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STYDYING SEAS AND OCEANS FROM SPACE

Iceberg Drifting and Distribution in the Vilkitsky Strait Studied by Detailed Satellite Radar and Optical Images

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Abstract—This paper is devoted to the detection and identification of icebergs in the Russian Arctic Seas from the use of high- and medium-resolution radar and optical images from EROS-B, Radarsat-1, Radarsat-2, SPOT-4 and SPOT-5 Earth observation satellites. In July–September of 2011–2013, the SCANEX Research and Development Center, the Federal State Unitary Enterprise Atomflot, and other partner organizations provided operational satellite monitoring of icebergs in the Kara Sea and the Laptev Sea. More than 130 highly detailed optical and radar images were received and processed. The Vilkitsky Strait—one of the narrowest and most dangerous places within the Northern Sea Route—was chosen as an experimental polygon. As a result, iceberg location in the strait during the 2011–2013 navigation periods was analyzed, as were the iceberg size, area, drift direction, and height.

Keywords: Vilkitsky Strait, icebergs, satellite monitoring, radar and optical images
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ICEBERGS IN THE VILKITSKY STRAIT

Satellite monitoring of potentially dangerous ice bodies (ice fields, icebergs, stranded ice, etc.) in the Arctic Region of the Russian Federation is essential for ensuring the safety and efficiency of operations on the shelf, especially in relation to a new stage in the development of economic activities in the Arctic Region. The Arctic sea ice is an important component of the ocean–atmosphere system, which affects not only the climate and the weather but also a human being and his habitat. The data on ice drift, ice spatial distribution, types, age, presence of icebergs and stranded ice are very important for shipping, fishing, and oil and gas production in the polar seas. Today, remote sensing by radar and optical survey systems is the most efficient observation method. This issue has been studied in many scientific publications; for instance, the works of (Johannessen et al., 2006; Aleksandrov et al., 2008; Smirnov, 2011, 2012) focused on various aspects of monitoring of ice and ice bodies in the Arctic Seas with involvement of the satellite data.

The Boris (B.) Vilkitsky Strait separating the Taimyr Peninsula from the Severnaya Zemlya Archipelago and connecting the Kara Sea with the Laptev Sea was discovered in 1913 by a Russian hydrographic expedition travelling on the ships “Taimyr” and “Vaigach.” The strait was named in honor of the expedition head, the Russian naval officer and hydrographer B.A. Vilkitsky (Pospelov, 2003). The strait is longer than 104 km, its width at the narrowest point is 56 km, and the sea depth ranges from 32 to 210 m.

Under the development of shipping in the Russian Arctic Region, the Vilkitsky Strait became a critical area of the Northern Sea Route. Based on the analysis of the navigation satellite monitoring data by vessel AIS system signals, we noted that about 67 ships (92%) passed through the Vilkitsky Strait, while only six ships bypassed the Severnaya Zemlya Archipelago from the north (Fig. 1; online-version of the paper with colored figures is given at the e-library website www.elibrary).

Icebergs formed on the outlet glaciers of the Severnaya Zemlya Archipelago are highly dangerous for the navigation in the Vilkitsky Strait. The glaciers such as Academy of Sciences, Rusanov, Karpinsky, Universitetsky, Semenov–Tyan-Shansky and Grottoes play a special role in the iceberg generation. The iceberg frontal cliffs with a height of 15–30 m cover about 191.5 km of the 500.8 km glacial shores in the Severnaya Zemlya Islands (Savatyugin and Shevnina, 2003).

The iceberg frequency occurrence in the Vilkitsky Strait can be estimated by the data published in the Atlas of Arctic Icebergs (Abramov, 1996). The maximum number of icebergs averaged over August by squares of 100 × 100 km in size reaches from 40 to 100. Similar rates in the Russian Arctic Region are charac-

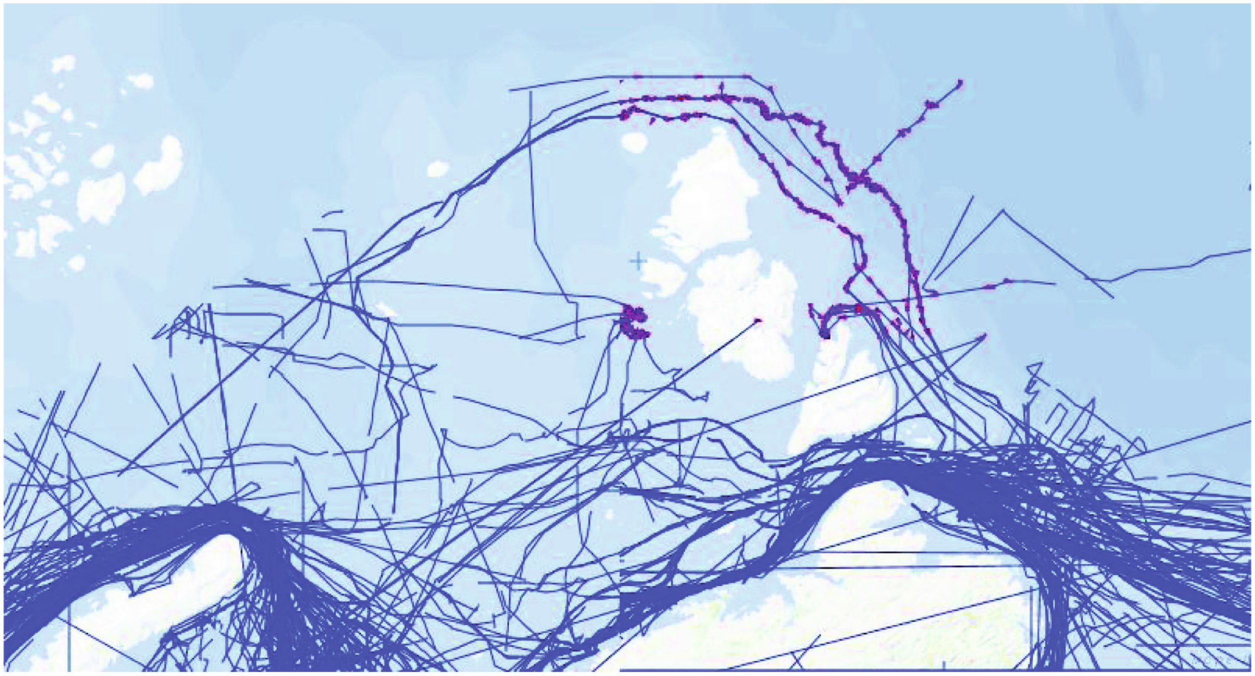

Fig. 1. Navigation intensity near the Severnaya Zemlya Archipelago in 2013 (exactEarth data, 2014).

teristic of the Komsomolets Island and the Franz Josef Land Archipelago only.

