Study of the metocean conditions for the Russian Arctic Shelf development projects approaches and results: Review for the period of 2012-2021

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Abstract. The FSBI AARI is the leading State Scientific Center of Russia, which is involved in studying the natural environment of the Polar Regions and its impact on human activity for over a century. In the last 30 years, the new sphere of activity, dealing with the specialized metocean (including ice) surveys for the purpose of Arctic Offshore Development was successfully developed here. For the most important Arctic Offshore projects the full set of these specialized studies was conducted by the Institution. The paper gives an overview of AARI’s scientific and applied scope and tasks, a general chronology of the surveys on the Russian Arctic Shelf since 1990-s, a description of the main study methods, and an overview of the main results of studies for the last ten years (2012-2021). It is demonstrated that the role of detailed ice and metocean surveys is often determinative in sense of design and construction of Arctic Offshore objects.

1. Introduction
AARI is responsible for study of natural environment of the Polar Regions and its impact on human activity for over 100 years. Since early 1990-s a new sphere of activity, dealing with specialized metocean surveys of the Russian Arctic Offshore for the purpose of its development was successfully evolved here. The article gives a short description of AARI’s scope and tasks as well as general review of the main Arctic Offshore Projects and the main results of studies of metocean conditions there for the period 2012-2021. The chosen period covers a number of comprehensive metocean and ice surveys in the Kara, Laptev and East-Siberian Seas for the aims of Offshore Development and the large-scale projects of development of oil and gas deposits in the Ob-Taz region. In all these areas and projects AARI is actively involved both in the fields of surveys as well as data analysis and expertise.

2. FSBI AARI: The main tasks
The Federal State Budgetary Institution “Arctic and Antarctic Research Institute” (AARI) is a State Scientific Center of the Russian Federation that conducts fundamental and applied research in hydrometeorology, oceanography, climatology, geophysics, water resources and environmental protection in the Arctic and Antarctic regions. The Institute carries out scientific studies, research engineering and research production activities [1].

The FSBI AARI has special-purpose research vessels designed to operate in polar regions (R/V “Akademik Fedorov”, R/V “Akademik Treshnikov”) and an Ice Tank to conduct various experiments. The major (but not all-inclusive) scientific goals of the FSBI AARI are:
• Diagnostic assessment, calculation and forecasting of meteorological, hydrological, ice, geophysical processes and phenomena in the Arctic and Antarctic;
• Study of the ice regime, ice cover of the seas and oceans as a physico-geographical environment, and ice as a physical body and
• Study of the interaction between the ocean, ice cover, atmosphere and land.

As part of the FSBI AARI scientific studies, data on the natural environment are collected on an ongoing basis at the Cape Baranov permanent station (Severnaya Zemlya archipelago), RAE-S (Russian Scientific Center at Svalbard archipelago), and at Russian Antarctic stations. Occasional observations for a wide list of environmental characteristics are performed in integrated expeditions (for instance, “Transarctica – 2019” or the international expedition under the MOSAIC project), etc. Large-scale processes occurring in the Polar Regions are diagnosed upon the data and forecasts about their future state are developed.

The major (but not all-inclusive) goals of FSBI AARI in operational-production activities are:
• Collection, processing and dissemination of information about the current ice, metocean, geophysical situation and processes, state of the environment in the Arctic, Antarctic and North Atlantic;
• Development of baseline long-range and ultra-long-range forecasts for ice, meteorological, marine hydrological, geophysical phenomena and processes in the polar regions;
• Providing calculations, briefing papers, recommendations, annual reviews and consultations on metocean observations and works in the Polar Regions.
• Setup, maintenance and use of operational reference banks in the Polar Regions by sections: meteorology, oceanology, hydrology of river estuaries, sea ice (National and Global banks);
• Prompt support to navigation and other maritime activities in the Polar Regions;
• Performing transport operations in the Arctic and Antarctic, accompanied cargo transportation.

Through the operational production activities, a great amount of initial information about the natural environment of the Polar Regions is accumulated in the FSBI AARI; it is further translated into various forecasts and recommendations needed there in everyday practical activities and diverse information support for such activities is provided.

