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ECOLOGY

The Possibility of Using High Resolution Satellite Images for Detection of Marine Mammals

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Abstract—The possibility of using modern systems of remote sensing in the optical range from high spatial resolution satellites for detection of marine mammals and traces of their activity is investigated. An image obtained by the GeoEye satellite within the FEAC project was used for the analysis. The image covers Herald Island and adjacent waters, which are a part of the Wrangel Island Reserve, during the seasonal thaw (June 2009). It is shown that marine mammals (polar bears, walruses, and whales) can be identified on such images. The absence of synchronous ground truth observations reduces the reliability of the results.

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The inaccessibility of the Arctic and the lack of effectiveness of traditional methods of studying marine mammals in the region has forced us to use methods of remote sensing of the Arctic habitat with measuring instruments. The latter is constantly being improved primarily due to the increased sensitivity of sensors and, consequently, increasing spatial resolution. In 2008, the GeoEye-1 satellite was launched, which is equipped with instruments that make it possible to obtain panchromatic images with a resolution of 0.41 m. Their commercial distribution is carried out with a resolution of 0.5 m throughout the image. However, optical systems have a significant drawback; i.e., they cannot conduct surveys in winter and night periods and in cloudy conditions. Radar sensing lacks these drawbacks, but it does not provide such a high spatial resolution; i.e., the highest spatial resolution currently available in the X-band is 1 m (COSMO-SkyMed satellite, Europe; TerraSAR-X satellite, United States), and in the C-band it is 3 m (RADARSAT-2 satellite, Canada).

The resulting optical and radar images have recently begun to be used to study the distribution and number of marine mammals in the Arctic region. In 2010, during the breeding season of seals, a project on satellite control of shipping in the White Sea was implemented (using satellite radar data (RADARSAT-1 satellite, Canada, for rapid assessment of the ice situation) and optical images (EROS-B satellite, Israel) with a spatial resolution of 0.7 m in order to identify potential areas of whelping of harp seals) (ScanEx company News ..., 2010). In order to count Weddell seals on fast ice images obtained by QuickBird-2 (0.6 m) and WorldView-1 (0.6 m), satellites were used (LaRue et al., 2011). The results obtained with the use of remote sensing data were highly consistent with the results of ground counting. Using the image obtained by the EROS-B satellite on July 28, 2011, the hauling ground of Atlantic walruses was found in the coastal area of Matveyev Island in the southern part of the Barents Sea (Semenova et al., 2011). The spatial resolution of 0.7 m made it possible to identify animals of 2.5–3 m and estimate the size of the cluster as 200 animal units.

The preliminary results of visual analysis of the GeoEye panchromatic image with a high resolution (0.5 m) are given for detection of marine mammals. In the optical image with a resolution of 0.5 m, an adult polar bear with a body length of 2–2.5 m occupies 4–5 pixels, which makes it possible to detect the animal under certain environmental conditions.

The waters adjacent to Herald Island, which is a part of the Wrangel Island Reserve, were selected for this study. The advantage of Herald Island and the adjacent waters is the lack of human activity that could introduce errors in identifying animals. The absence of human influence eliminates the detection of traces of behavior, such as the urge of the polar bear to dive into the water in case of danger.

MATERIALS AND METHODS

For the analysis we used an image made on June 19, 2009. It covers Herald Island and the adjacent waters. The image is shown in Fig. 1 in the form of a preview. The metadata from the image catalog (as of June 2, 2011) is given in the table. In contrast to the stated projection of EPSG: 4326 (Evenden, 1990), the obtained image has the projection of EPSG: 32601 (+proj=utm +zone=1 +datum=WGS84 +units=m +no_defs). Geographic transformations were not car-

Fig. 1. Image 20090619234633885GE10280165_001 in preview mode.

ried out in analysis of the image. The north is always at the top in all illustrations.

In order to identify marine mammals in the image, the visual analysis of fragments (frames) of the panchromatic image in the Quantum GIS environment was used (*Quantum GIS* ..., 2011). Each fragment is an area of 350 × 250 or 1/3600 of the total area of the image. The size of the fragment is chosen so that the image pixel takes at least one and a half monitor screen pixels (thus, 1 m contains 3.3 pixels). A three-phased scanning of the image was conducted, i.e., along the waterfront, along the border of fast ice and shore of Herald Island, and a step scan of the entire image field. Scanning was carried out by vertical tacks coming in touch with each other. The step width was 1/4 of the fragment in the vertical or horizontal direction. During the scan objects of potential interest were marked by geometric forms such as polygons and points with assignment of symbols and the ability to add comments. In some cases images in the near infrared range (2 m resolution) and a color composite of red, green, and blue bands constructed by separate channels (2 m resolution) were used as a base map.

