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Title of Thesis

Cluster Development of the Barents and Kara Seas Oil and Gas Fields from the Archipelago Novaya Zemlya

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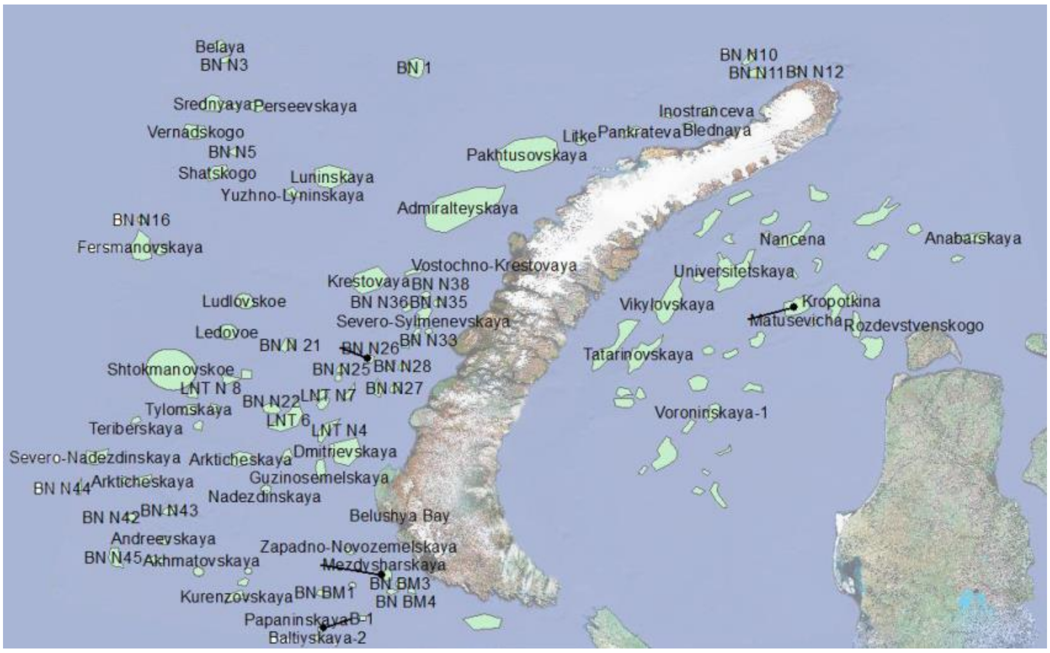
ABSTRACT

Russian Arctic region is extremely rich of hydrocarbon resources. Most of them are located in 2 giant seas: Kara Sea and Barents Sea. Drilling for oil or gas in harsh areas such as arctic or ultra-deep waters is a dangerous, high-risk enterprise and an oil spill or a gas leak under these waters would have a catastrophic impact on one of the most unique and beautiful landscapes on earth. Nowadays the risks of that accident are present and the oil industry requires new solutions to such challenges.

The Barents Sea is well-known for its promising fields like Shtokman and Prirazlomnoye. The Prirazlomnoye field is developed now. Moreover, there are other fields located near to shelf or far from shelf (Map 1).

The Barents Sea region is thought to play a key role in Russian and Norwegian oil and gas field development and hydrocarbon resources production. Both countries are moving petroleum activities into the Barents Sea due to the high potential of hydrocarbon occurrence.

Another area is the Kara Sea and it is now under active exploration. The Kara Sea compared to the Barents Sea is harder to explore and develop because of tremendous ice cover, icebergs and severe meteorological conditions. An example of a field that was explored and developed in this area is the Universitetskoye field. The first well in this field was drilled and the first oil was produced. However, nowadays exploration of that field has been suspended. There are also other fields located in this region (Map 1).



Map 1 Oil and gas potential of the Barents-Kara region (Source: Onepetro's thesis [34])

These areas are divided between two Russian major companies – Gazprom and Rosneft. They have several projects with their foreign partners: Statoil and Eni in the Barents Sea, ExxonMobil in the Kara Sea. Either experts or managements of the companies agree that production from this region requires enormous investments at a potential high-risk level due to very harsh environmental conditions.

Due to close location of these regions to each other, the best solution is cluster development from Archipelago Novaya Zemlya. This project offers a new concept that proposes to use the Novaya Zemlya archipelago as a base for development of the whole regions. That might improve economics of field development due to less overall investments in common infrastructure.

Starting with a comparison of sea-state parameters and metocean conditions of the Barents and Kara Seas, this thesis will discuss the challenges for development of potential hydrocarbon fields in the Barents-Kara Area. The main accent of this master's thesis will be placed on possibilities of the technological challenges for choice of platform and construction of common infrastructure on the base of archipelago.

One of the hard challenges is what type of platform to choose. The fields located in severe conditions are supposed to be developed by drilling and construction with subsea completions. The subsea systems are designed for harsh and deep offshore oil and gas development and ensure year-round drilling irrespective of climatic and ice conditions. Produced hydrocarbons will flow through subsea pipelines to Archipelago where will be implemented hydrocarbon processing.

Use of all of techniques to tackle these challenges, allow to:

• Reduce the high capital and operating costs of large offshore structures.

• Dramatically reduce the environmental impact on the marine and coastal areas.

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ABBREVIATIONS

HC – Hydrocarbons

LNG – Liquefied Natural Gas

MODU – Mobile Offshore Drilling Unit

NPV – Net Present Value

OSR – Oil Spill Response

UN – United Nations

WWF – World Wildlife Fund

INTRODUCTION

Nowadays, Russia submitted its new Arctic shelf claims to the UN Commission on the Limits of the Continental Shelf. The Russian continental shelf stretches beyond the North Pole, the Russian government asserts. The country submitted its renewed claims for the Arctic shelf to the UN Continental Shelf Commission. [24]

Estimates indicate that the area include 594 oil fields and 159 gas fields as well as two major nickel fields and more than 350 gold deposits. Initial recoverable fuel resources are estimated to 258 billion tons of fuel equivalent, representing 60 percent of Russia's total hydrocarbon resources mostly in the form of gas on its continental shelf. [24]

A number of fields and perspective structures have been discovered within different parts of Russian Arctic Shelf making this region one of the most perspective for the petroleum industry. However, there are still significant geological uncertainties about the amount of petroleum resources to be found, which is also reflected in the different estimates of existing oil and gas resources.

Most of the hydrocarbon resources are located in 2 giant seas: Kara Sea and Barents Sea.

The well-known Barents Sea is promising area with its unique fields like the Shtokman, Prirazlomnoye. Now we can witness a high activity situation around the western part of Russian Arctic: the "Prirazlomnaya" platform is already producing petroleum. The Barents Sea region is a key role in Russian and Norwegian oil and gas field development and hydrocarbon resources production. Both countries are moving petroleum activities into the Barents Sea due to the high potential of hydrocarbon occurrence.

Another area is the Kara Sea and it is now under active exploration. The Universitetskoye field is an example of a field that was explored. The first well was drilled and the first oil was produced. However, nowadays exploration of that field has been suspended. This sea is even harder to explore and develop than the Barents Sea because of tremendous ice cover, icebergs and severe meteorological conditions.

Chapter 1. Background

The industrial development of the Arctic region is limited due to technological reasons and environmental conditions. Among them, the most vulnerable factors are the following:

- harsh natural conditions;
- lack of infrastructure;
- high investments and costs;
- environmental vulnerability.

All listed factors necessitate a thoughtful planning of a regional development. To technically overcome these vulnerable factors we integrate approaches that involves:

- grouping of fields;
- construction of common infrastructure on the base of archipelago;
- and building of transport systems from the fields to the base.

At the beginning, all fields have to be named (Table 16 and Table 17 in the appendixes).

As an example of complex development we can take the project "Sakhalin 3" with the development of Kirinskii block, which is under the ownership of Gazprom.

Gas production is carried out by means of subsea production systems. These systems allow to extract hydrocarbons in the most difficult climatic conditions, even under the ice, without the construction of platforms and other surface structures. Produced gas in a marine pipeline is delivered to an onshore processing facility. Moreover, the facility is designed to receive gas not only from Kirinskoye field, but also from others fields of "Sakhalin-3" project.

Chapter 2. Cooperation between Russian oil and gas majors

At the XI International Investment Forum “Sochi – 2012” in the presence of Dmitry Medvedev, Prime Minister of the Russian Federation Alexey Miller, Chairman of the Gazprom Management Committee and Igor Sechin, President, Chairman of the Rosneft Management Committee have signed the Cooperation Agreement on the joint pre-development of offshore hydrocarbon fields. [14]

The aim of document was to stipulate further partnership between the companies in searching for the most effective methods, ways and solutions to enhance the Russian Federation continental shelf exploration as well as to develop and replenish its resource base. [14]

Under the Agreement, the parties had to elaborate a Cooperation Plan aimed at achieving the following goals:

– organization of research and development, provision of engineering services in the field of geological exploration;

– accomplishment of infrastructure support of offshore operations, including construction of offshore platforms, pipelines, onshore bases and other necessary structures and facilities;

– elaboration of measures in the sphere of environmental protection and process safety.

Chapter 2.1. Rosneft projects in the Arctic

The Russian oil company Rosneft launched all its projects in the Arctic region in 2010 after obtaining some licenses to explore Russia's Arctic shelf.

Three of these licenses relate to blocks in the Kara Sea (East Prinovozemelsky 1, 2 and 3), next three licenses relate to blocks in Northern part of the Barents Sea (Albanovsky, Varneksky and West Prinovozemelsky) and the last one is for the South-Russky block in the Pechora Sea. The blocks are estimated to hold more than 21.5 billion tons of oil equivalent.

Except from these licenses, the company owns more blocks. Nevertheless, we will focus our attention to the blocks located on the maps below. (Map 2, Table 1)

Map 2 Rosneft projects in the Barents-Kara region (Source: Rosneft)

Table 1 Rosneft projects in the Barents-Kara region

№ on the map	Name of block
1	East Prinovozemelsky blocks 1, 2 and 3
2	Varneksky
3	Albanovsky
4	West Prinovozemelsky
5	South Russky block

1. The East Prinovozemelsky blocks 1, 2 and 3 in the Kara Sea.

The Prinovozemelsky blocks of the Kara Sea have been explored using 2D seismic. Estimated recoverable oil resources in the three blocks stand at 6.2 billion tons and hydrocarbon resources at up to 20.9 billion tons of oil equivalent.

2. The Albanovsky, Varneksky and West Prinovozemelsky blocks in the Northern Barents Sea

These three fields are located in the Arctic Ocean. The area is covered with ice more than half of the year.

The Albanovsky section of the shelf contains 144.2 million tons of oil, 43.3 million of which is extractable, and 1,254.4 billion cubic meters of gas. The deposits at Varnetsky block are estimated to be 2,081 million tons, of which 542 million is extractable. Recoverable resources of the West-Prinovozemelsky block are: oil and gas condensate - 1434 million tons, gas - 1893 billion cubic meters.

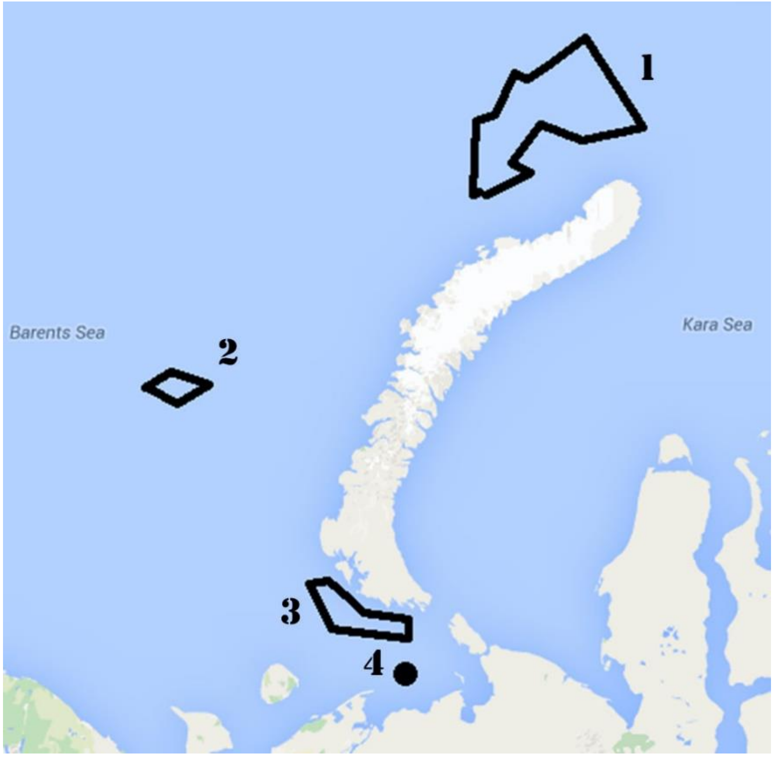
3. The South-Russky block in the Pechora Sea

Rosneft have conducted comprehensive geological and geophysical surveys on the South Russky block to evaluate hydrocarbon resources and geological risks. In the result the data was that deposit lied in the South-Russky block contains 13 million tons of oil and 52 billion cubic meters of gas.

Chapter 2.2. Gazprom projects in the Arctic

In 2011 Gazprom Group created a strong reserve base of 6.8 billion tons of fuel equivalent at the Arctic and Sakhalin shelves, of these gas comprises 6.3 trillion cubic meters for commercially viable.