The FSBI AARI research engineering activities include:
• Integrated expeditions to study hydrometeorological and geophysical processes in the Polar Regions;
• Improvement of methods for monitoring the environmental state and pollution; methods of ice, meteorological, hydrological calculations and forecasts for the polar regions;
• Performance evaluation of hydrometeorological support for navigation and economic activities in the Arctic and Antarctic;
• Development of applied scientific manuals and reference books on the natural environment of the Polar Regions.

Engineering hydrometeorological surveys (EHMS) on the Russian Arctic shelf refer to the research engineering area of the FSBI AARI activities, where the major objectives are:
• Conduct engineering surveys when designing and building structures and facilities onshore and offshore;
• Environmental impact assessment of the projected and operating enterprises, economic activities, and environmental impacts on engineering structures;
• Prepare materials for State hydrometeorological expertise of Feasibility Studies, construction projects and surveys, as well as other activities in the Polar Regions, including those on the shelf and coasts of freezing seas, participation in the expertise process.

Since the early 1990s, the FSBI AARI participates extensively in the studies of the Russian Arctic shelf. To date, complex technical facilities have been designed, built and operate in this region, such as the Pirazlomnaya Offshore Ice-Resistant Stationary Platform (OISP) (Gazprom Neft Shelf LLC), the Varandeyisky Oil Export Terminal (PJSC Lukoil), the Arctic Gate terminal (Gazpromneft-Yamal LLC),
Sabetta international seaport (including the Utrenny terminal) designed for transportation of liquefied natural gas (LNG) from the Yuzhno-Tambey field and the supply of natural gas, oil and gas condensate to foreign markets by sea transport (operators – Yamal LNG OJSC, Gazpromneft-Yamal LLC, Arctic LNG-2 LLC [2]). Constructing and steady operation of these and other facilities would have been impossible without high-quality engineering and hydrometeorological surveys that precede their design and construction.

3. Why study the hydrometeorological and ice conditions of the Arctic Shelf?

Conducting special-purpose (engineering hydrometeorological and ice) surveys in the period preceding the start of major projects on the Arctic shelf is essential for getting the most comprehensive information about the environment. At the initial stage, underestimated natural conditions may lead further to the amendments in development strategy, as well as additional costs for design and construction (we will illustrate this thesis below with cases from Russian practice). At the same time, their overestimation is likely to cause unscheduled and considerable costs later. Thus, the balanced estimates are required, which would provide the correct ratio between the funds spent and the result obtained, without risks to the reliability of complex engineering facilities to be operated in the harsh Arctic nature, sensitive to the anthropogenic impact.

Such surveys are principally conducted for designing and construction of infrastructure facilities of ports and deposits intended for operation in severe Arctic or sub-Arctic conditions. This determines the range of main consumers, i.e., designers of ice-resistant structures, shipowner companies, operators of Arctic and freezing ports, mining companies (including oil and gas companies) that have license areas on the Arctic shelf or those involved in transportation of minerals (hydrocarbons, coal, ores, etc.) by sea vessels and pipelines from deposits located in the region.

The study objects are: the ice cover (drifting and fast ice, various ice formations), aquatic environment (currents, waves, sea level fluctuations, etc.), the surface atmosphere (meteorological characteristics – temperature, wind, humidity, etc.), lithodynamic conditions (bottom sediments movement, bottom gauging (ploughing) by keels of ice formations, etc.), dangerous and disastrous hydrometeorological phenomena.

The role of the FSBI AARI in the Arctic shelf projects is to collect and analyze data on the ice and hydrometeorological regime and provide Designers (or Customers) with estimates of the environmental parameters. If necessary (the lack of baseline environmental data, in the common case), mathematical and physical modeling is undertaken. The expedition results are presented to the Customers in a standard format of scientific technical reports. Additionally, the AARI experts can provide other documents: recommendations (e.g., selection of the port location, etc.), concept developments (e.g., ice management systems), and various purpose-oriented technical specifications for construction projects (Local Technical Conditions (LTC) / Temporary LTC).