The environmental conditions typical of the studied area in June 2009 are shown in Figs. 2 and 3. Due to climatic features of air transfer over long distances, the studied area was extended to the central Arctic and the northern part of the Pacific Ocean (Figs. 2, 3).

Figure 3 shows monthly anomalies, i.e., geopotential heights (Fig. 3a, contour), wind speed and direction (Fig. 3a, arrows), and surface temperatures (Fig. 3b, white outline) at the level of 1000 mb. Figure 3b also shows concentrations of the sea ice classified at the 15 and 50% levels (gray scale) and the concentration anomalies (black outline) at levels of 15% (thin line) and 30% (thick line). In both figures a positive anomaly corresponds to a short dotted line, while negative anomalies are indicated by a long dotted line.

For a more detailed analysis of ice conditions in the studied area, a series of weekly review ice charts ESIMO AARI (St. Petersburg) were used (http://www.aari.ru/odata/_d0015.php), which are shown in Fig. 4. Manifestations of the central branch of the Bering Sea currents and reduction of the concentration of ice were

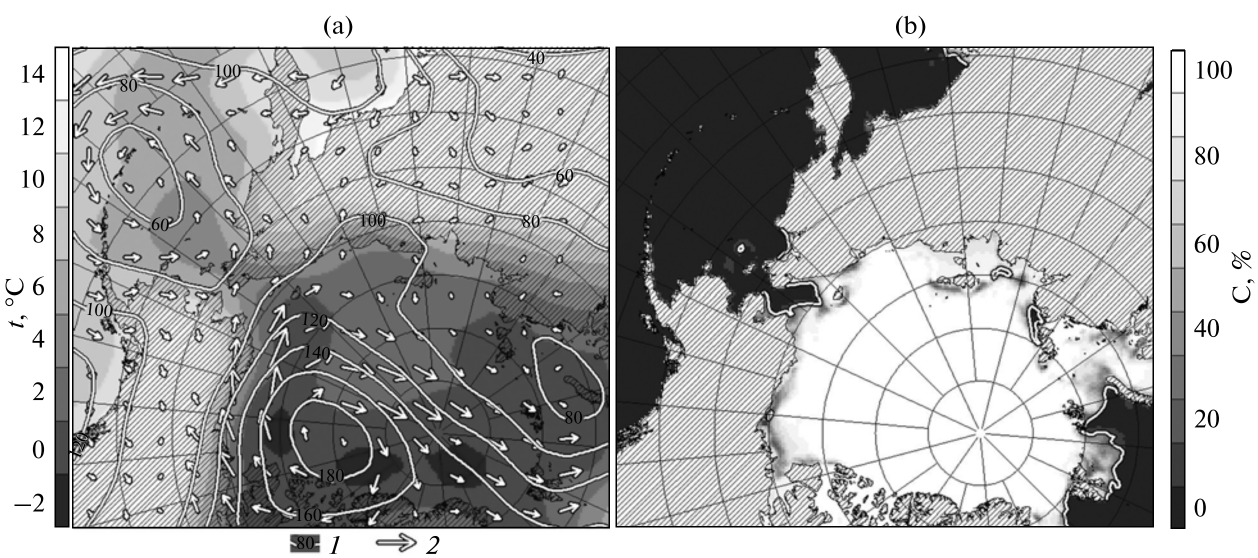

Fig. 2. Environmental conditions in June 2009: (a) the average monthly air temperature, geopotential heights (*1*), wind speed and direction by the level of 1000 mb (*2*); (b) the average sea ice concentration (C) and the boundary of the ice edge by the concentration level of 15% (contour line).

Metadata of image 20090619234633885GE10280165_001 from June 2, 2011

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SOURCE	GEOEYE-1
SENS_MODE	PAN_MS_HR
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SCENE_ID	20090619234633885GE10280165_001
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MONTH	6
YEAR	2009
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SQKM	322
SPATIALREF	EPSG:4326
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ELEV_ANGLE	61.1011
AZIM_ANGLE	359.891
CLOUDS	0
SUN_ELEV	42.2318
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STEREO_ID	
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UR_LAT	71.456781
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LL_LON	–175.953523
LR_LAT	71.304782
LR_LON	–175.446422
GEORECTIFY	1
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WORLD_URL	http://geofuse.geoeye.com/static/browse/geoeye/GE1/2009/6/19//20090619234633885GE10280165_001.jgw
METADATA	http://geofuse.geoeye.com/landing/image-details/Default.aspx?id=20090619234633885GE1028016520090619234633885GE10280165_001
PRODUCT	http://www.geoeye.com/CorpSite/products/Default.aspx

observed, which can also be caused by the influence of warm, relatively deep waters of the Bering Sea.

