was excluded from the table, because it has minor contribution to total iceberg production.

Table 1. Ice velocity, ice flux, and other iceberg-related parameters of Vershinsky, Rozhdestvensky and Roze glaciers

Glacier characteristics	units	Roze	Rozhdes-tvensky	Vershin-sky
Annual ice surface velocity	m/day	0.148	0.165	0.553
cold period (Oct-June)	m/day	0.130	0.150	0.510
warm period (July-Sep)	m/day	0.200	0.210	0.680
Ice flux at frontal gate	кm^3/year	0.040	0.013	0.124
cold period (Oct-June)	km^3	0.026	0.009	0.086
warm period (July-Sep)	km^3	0.014	0.004	0.039
Glacier length change	m/year	-80	-50	-70
Glacier area change	km^2/year	-0.59	-0.24	-0.46
Mean ice thickness at glacier front	km	0.063	0.119	0.104
Ice discharge at glacier front	km^3/year	0.077	0.041	0.172
to flotation zone	%	6-10	4-8	10-15
Glacier area at floatation limit	km^2	0.06	0.05	0.53
Glacier bedrock area below sea level	km^2	54.3	44.6	87.4

Icebergs today				
Average length (aerial photography)	m	54	52	63
Mass, max/average (aerial photography)	10^3 ton	84/31	260/-	245/50
Draft, average (estimate)	m	28	32	27
Length, maximum (aerial photography/satellite)	m/m	88/76	94/123	118/104
Dimensions of largest iceberg, length*width *draft (estimate)	m	120*70*60	150*90*100	200*150*100
Future projections (50+ years)				
Duration of icebergs production (estimate)	years	250	240	214

Conclusions for Vershinsky, Rozhdestvensky and Roze glaciers

Continuous two-year data of glacier flow velocity measurements allowed us to distinguish two main seasons with fast and slow velocities. In the warm season the speed at glacier terminus is on average by 25-30% higher than in the cold period. However, the total ice flux arriving to the glacier terminus in the cold period is greater by 1.8-2.2 times than in the warm period because of the longer duration of cold season. As a result of reduction of glaciers in their terminus parts, additional losses of ice into the sea appear, which are from 30% to 70% of the total loss of ice into the sea, thus being an important component of iceberg production.

Radio echo-sounding data show that the studied glaciers have a great potential for iceberg production, i.e. at the current rate of retreat of their fronts, the glacier calving will continue for at least 200 years. At the same time, the intensity of calving, expected planar size and draft of icebergs may even increase in future when glacier fronts recess to the areas with deep subglacial bedrock basins.

Data of aerial and space surveys show that the modern size of icebergs found at the fronts of the studied glaciers reaches 120 m in length (in average 50-60 m), and their mass reaches 260 thousand tons (in average 30-50 thousand tons). At present the maximum draft of icebergs is up to 100 meters.

CONCLUSION

For information support of offshore field exploration and development in bergy waters, knowledge of distribution of characteristics of icebergs, produced by glaciers, is necessary. Glaciological studies should fill that gap. This paper describes the expedition works performed in the course of studying the glaciers of the Russian Arctic during 2012-2017 with preliminary results. The methodology for characterization of the glacier as iceberg factories is presented. Some capabilities of glacier monitoring in real time are tested. The case study for the Vershinsky glacier on the eastern coast of Novaya Zemlya is illustrated.

There are approaches to reconstruction of a three-dimensional glacier model including bedrock by solving inverse problem using only satellite data as an input such as free surface elevation and velocity (Sellier M. & Heining C. 2016). The data gathered with GPR could also be useful for verification and calibration of such models on a group of glaciers with presumably similar structure, analogs (Carr et. al., 2014).

In the warm season of the year, a relative increase in surface velocities is of the glaciers is observed. This ratio increases with distance from the front of the glacier upstream.

Observed 4-times seasonal difference in icebergs area-mass ratio in the Kara Sea is due to seasonal melting. This indicates that empirical relationships usually derived for the mass and geometry of icebergs should be systematically different for cold and warm seasons or even months of the year. In particular, correlations applied for estimation of iceberg mass from satellite data should be different for cold and warm seasons.

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