By 2030 Gazprom expects the growth of reserves by more than 11 billion tons of fuel equivalent. Mainly that growth relies on actively produced field such as Prirazlomnoye and on already owned licenses. The most valuable licenses are shown below. (Map 3, Table 2)



Map 3 Gazprom projects in the Barents-Kara region (Source: Gazprom)

Table 2 Gazprom projects in the Barents-Kara region

№ on the map	Name of block
1	Heysovskiy block
2	Shtokman field
3	Severo-Zapadniy (North West) block
4	Dolginskoye field

1. **The Heysovskiy block in the northern part of the Barents Sea**

The Heysovskiy block is located in the northern part of the Barents Sea, west of the Novaya Zemlya archipelago. The distance from the mainland is about 1,000 kilometers. This northern Barents Sea is characterized by extreme environmental and climatic conditions. The north-western and north-eastern parts of the block can be ice-bounded throughout the year.

Data on the block is currently limited. While commercial oil and gas reserves are, as yet, unproven, the volume of D2 reserves is estimated at 140 million tons of oil and gas condensate, as well as two trillion cubic meters of gas.

2. **The Severo-Zapadniy (North West) block in the Pechora Sea**

The Severo-Zapadniy block is located in the Pechora Sea, relatively close to Gazprom Neft’s other Arctic-Shelf assets, the Dolginskoye and Prirazlomnoye fields. The sea around this block extends to a depth of approximately 200 meters. The block estimated to store more than 105 million tons of oil and gas condensate, together with 60 billion cubic meters of gas.

3. **The Shtokman field in the north-western part of the Barents Sea**

Yet in 2006, Gazprom completed drilling of appraisal well. Russian scientists have warned that the Shtokman's development may face problems. Now the project is frozen due to these problems. Its reserves are estimated at 3.8 trillion cubic meters of natural gas and more than 37 million tons of gas condensate.

4. **The Dolginskoye field in the central part of the Pechora Sea**

The Dolginskoye field lies in the central part of the Pechora Sea, 120km south of the Novaya Zemlya archipelago and 110km north of the mainland. The sea is about 35-55m deep in this area. Recoverable reserves at the field are currently estimated to be over 200 million tons of oil equivalent.

Chapter 2.3. Other projects of the Barents-Kara region

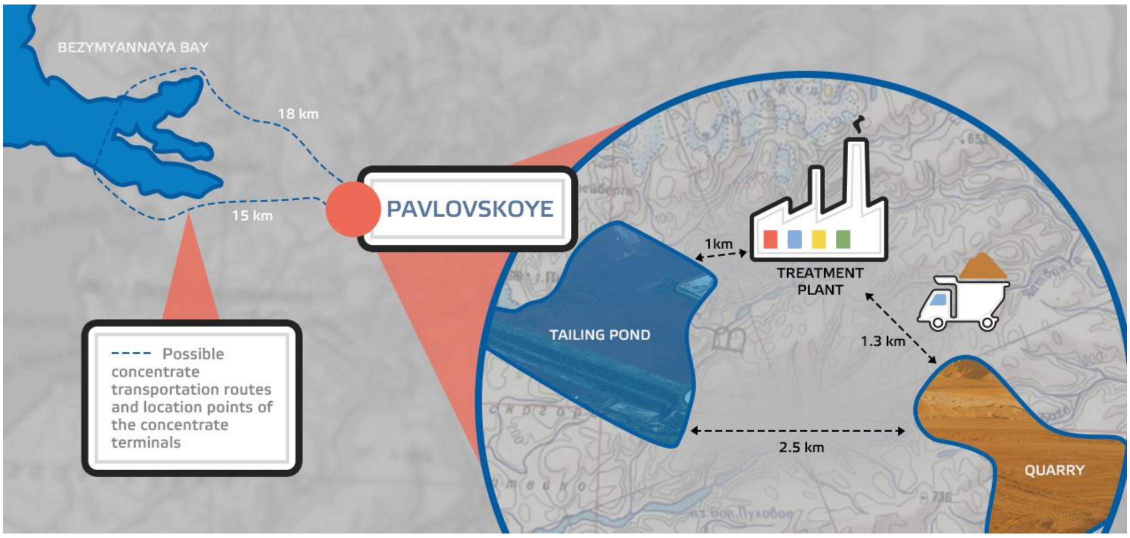
Except of oil and gas projects, there is another one – development of ore fields. The archipelago Novaya Zemlya is rich in resources such lead or zinc ores.

1. **The Pavlovskoye field (Map 4)**

The Pavlovskoye ore field occupies an area of over 12 km^2. Two productive deposits of lead and zinc ores of the Pavlovskoye field (Eastern and Central) were discovered, which have a band-like morphology and variable thickness from 10 to 100-120 m.

This field was discovered by JSC The First Ore Mining Company in 2001, which reserves of lead-zinc silver-containing ores of C1 and C2 category, in the amount of 37 million.

The Pavlovskoye field is already now ranked among five largest polymetallic deposits of Russia and given its mineral and raw materials potential, it may be among the leaders.



Map 4 Ore field on the archipelago Novaya Zemlya (Source: Joint-stock company [19])

Chapter 3. Structure of the report

Part I (Introduction) provides the general information about the exist projects in the Barents-Kara region. Mainly these projects are owned by Russian majors – Gazprom and Rosneft. Except of that, the first part considers an ore project on the archipelago.

Part II (Metocean Parameters and Conditions) provides the environmental data with metocean and ice conditions. Such conditions that require a consideration are topography, winds, waves, temperatures, ice duration, iceberg's occurrence, environmental concern.

Part III (Offshore Field Development) considers a short description of development of different areas in the region.

Part IV (Pipeline Route Selection) provides a calculation in the specialized program. It is guaranteed a successful offshore pipeline laying from the fields to the center located on the archipelago. All data are gathered in the one map – cost distance map/surface.

Part V (Economical Aspects of the Project) considers a short economic conclusions of the project. It discusses the main advantages.

Part VI (Conclusions) provides final remarks that sum up all material assembled in this project.

METOCEAN PARAMETERS AND CONDITIONS

PART 2

This part considers a comparison of metocean conditions of the Barents and Kara Seas; it will also discuss the bathymetry profiles, iceberg and ice ridges information, sea ice coverage and environmentally fragile areas of the seas. Emphasis will be placed on ice management.

There are a lot of challenges hindering the development in the Barents and Kara zones, such as

Environmental challenges for the Barents Sea:

- high pressures on seabed;
- warm surface currents of Atlantic water;
- ice coverage;
- atmospheric variability (extreme temperature gradients and strong wind;
- occurrence of icebergs and ice ridge;
- presence of environmentally fragile areas.

Environmental challenges for the Kara Sea:

- uneven bottom topography (slopes);
- cold surface currents of Arctic water;
- ice coverage (for most of the year);
- atmospheric variability (extreme temperature gradients);
- occurrence of icebergs and ice ridges;
- presence of environmentally fragile areas.

Chapter 4. Environmental conditions

The environmental data and statistics of seas' conditions are recorded every year by several meteorological stations. These following data that are recorded:

- Wind and air temperature;
- Sea level, waves and currents;
- Ice cover and icebergs.

Chapter 4.1 Geography of the Barents Sea

The Barents Sea is a marginal sea. It is located off the northern coasts of Norway and Russia with vast majority of it lying in Russian territorial waters. It is a shallow shelf sea, with an average depth of 230 meters, and is an important site for hydrocarbon exploration and development.

The Barents Sea is bordered by the Kola Peninsula to the south, the shelf edge towards the Norwegian Sea to the west, and the archipelagos of Svalbard to the northwest, Franz Josef Land to the north east and Novaya Zemlya to the east.

Novaya Zemlya Archipelago, an extension of the northern part of the Ural Mountains, separates the Barents Sea from the Kara Sea (Map 5).

Map 5 Map of the Barents Sea (Source: Worldatlas [25])

The exact size of the Barents Sea is difficult to determine, especially where the sea actually ends. Due to the warm coastal and Atlantic currents, the port city of Murmansk and other ports along the southern reaches of the sea remain ice-free throughout the year.

There are three main types of water masses in the Barents Sea:

- Warm, salty Atlantic water (temperature >3 °C, salinity >35) from the North Atlantic drift;
- Cold Arctic water (temperature <0 °C, salinity <35) from the north;
- Warm, but not very salty coastal water (temperature >3 °C, salinity <34.7).

Chapter 4.2 Geography of the Kara Sea

The Kara Sea is part of the Arctic Ocean north of Siberia. The Kara Sea, an extension of the Arctic Ocean, is located off the coastline of Siberia in far northwestern Russia.

It is separated from the Barents Sea (in the west) by the Kara Strait and Novaya Zemlya Archipelago; and from the Laptev Sea (in the east) by the Taymyr Peninsula and Severnaya Zemlya (Map 6).

Map 6 Map of the Kara Sea (Source: Worldatlas [25])

In the Kara Sea the bottom topography is uneven; the average depth of the sea is 111 m and the maximum depth 600 m. The sea is ice-bound for most of the year; the sea is generally navigable only during August – September season.

Compared to the Barents Sea, which receives relatively warm currents from the Atlantic, the Kara Sea is much colder, remaining frozen for over nine months a year. The Kara receives a large amount of fresh water from the Russian rivers.

The Kara Sea is almost non-seismic; however, there were four events with source depths of 10 to 25 km and magnitudes up to 5 on the Richter scale, two of which occurred on the island of the October Revolution.

There is one main type of water mass in the Kara Sea:

- Cold Arctic water (temperature <0 °C, salinity <35) from the north.

Chapter 4.3 Air Temperature profile

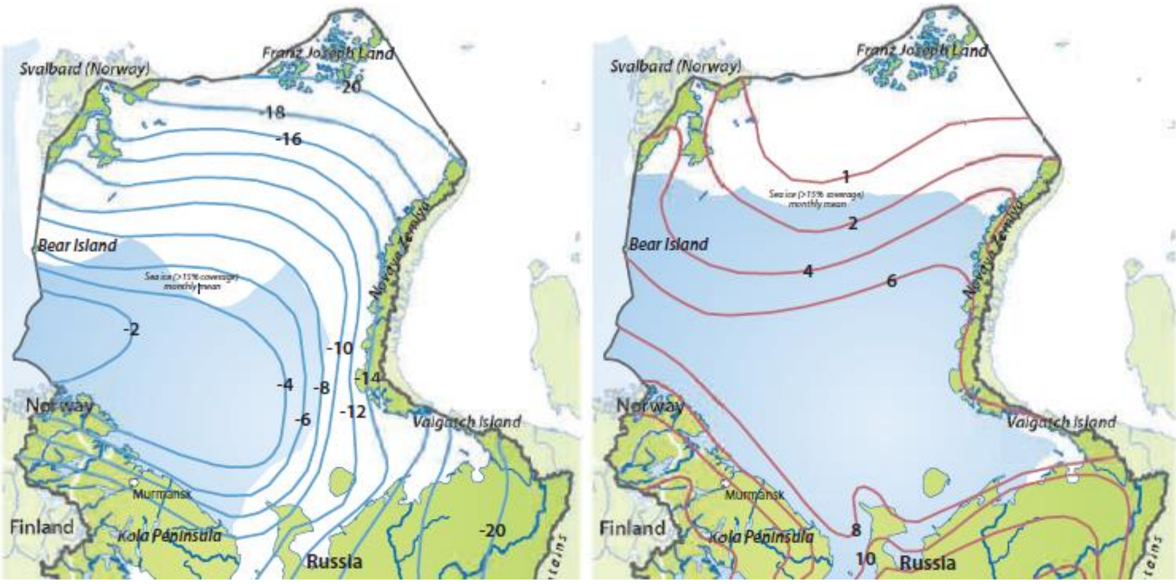
Novaya Zemlya Archipelago is a barrier for warm Atlantic air and water, the polar maritime climate of the Kara Sea is more severe than the climate of the Barents Sea. The air temperature is below 0 ° C retained in the north of the Kara Sea 9-10 months, in the south - 7 - 8 months.

The average January temperature is about -20 to -28 ° C (minimum can reach -50 ° C), July -6 to +1 ° C (maximum can reach +16 ° C).

The relative humidity is high throughout the year (80-85% in winter, 90- 95% in summer). Fogs at the sea are most frequent in July and August. The number of days with storms – is 1-2 month in the summer months and 6-7 in the winter. The greatest number of storms is observed in the western part of the sea.

The climate of the Barents Sea is warmer than the climate of Kara Sea. It is because of warm Atlantic current and warm coastal current (Map 7).

The average January temperature varies through the sea from -2 to - 20 ° C, July -1 to +10 ° C.