In June 2009, the western part of the Chukchi Sea was dominated by winds of eastern bearings (Fig. 2) due to the positive pressure anomaly in the Canadian Arctic (Fig. 3). As a consequence, ice advection occurred, which led to a shortage of ice in this part of the sea, compared with the average value for the decade period (2000–2009). The air temperature was +1° to +2°C. It was sufficient to initiate surface melting of ice and snow. In June 2009, the movement of the ice edge (opening) in the western part of the Chukchi Sea

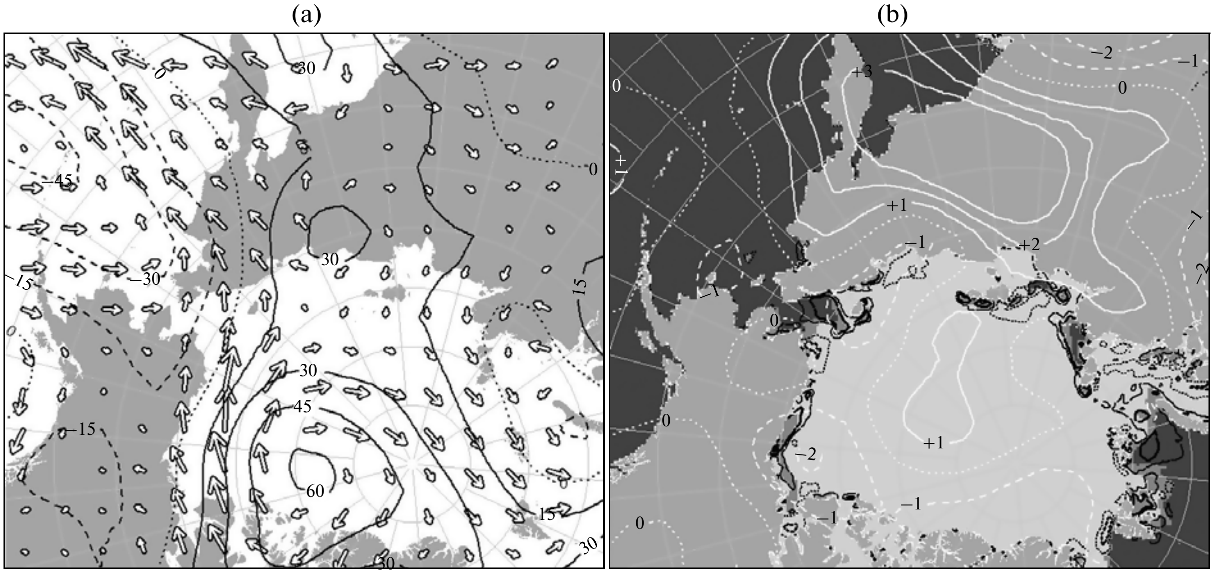

Fig. 3. Anomalies of the environmental conditions in June 2009 compared with the base period of 2000–2009. (a) Geopotential heights (contours), speed and direction of the wind (arrows), the surface temperature by the level of 1000 mb (white line), (b) the concentration of the sea ice: by levels of 15 and 50% (gray scale), abnormal concentrations (black outline) at the level of 15% (thin line) and 30% (thick line), (a), (b) positive (short dashes) and negative (long) anomalies.