Under the largest offshore projects implemented in the Arctic and freezing seas of Russia, the FSBI AARI performed a full cycle of ice surveys: acquisition of information (archival and field materials), data processing (including modeling), providing designers with baseline parameters (shaped as LTC/TLTC) for the environment and submitting reports on engineering hydrometeorological surveys (including ice).

All surveys on the Arctic shelf are carried out strictly within the Russian regulatory framework (GOST, SNiP – i.e. Russian analogs of ISO, etc.) in force. The gained experience allows the AARI experts to take part in the revision of available regulatory documents and in the development of their updated versions.

4. General chronology of studying the environmental conditions of the Russian Arctic Shelf

Figure 1 shows the chronology of engineering hydrometeorological surveys (EHMS) on the shelf of the Arctic/ freezing seas, according to the activities of G.K. Zubakin Arctic Shelf Laboratory (ASHL) of FSBI AARI [3]. The ASHL represents a specialized AARI department established in 1991 to provide assessments of the hydrometeorological and ice regime at various phases of design, construction,
operation and disassembling of hydraulic structures (platforms, terminals, underwater pipelines, communication cables, etc.) in the shelf zone of the Arctic and freezing seas. Through the period of 1991-2021, the ASHL team prepared over 450 information and scientific technical reports on different offshore objects of the Arctic and freezing seas; its members participated in almost all projects on the Russian Arctic shelf (Figure 2).

Historically, the Russian Arctic shelf is developed in West-East direction, from the relatively mild (in terms of ice conditions) Barents Sea to deposits located in more severe Arctic conditions – the Kara Sea and eastward. Figure 1 reflects the 3-decade general trend (the interests of mining companies shift gradually from the west to the east) and indirectly confirms the progress in methods and technologies achieved in the offshore mining industry since the early 1990s.

**Figure 1.** Chronology of engineering hydrometeorological surveys on the shelf of the Arctic/freezing seas from 1991 to 2019 according to the data of ASHL [3, updated].

**Figure 2.** Sites in the Russian Arctic where the engineering hydrometeorological surveys have been performed in the period 1991-2019 (according to ASHL data) [3].

Information about the engineering hydrometeorological surveys conducted by the ASHL team at the most well-known sites, as well as the status of projects (to date) is listed below.

1. The Shtokman Gas Condensate Field: a full cycle of ice regime surveys was carried out; local technical conditions (LTC) and ice specifications for design purposes were prepared. Currently, the project is suspended by the license holder for the search, geological study and production of gas and gas condensate (i.e. Gazprom PJSC).
2. Prirazlomnoye Oil Field: a full cycle of ice regime surveys was carried out. Estimates of the hydrometeorological regime (as LTC) are provided to designers to develop the Prirazlomnaya OISP (offshore ice-resistant stationary platform), which has been installed and is operating at the field.

3. Yuzhno-Tambeyskoye field: a full range of engineering hydrometeorological surveys was carried out for designing a port to ship off the liquefied natural gas (LNG). The LNG processing plant and the Sabetta port were built.

Figure 1 shows that during the reviewed period, 2012-2021, the Arctic shelf surveys were conducted mostly in the Ob-Taz region, as well as in the Kara, Laptev, and East Siberian seas (at license areas of the PJSC Rosneft Oil Company). At the moment, the Ob-Taz region is probably one of the most dynamically developing areas at the Arctic shelf and its development is proceeding at a fast pace. During this period, such complex technical facilities as the Arctic Gate oil terminal, Sabetta international seaport (including the Utrenny terminal) intended for the transportation of liquefied natural gas (LNG) from the Yuzhno-Tambeysky gas processing plant and the supply of natural gas, oil and gas condensate to foreign markets by sea, were built here and are now successfully functioning. A series of 8 summer and 7 winter expeditions for the Yuzhno-Tambeyskoye and Salmanovskoye fields (Sabetta port) was carried out through the period of 2005-2017, while the survey parties were based both onshore and on the vessel [3].