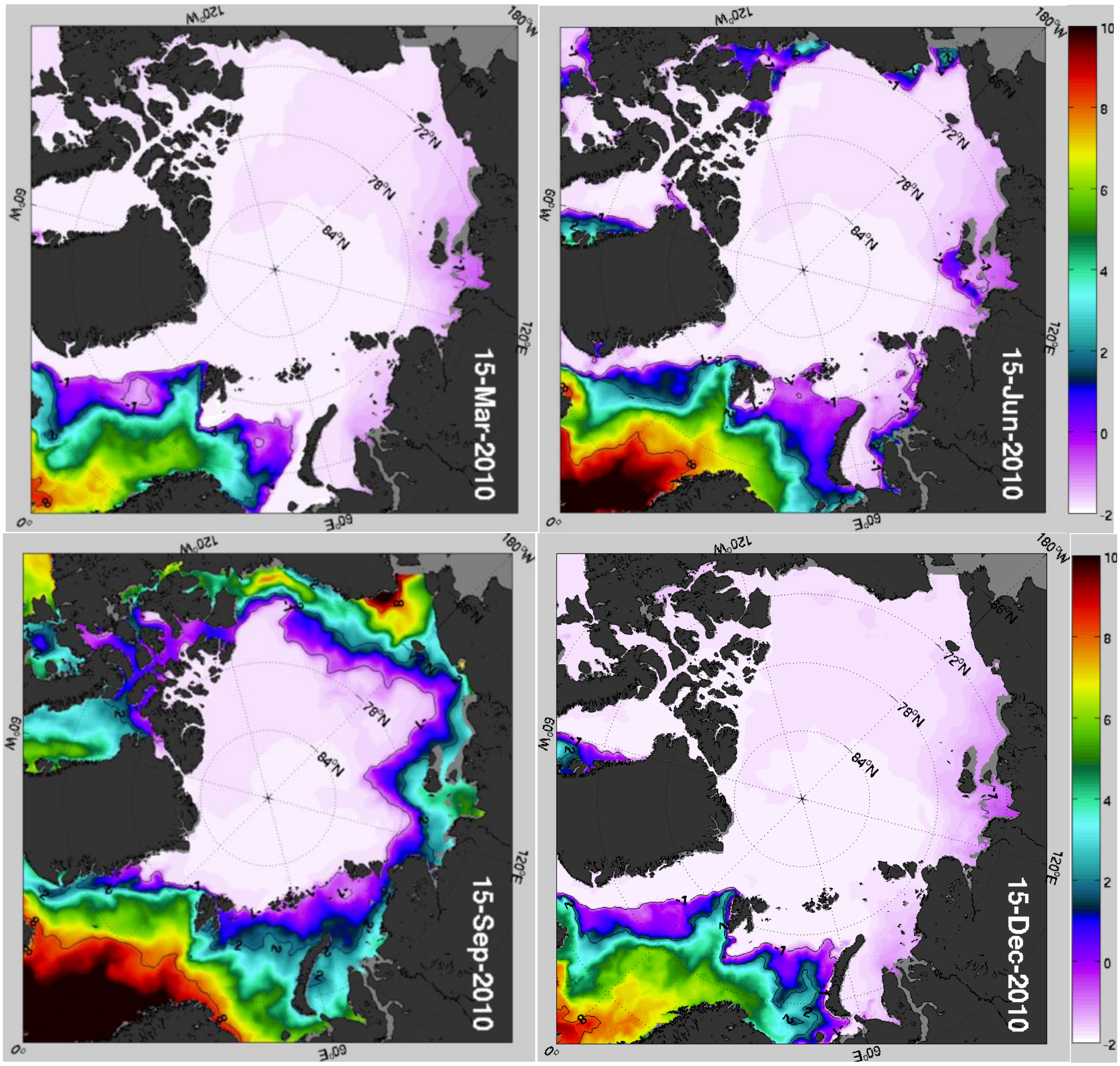


Map 7 Average long-term air temperature in the Barents Sea (left – January, right – July) (Source: GIWA [50])

Chapter 4.4 Water temperature profile

The sea temperature defines ice extent and ice concentration. A simple sea water temperature profile is shown on the Map 8.

As we see the temperatures of the Barents Sea is higher than in the Kara Sea. That is why the Kara Sea is ice bounded fully and the Barents Sea is freezes only along the Archipelago Novaya Zemlya.

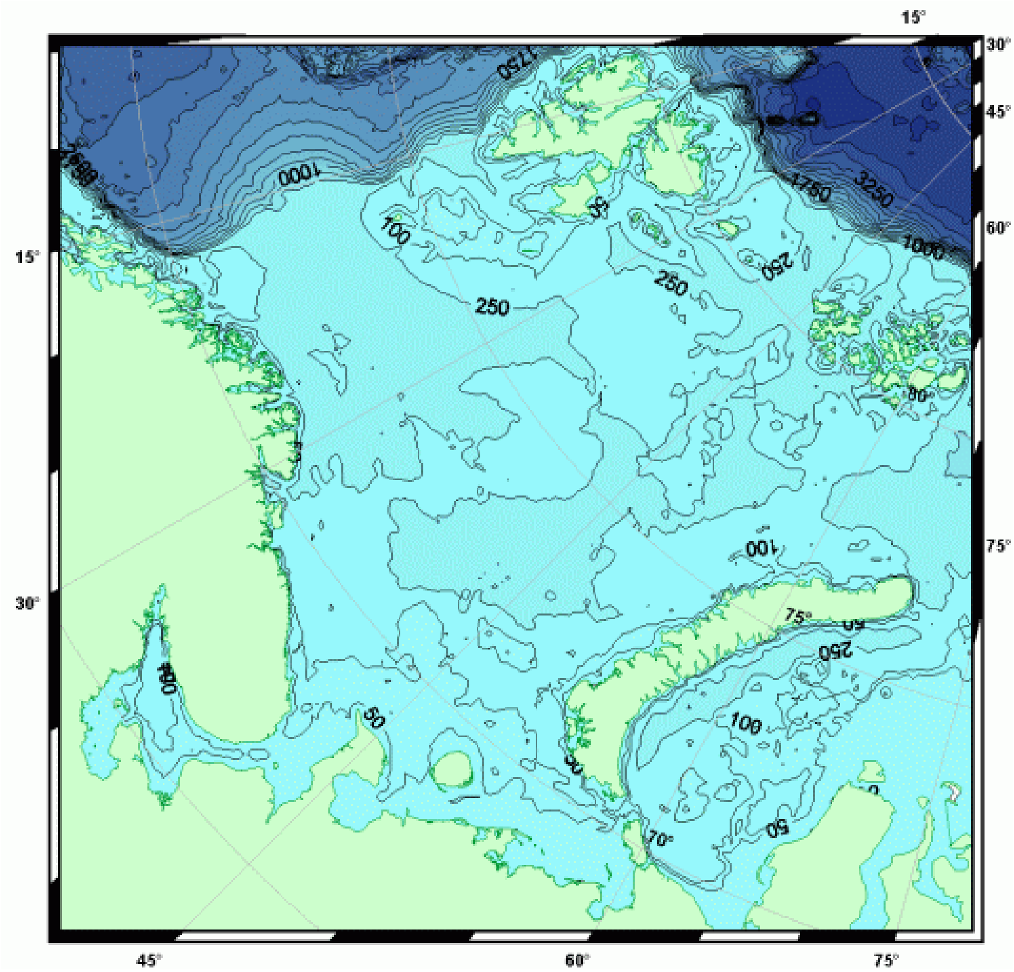


Map 8 Average long-term water temperature in the Barents-Kara region **(Source: http://topaz.nersc.no [9])**

Chapter 4.5 Sea level profile

Water depth is one of the main factors that defines a choice of production facilities and pipelines. To support these needs a bathymetry map for the Barents-Kara area should be created.

As one can see on the Map 9 that the Barents Sea shelf is rather deep. In the Barents Sea more than 50% of the area has depths of 200-500 m. The average depth is approximately 200 m and a considerable part of the shelf consists of shallow bays with an average depth of only 67 m and a maximum of 350 m.



Map 9 Bathymetry map of the Barents-Kara region (Source: AARI [11])

On the other hand the most prominent features of the Kara Sea bathymetry are the St. Anna (with depths up to 610 m) and Voronin (with depths up to 450 m) troughs. Between these toughs is the Central Kara plain with depths of less than 50m. Along the Novaya Zemlya Sea depth is more than 400 m.

Overall, 64% of the Kara Sea area has depths less than 100 m, and 2% have depths greater than 500 m.

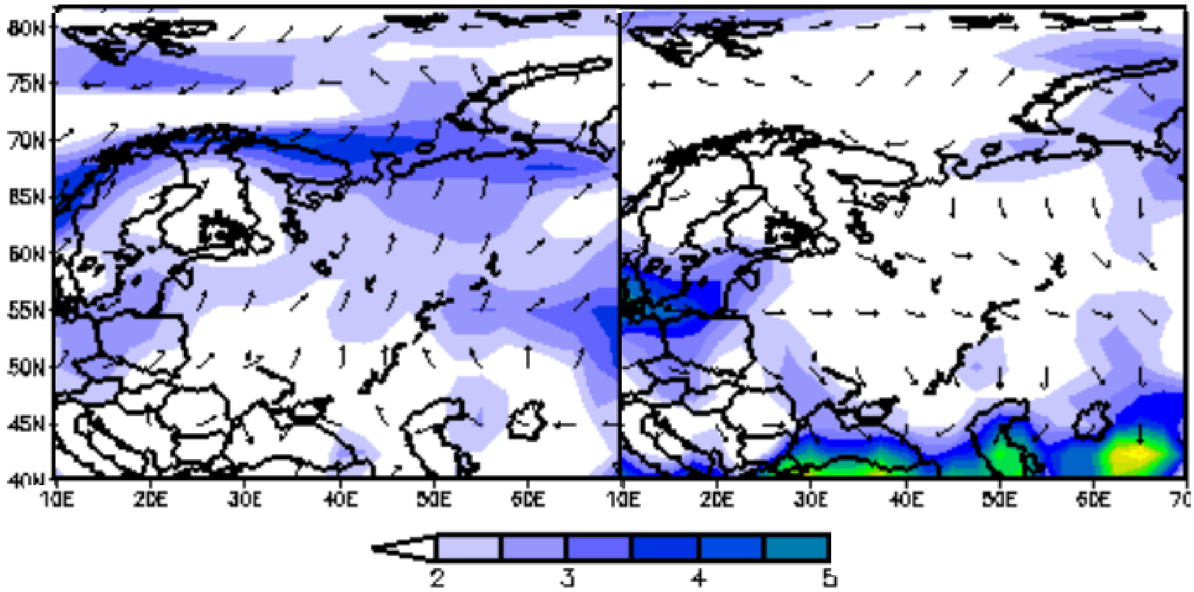
Chapter 4.6 Wind profile

In winter, we can observe atmospheric variability of the Barents Sea (Map 10). The southern Barents Sea is usually dominated by southwesterly winds, which contribute to increase in advection of warm Atlantic water to the area. The result is strong winds with speed of 5 m/s.

In the northern part of the sea, cold northeasterly winds predominate. The wind speed of them is not high; it is about 3 m/s.

In summer, contrasts in sea level pressure are well pronounced only over the northeast Atlantic. In the Barents Sea, horizontal gradients of pressure are rather small and, as a result, light winds of different directions blow over the Barents Sea and Kara Sea.

In the southwestern part of the sea, the average annual rainfall is from 300 to 400 mm; from 200 to 350 mm in the north-east.



Map 10 Average surface wind speed (left – Dec to Mar, right – Jun to Aug) (Source: Institute of marine research IMR [18])

Chapter 4.7 Current profile

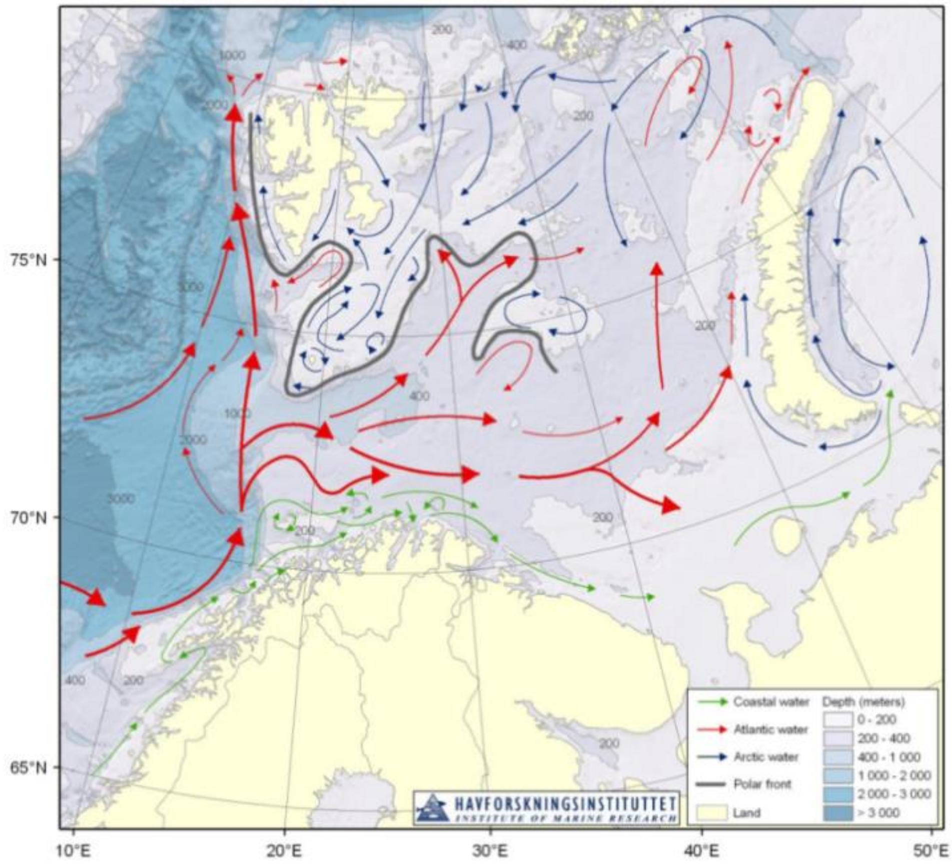
The system of currents in the Barents Sea is provided by three different water masses (Map 11).