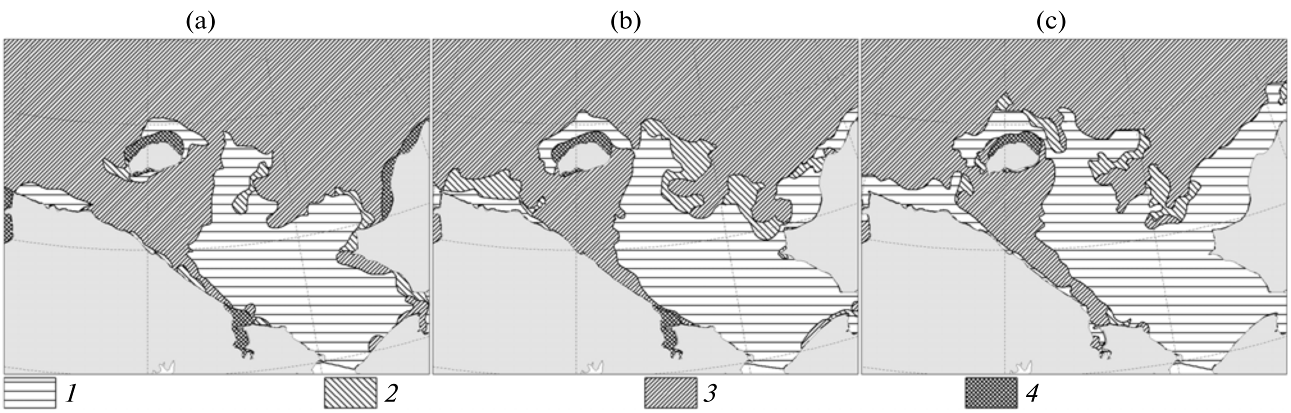

Fig. 4. Ice charts AANII on June 15–17, 2009 (a), June 22–24, 2009 (b), June 29–July 1, 2009 (c). Clean (*1*), the concentration of 1–6 points (*2*), 7–10 points (*3*), and fast ice (*4*).

occurred at almost a constant speed in the western direction (east to west). The emergence of the Zavrangelskaya polynya was noted to the north of Wrangel Island (Fig. 4). On the northern coast of Chukotka, ice remained until the end of June. Compared to the same period in 2010, June 2009 was more sunny (composite cards MODIS, Terra satellite, United States).

Some environmental conditions on the day of shooting (June 19, 2009) can be identified from the image itself. There were no signs of agitation of the sea surface to the north of Herald Island, and the waves with a period of 5–7 meters to the south of the island may be swelling.

The GeoEye orbit is sun synchronous (equator crossing time 10:30, inclination 98°) but the analysis of the shadow of the northern rocks indicates the presence of the Sun in the south and that it was close to the zenith. For a point (71°22.76′ N, 175°39.35′ W) at a difference with GMT of 12 hours, at 12:00 (10:30) local time June 19, 2009, the azimuth of the Sun was 184.97° (157.46°) and the height of the Sun was 41.97° (40.86°). In most cases, we can assume that the size of the shadow in the northern direction corresponds to the height of the object.

There was decaying first year ice in the area as well as fast ice with a complete lack of multiyear ice. Individual ice floes had undergone heavy surface melting. As a result their underwater surface area exceeded the area above the water.

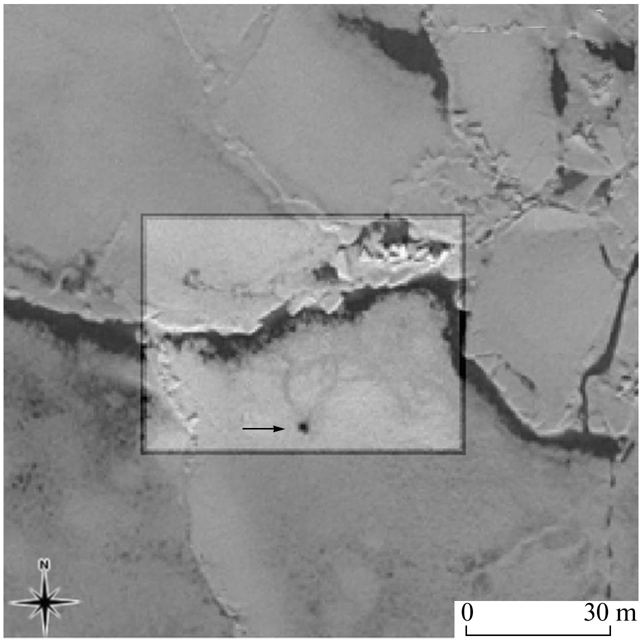

Fig. 5. Tracks and a hole (arrow).

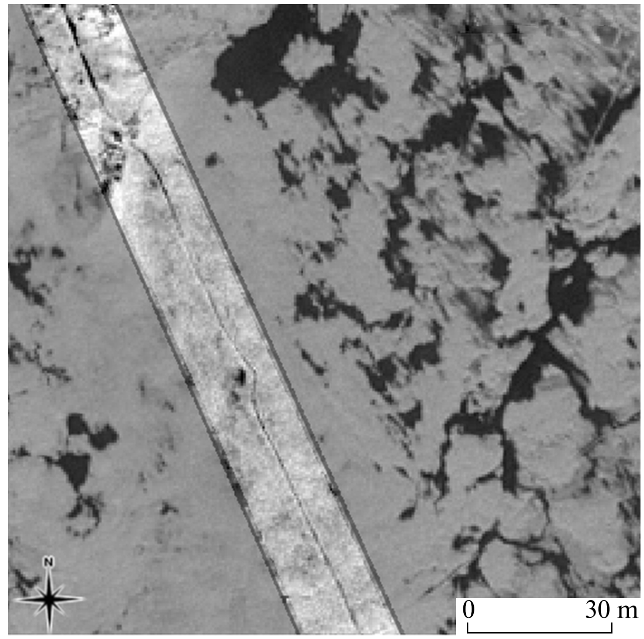

Fig. 6. Potential trace of a polar bear (highlighted line).