In the period of 2012-2020, ROSNEFT conducted large-scale environmental studies at the license areas located on the Russian Arctic shelf. The FSBI AARI acted as the chief executor in these studies: planned, organized and performed 4 winter and 13 summer expeditions to the Arctic for this Oil Company. The expedition studies were characterized by both vast water areas and the exhaustive list of the examined characteristics of the ice cover, aquatic environment, glaciers and icebergs. For instance, the Kara-Winter-2014 was the longest by that time marine expedition in the history of Arctic exploration conducted during the maximum development of the ice cover [4]. These studies included morphometric and physico-mechanical characteristics of the ice cover and icebergs, their drift, oceanographic characteristics (sea level fluctuations, waves, currents, thermohaline characteristics of water masses), iceberg-producing glaciers; the iceberg management technologies (iceberg towing) were studied and implemented, and other tasks were performed as well [3]. The detailed chronology and characteristics of these works are described in the new book dedicated to AARI’s Centenary [5]. The obtained results have been partially published (see, for example – a feature issue on Russian Arctic Ice by IJOPE (2019) [6], one of the papers won an ISOPE 2020 Best Paper Award [7]).

5 The main technologies used and the data obtained
The main methods used for studying the ice cover and glaciers in the working period 2012-2017 (and earlier, for the Shtokman project) are listed below (see Figures 3, 4).

![Figure 3. The main remote sensing methods for studying the ice cover and glaciers used in the AARI winter expeditions, 2012-2017 [8].](image-url)
The use of the Satellite imagery of various ranges: for ice edge monitoring, to determine ice age composition, concentration, ice cover fragmentation, floe sizes, iceberg detection.

The use of a remotely operated underwater vehicle (ROV) and side-scan sonar - to generate video images and 3D pictures of the underwater parts of hummocks and icebergs, to determine their volumes.

The use of airborne photographic survey (since 2014 a digital complex was used for this purpose): to obtain information about dimensions of hummocks and icebergs, to construct 3D surfaces of their upper part, and to determine its volume.

Glacier radar studies at the FJL, Novaya Zemlya and Severnaya Zemlya archipelagos: to determine the glacier thickness, ice volumes, iceberg formation potential, the maximum iceberg size, assessment of glacier retreat (performed mostly by AARI’s scientific partner - IG RAS team).

Figure 4 (the left-hand side) presents the methods for studying morphometric features and the internal structure of hummocky formations (geodetic survey and through-ice drilling). Further, methods for studying the physico-mechanical properties of the ice cover (temperature, salinity, density, structure, strength properties) are shown [9]. Examples of studying the dynamics of ice cover and icebergs using radio beacons are presented at the right-hand side [10, 3]. The far right column shows examples of large-scale experiments with the ice cover in 2014-2015 [11]. It should be noted that similar methods (except for glacier and iceberg studies, as well as large-scale experiments with the ice cover) are also used in studying the ice cover in the Gulf of Ob.

During the ice-free period, hydrological and lithodynamic studies are performed in the waters of license areas. Hydrological surveys and mounting autonomous bottom stations are carried out from specially equipped vessels, which allow getting long-term data series on sea level fluctuations, waves, current parameters, as well as the draft of the drifting ice cover at a specific point (Figure 5, left-hand part). The use of geophysical and hydrographic methods allows conducting lithodynamic studies (for these works, the AARI recruits relevant subcontractors). These studies include the determination of the water area bathymetry, bottom and coast dynamics, direction of the sediment flows/washouts. They allow for mapping bottom sediments and ice gouging (bottom ploughing by the keels of ice formations) (Figure 5, right-hand part).

The methods used for collecting baseline information allow us to produce data series of different duration and discreteness. For instance, a series of currents observations can reach a length of one year with a step of 10 minutes; duration of observations of ice formations drift can exceed 3 months with a
step of 1 hour; duration of parameter measurements in large-scale experiments with ice cover take some minutes with a discreteness of 100 measurements per sec (100 Hz). Note that in cases where battery-powered recorders are used to register various environmental parameters, the length of the observation series is often limited only by the battery life (i.e., the battery charge). In general the volumes of the data gathered could be characterized by the following example. During the ice cover surveys for the Prirazlomnoe Oil Field Project (1996-2004), 98 ice study sites (i.e. “stations”) had been executed with 137 ice ridges and stamukhas studied on them. The ice cover surveys consisted of 5440 ice thickness measurements with the help of thru-ice drilling, 477 ice column spicemen had been taken from the ice ridges. The 2300 measurements of temperature, salinity and density of ice been performed, more than 3500 measurements of ice strength limits (bending, shear and pressure) and 350 measurements of deformation modulus (pressure and bending) executed. Also the large scale strength measurements of the ice cover (pressure and bending) been executed – 4 and 6 times, respectively.

