Research of the physical-mechanical properties of sea ice at the scientific research station «Ice base the cape of Baranov»

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Abstract. In 2013, on the island of Bolshevik, the Northern Earth archipelago, the scientific research station “Ice base the cape of Baranov” resumed a permanent work. The composition of complex studies of sea ice cover is continuously expanding and now it includes: standard visual ice observations; researches of morphological characteristics of level ice; researches of the physical-mechanical properties of ice; researches of the dynamics of the ice cover; the study of spatial and temporal non-homogeneity of the fast ice structure and physical properties.

1. Introduction
In present time the research station "Ice base the cape of Baranov" is the only station in all western part of the Laptev Sea where it is possible to make regular complex observations for a status of a sea snow-ice cover and land ice. The main task of ice research works is expansion of a full complex of cryospheral observations in accordance with standards of World Meteorological Organization. For the solution of this task the following ice research works are carried out at the station: standard ice observations, measurements of morphometric characteristics of level ice, ridges and icebergs, research of physical-mechanical properties of sea ice, creation and introduction of new techniques of ice experiments and observations. In 2015 by the decision 17 of the Congress World Meteorological Organization the "Ice base the cape of Baranov” along with observatory of Tiksi is included in the list of 36 ground stations for observing the Global Cryosphere Service network.

2. Main Part
Visual observations over a status of the ice cover on a visible space in Shokalsky Strait in the water area of the "Ice base the cape of Baranov" are made for the purpose of mapping and prediction of an ice situation in an adjacent section of the Laptev Sea. The main objective of observations is systematic and complete fixing of all characteristics of a status of an ice cover in the studied territory. Operations are carried out by the observer according to Manual, 1984 [1] and the Order of 12.02.2015 No. 64 of Federal Service on the hydrometeorology and monitoring of the environment defining a transmission order of sea coastal hydro-meteorological observations and offshore ice observations in high latitudes [2].

Observations are performed from the observation post organized according to normative documents in a point with coordinates 79° 16'49"N and 101° 37'20"E., located on the steep coast (height above sea level 24 m) in the territory of the station. Estimated distance of the visible horizon...
from observation point under favorable weather conditions is 18 km. Observations are performed on the main and additional object of ice observations (Figure 1).

![Figure 1](image)

**Figure 1.** The layout of the main and additional areas for ice observations at the "Ice base the cape of Baranov". 1 – main object (red sector), 2 – additional object (blue sector).

As the main water object for ice observations (the sector of the review of a sea surface) the northern part of the Shokalsky Strait dividing islands the Bolshevik and the October Revolution of the archipelago of Northern Earth adjacent to the western part of the Laptev Sea is used. The greatest width of the passage around observations is 45 km, depth is up to 350 m. The coastal territory, adjacent to an object, is characterized by existence of powerful (up to 800 m) dome-shaped glaciers. The object of observation is the wide range of natural ice: sea fast ice and drifting ice, icebergs. The sector of observations from ice point and its alignment is designated in Figure 1 (the red sector). As additional subject to ice observations the bay Amba, which is an internal bay of Bolshevik island. The additional sector of observations from ice point and its alignment are designated in Figure 1 (the blue sector).

A task of the observer with perhaps bigger accuracy is to note all characteristics of the ice cover and to fix all changes occurring in it. In the case of suitable light conditions, the photo fixing of an ice situation is carried out. As a standard terminology at the description of results of observations the terms and symbols defined in [3, 4] are used.

The research of morphological characteristics of unstrained ice and snow in space and in time allows to monitor increase and melting of the ice cover, change of its physical properties during all annual cycle. Besides, regular measurements of thickness of ice of different age and its physical properties are the one of key parameters of estimation climate state of the Arctic basin.