Polar bears can be near Herald Island and on the island itself at any time of the year (personal message of S.E. Belikov). In June, the presence of fast ice can attract the polar bear not only as a platform for movement but also by the presence of molting seals. The destruction of the ice cover noted at the time of shooting in the low spatial resolution leads to a reduction of the regional sea-ice concentration, and due to the destruction of the ice cover in the direction of the prevailing wind, it can be assumed that there is a movement of the ice edge to the west. In June, in the Chukchi Sea, there is a seasonal migration of walruses (females with cubs and young stock) by the ice edge so at the time of shooting the formation of glacial herds of this type of pinnipeds is possible (Belikov et al., 1984). The appearance of individual floes increases the length of the ice edge. It can contribute to a safer rest of pinnipeds on the ice; i.e., seals can spend more time on the ice. Bowhead whales, as well as walruses, follow the ice edge. Bearded seals can be observed in the studied region with the available depths at any time of year.

RESULTS AND DISCUSSION

Trace pattern analysis. As noted above, the average monthly temperature in the studied area is slightly above 0°C. This can cause refreezing of snow. At night it can freeze and melt in the daytime. When a polar bear walks on wet snow, the snow becomes much denser and, therefore, has darker features in the visible range. Fresh tracks appear darker than the surrounding snow in the image. Old tracks and paths are eventually buried in snow. The wind forms small snowbanks which in images in the case of the setting sun can seem a little lighter than the surrounding ice and snow.

The tracks of a polar bear in the image can be similar to a crack in the ice but unlike a crack, they have a fixed width. If a polar bear walked on thin ice, it could lead to the formation of a crack, which sometimes narrows and sometimes expands. The width of the trail of an adult polar bear is commensurate with the resolution of the image. When a female polar bear with cubs moves, the cubs try to keep up with the mother. If the snow is deep, they try to walk in single file. If there is small amount of snow, the trace pattern of movement of the family becomes more complicated and it may be more visible on satellite images of advanced optical sensors.

Traces of the possible presence of marine mammals are shown in Fig. 5, i.e., a hole and traces leading to it. There are no hummocks on the marked ice floe, and the snow is trampled in its northern part. Dark tracks are likely to show recent activities of seals or, which is unlikely, of a polar bear due to the high density of tracks. These are trampled tracks which have not yet been snowed upon.

In Fig. 6 an extended object is selected that is apparently bear tracks. Such a conclusion can be made on the following grounds: the width of the visible line is almost the same, the line itself is similar to the track left by a polar bear during purposeful movement, the depth of tracks varies but their dark side could have been caused by a deep snow in the path. A dark spot can be observed, which may be a melted lake, and the line of tracks goes around it. However, for at least 100 m in the

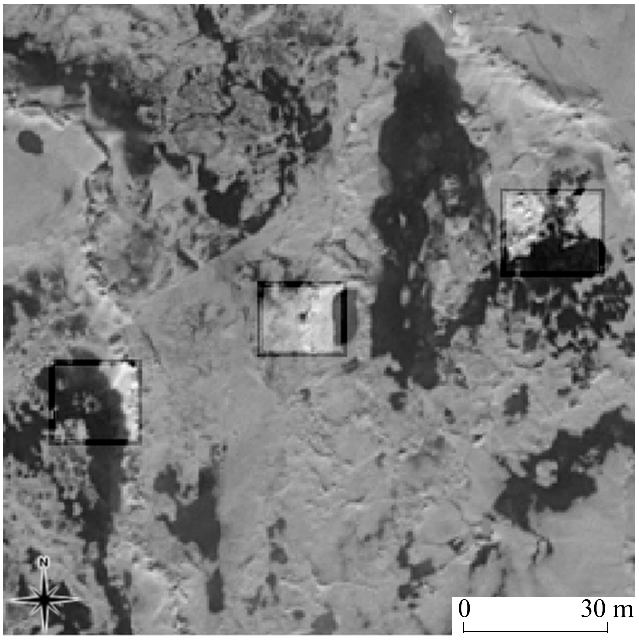

Fig. 7. Holes (marked).