![Hydrological works](image1)

![Lithodynamic studies](image2)

**Figure 5.** Hydrological works and lithodynamic studies in the summer period.

Data collected through the field research are subjected to the scientific engineering analysis that includes:

- Statistical data processing, identification of trends, fitting distribution types and parameters;
- Study of seasonal and interannual variability;
- Adjustment of the regime values of the environmental characteristics;
- Study of interconnections between various processes and phenomena;
- Construction of maps, profiles, and sections of hydrological, ice, lithodynamic characteristics;
- Determination of standard values of ice and hydrological characteristics for calculating ice loads [8].

Speaking about the results of analysis, it should be said, that the final version of the Local Technical Conditions document that had been forwarded to the Designers provided the information on 53 parameters of the ice regime and the ice cover. 9 of them were describing the ice regime of the water area, 30 – the morphometry of the ice cover, 6 – ice cover dynamics, 8 – the physico-mechanical characteristics of the ice cover and snow in the area of Prirazlomnoe Oil Field.

6 **The Ob-Taz region as the most intensive area of the Arctic shelf**

Transportation of end products (oil, gas condensate) from the fields located on the Yamal and Gydan peninsulas and the waters of the Gulf of Ob is possible, in most cases, only by sea via year-round operating ports or shipping terminals. The most striking example of such an object is Sabetta port built under the Yamal-LNG project.
A LNG processing plant and a purpose-oriented Sabetta port for its export, both built from scratch on the Arctic coast, are complex technical facilities. The projected capacity of cargo terminals makes 30,317.8 thousand tons per year [2]. During the design and construction of this port, the AARI experts ran the full cycle of surveys and targeted studies, starting from the analysis of archival materials with the selection of a construction site, up to the determination of specific values of hydrometeorological parameters.

Due to the efforts of the AARI experts (primarily, from the AS hL), the port configuration was determined, which should necessarily include ice-protection fence structures. A number of other corrections were made to the initial project, which improved significantly the safety and efficiency of the year-round operation of this transport infrastructure facility. The functioning and development of the port of Sabetta required the supplementary EHMS to be conducted in the north Ob Bay. In recent years, surveys have been carried out for the Utrenny remote terminal (arrangement of the Salmanovsky (Utrenny) OGCF on the Gydan shore), as well as feasibility studies for the Sea channel modernization project on the bar of the Ob Bay [8, 3].

For the purpose of increasing the transit passage in the Ob Bay the decision was made to widen the approach channel to Sabetta seaport, which was built and put into operation in 2019 [12]. The AShL specialists together with experts of the Krylov State Scientific Center took part in scientific substantiation for the modernization parameters of the sea channel in the Ob Bay. The reconstruction project is implemented in two phases; upon completion of dredging works in 2022, the channel width will reach 573 m. This will increase the number of ship passes from 4 (currently) to 9 per day, i.e., 1,500 per year, which will significantly increase the export of hydrocarbon raw materials from the deposits of the region. Moreover, the channel expansion will ensure delivering the gravity bases of the Utrenny LNG-LGC terminal (its construction is scheduled under the Arctic LNG-2 project) to the place of permanent installation.

An important aspect of ensuring continuous operation of the Arctic and freezing ports in the winter is to track the accumulation of brash ice (crushed ice) on ship routes and the associated evolution of ice channels in a solid ice cover. The configuration of approach channels and port gates is often determined by the minimum required number of ice channels and their geometry. The accumulation of brash ice in a freezing port can reach a critical level and ultimately terminate shipping. To prevent such a situation, potential zones of the greatest accumulation of brash ice should be identified; the heat costs to maintain the required ice thickness there should be estimated and the optimal parameters of the brash ice management system (BIMS) to be determined. Similar studies were performed in AARI for the Sabetta port with full-scale experiments on the “minor” BIMS in 2014-2016, as well as modeling of these processes (Figure 6). The results obtained were considered in arranging the water area of the port.