Icebergs are regarded as dangerous ice bodies of continental origin on the shelf of freezing seas. In general, the following types of continental ice are considered to be dangerous (Smirnov, 2012):

(1) An *ice drifting island* is a large piece of floating ice that splits off from the Arctic ice shelf (thickness is 30–50 m, area is from a few thousands km^2 up to 500 km^2 and more);

(2) An *iceberg* is a variably shaped massive piece of ice split off from the glacier that protrudes above the sea level by more than 5 m;

(3) An *iceberg fragment* is a large piece of floating glacier ice that generally protrudes above the sea level by 1–5 m (about 100–300 m^2 in area);

(4) An *iceberg piece* is a piece of continental ice with a smaller size than the ice fragment or a large floeberg that protrudes above the sea level by more than 1 m (about 20 m^2 in area).

The possibilities of iceberg satellite identification and methods of integrated satellite iceberg monitoring on the water surface, fast ice, and drifting ice were studied by scientists of the Arctic and Antarctic Research Institute (AARI) and Nansen Environmental and Remote Sensing Center (Aleksandrov et al., 2008; Matskevich and Smirnov, 2011; *Sputnikovye metody*..., 2011; Smirnov, 2012).

The basic tools for iceberg satellite monitoring include multimode radars with a synthesized aperture (RSA), while additional tools are multispectral scanners with a medium and high spatial resolution. The results of the ice environment study obtained in the Vilkitsky Strait are given below. The investigation was carried out with the use of subsatellite data from AARI and the FSUE Atomflot.

ICE ENVIRONMENT IN THE VILKITSKY STRAIT IN 2011

The specific features of the Vilkitsky Strait navigation in 2011 are as follows: stable fast ice was not formed in the strait during the year; an uncommonly large number of icebergs in the strait was noted in both data of travelling vessels and satellite images.

The following factors could be among those that affected the formation of the described anomalous conditions. Winter and spring of 2011 were characterized by cyclonic travel through the Barents and Kara seas to the east; the hollows of cyclonic centers were directed towards the Severnaya Zemlya Archipelago, thus contributing to the considerable heat advection to the east of the Kara Sea and west of the Laptev Sea (based on the surface analysis data given at AARI website http://www.aari.nw.ru/main.php?lg=0). As a result of such synoptic process development, the average temperature in the March–April–May period in 2011 became the highest throughout the observation period (NASA data, http://data.giss.nasa.gov/gistemp/station_data/#form); this factor, in its turn, contributed to the development of such light ice conditions and the formation of numerous icebergs.

According to satellite observation data on the Vilkitsky Strait, its southern part was under the ice with a concentration of 8–9 points even in April–May, the

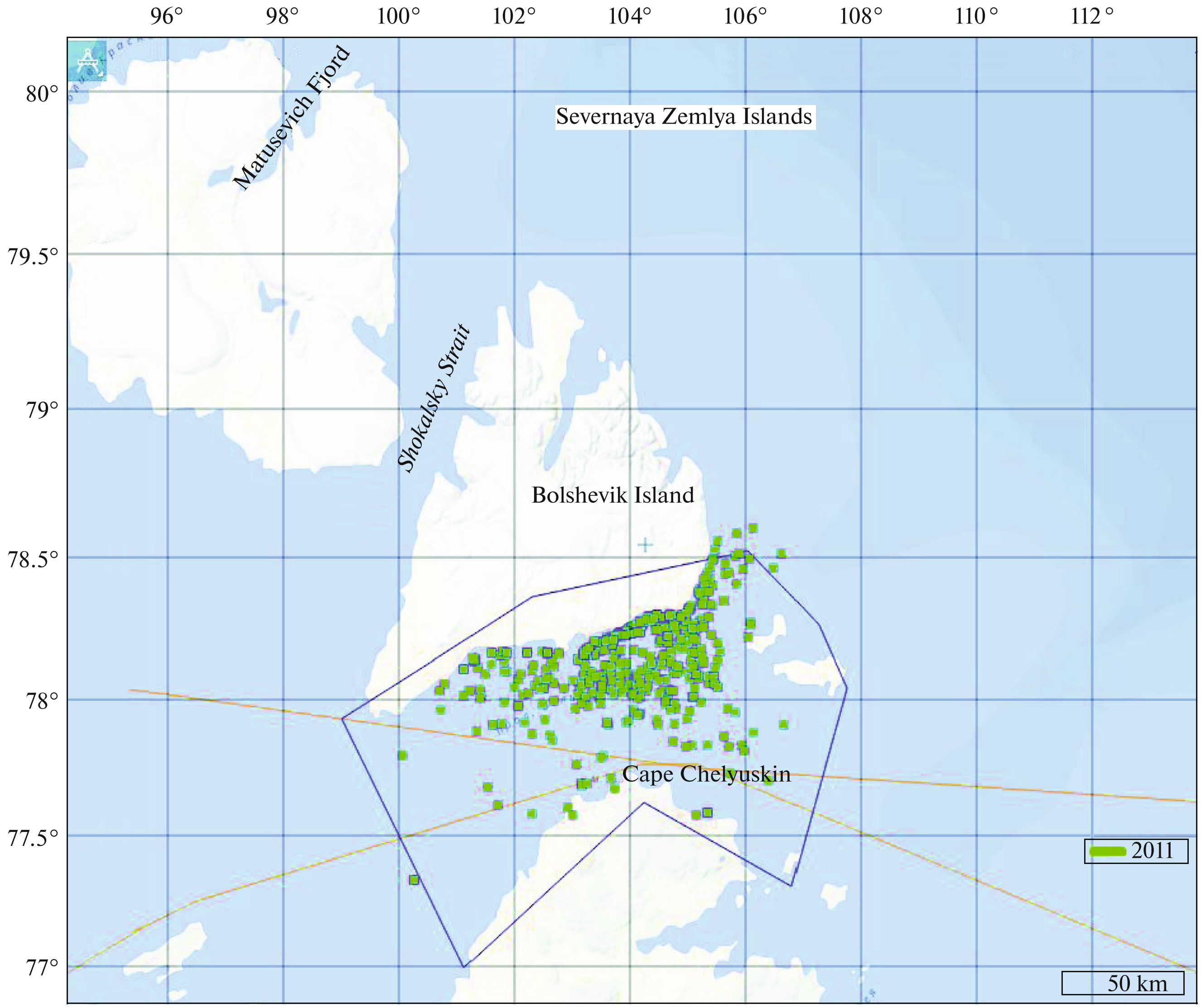

Fig. 2. Distribution of icebergs and their fragments in the Vilkitsky Strait during the navigation of 2011, according to the satellite survey and vessel observation data (the strait is indicated with a contour).

period of maximum ice cover development, while fast ice did not form there at all. As early as in the second half of July, the strait was almost cleared of ice, and light ice conditions were observed there until the end of October, the time of ice formation.