- Warmer, more saline waters from the Atlantic (red).
- Colder, less saline waters from the Arctic (blue).
- Warmer, less saline coastal waters (green).

The warm deep current enters the Barents Sea from the Arctic Ocean. It flows into the Barents Sea below colder and fresher upper waters. Another current is coastal warm current that protects ice cover along the south part of the sea.

The system of currents in the Kara Sea is provided by circulating water of the Arctic Basin. The currents are characterized by a cyclonic circulation in the southwestern part and multi-directional flows in the southern, central and northern regions.

The flow velocity of current is usually small. The tides in the Kara Sea are clearly marked, but relatively small (0.5 - 0.8 m), in the Ob Bay – speed is more than 1 m. Speed of tidal currents reaches significant values.



Map 11 Surface currents in the Barents-Kara area (Source: BarentsWatch [27])

In the Kara Sea, currents form slow anticlockwise cycle that envelopes the southwestern and northeastern parts of the sea.

Chapter 5. Ice information

Chapter 5.1. Sea ice coverage

The Barents and Kara Seas are characterized by large year-to-year variations in ice conditions. The variability in the ice coverage is closely linked to the amount of the inflowing Atlantic water. Sea ice coverage is important parameter influenced on the choice of platform. Thickness, size and concentration of ice are the most relevant and restrictive factors.

In the Barents Sea, the ice reaches its greatest extent in March and April (up to 1.5-4.5 m height), melting taking place rapidly between July and September, after which freezing starts again (Figure 1).

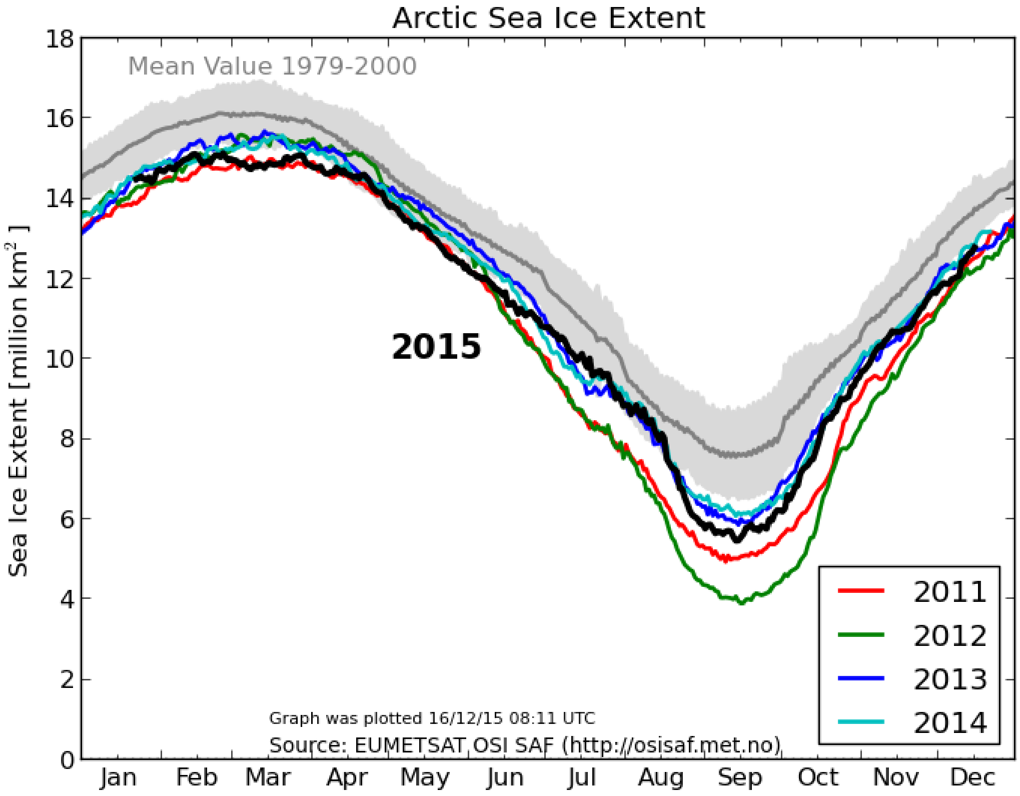
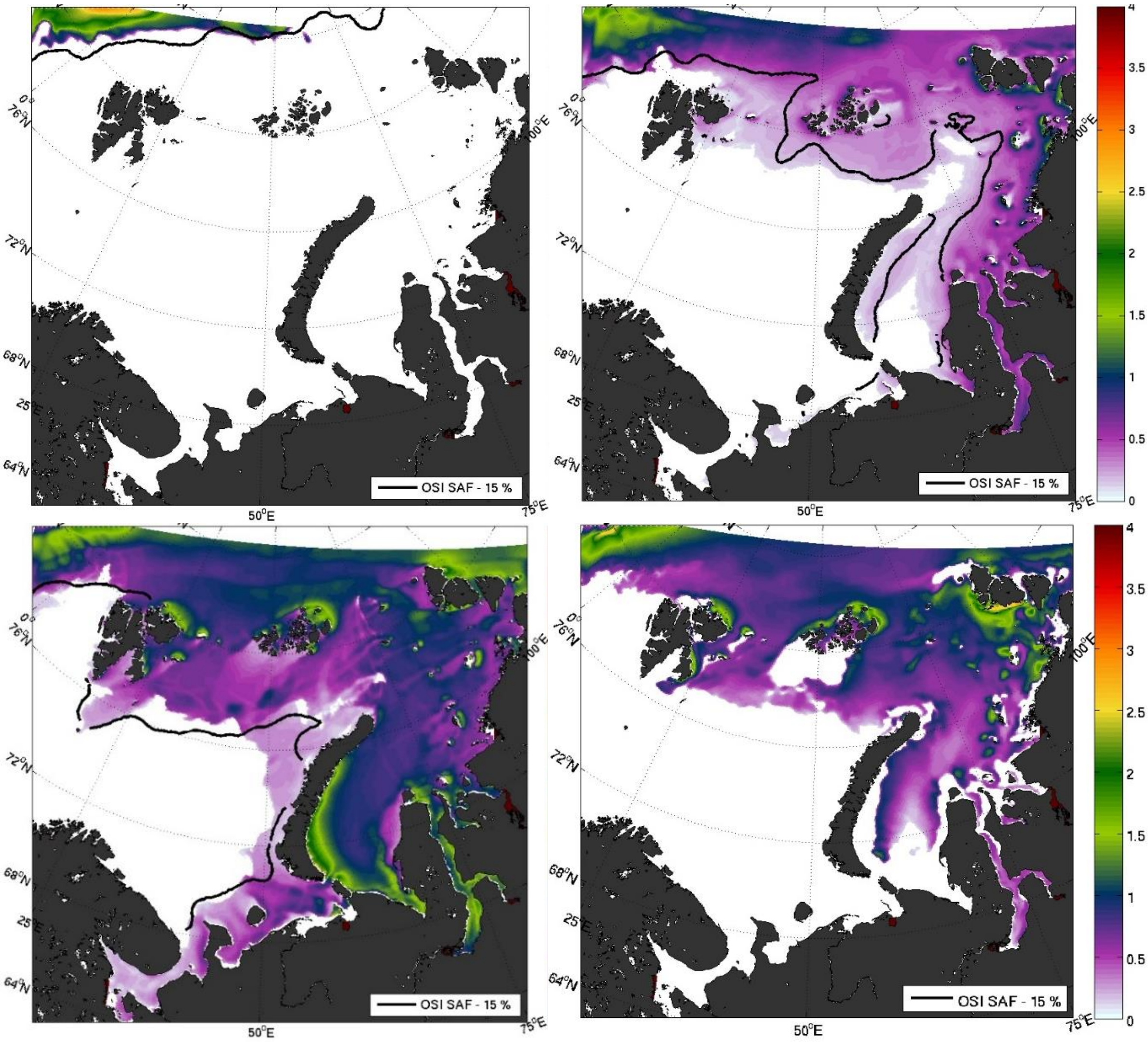


Figure 1 Up-to-date daily sea ice extent (Source: OSISAF [5])

In the Kara Sea, ice covers for most of the year from October to August (Map 12).

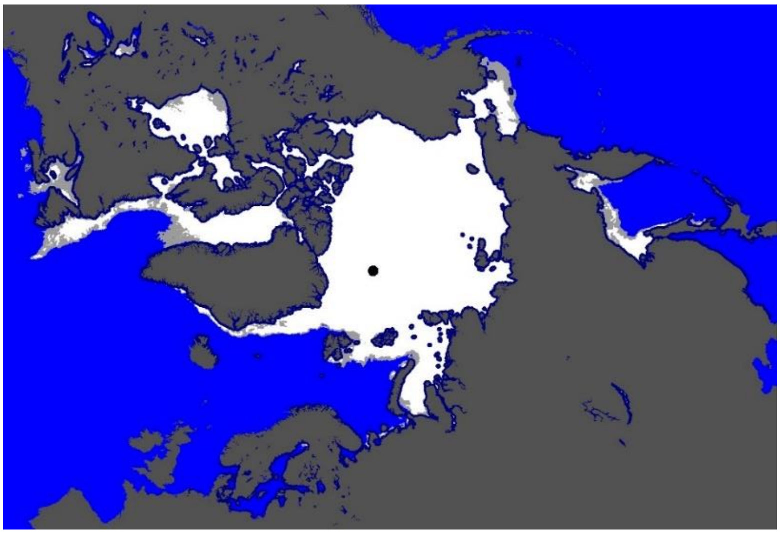
Sea ice is problem where low temperatures can cause the sea surface to freeze into level ice. That cause large loads on the structure, and is a complicating factor in maintenance and other operations. On the Map 12 averaged ice conditions for the Barents-Kara area are presented. Here only ice presence and concentration are shown.



Map 12 Change of the ice concentration during a year (Sep. 2012 – Dec. 2012 – Mar. 2013 – Jun. 2013) (Source: http://topaz.nersc.no [9])

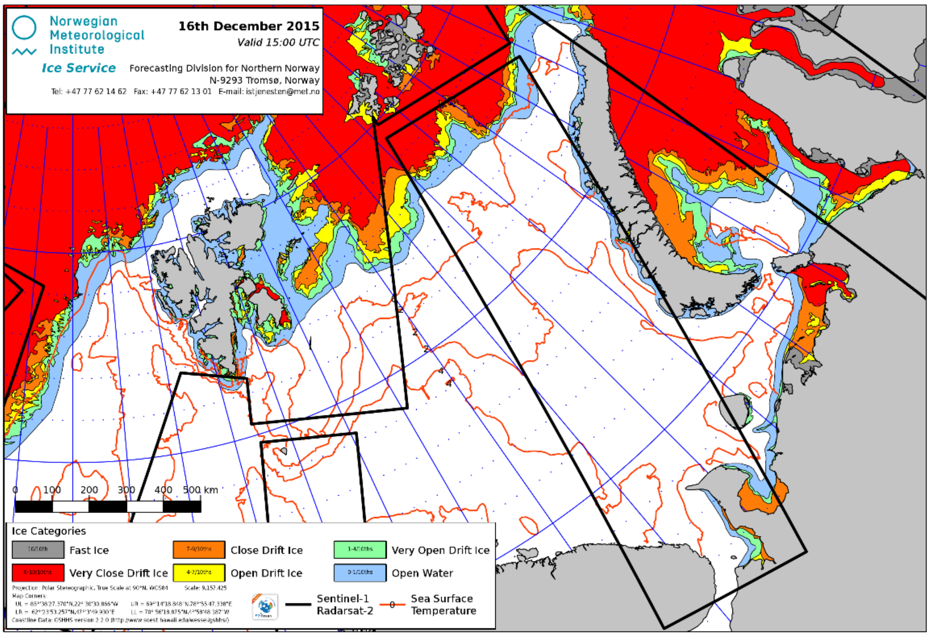
The ice cover can be a combination of first-year ice, multi-year and icebergs. In general, throughout the whole territory of the Barents Sea during the formation of the ice cover 10% is occupied by multi-year ice, first-year ice occupies about 15%. Besides them the Kara Sea is occupied by icebergs and ice ridges.

Mean ice edge in winter season for the Arctic Seas is shown on Map 13. The most problematic area is the Kara Sea which is ice-bounded almost a year.



Map 13 Mean ice edge in winter season (Source: OSISAF [5])

In real time all ice motion and concentration can be tracked. Such example of tracking is shown on the Map 14. Many meteorological institutes study that. All ice charts are available on special sites. [6], [10]



Map 14 Forecasting ice chart in the Barents-Kara region (Source: MET Norway [10])

Chapter 5.2. Ice gouge information

Local and detailed sea ice information, including ice drift, ice concentration and ice thickness, will in the future, be essential for safe navigation and operations in the Barents and Kara Seas. [4]

Icebergs are considered as an important factor in designing and building offshore structures, subsea equipment and communication lines. In winter season and in cold regions design and installation of pipelines imposes certain challenges that do not apply elsewhere.