![Figure 6. Cases of analytical and in situ works for monitoring the ice situation in the area of Sabetta port [6, 3].](image-url)
No less important aspect that determines the uninterrupted and accident-free operation of Sabetta port is the passage of Yamalmax-type gas carriers (length — 299.0 m, width — 50.13 m, draft — 13.0 m) via a narrow Sea channel located on the bar of the Ob Bay. It should be noted that this is the main channel for ships that transport LNG and gas condensate from the Novatek fields. To determine the time periods with ice drift allowed for the gas carriers’ passage, elements of the Ice Management System (IMS) were introduced in 2018, according to the AShL AARI team proposals. The idea was to promptly get and provide the data needed for an expert forecast of ice drift. Primarily, these are data on the actual drift of ice floes, tides (level fluctuations) and wind – throughout the entire ice season. For this purpose, radio beacons transmitting their coordinates were installed directly on the ice, as well as level gauges and weather stations. Technologies were developed for automated data acquisition, processing, and visualization of all information (coming from these devices and other equipment) on the Web GIS (geoportal) [13] (Figure 7).

![Operational data on:]
- Ice drift
- Sea level
- Weather conditions
  - Geoservices
  - Web GIS
  - Database

Figure 7. Introduction of the IMS elements in the northern part of the Gulf of Ob and the geoportal elements [13, 3].

A special feature of the development was that the geoportal was adapted for use from any mobile device. Currently, work on this project has not yet been completed, but it can already be reasonably said that the introduction of the above-described IMS elements made it possible to obtain information about the drift of the ice cover in real time, and to correct accordingly the movement of LNG tankers and minimize their icebreaking support.

7 The impact of engineering hydrometeorological surveys (including ice surveys) results on the design and construction

The practice of the Arctic shelf development shows that the role of engineering hydrometeorological and ice surveys in the design and construction of objects is often determinative, since in some cases the obtained results modify significantly the initial design solutions to the deposits’ arrangement and related infrastructure. Relying on the experience of environmental studies for large-scale projects of the Russian Arctic shelf development, we will illustrate this statement with two important cases:

- In the late 1990s-early 2000s, the problem of the impact of icebergs on production platforms at the Barents Sea shelf was not taken in earnest by Russian top managers and was held on the periphery of their attention. This continued until May 2003, when the discovery of a large group of icebergs in the water area of the Shtokman GCF by the AARI expedition caused a kind of sensation and led to a reassessment of the iceberg threat. The derived estimates [14] showed that, considering the data of 2003, the frequency of iceberg intrusions into the platform area and
the probability of their collision with it increased threefold. The increase in risks led to the rejection of the TLP/SPAR concept for the mining platform in favor of FPU [15, 16] during the works on the SGCF arrangement. This decision surely complicated and decelerated the project implementation (which was further suspended for various reasons).

- The results of the ice regime study in the area of Sabetta port construction showed the reverse drift of the ice cover [17] and explained the need for the design and construction of an additional (northern) section of ice protection structures. This led to a significant increase in the project cost but significantly reduced the risks for the port operation in the winter-spring period and secured its year-round operation.

Both cases demonstrate the important impact of actual environmental conditions on the initial plans of designers and future users of hydraulic structures, which led to their essential adjustment. The underestimated power of Nature once again turns out to be greater than the initial plans of human being.

8 Key conclusions

The FSBI AARI is the main State Scientific Center of Russia, which is involved in studying the natural environment of the Polar Regions and its impact on human activity for over a century. In the last 30 years, the new sphere of activity, i.e. - engineering hydrometeorological (including ice) surveys (EHMS) was successfully developed here. 

Huge amounts of data collected both during the large-scale study of the Arctic region (prior to 1991) and in the subsequent period of more targeted surveys for specific offshore projects; experience in acquisition, analyzing and interpreting metocean and ice information, which is essential at all stages of design and construction of hydraulic engineering facilities for various purposes; great experience in organizing and conducting exploration work on the shelf of the Arctic and freezing seas – allowing AARI to perform the full set of EHMS studies for the most important projects on the Russian Arctic shelf.

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