Travelling vessels and satellites recorded an uncommonly large number of icebergs and their fragments in the studied strait, almost throughout the navigation period in 2011. The iceberg spatial distribution by satellite and ship observations in 2011 is shown in Fig. 2.

It is necessary to note the high concentration of icebergs and their fragments along the northern shore of the Bolshevik Island strait, where they occurred due to the constant stream along the northern shore of the strait to the west at a speed of 0.2 knots. The iceberg drift to the west could also be caused by the tidal flows from the Laptev Sea to the Kara Sea and also by the flows formed by northern and eastern winds. Stranded icebergs were often observed near the Bolshevik Island shore. Later, under ice formation, they could be frozen into the fast ice. Icebergs that went aground near the Taimyr Peninsular shore were observed much more rarely.

ICE ENVIRONMENT IN THE VILKITSKY STRAIT IN 2012

At the end of 2011, ice formation in the Vilkitsky Strait started on October 23–25, 25 days later than previously. Fast ice was formed at the end of the first decade and in the second decade of April 2012, existed for about two months, and was broken at the end of May.

In the middle of June, the western part of the Vilkitsky Strait was characterized by an ice concentration of 8–10 points (field fragments, coarse- and fine-bro-

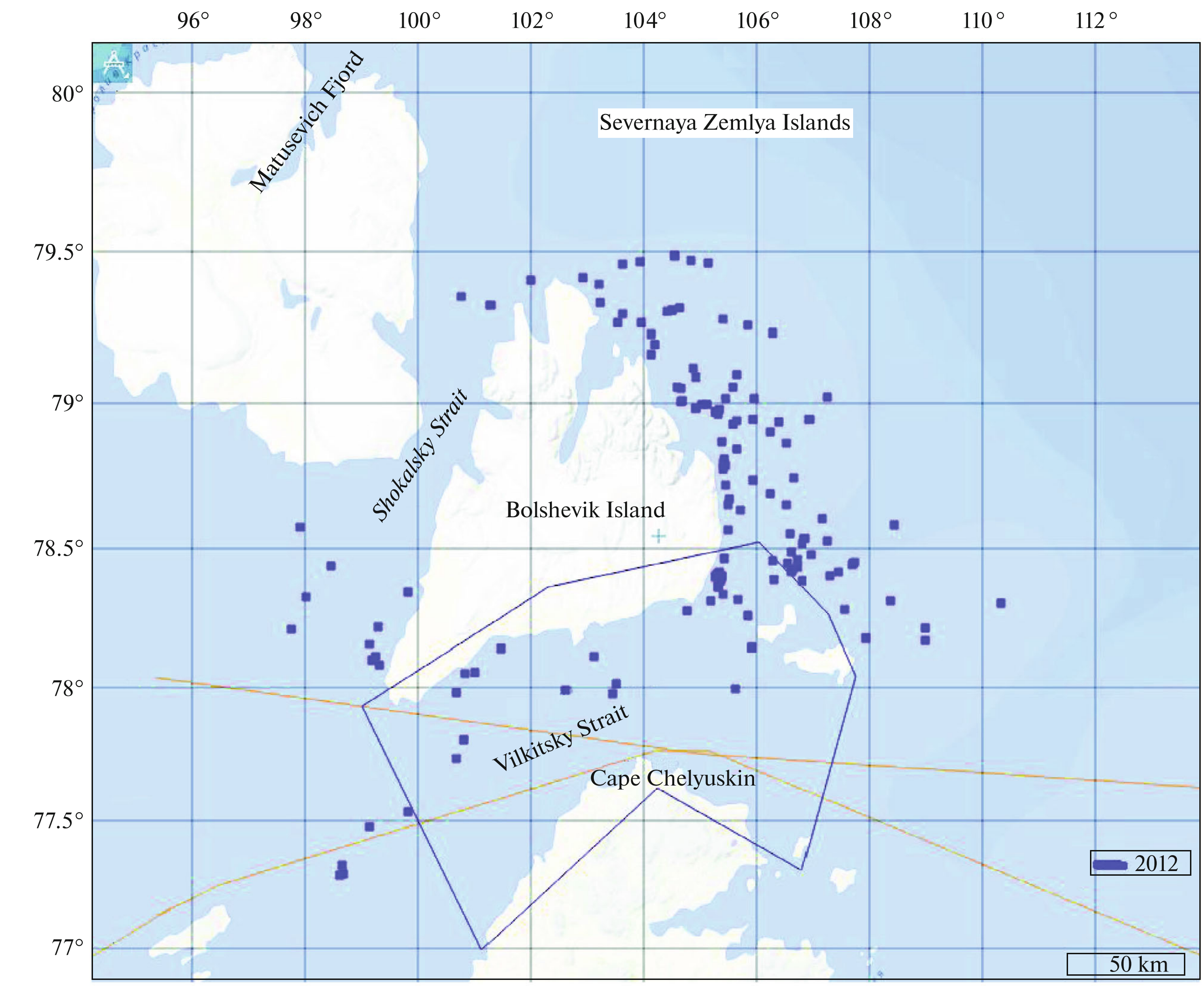

Fig. 3. Distribution of icebergs and their fragments in the Vilkitsky Strait during the navigation of 2012, according to the satellite survey and vessel observation data (the strait is indicated with a contour).

ken ice), while the east was characterized by 4–6 points. Fast ice with a width of from one to a few miles was noted only in the southern coast of the Bolshevik Island and along the Taimyr coast. This distribution of drifting ice in the strait remained unchanged until the beginning of August: the ice concentration was 8–10 points in the west due to ice removal by northwestern winds along the western coast of the Severnaya Zemlya Archipelago beside the Cape Neupokoev and 4–6 points in the east. The strait was finally cleared from ice at the beginning of the third decade of August.