Ice gouging is probably the main threat to offshore pipelines in the Arctic, being therefore the key design parameter in both pipeline design parameters and route selection. The problem is caused by ice structures with deep keels moving in shallow waters, cutting deep gouges into the seabed.

Gouging features are typically divided into two classes based on type of cause: icebergs and ice ridges (Figure 2).

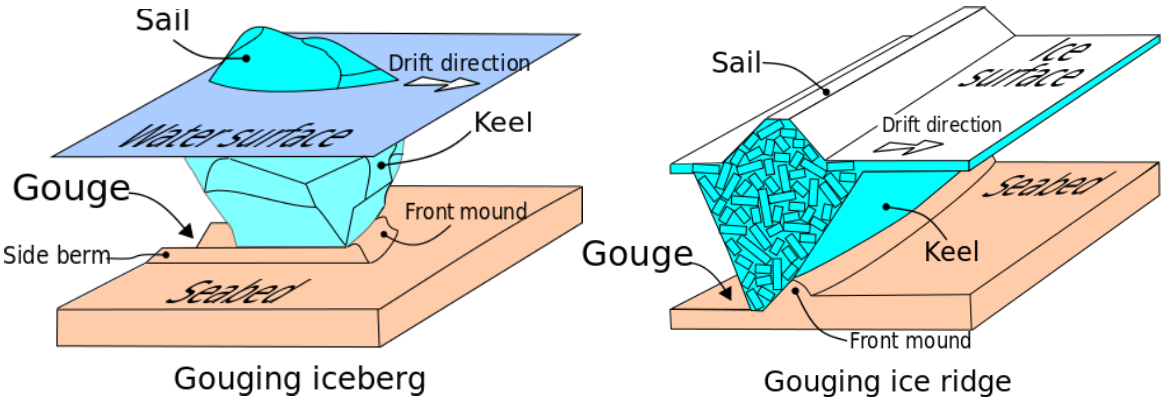


Figure 2 Schematic representation of two types of gouging (Source: Wikipedia [26])

All pipelines must be designed to withstand unique loading conditions of seafloor gouging by drifting sea ice ridges and icebergs. Offshore arctic regions may contain several types of ice features that are capable of scouring the sea floor, including icebergs, first year ice ridge keels, and multiyear ridge keels. The ice features are continuously moving under the action of environmental forces (e.g. wind and ocean currents). [31]

Pipelines that cannot withstand the contact with ice gouging are assumed incapable of safely and therefore must be buried deep enough for contact to be avoided. In addition, ice gouging creates 2 significant displacement zones in the soil region directly beneath the gouging surface. They are large deformation and small deformation zones (Figure 3). [31]

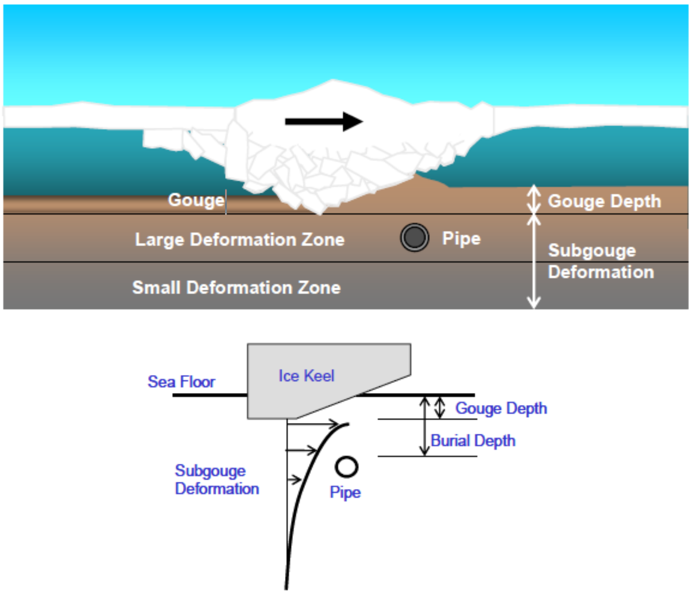
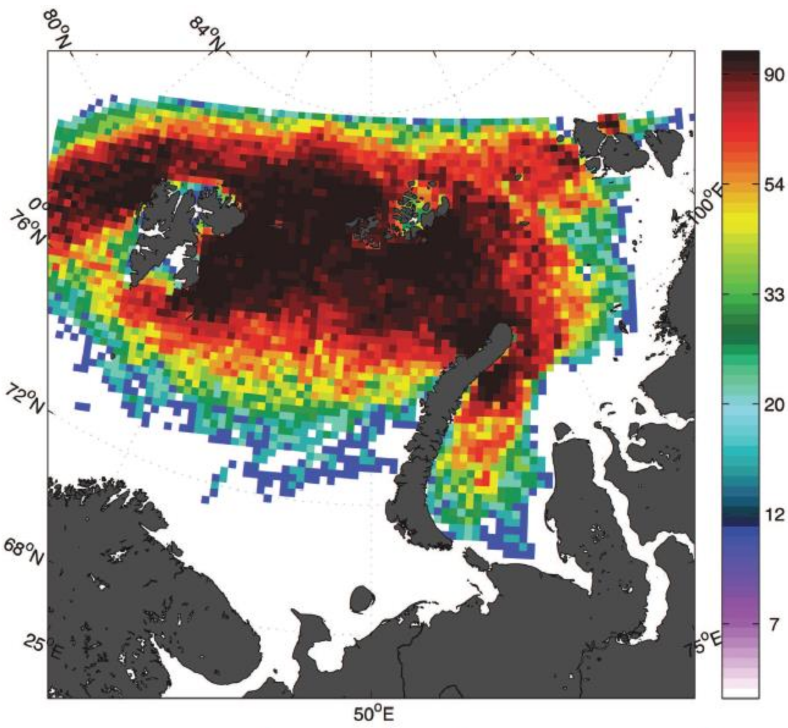


Figure 3 <u>**Sub-gouge deformation**</u> **(Source: Onepetro's thesis [45])**

Chapter 5.3. Iceberg frequency

To quantify iceberg information about annual probability of iceberg occurrence in the Barents and the Kara seas was put on the map data. On the Map 15 annual probability of occurrence per 25 x 25 km cell is shown.

Most of icebergs are appeared in the Kara Sea. Therefore, development of this sea is more hard.



Map 15 <u>**Probability of encountering an iceberg within the year**</u> **(Source: http://msc.nersc.no [4])**

Chapter 5.4. Methodology of ice gouge depth calculation

The downward transmission of the gouge cutting force causes subgouge. Gouging ice keel is extremely blunt, acting as a cutting device, it applies force that spreads outward and deforms a large volume of soil. Pipeline can be damaged severely by those deformation.

Estimating the extreme maximum gouging depth has been the most conventional approach, coupled with estimation of extent of subgouge deformation and a safety margin require that the pipeline top be trenched below that depth. Extreme gouge depth and subgouge deformation are not fully studied and understood. Erosion allowance must be considered to mitigate any possible seabed erosion or wave and current action. The trench must be extremely deep which brings additional undesirable consequences including environmental impact and the increased difficulty of external monitoring when pipeline begins operation.

A weak layer can help prevent the downward transmission of the force if placed immediately above the pipeline but below the gouging depth. Figure below illustrates this idea. The pipeline is layed at the bottom of the trench, and an intentionally weak layer is installed over it. The layer is too weak to transmit downward the shear forces that provide subgouge deformation.

The disadvantage of this scheme is that the weak layer can be severely damaged by the keel passage, and can't prevent damage by yet another keel that crosses at the same place. However, the layer is primarily used to protect against subgouge deformation rather than against direct contact with a keel. The weak layer is placed below the design maximum gouging depth, almost certainly estimated and with some safety margin.

It is complicated to correctly interpret the gouging profile due to many factors, such as the time history of gouging, the soil infill due to repeated gouging, and the normal seabed sediment process due to waves and currents. Nevertheless, the most of gouges have constant cross-section for quite long distance.

The ice ridge scouring the seabed could damage marine pipeline. But except ploughing process itself, intensive deformations occur beneath the gouge, and a pipeline would still be damaged by being dragged with the soil. Hence it becomes clear, that the required depth for pipeline burial should be:

$$D_b = d + b$$

Where d – is the gouge depth and b – cover depth.

Anticipating the certain conditions of the ridge and environment, the gouge depth could vary from place to place. The accuracy of its value determination is high: from one hand it is cost, from another – safety of the pipeline system.

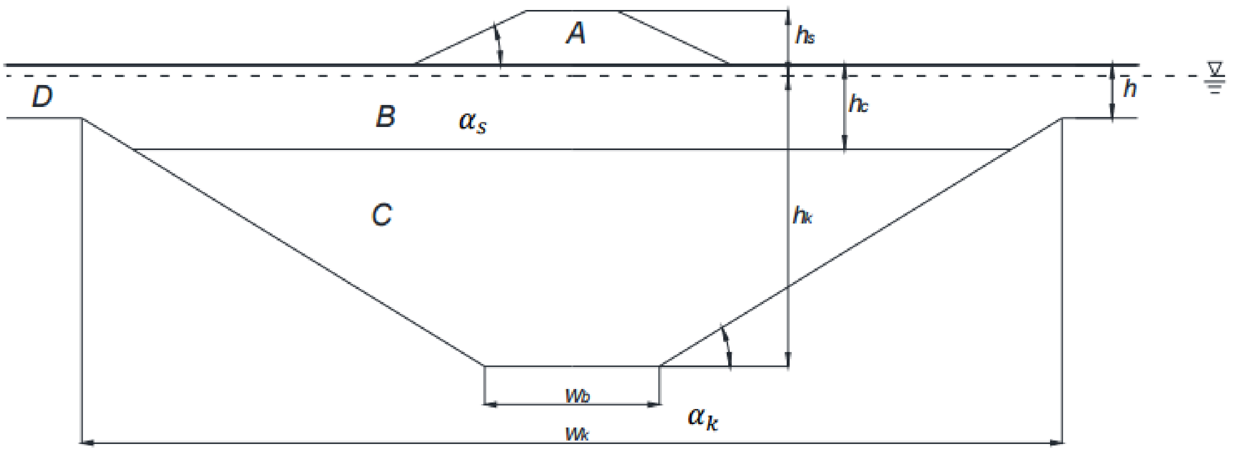


Figure 4 Geometrical parameters for typical first-year ice ridge (Source: International Standard [41])

ISO 19906 [41] recommends a typical cross-section of a ridge, shown in Figure 4, where

A – sail;

B – consolidated layer;

C – keel;

D – level ice;

h_c – is the thickness of consolidated layer;

h_s – sail height; h – level ice thickness;

h_k – keel height (from the sea level to its bottom);

w_k, w_b – keel width at the sea level and at the bottom, respectively.

Information about the correlations between the mentioned parameters has important implications for the loads the ridge could exert either on the seabed or on the pipeline.

The research of ice gouge estimation has been carried out by Phillips et al. [53], where the maximum gouge depth was estimated at the moment of keel destruction, based on the keel cohesion values.

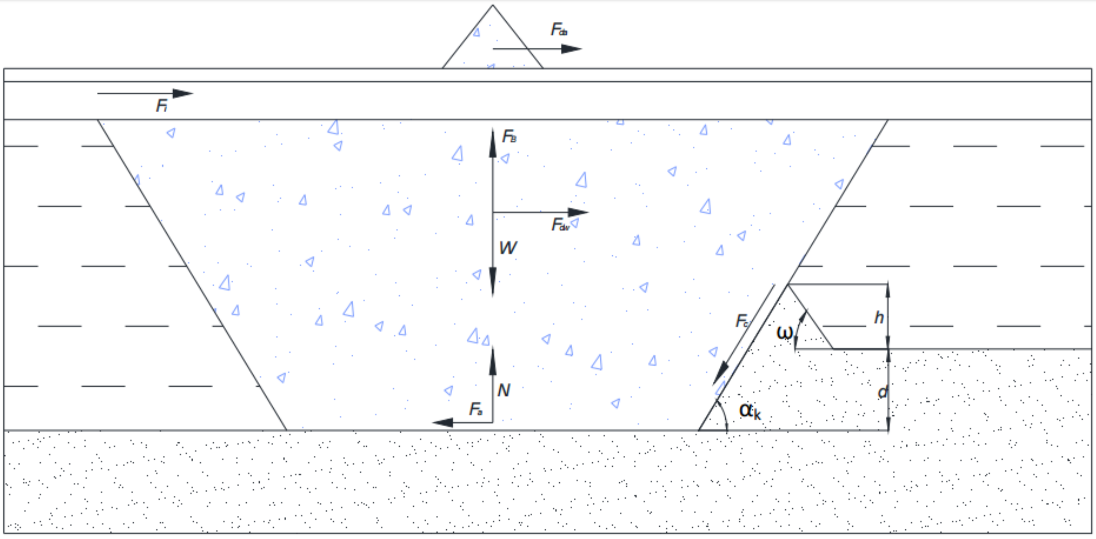


Figure 5 Force system on the ice ridge (Source: Onepetro's thesis [30])

Where

F_{da}, F_{dw} – drag forces from air and water respectively;

F_b – buoyancy force;

W – weight of the ridge;

N – reaction from the seabed;

F_a – friction force on the bottom of the ridge;

F_c – Coulomb's passive friction force, acting in front and on both sides of the ridge;

F_i – driving force from surrounding floe;

ω – angle of the front surcharged soil slope; αk – keel angle;

h' – height of the frontal mound;

d – scour depth.