The purpose of work is the research of evolution of morphometric characteristics of level ice and snow cover during an annual cycle taking into account an ice structure near Shokalsky Strait, at the following tasks are solved:
– collection of data about change of the main morphometric characteristics of unstrained ice and snow on the ice ground near a station by method of contact drilling;
– collection of data about thickness of level ice by a contactless method by means of the EM31 Ice device;
– performance of a complex of temperature measurements of a snow surface, temperature on snow/ice border; construction of vertical profiles of temperature, salinity and density of ice; performance of a textural and structural analysis;

– test of strength of thin plates on a flexure.

Morphometric measurements by the contact way are carried out on the polygon by the size 80×100 m with internal profiles through each 10 m for the main (central) profile and 20 m for other profiles. Ice thickness, snow height (or depth of a meltwater pool), excess of the top surface of the ice cover over water level are measured in each point of the polygon. Repeatability of works on the ground of 5-10 days during the periods of intensive processes of thawing or increase (October-November and June-July) and 10-15 days during other periods. Measurements are taken by ice auger drilling. The error of measurement is up to 1 cm.

Measurement of physical properties of ice in a control point of the polygon is carried out by the established techniques within the time limits close to carrying out metric measurements on the polygon (with a difference of 0-2 days).

Measurements are taken in the contactless way on the same polygon by means of EM31Ice within the time limits as close as possible to date of contact measurements. The measurements of ice thickness with EM31Ice are carried out with use of a snowmobile on long profiles on level ice. After the end of measurements in several points of the profile the control measurements of ice and snow thickness with a contact method are made.

On the control point a core is taken for textural and structural analysis in laboratory conditions. Before taking the core is necessarily oriented by sides of the world. In the laboratory a description of ice texture and photographing of vertical and horizontal sections taking to account their orientation is carried out, making (preparation) of thin sections for structure analysis is performed.

The main tasks of researches of ice cover properties are:

– the study of physical-mechanical characteristics of level ice and ridges by traditional methods on samples (texture, density, temperature, salinity, ice strength characteristics);

– the evaluation of spatial and seasonal changeability of total-scale strength of the fast ice on total thickness by method of borehole probe-indenter and comparative test of ice samples strength;

– obtaining of new data for solution of engineer tasks of bearing capacity of ice at load operations on the fast ice by a method of control of parameters of deflection under load and registration of flexural stresses in the ice field;

– obtaining of nature data of large-scale dynamic processes in the system "ice-water" for estimation ice impacts onto shores and sea bottom.

For solution of these tasks in a character place of the fast ice the polygon is marked. In the nodes of the grid by a auger motodrill holes are drilled at total ice thickness. In the holes by a borehole probe-indenter ice strength tests to compression (local strength) are carried out. On the polygon in one point a taking of ice samples as cylinders for evaluation of physical properties and performing of strength tests of ice samples is made. The test is carried out on hydraulic press and field test machine.

The samples at uniaxial compression are made of the same horizons on which local strength was evaluated.

On the fast ice the following tasks are solved:

– influence of ice construction (structure and texture) onto local strength on several polygons, different by dominating ice types [5];

– influence of azimuthal anisotropy onto local strength caused by stable flow and formation of azimuthal anisotropy. The most part of crystals has the main optical axis directed along the flow. Therefore, change of strength of "horizontal" ice samples in dependence of their orientation occurs. The strength of ice samples at the uniaxial compression has 2 maximums and one minimum. Maximums of strength of ice samples are achieved at sawing out the samples parallel and perpendicular C-axis, the minimum with angle of 45°. Since local strength is a strength of ice in the conditions of uniform compression the azimuthal anisotropy of local strength is expressed less than
one of samples of ice at uniaxial compression;
– detection (reveal) of changeability of ice structure at penetration of the indenter into wall of ice borehole. The core with failure zone is drilled out and transported in the ice laboratory where the failure zone, changes of texture and structure of ice are studied. The ice plates are photographed with high resolution;
– influence of indenter diameter onto character of destruction. For investigation of "scale effect" at evaluation of local strength experiments of penetration of indenters of different diameters (6, 9 and 12 cm) are performed.
– influence of penetration velocity of the indenter to ice.