Ice formation in the Vilkitsky Strait began on October 19–20, 2012 and developed slowly due to the warm air advection; prevailing southwestern winds brought out the formed ice to the Laptev Sea, and the end of the first decade of November was still dominated by primary and young ice. Mid-December was still dominated by gray–white ice. Fast ice formed in the straits along the Taimyr coast was 49 cm in thickness in the Cape Chelyuskin on December 13.

In the Laptev Sea, ice formation began in the third decade of October 2011 from the northern areas of the sea, which is 1.5 months later than the average annual terms. June and July of 2012 were marked by ice melting and destruction. The thawing hole in the ice expanded; most of the water area was clear of ice by the end of June, and it was absolutely ice-free by early August. In early September, passing ships recorded icebergs of up to 1000 m in size in the north of the Laptev Sea, between 77°10′ and 77°22′ N, 114°00′ and 124°30′ E.

The ice environment and number of recorded icebergs in the studied strait during the navigation of 2012 can be attributed to the moderate conditions. The spatial distribution of icebergs detected with the help of satellite images and ship observation data in the Vilkitsky Strait in 2012 is shown in Fig. 3.

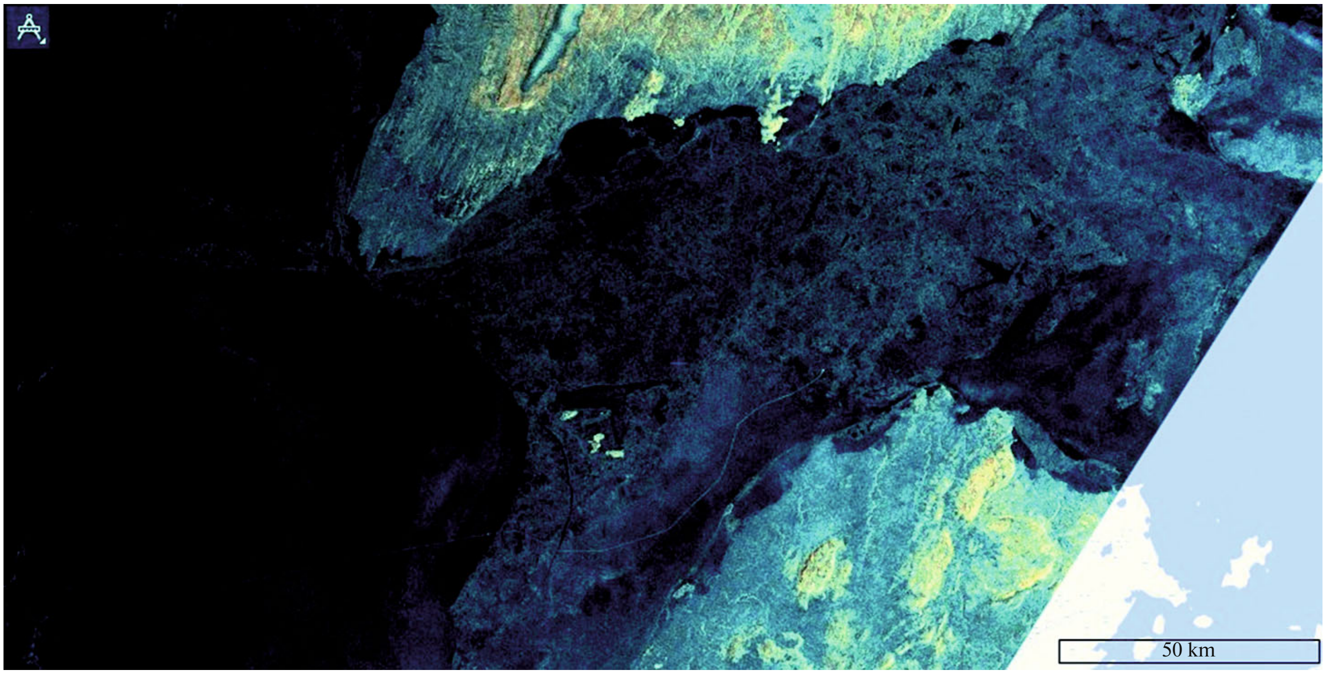

Fig. 4. Ice environment in the Vilkitsky Strait on May 21, 2013. Radarsat-2 radar images. MDA, SCANEX.

ICE ENVIRONMENT IN THE VILKITSKY STRAIT IN 2013

Fast ice was formed almost throughout the water area in the Vilkitsky Strait by the mid-January of 2013. Fast ice reached 95 cm in thickness in the Cape Chelyuskin in early February and 128 cm in late February. In late February, the fast ice edge passed a few miles east of the Minor Taimyr Island. In mid-March, the fast ice was 145 cm in thickness in the Cape Chelyuskin.

Figure 4 illustrates the ice conditions in the studied strait on May 21, 2013. It is clearly seen that the fast ice is relatively smooth in the area from the Russky Island to the Heiberg Islands. In addition, a narrow band of the smooth fast ice passes along the Taimyr coast. Ice is highly ridged in other water area. If observing attentively, we can see traces of the vessel convoy, which is moving eastwards along the flat fast ice, without going to the ice hummocks owing to the use of satellite reconnaissance data on ice.

The destruction of the fast ice began in July from the east, and the fast ice was cracked up to the Heiberg Islands by the end of July–beginning of August. Meanwhile, the fast ice spread to 93° E in the Kara Sea. The ice edge was firmly pressed to the fast ice by western winds in the Kara Sea, and the ice spread to the west approximately to 85° E. The fast ice was finally broken at the end of the second decade of August.

The most favorable floating conditions were formed near the Taimyr coast through the Mathisen Strait: the ice concentration reached 4–6 points there, while the northern part of this strait was characterized by 7–10 points. By mid-September the ice concentration in the western part of the strait was 4–6 points (the most favorable floating conditions), while its eastern part was dominated by concentrated ice bands formed under the influence of the western wind. The vessel convoys commonly travelled through the Mathisen Strait and then along the Taimyr coast (Fig. 5). An ice spot with a concentration of 8–10 points, which was preserved up to the beginning of the ice formation, was noted southeast of the Cape Neupokoev.