A set of assumptions has been made in order to fulfill the model integrity:

• Ridge is assumed to be initially motionless such that all forces exert their maximum values. Otherwise drag force from current could act in opposite direction: wind accelerates the ridge and it moves faster than the current. And water resists the ice ridge movement.

• The seabed in the presented model is even and has no inclination. It was neglected in order to simplify the system without considerable error.

• Ice ridge is an absolutely rigid body with negligibly small elasticity, which doesn't consume energy for its structure reorganization.

• Ridge keel bottom has an infinite strength, so it is not being destroyed scouring the seabed.

• Substantial surface ice restricts the ridge upward motion.

The equations of equilibrium in either direction are given by:

Horizontal direction:

$$F_{da} + F_{dw} + F_i - F_a(d) - F_{cx}(d) = 0 \tag{1}$$

Vertical direction:

$$F_b - W - F_c \cdot \sin\alpha_k + N = 0 \tag{2}$$

Each force component of the system is defined below.

Drag force from the wind:

$$F_{da} = \frac{1}{2} \cdot \rho_a \cdot C_{da} \cdot A_{a1} \cdot {u_a}^2 + C_{sa} \cdot \rho_a \cdot A_{a2} \cdot {u_a}^2 \tag{3}$$

Drag force from the current:

$$F_{dw} = \frac{1}{2} \cdot \rho_w \cdot C_{dw} \cdot A_w \cdot {u_c}^2 \tag{4}$$

Weight:

$$W = \rho_{iw} \cdot B \cdot g \cdot [\frac{\rho_{ia}}{\rho_{iw}} \cdot \left(h_s - \frac{\rho_w - \rho_i}{\rho_w} \cdot h_i\right) \cdot \cot\alpha_s + \frac{\rho_i}{\rho_{iw}} \cdot h \cdot w_k + \tag{5}$$

$$+\frac{1}{2} \cdot (w_k + w_b) \cdot \left(h_k - \frac{\rho_i}{\rho_w} \cdot h\right)]$$

Buoyancy force:

$$F_b = \rho_w \cdot B \cdot g \cdot [\frac{1}{2} \cdot (w_k + w_b) \cdot \left(h_k - \frac{\rho_i}{\rho_w} \cdot h\right) + \frac{\rho_i}{\rho_w} \cdot h \cdot w_k] \quad (6)$$

Ice force:

$$F_i = 0.43 \cdot 4.059 \cdot B^{0.622} \cdot h_i^{0.628} \quad (7)$$

Passive friction force:

The equation for horizontal component of Coulomb's force is:

$$F_{cx}(d) = \mu \cdot P_f(d) \cdot \cos\phi_w \cdot \cos\alpha_k + \mu \cdot P_s(d) \cdot \cos\phi_w \quad (8)$$

The equation for vertical component of Coulomb's force is:

$$F_{cy}(d) = \mu \cdot P_f(d) \cdot \cos\phi_w \cdot \sin\alpha_k \quad (9)$$

Active friction force:

This force is a function of soil reaction:

$$F_a(d) = \mu \cdot N(d) = \mu \cdot F_{cy}(d) \quad (10)$$

Replacing all forces with outlined formulas, the quadratic equation with respect to the gouge depth d is derived and easily solved.

$$F_{da} + F_{dw} + F_i - \mu \cdot F_{cy} - F_{cx} = 0 \quad (11)$$

Chapter 5.5. Remedial measures

The Arctic conditions dictate both pipeline trenching equipment and the associated project execution plan. The equipment is supposed to operate in any environment and be able to create a trench profile in the specific soil conditions. An option suitable for deep water may not work for near shore areas.

For operation in arctic conditions, significant changes in existing equipment may be required. The vessels will require preparation for winter operation in conditions of freezing and the hulls may require reinforcing to be able to withstand ice loads. If construction cannot be completed in a single season, attention should be paid to the mobilization and demobilization of equipment or preparing the equipment for winter. [31]

Several trenching techniques could be used. Some are applicable only to pre-lay i.e., before the pipeline is installed, whereas others are best suited to post-lay installation. These methods include, but are not limited to:

- Conventional excavation;
- Hydraulic dredging;
- Ploughing;
- Jetting;
- Mechanical trenching.

Protection of the installed pipeline could be provided by pre- or post-lay techniques. However, a pre-lay method or post lay immediately following installation of the pipeline would most likely be required for Arctic conditions since the pipeline would otherwise rest on the seabed and be potentially exposed to the action of ice keels moving into the area.

Chapter 6. Environmentally fragile areas

The Barents and Kara Seas contain vast clean and relatively undisturbed marine ecosystems. Every year numerous reports about marine life include large colonies of seabirds and fish, rich variety of sea floor communities and marine mammals.

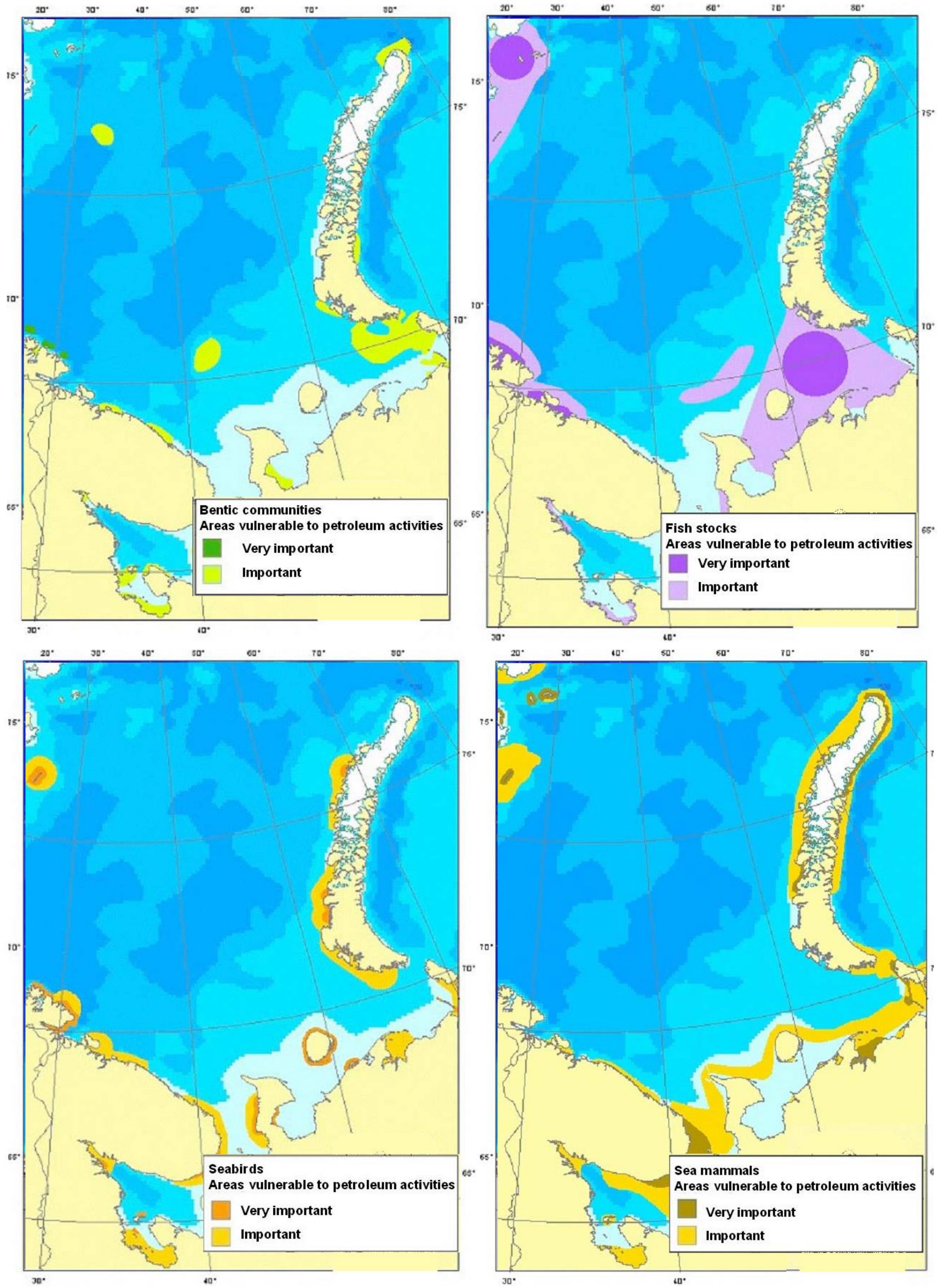
Nowadays when development of these regions is necessary the unique values threatened by a new and potentially extremely damaging activity: oil and gas development. A large oil spill and gas leak would cause dramatic consequences to the wildlife in this area, such as seabirds, mammals and fish-stocks.

To avoid these consequences the right decision is to study these environmentally fragile areas. The distribution of these marine resources was taken from Barents Sea report by WWF-Norway. [29]

The most valuable and sensitive living marine resources are as follows:

- Life on the sea floor – Benthos;
- Life in the seawater – Fish;
- Life in the air and along the coast – Seabirds;
- Life on the ice and in the sea – Marine mammals.

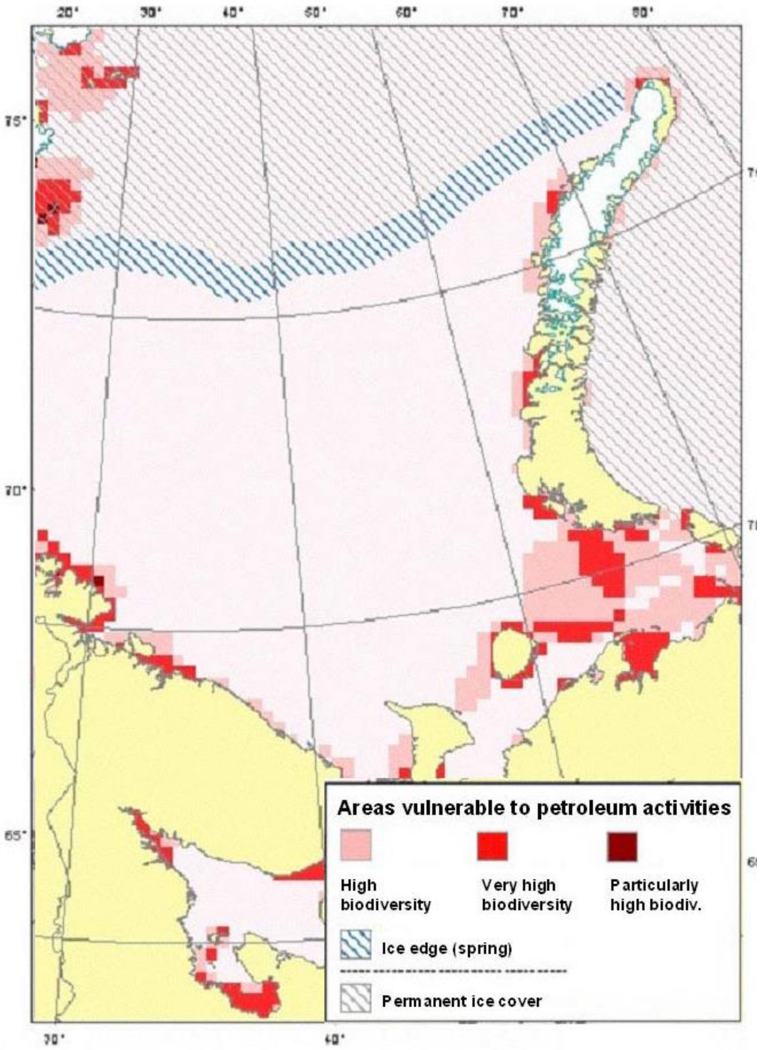
These fragile areas are shown on the Map 16.



Map 16 Different areas of environmental concern (Source: WWF [29])

By combining all these areas the highest concentrations of sensitive biological values can be found.

Next map is the result of strict priorities from WWF, and shows the areas that are absolutely critical to protect from the threats posed by oil and gas activities. (Map 17)



Map 17 Combined areas of environmental concern (Source: WWF [29])

Field development as well as production and transport of oil and gas always have a risk for oil spill and gas leak. Due to harsh conditions and climate of the Barents and Kara Seas, timely cleaning and rescue works are hard to implement what increases hazard category of accidents.

The best solution is to analyze all activities before they will be implemented and to distinguish petroleum-free zones that must be protected.

Chapter 7. Data summary

The main idea of this part was to understand metocean conditions of both seas. All data will help to develop an approach for development of offshore fields in the Barents-Kara area. All results were combined into the Table 3, where we have also distinguished the Pechora Sea as a separate region.