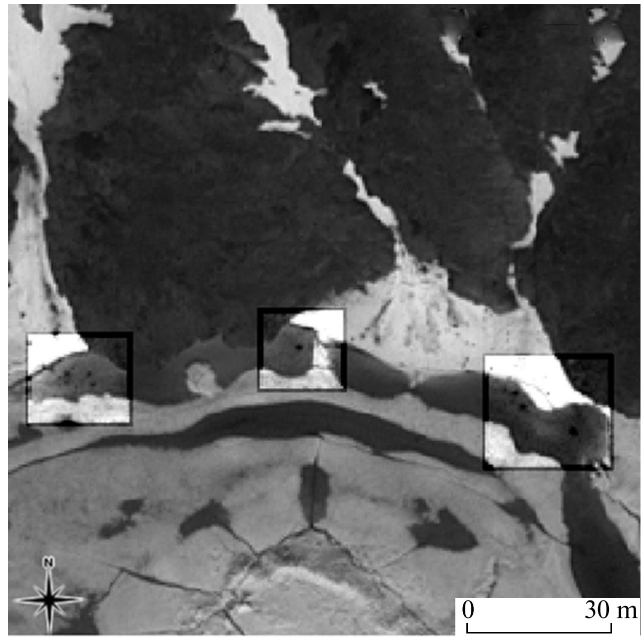

Fig. 8. Holes in the coastal area (highlighted).

direction of this spot, the line of tracks remains the same.

A light line in the other part of the fragment (top right) may be an old snow-covered trail. The presence of these lines on the dark surface (most likely heavily melted snow) can be explained by the fact that that trail was covered many times with snow and frozen and, hence, is ice framed. This ice is lighter than the surrounding snow, so it absorbs less heat and, therefore, it is less prone to melting. Near the crack ice movements are likely, so most probably an offset of the pattern on opposite sides of the crack would be noticeable.

Analysis of holes. Single holes presumably belong to the seals, and the sequence of holes in a certain direction on thin ice can belong to any mammal, including a polar bear, if the ice does not maintain its body weight. Such a pattern can be observed in the image areas with low brightness of pixels.

In Fig. 7 three quadrangles are marked at the center of which there are potential pinniped holes. They are almost in a straight line, and the distance between a pair of adjacent holes is almost identical, which can be determined by the time a pinniped stayed underwater. The identification of the farthest hole is least error-prone, since it is found on thin ice. Surfacing is accompanied by ice faults around the hole, so the edges of the hole appear lighter than the surrounding ice. This effect is clearly visible in the ship observations and in photographs during aerovisual study, so we can assume its manifestation in high resolution satellite images. The average hole is located in the snow, and the detection error of such a hole is higher, since it can be confused with the formed meltwater lake.

The appearance of holes in the coastal area can be due to fragility of the ice. Vertical heat fluxes arising from the coast are not conducive to the formation of solid ice, which could withstand the weight of the animal, which is was forced to move in the water. Such a situation can be seen in Fig. 8. The diameter of dark spots is commensurate with the size of holes left by a large pinniped or a polar bear. However, these spots of open water may also be a consequence of melting due to heating.

In Fig. 9 there is a small bright spot with a diameter of about 1 m, from which bright lines go in different directions, against the background of the dark ice. The dark surface of ice is probably hydrated, or there is no snow on it. The bright spot might have been caused by reflection of the sunlight from the ice fragment at the edge of the hole. In this case, bright lines are the frozen trail of a polar bear.

Analysis of beaches. Special attention in the analysis of the coast line is paid to estuaries, which are comfortable areas that bears use as a starting point to move to the interior of the island to latibulize and a place where female bears come with cubs (Ovsyanikov, 1995).

Bright objects of volumetric shape on the rather flat land of the shoreline (Fig. 10) are probably polar bears. This area is the southern section. It is well warmed by the sun. It is the coast of the island. The dark surface of the beach is well heated, so the presence of ice blocks in this place and at this time is almost impossible. For female bears and cubs, the warm surface is attractive for recreation. Recent activity of polar bears in the area is also indicated by the sufficiently deep