Ice formation in the strait began at the end of the third decade of September in 2013. By the end of October, the Vilkitsky Strait area was dominated by gray–white ice with a concentration of 8–10 points with residual broken ice inclusions. Fast ice formed along the coasts and around the islands in November, while the other area was dominated by gray–white and one-year thin ice with a concentration of 9–10 points. Fast ice completed its formation in most part of the strait by the end of December in 2013, but a narrow band of gray–white one-year ice was preserved north of the Cape Chelyuskin.

The ice environment in the Vilkitsky Strait during navigation of 2013 can be considered to be hard. The spatial distribution of icebergs identified with the help of the satellite ship observation data in 2013 in the Vilkitsky Strait is shown in Fig. 6. The integral map of icebergs identified with the help of the satellite and ship survey data in 2011–2013 in the studied strait is demonstrated in Fig. 7.

In general, the ice environment in the Vilkitsky Strait can be described as light (2011), moderate (2012), and hard (2013). The highest number of ice-

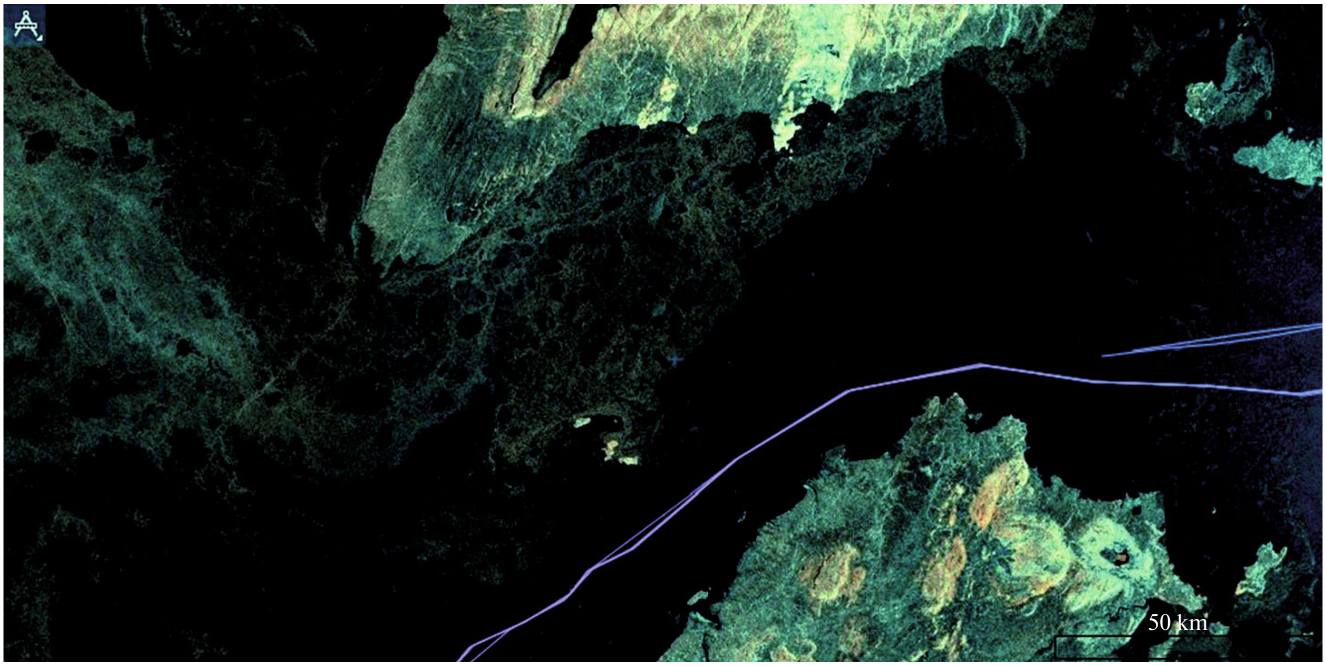

Fig. 5. Travelling of the vessel convoy in the Strait on August 26, 2013, over clear water along the Taimyr shore with account for the formed ice environment. The Radarsat-2 radar image fragment shows the vessel convoy track based on the S-AIS data. MDA, SCANEX, and exactEarth.

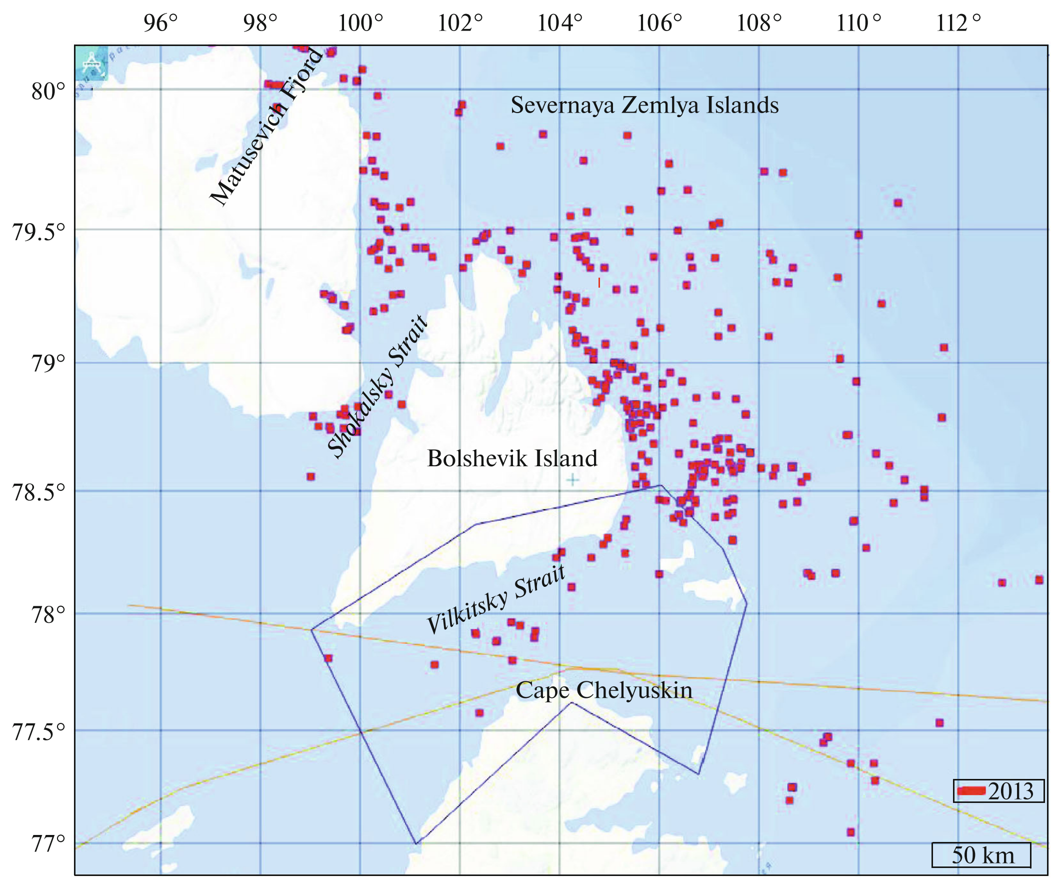

Fig. 6. Distribution of icebergs and their fragments in the Vilkitsky Strait during the navigation of 2013, according to the satellite survey and vessel observation data (the strait is indicated with a contour).