In the place of tests works of measurement of ice physical properties similar to measurements on the control point of the ice polygon are made.

During studies of ice properties and ice cover a technology of monitoring of physical-mechanical condition of the fast ice at impact on it both natural and anthropogenic factors was developed. As a rule, the fast ice during total period of existence is undergone natural oscillation and wave processes causing flexural stresses in the ice. Data about appearance in the fast ice trains of waves with duration to one hour with a period of oscillations 30–50 seconds and amplitude more than one centimeter. The most probable cause of appearance of these oscillations is swell waves from storms in open sea during iceberg formation. On the fast ice several tens such events were fixed. In the Figure 2 features of propagation of flexural-gravity waves with horizontal polarization of wave process are marked. It is obvious that in this case a process of remote storm sea on the open water is registered. Physics of wave propagation from source is characterized not only long-period oscillations of fast ice but and clearly distinguished components of horizontally polarized waves.

Figure 2. Initial record of long-period oscillations in the fast ice with three-component seismometer SME. The scales are same. Ice base the cape of Baranov, 01.07.2015.

Records of ground mechanical oscillations on the coast of Laptev Sea revealed two important moments: oscillations occur both from local and remote earthquakes and from processes caused by "icequakes" (impact of fast ice onto sea bottom and shore, dynamics of glaciers, plowing by icebergs the sea bottom …). Earthquakes are registered with clear detection of volume and surface seismic waves. Events of impact of seismic waves onto fast ice and glaciers as triggers of ice destruction are considered.

In the first time experiments for registration of wave processes at movement of atomic ice-breaker "Yamal" in the fast ice are performed. For a few kilometers devices fix ice breaking signals accompanied by flexural-gravitational waves with a period of up to 15 seconds. Total process of ice-breaker movement gives the extend information for large-scale experiments. Applicable (suitable) approaches for determination of elastic and strength properties of fast ice, study of mechanism of deforming and destruction of level ice field and control of bearing capacity of ice during operations at the fast ice are developed.
The main tasks of study of dynamic properties of ice formations are:

– dynamics and mechanics of the fast ice deforming as an indicator of local and large-scale processes of sea ice interaction in the system ice-water in the Laptev Sea;

– large-scale physical-mechanical processes of deforming and destruction of ice with purpose to obtain data for development and introduction of a method of short-term forecast of fast ice destruction and break-off the with advance time of several hours;

– parameters of mechanics of the fast ice deforming and dynamics to determine relative deformations of the fast ice at compression, shearing and hummocking;

– spectra of flexural-gravity waves and self-excited oscillations in the ice cover caused by compression and hummocking;

– characteristics of swell waves in the ice cover from storms in open water as precursors of the fast ice destruction;

– horizontal and vertical motions of the fast ice at tidal and wind impacts;

– parameters of free waves at calvings of outlet glaciers;

– parameters of free oscillations of icebergs in the fast ice;

– characteristics of plowing processes by ridges and icebergs of the sea bottom.

Performing of instrumental monitoring of the fast ice dynamics, processes of fracture of outlet glaciers, collapse of glacier fragments and formation of icebergs, plowing by ridge keels and icebergs of the sea bottom is provided by observation methods. For this purpose, three-component seismometers and two-component tiltmeters are used. Sensibility of seismometers CME 4 kV/m/s in the frequency range 0.01-100 Hz, tiltmeters is $10^{-6}$ V/rad. Seismometers are installed on both the fast ice and on coast ground in specially equipped bunker. Then oscillation velocities of displacement of three components horizontal and vertical are registered. On the fast ice the devices are installed at distance not less than 300 m from tide crack; on the coast at 500 m from place of the minimum anthropogenic influence. Frequency of signal for each channel is 100 Hz.