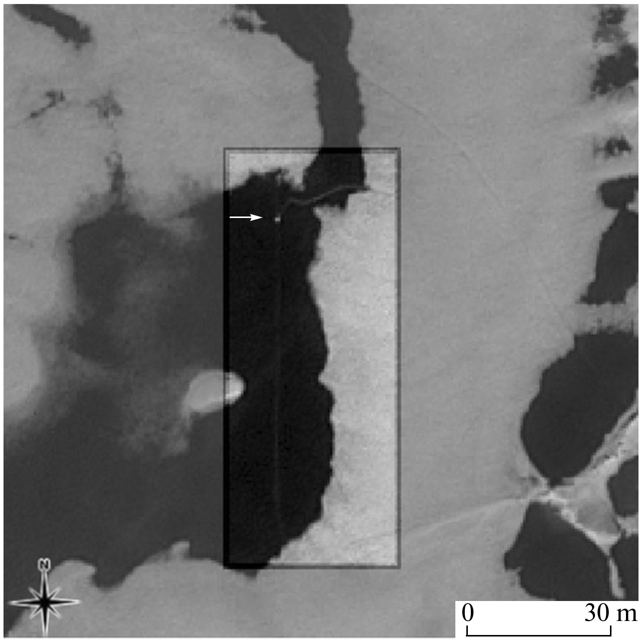

Fig. 9. Frozen tracks and frozen hole (arrow).

double track going up the creek. In both selected areas, there are at least eight bears.

Finding polar bears on the ice. Polar bears, large pinnipeds, and ice hummocks can easily be confused with each other (Fig. 11). The size of the bright object, on top of which there is a dark spot, is about 2.7 m. The absence of linear deformations near the object may be an indicator that this object is an animal. One can assume that this is a large seal, walrus, or bearded seal and that the dark spot is the hole. However, the edges of the dark spot are too vague and the hole itself is located close to the hummocky ice which limits the field of view for a seal. Therefore, a more plausible alternative suggestion is that it is a standing white bear (the size of the object is close to the size of a large polar bear, and the dark spot to the north of it is its shadow). The form of cracks in the ice floe is similar to the form of bear tracks.

Pinnipeds on ice. We cannot unambiguously suggest the look of pinnipeds on ice floes. Until the melting period of ice and snow comes, the snow albedo is very high, and a seal is darker than the snow, so it is not difficult to find. When the Arctic spring comes, the snow albedo decreases, so we can assume that some objects become lighter than snow. If a seal has just left the water and has not yet dried off, perhaps, its wet hair could reflect more sunlight than the surrounding snow. A number of distinctive features (e.g., animal behavior) can reduce the error of seal detection. Pinnipeds prefer to stay on the ice edge so that in the event of danger they can quickly slip into the water. Since pinnipeds are not planar objects, they cast a shadow, which, if not darker than the seal itself, is darker than the snow or ice around the mammal. On the northern part of the ice floe, a shadow check is impossible due to the fact that it is harder to detect the shadow in the water.

At the moment, we do not have a clear understanding of the reflection of sunlight from pinniped skin. For example, bumps of walrus bulls can have low reflectivity, and the smooth skin of young females and young stock can sparkle in the sun.

Wave surface analysis was conducted to identify large whales and pinnipeds. The lack of rocky islands and shoals in the studied region reduces the detection of false objects. Findings of large whales on the surface can change the pattern of waves in the image. Dives of marine mammals can leave a certain pattern on the surface of the size making it possible to identify it on high resolution images.

According to the results of the image analysis (Fig. 1), the expected features were not revealed. An interesting effect was observed in one of the areas of open water in which a bright spot of an extended form was found. If it had been an object above the water, the pattern of waves would change, but in this fragment of the image this effect is not observed. We can assume that, in the optical range images, large sea mammals that are underwater at a very shallow depth or traces of their vital activities, such as spouting, can be identified. White whales, for example, are detected well in sufficiently clear surface waters. In the absence of ripples, a bowhead whale can be identified. The spouting, which reflects the sun in a mix of water and air, contrasts to the relatively dark surface of the ocean. However, the use of high resolution satellite imagery to account for whales is more effective in clusters of animals.

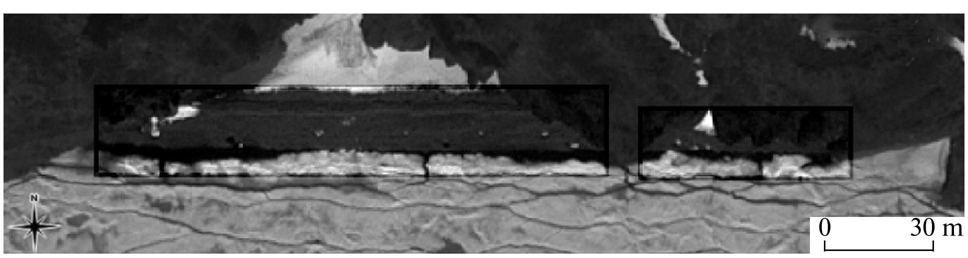

Fig. 10. Beach.