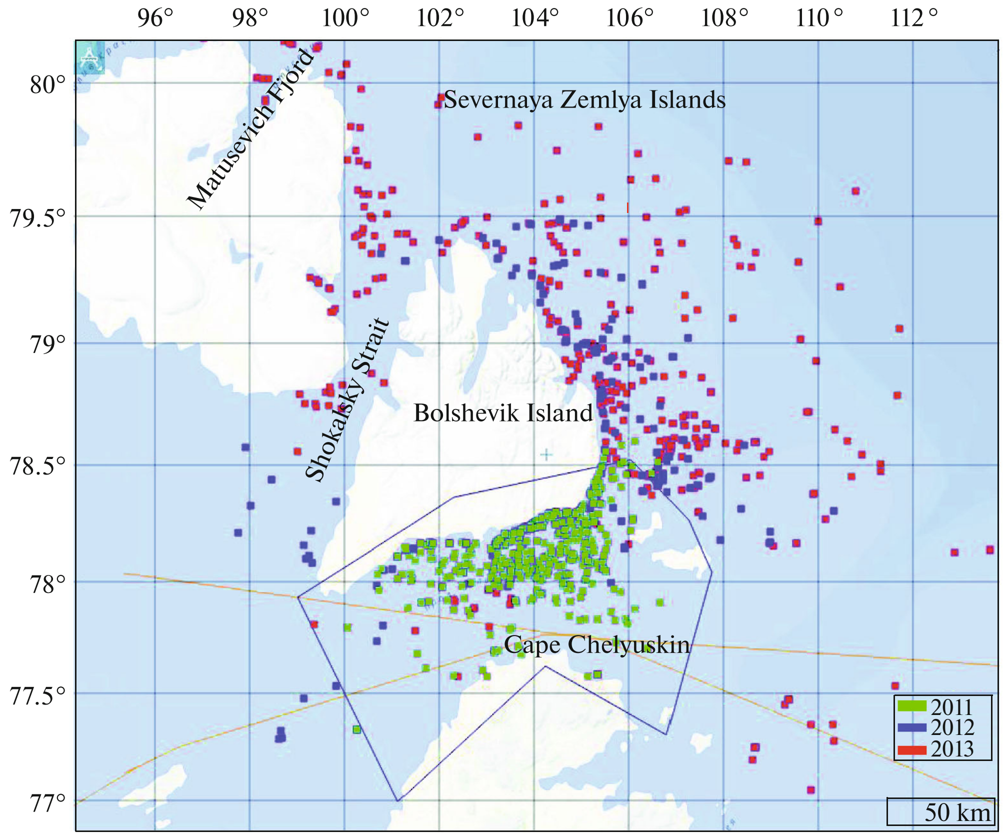

Fig. 7. Integrated map of icebergs identified by the satellite survey and vessel observations in 2011–2013 in the Vilkitsky Strait (the strait is indicated with a contour).

bergs in the strait was recorded in the navigation of 2011 and the lowest number was recorded in 2013.

SATELLITE MONITORING OF LARGE ICEBERGS

Iceberg drifting was monitored by multisatellite integrated survey with operational planning processes and treatment of the data obtained from four optical and radar commercial satellites such as Radarsat-1 and Radarsat-2, EROS-B, and SPOT-5. In contrast to the well-known PolarView services for the monitoring of ice conditions and icebergs, the applied technology is distinguished by a greater level of detail due to the use of high and ultra-high resolution survey tools and high speed of data processing, which is necessary to ensure navigation safety.

The icebergs were monitored with radar images from Radarsat-1 and -2 satellites, which were obtained under the SCN and SCW observation survey with a spatial resolution of 50 and 100 m, and also under the Fine and Standard detail survey with a resolution of 10 and 25 m. Drift velocity and direction were estimated by paired shooting with the obtainment of two images within the relatively short time range of 3–4 h to one day. As follows from the received experience, the survey period should not exceed one day in order to provide stable icebergs identification and tracking.

As is known, general radar images in a wide swath do not provide a high probability of detection and identification of small icebergs, while detailed radar images do not cover the entire area of the studied strait. A new so-called “expanded” Wide Fine survey mode was tested in 2011. It was developed by MDA after the start-up of Radarstat-2. It combines a wide swath of up to 170 km with a high spatial resolution of 10 m and the ability to survey with signals of two polarization types (Fig. 8).

In the future, for the purposes of detection and tracking of iceberg drift in the Vilkitsky Strait, it is advisable to obtain one or two radar images with a swath of 150–170 km in width, resolution of 5–10 m, and signals of two polarization types (HH and HV) on a daily basis. Under favorable weather conditions, it is necessary to use optical images with a frame width of 60 km and a resolution of 2–5 m.

A few plateau-shaped icebergs with a size of 700–1500 m were identified in the Vilkitsky Strait in 2011. Through the use of integrated operational monitoring technology, we managed to track in the strait the drift of a flat iceberg, which was 710 × 460 m in size and tabular in form (Fig. 9), for five days, from October 6 to