Table 3 Hydro-meteorological conditions in the Arctic

Parameter	Kara Sea	Barents Sea	Pechora Sea
Temperature mode: air temperature, ^{0}C			
Minimum/average in January	**-49/-26**	-39/-24	-46/-20
Minimum/average in July	+27,0/+7,5	**+9,0/+0,9**	+29,0/+9
Min/max water surface temperature	-1,8/+9,0	**-1,8/+2,5**	-1,8/+10,9
Air mode			
Velocity of 100-year wind 10 m. above, m/sec	**40**	38-40	36
Gusts of 100-year wind 10 m. above, m/sec	50	50	50
Wave mode: 100-year wind wave conditions			
Wave height (50% probability), m	8-10	**19**	10
Average period, sec.	12	**16**	9,5
Average wave length, m	220	**300**	116
Ice mode			
The duration of ice period (mean value), days	**289**	258	242
Thickness of one-year drift ice, cm			
50% probability	**220**	84	65
Maximum observed	**270**	195	150
100-year	-	**200**	180
Drift ice velocity, cm/sec:			
Minimum	**30**	19	**30**
Maximum observed	80	**97**	80
100-year	-	125	**130**

Such complex development of the region can have a significant advantage. Moreover, this advantage is scale of investments when they are made for the infrastructure that will serve for several fields and projects.

In that case, oil and gas fields in the eastern Barents Sea might be reconsidered and become more economically efficient. Novaya Zemlya Archipelago can be considered as a center for development of the eastern Barents and the Kara seas for several reasons: shorter distances to fields, possibility to use different ways of transportation of materials, equipment and personnel and possibility to construct onshore facilities and have a safe export of hydrocarbons to any market.

That idea is based on observations and features that were made in the project.

These special features are as follows:

- Sea ice, icebergs, icing and wind chill are new elements that may increase both frequency of accidents and the consequences thereof. Data on ice and iceberg are insufficient.
- Ice cover, icebergs and short ice-free period in the western Kara Sea limits technical solutions and development schemes that can be applied here.
- Large annual variations in temperature relative to ice coverage.
- Less reliable weather-, ice- and iceberg forecasts combined with small scale, very local atmospheric phenomena.
- An uneven seabed, which makes building of infrastructure harder.
- One of the largest concentrations of sea birds in the world.
- Management of living marine resources in the Barents-Kara region.

Piping engineer must make a definite decision on the depth of the trench, and to make a decision based of the mass of statistics data. Much of this evidence is more or less uncertain. If the path of the solution too complex, there is a risk that the multiplication of uncertainty will lead to a final number, which leads unacceptably wide confidence.

Very deep trench is not the only way to protect the Arctic marine pipelines from ice gouging strudel erosion. Optimum scheme requires a combination of several ideas.

During the expedition in 2013 ice gouges were found in a depth of 0.5 m in locations of Universitetskaya structure. The gouge was caused by icebergs, not by hummocks, which leads to the appearance of fissures in deep water. The maximum depth of the Sea, where plowing was found was 60 m.

OFFSHORE FIELD DEVELOPMENT

Development life-cycle of an offshore hydrocarbon field goes through several stages, from geological surveys as the first step of exploration to removal of all installation as the final step of decommissioning. A brief development description is given in Figure 6.

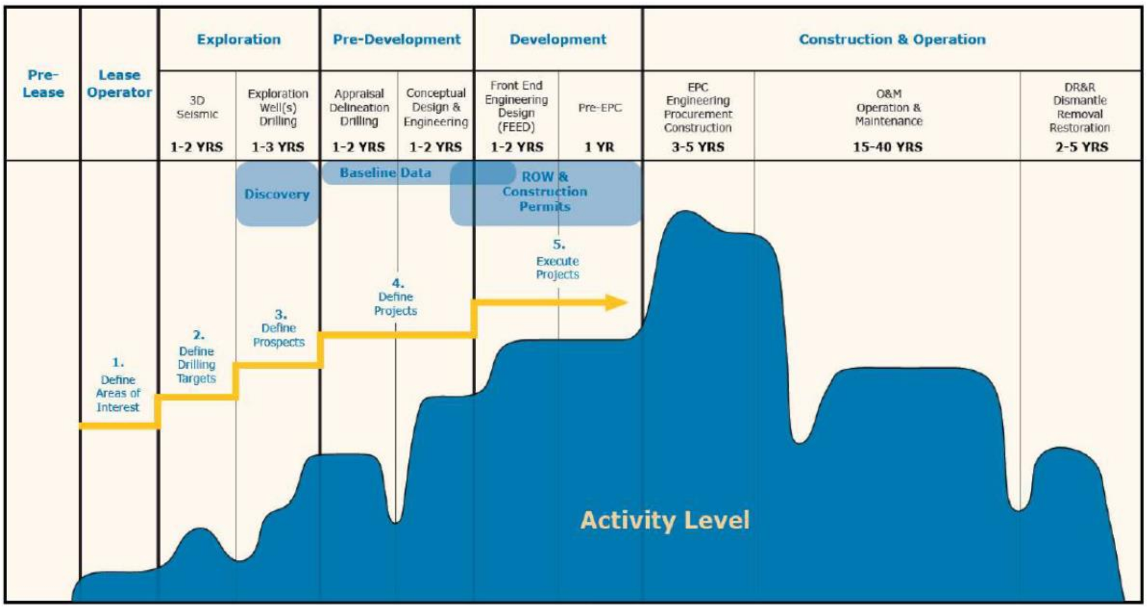


Figure 6 Overview of development life-cycle for an Arctic potential projects (Source: Report [56])

This part goes through the different problems associated with the different major steps in Exploration and Production of an Arctic installation. The idea is to give a life-cycle perspective to Arctic E&P.

In an Arctic development the largest loads inflicted will be caused by pack-ice and icebergs. In addition the cold climate and remoteness will cause problems for infrastructure, drilling, production, logistic and personnel working here.

The Barents Sea has already been identified as an area of great interest for the oil and gas industry. There is a producing field in the area and several additional discoveries. Most of the Barents Sea is classified as harsh environment and some of it where permafrost might be present as sub-Arctic environment. The Northern part and South-Eastern part in the Pechora Sea with a water depth of around 20m are covered part of the year with pack-ice, leaving the central part of the Barents Sea with about 300m water depth and harsh environment.

The Kara Sea is classified as harsh environment through the entire North-Western part, where pack-ice is present 9-10 months in a year and with a water depth of 50-500 m. The region is especially characterized by high occurrences of icebergs.

Chapter 8. Drilling operations

The discoveries in the Kara Sea have shown that the petroleum system is present in the area. As was mentioned the Kara Sea is classified as High Arctic with multi-year ice present and shallow water area with a short open water season. Figure 7 shows the ice-infested Kara Sea in 2001.

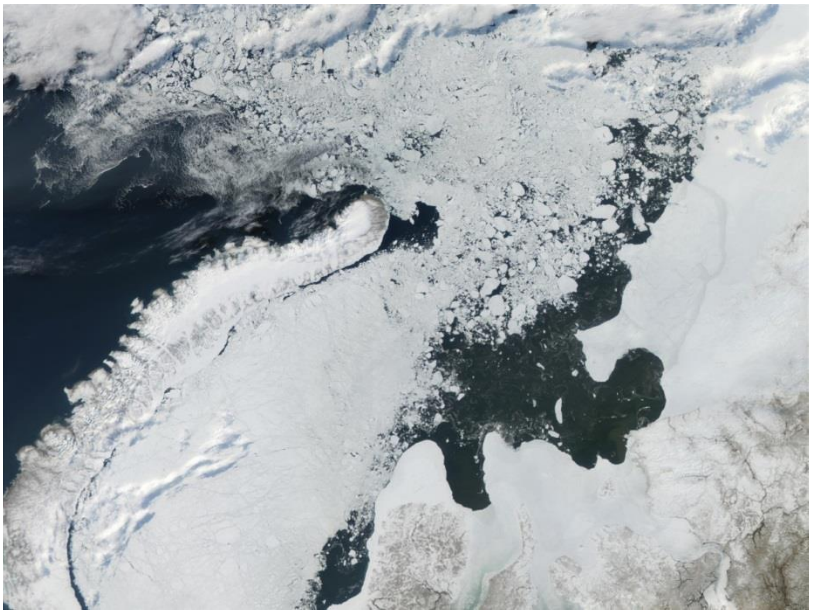


Figure 7 Novaya Zemlya and Kara Sea (Source: Unknown)

The exploration drilling activity can be implemented with utilizing a winterized semisubmersible to drill the prospect at 80-100m sea depth. The semisubmersible usual relies on open waters and that only gives a very short drilling window. But some of semisubmersible design could provide a much longer drilling season.

Others alternatives are MODUs (mobile offshore drilling units) that seem to be a better match for the area. Another part in Kara Sea with less than 50 m water depth also seems ideal for the MODUs. Ice management will be needed to support the different MODUs in the Kara Sea.

The shallow waters (up to 20m) in the Kara Sea make development with bottom-founded structures a good alternative, alternative being steel-based or gravity-based structure. The different water depths will determine which of the two are applicable to use. Since the area is quite a distance from the nearest harbor, about 5 days, ice management, logistics and planning will be a crucial part of operation and development of the fields in the Kara Sea

Open water conditions in the arctic vary a lot. This will affect how and when drilling is possible. Before drilling in an area can start, it is important to have an ice management program capable of handling the potential pack-ice and icebergs, which could inflict the area during the drilling campaign. Drilling season is affected by how much time the specific area has open waters throughout the year, and what type of drilling vessel is possible to be used in the area.

In the Southern and Central Barents Sea excluding the Pechora Sea, there is a history for year-round open waters with the possibilities for some infrequent icebergs. That gives the potential for year-round drilling operation. Drilling in the Barents Sea has been performed for several decades, but the trend is that the operation is going further north.

Pechora Sea has normally a long open water season of over 120 days. Providing a drilling window long enough for exploration wells to be drilled in one single season, this is important for the economics of a drilling operation.

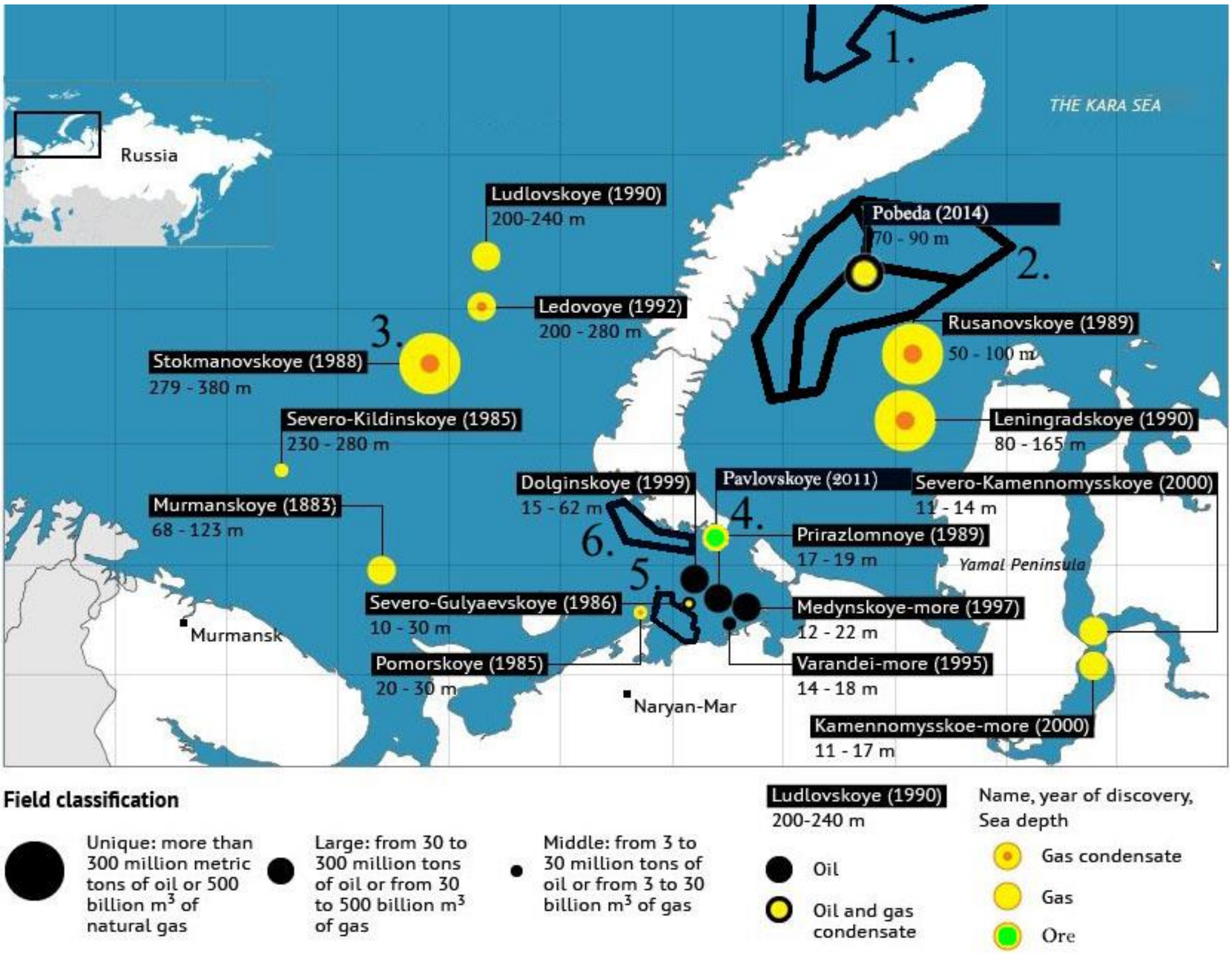
Chapter 9. Offshore field development building blocks

Due to a big amount of fields and structures in the region it is better to integrate some fields with similar parameters and owned by one company in groups that can be developed as one production unit with main and satellite fields. This will simplify installation, shorten pipeline length and implement utilization principle when small fields are also developed. The last point is very important because small fields are often found economically insufficient when developed separately.