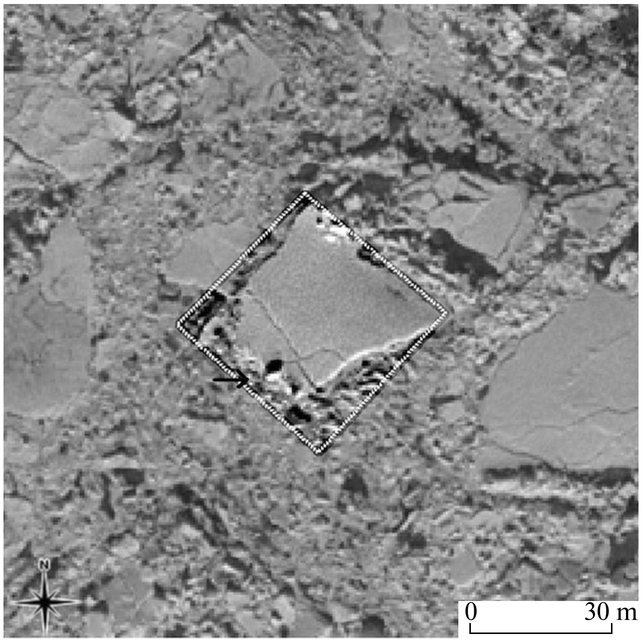

Fig. 11. A floe and a hummock (arrow).

Thus, the conducted analysis of the high resolution image for the detection of marine mammals in it makes it possible to draw some conclusions and make recommendations for selecting images for this purpose and their use.

In the proposed method, the accuracy of the detection of marine mammals increases when the identified objects have greater contrast with the environment. Dark pinnipeds can be quite clearly identified against the light snow on the surface of ice or land (Semenova et al., 2011; LaRue et al., 2011). Polar bears with their light colored fur contrast with dark surface regions, and thus, they can be detected in the coastal area if there is no snow.

Compared with other marine mammals, polar bears use the surface of ice and land much more actively; therefore, analysis of the trace pattern was a part of this study. Such an analysis by satellite data of ultrahigh resolution was conducted for the first time. In improving satellite equipment up to a spatial resolution above 0.2 m, not only can the trail be identified but so can some animal tracks, which will make it possible, for example, to register the movement of a female bear and her cubs.

The deformed ice serves as a hiding place for the polar bear. It is a negative factor in interpretation of the image. The presence of hummocks, commensurate with a polar bear, leads to an increase in false detection of objects. Therefore, when selecting the scenes, the season and ice conditions should be taken into consideration, and if possible, scenes with smooth ice should be selected. The more uniform the environment, the fewer false objects are detected in the analysis. The most favorable season is autumn ice formation. Fresh snow can cover such ice evenly. The winter season does not make it possible to conduct satellite measurements due to lack of light. In spring ice starts to melt and the heterogeneity of the surface increases. The shadow of the sun makes it possible to estimate the height of the object. However, when the potential object is in the shadow of rocks, the reliability of detection can be increased by more contrasting signatures of the object and the environment.

The conducted analysis is very laborious; i.e., even when matching nonoverlapping fragments are selected, it is necessary to analyze about 3600 frames. It is advisable to carry out analysis once again with the help of an independent expert (with results of the previous analysis hidden from the researcher). It is possible to use another bypass rule, for example, horizontal tacks.

In order to obtain more accurate information, it is necessary to conduct ground measurements. This will reduce the likelihood of false detections and increase the effectiveness of the proposed approach in solving problems of counting the number of animals. A positive effect can be obtained from the use of tracks indicating movements of radiolabeled species. In order to conduct ground truth measurements, drones can be used. The advantage of the latter is that they allow for measurements in heavy clouds.

Further development of the method of detection of marine mammals using data of satellite high-resolution images is vital since it can be introduced into the monitoring of habitats by unmanned aerial vehicles. In addition, it is necessary to consider the possibility of radar imagery. The new RADARSAT-2 satellite allows for imaging in three polarization modes HH, HV, and VV (the RADARSAT-1 satellite supports only the HH mode). The spatial resolution of the radar is currently insufficient for detection of unique individuals, but this type of all-weather and light independent shooting can be used to identify and assess concentrations of animals, for example, in assessing the number of walruses in coastal rookeries.

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