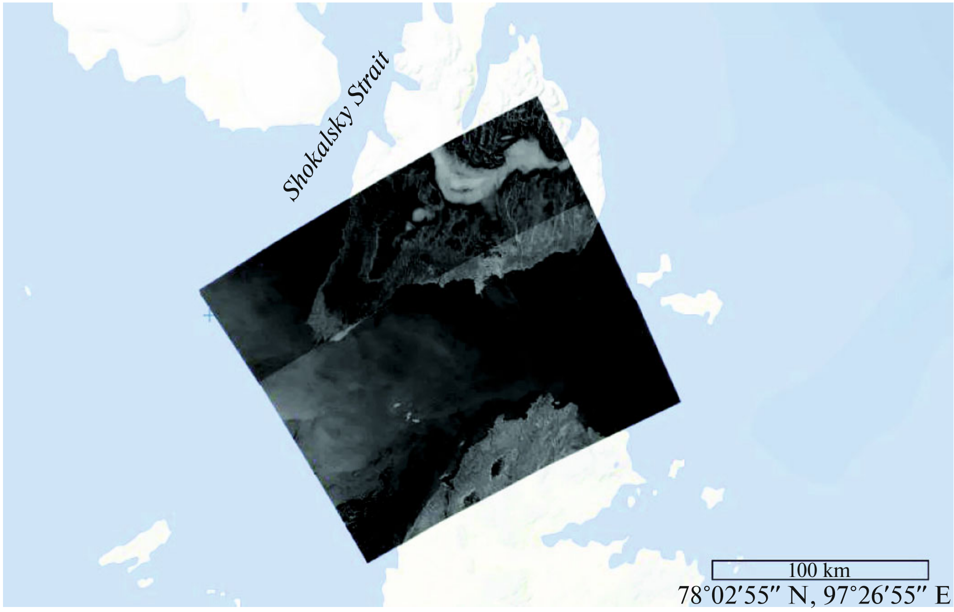

Fig. 8. Radarsat-2 radar image of the Vilkitsky Strait under the Wide Fine mode with a shot dimension of 150 × 170 km and a spatial resolution of 10 m. MDA, SCANEX, 2011.

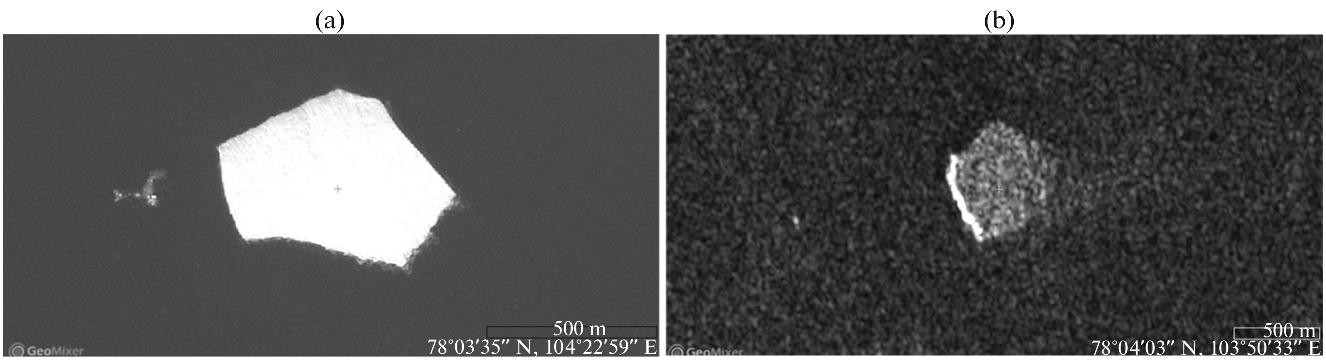

Fig. 9. Large flat iceberg 710 × 460 m in size drifting in the Vilkitsky Strait in the period from October 6 to 10, 2011. Fragments of SPOT-5 optical image (a) and Radarsat-2 radar image (b) as of October 7, 2011. AIRBUS DS, MDA, SCANEX, 2011.

10, 2011. In the observation period, the iceberg drifted westwards, turned northwards, and then drifted in a reverse direction. The averaged linear velocity of the iceberg drift, which was measured with pairs of images as of October 6, 2011, and October 7, 2011, in the short time interval of 3 h, 23 min and 53 min, reached 0.9 and 0.8 km/h. Pairs of images (two radar images or one radar image and one optical image) obtained during the day make it possible to determine the direction and the average drift velocity and to identify icebergs that went aground in the coastal zone.

Iceberg drift modeling carried out with the help of the SkanDrifter software yielded satisfactory results (Fig. 10). It is known that iceberg drift forecasting is challenging because of the many unknown parameters, including the size of surface and underwater parts. As is seen in the given example, the SkanDrifter software makes it possible to obtain a short-term forecast based on real data on the previous drift.

Optical high-resolution images make it possible to define iceberg height by the length of a thrown shadow. The calculations were carried out with the use of the ScanEx Image Processor software and approved by the measurement of height of bodies with known dimensions by shadow length or by length of a visible side face (for survey with a deviation from nadir). The Sun site angle values obtained from image metadata were used as additional information. The most accurate iceberg height is obtained from the length of a shadow cast on the fast ice; meanwhile, it is possible to measure height by shadow length on the sea surface. The performed experiments involved highly detailed EROS-B and SPOT-5 optical images (spatial resolution of 0.7 and 2.5 m, respectively). An example of determination of the height of drifting icebergs and