With a purpose to obtain the fullest information about seismicity of coast of Laptev Sea since 2016 year on the station with Federal State Budgetary Institution of Science "Federal Research Center for Comprehensive Arctic Studies of the Russian Academy of Sciences (FRC CAS RAS) observations of oscillations of coast ground are performed. Seismic observation point of "Ice base the cape of Baranov" was organized in accordance with methodological directions [6]. The selected place with coordinates 79.276°N и 101.657°E is indicated in the Figure 3 (number 4).

In October, 2016 in the seismic bunker CMG-6TDc seismometer which at the same time measures three components of oscillations of an earth surface in the range of frequencies from 0.033 to 50 Hz was set with GPS antenna. Data are transferred with using of the software package of Guralp Systems directly to AARI and FRC CAS RAS.

Results of the described techniques and further tasks are necessary for development and deployment of the short-term forecast of the fast ice destruction. Appearance of long-period ripple waves, rise of cyclic offsets of ice, signals of crack formation in ice, etc. can serve as warning. In combination with rising tide and squeezing wind these natural phenomena supplement an overall picture of ice destruction and release of the fast ice in the sea. The received results can be used in case of the decision of engineering tasks of hydrotechnical construction and exploitation of sea constructions on the Arctic shelf and also in case of support of the security regulation by operations on ice.

One of the main results of work is improvement of the forecast of a dynamic state of the sea ice which is based on contact and remote measurements of large-scale mechanics of ice (swell, flexural and gravitational waves, large-scale strength of ice, interaction of the drifting ice and the fast ice, seismic waves from earthquakes and "icequakes", estimate of large-scale parameters of physical-mechanical properties of ice). For this purpose, installation on the coast of ice base the remote measuring system allowing to obtain information about ice processes coming on removal up to 50 km from base in real time is planned. This technology is used for studying of dynamics of glaciers and sea ice on the Arctic shelf and in Arctic Ocean (at the drifting stations "North Pole" and in coastal zones).
Measuring devices are installed on ice, electric signals are given by a radio channel on the registering complex. For preliminary processing special programs in statistics, the spectral analysis, etc. are used. At this stage testers of remote system directly from the coast of station "Ice base the cape of Baranov" in 2019 are prepared.

![Location of seismic equipment at Ice base the cape of Baranov in 2016.](image)

**Figure 3.** Location of seismic equipment at Ice base the cape of Baranov in 2016. 0 – Recording equipment, 1 – ground seismometer, 2 – seismometer on the fast ice, 3 – seismometer with the "Baikal 7 HR" logger, 4 – « seismic bunker», 5 – location of recording equipment, 6 – seismometer with the "Baikal 7 HR" logger. Lines 0-1-2 and 4-5 – cable communication lines.

The task of spatial heterogeneity of a structure and physical properties of fast ice research is monitoring of the spatial and temporary heterogeneity of a structure and physical properties of equal fast ice arising at various hydro-meteorological conditions during its formation begun in 2014 and also development of a technique of mapping of the level ice cover on the prevailing ice types.

In the water area of station "Ice base the cape of Baranov" places are revealed according to their geographic location or ice formation conditions that have differences from the place of an arrangement or to site ice formations conditions where the main ice ground is chosen. It can be bays, available on technical capabilities, passages, feuds, zones of the frozen leads or sites close to the ice hole behind fast ice, a coastal zone with an intensive snow accumulation, ice around icebergs and at hummocks.

The choice of the place of works is defined according to technical capabilities of base, especially with a possibility of delivery of people and the equipment to the chosen place.

On the chosen site are carried out ice lines from several points, ice polygons or certain ice stations where are carried out works similar to measurements on a control point of the main ice ground. The quantity of points is chosen taking into account the fullest illumination of the studied ice object.

**Acknowledgments**

Work is performed within planned scientific thematic of AARI on the project of Roshydromet "Scientific and methodical developments of monitoring of a physical-mechanical state of ice in the Arctic in real time for short-term forecasting of the critical and dangerous ice phenomena".

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