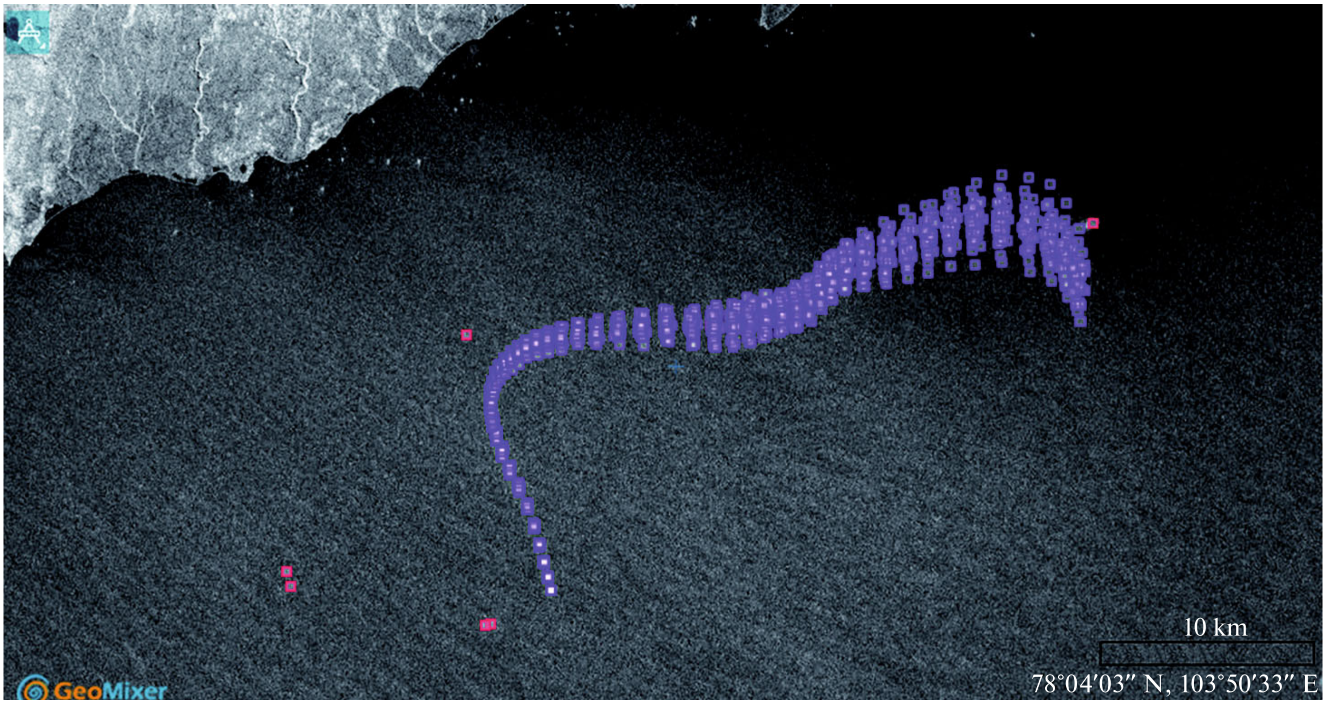

Fig. 10. Results of the large iceberg drifting modeling with the help of the ScanDrifter software. The Radarsat-1 radar image as of October 10, 2011, is shown as a background image. Groups of small icebergs are observed along the southern shore of the Bolshevik Island. MDA, SCANEX.

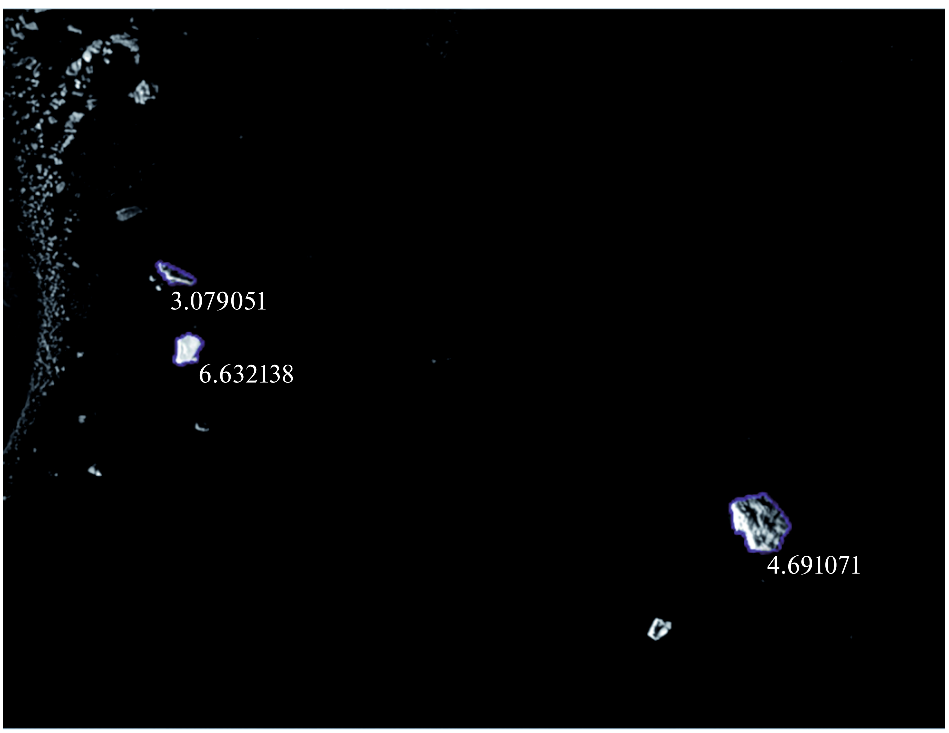

Fig. 11. Height of icebergs and their fragments calculated by shadow length on the sea surface. The EROS-B image as of September 3, 2012; digits show height values. ImageSat Int., SCANEX.

their fragments by shadow length on the sea surface is shown in Fig. 11. An iceberg height can also be estimated with Landsat-8 optical medium-resolution images (resolution of up to 15 m).

CONCLUSIONS

The efficient use of Arctic resources and fulfillment of the local population's needs are closely related to further infrastructure development in this region.

The arrangement of the most critical sea route in this Russian region—the Northern Sea Route—is of special importance. The stage of new development of the Russian Arctic Region should take into consideration iceberg observation and the iceberg monitoring system, especially under development and transportation of the Arctic shelf resources.

The number of icebergs in the Vilkitsky Strait should be forecasted on the basis of data on the development of the ice environment in the strait and the surrounding seas. The number of icebergs in the strait is maximal under light ice conditions characteristic of 2011. Most identified icebergs occur in the strait from the Laptev Sea as a result of drifting from the outlet glaciers in the northeastern coast of the Severnaya Zemlya Archipelago. The icebergs are largely located along the southern coast of the Bolshevik Island.

Iceberg drifting in the Vilkitsky Strait should be identified and monitored with the use of radar images with a resolution of 10–25 m, with a swath of 50–170 km and with two polarization types, and also optical images with a resolution of up to 2 m and a swath width of 60 km. According to the experience obtained in the course of strait survey in 2011–2013, in the period of active navigation in the strait, it is advisable to obtain images with a frequency of at least 1–2 times a day for the reliable detection of dangerous ice bodies, identification of icebergs, and measurement of their drift parameters, and also for identification of stranded icebergs. Radar images obtained under the ScanSAR survey modes, despite their wide swath, do not make it possible to detect icebergs reliably (especially in fast ice) due to the low spatial resolution.

Hence, we developed and tested the technology of operational satellite monitoring of icebergs on the example of the Vilkitsky Strait, the main components of which include multisatellite surveys with operational planning processes and interpretation, as well as geoportal solutions that make it possible to provide access through the Internet. The interpretation and analysis of complex and multifrequency satellite data make it possible to determine ice body characteristics such as type, size, direction and speed of drift, concentration zones, ice concentration, and, occasionally, height of the surface part. The basic requirements for the satellite monitoring system were stated. The implementation of such a system for monitoring dangerous ice bodies in operational practice will significantly improve the safety of Arctic shipping.

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