Based on the parameters discussed above and the ownership of company the grouping was performed in the next Chapter. (Table 4 and Map 18).

Table 4 **Current license areas**

№	Name of block	Water depth, m	The recoverable reserves of hydrocarbon		Owner
1	Heysovskiy block	200-500	105 mln.t. of oil and condensate	60 bln. m3 of gas	«Gazprom Neft»
2	East Prinovozemelsky blocks	40-350	6,2 bln.t. of oil	14,6 bln. m3 of gas	«Rosneft»
3	Shtokman field	320-340	3,8 trln. m3 of gas and 53,4 mln.t. of gas condensate		«Shtokman»
4	Pavlovskoye field	On the archipelago	46 mln.t. of lead and zinc ores		«Joint-stock company»
5	Severo-Zapadniy (North West) block	200	140 mln.t. of oil and condensate	2 trln. m3 of gas	«Gazprom Neft»
6	South Russky block	11-22	13 mln.t. of oil	52 bln. m3 of gas	«Rosneft»



Map 18 Oil and gas fields of Arctic shelf (Source: SputnikNews [8])

Chapter 10. Development scenarios

In the present, it is assumed that the development of hydrocarbon resources will occur in a sequence that reflects the degree of difficulty associated with operating in a given geographical region. As shown on the Figure 8, Arctic regions may be grouped into three levels of development difficulty: moderate, high and extreme. Modern advanced technologies and engineering enable the development of projects in sub-Arctic regions such as the Sakhalin and Pechora Sea. Through these and other projects in harsh offshore environments, the oil and gas industry has gained much valuable experience.

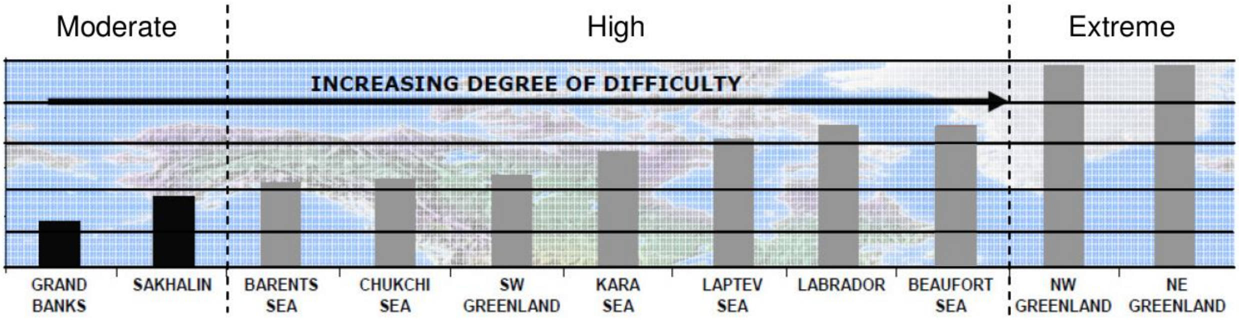


Figure 8 Relative degree of difficulty for development of different Arctic regions (Source: Report [56])

As offshore developments move farther north into more challenging environments, additional research and development will be needed to address issues that arise. Leveraging the experience gained from these existing operations in sub-Arctic regions will be essential in the development of more difficult regions.

While there are many possible combinations of different technologies that may be employed in the development of a given hydrocarbon field, the conditions outlined in the Table 5 below are meant to provide a representative sampling of the main challenges faced in a typical Arctic development project.

Details of the environmental conditions for each region and the associated development scenarios noted above are summarized below (Table 5).

Table 5 Scenario description of the seas

Scenario description				
№	**Region**	**Type**	**Structure type**	**Export method**
1	Kara Sea	Oil and Gas	Subsea	Pipeline
2	Central Barents Sea	Gas	FPSO + Subsea	Pipeline
3	North-Eastern Barents Sea	Oil	Subsea	Pipeline
4	Pechora Sea	Oil	Fixed Platform	Oil Tankers

Location’s features		Environmental conditions			
Distance to archipelago, km	**Water depth, m**	**First-year ice**	**Multi-year ice**	**Ice Ridges**	**Icebergs**
≈550	40-350	☒	☐	☒	☒
<600	200-400	☒	☐	☐	☒
<1000	50-200	☒	☒	☐	☒
≈250	10-60	☒	☐	☐	☐

Based on the high levels of offshore activity in these regions, four scenarios are considered for this region:

– oil and natural gas development on the continental slope (>100m) in Kara Sea;

– oil and natural gas development on the continental slope (>100 m) in central part of Barents Sea;

– oil and natural gas development on the continental slope (>100 m) in North-Eastern part of Barents Sea;

– on-shelf (< 100 m) oil and natural gas development in Pechora Sea.

A short analysis of the different technologies was conducted for each of these scenarios, and the main categories of technology required for these development scenarios is summarized in Table 6, Table 7, Table 8, Table 9 below.

As mentioned in Table 4 there are an active offshore oil and gas license agreements for the Kara Sea. This region is especially severe; it is characterized by high occurrence of icebergs and ice ridges and contains first-year ice.

Table 6 Categories of technology required for potential Kara Sea developments

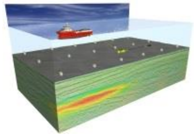
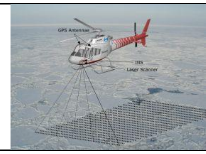
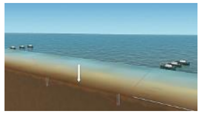
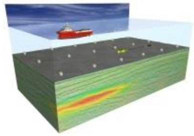
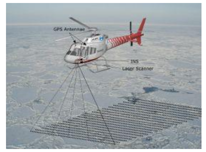
Exploration	Drilling		Development	Ice management
Geological surveys	Drillships	Semisubmersible rigs	Subsea production systems	Ice monitoring
				
2D, 3D, 4D electromagnetic and seismic surveys; geochemical, hydrogeological and other studies; topography mapping	Used in deepwater and ultra-deepwater applications up to 3000m; more greater mobility; has an arctic-class	Maximum water depth – 1500 m; good stability and dynamic positioning; used for severe Arctic conditions	Consist of manifold, well head, risers, flowlines, umbilicals, subsea communications; economically depends on water depth	Include technologies for surveillance and monitoring of environmental conditions: especially appearance of icebergs and ice ridges
Environmental protection	Transportation			Support
OSR	Offshore pipelines	Trenching	Pipe-laying ships	Vessels
				
Immediate actions to detect, contain and clean up spills in arctic environments; depends on spill category	Used to carry oil or gas to the shore; in conditions of ice gouge must be buried; requires route selection	Pipeline trenching and burial in soil, rock and permafrost due to ice gouging	Used for pipeline-laying on the seabed or below it inside a trench	Arctic/offshore patrol ship in case of emergency

Table 7 Categories of technology required for potential Central Barents Sea developments

Exploration	Drilling		Development		Ice management
Geological surveys	Drillships	Semisubmersible rigs	Subsea production systems	Floating structures	Ice monitoring
					
2D, 3D, 4D electromagnetic and seismic surveys; geochemical, hydrogeological and other studies; topography mapping	Used in deepwater and ultra-deepwater applications up to 3000m; more greater mobility; has an arctic-class	Maximum water depth – 1500 m; good stability and dynamic positioning; used for severe Arctic conditions	Consist of manifold, well head, risers, flowlines, umbilicals, subsea communications; economically depends on water depth	Includes floating production storage offloading (FPSO) vessels, floating production units (FPU), floating storage offloading (FSO)	Include technologies for surveillance and monitoring of environmental conditions: especially appearance of icebergs and ice ridges

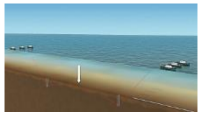
Environmental protection	Transportation		Support	
OSR	Offshore pipelines	Oil tankers	Icebreakers	Vessels
				
Immediate actions to detect, contain and clean up spills in arctic environments; depends on spill category	Used to carry oil or gas to the shore; in conditions of ice gouge must be buried; requires route selection	Ship designed for oil transport with Arctic category	Special-purpose ship or boat designed to move and navigate through ice-covered waters; sailing ships in the polar waters	Arctic/offshore patrol ship in case of emergency

Table 8 Categories of technology required for potential North-Eastern Barents Sea developments

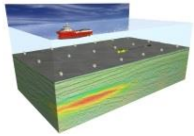
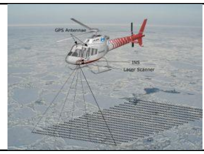
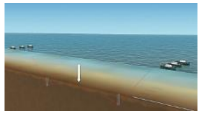
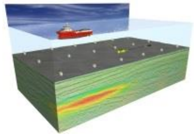
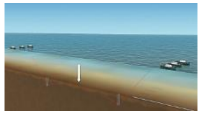
Exploration	Drilling	Development	Ice management	Environmental protection
Geological surveys	Semisubmersible rigs	Subsea production systems	Ice monitoring	OSR
				
D, 3D, 4D electromagnetic and seismic surveys; geochemical, hydrogeological and other studies; topography mapping	Maximum water depth – 1500 m; good stability and dynamic positioning; used for severe Arctic conditions	Consist of manifold, well head, risers, flowlines, umbilicals, subsea communications; economically depends on water depth	Include technologies for surveillance and monitoring of environmental conditions: especially appearance of icebergs and ice ridges	Immediate actions to detect, contain and clean up spills in arctic environments; depends on spill category
Transportation			Support	
Offshore pipelines	Trenching	Pipe-laying ships	Vessels	Icebreakers
				
Used to carry oil or gas to the shore; in conditions of ice gouge must be buried; requires route selection	Pipeline trenching and burial in soil, rock and permafrost due to ice gouging	Used for pipeline-laying on the seabed or below it inside a trench	Arctic/offshore patrol ship in case of emergency	Special-purpose ship or boat designed to move and navigate through ice-covered waters; sailing ships in the polar waters

Table 9 Categories of technology required for potential Pechora Sea developments

Exploration	Drilling		Development	
Geological surveys	Semisubmersible rigs	Jack-up drilling rigs	Gravity-based structures	Subsea production systems
				
D, 3D, 4D electromagnetic and seismic surveys; geochemical, hydrogeological and other studies; topography mapping	Maximum water depth – 1500 m; good stability and dynamic positioning; used for severe Arctic conditions	Used as exploratory drilling platforms; maximum water depth – 150m for shallow Arctic waters; self-elevating with three or four movable legs	Arctic-class ice-resistant platform; limited by water depth; able to withstand ice-loads all year round	Consist of manifold, well head, risers, flowlines, umbilicals, subsea communications; economically depends on water depth

Ice management	Transportation		Support	
Ice monitoring	Offshore pipelines	Oil tankers	Vessels	Icebreakers
				
Include technologies for surveillance and monitoring of environmental conditions: especially appearance of icebergs and ice ridges	Used to carry oil or gas to the shore; in conditions of ice gouge must be buried; requires route selection	Ship designed for oil transport with Arctic category	Arctic/offshore patrol ship in case of emergency	Special-purpose ship or boat designed to move and navigate through ice-covered waters; sailing ships in the polar waters

1) Development of the Kara Sea

The Kara Sea is characterized by severe conditions. The most effective case for drilling is to use semisubmersible rigs. The same rig Rosneft used to explore field Pobeda. For production, there is only one proper solution – to use subsea system. This system will helps to avoid danger from ice ridges and icebergs. To prevent ice gouging it will be needed to trench equipment and pipelines at places where it is required.

2) Development of central part of the Barents Sea

This part of the Barents Sea is characterized by first-year ice and occurrence of icebergs. Drilling is better to implement from mobile units like drillship or semisubmersible rig. For production, it is necessary to use subsea system with the help of floating ship. During of iceberg appearance the ship must be disconnected and dislocate to safe place. Due to high water depth preventing of ice gouging is not required.

3) Development of North-Eastern part of the Barents Sea

The second part of the Barents Sea is characterized by first-year and multi-year ice, icebergs and ice ridges. This region is rich by hydrocarbon resources but the development must be implement carefully. Mainly all drilling rigs and production systems should be used as in the Kara Sea. The blocks Albanovsky, Varneksky and West Prinovozemelsky and block Heysovskiy is not drilled yet. But the program of exploration is already created and it will start in 2020 year.

4) Development of the Pechora Sea.

Comparing to the other seas the Pechora Sea is already produced. There is a gravity-based platform that is producing oil. Whole sea is characterized not high water depth. The best solution of development for shallow waters is to use gravity-based platform. For the northern part where the water depth is more than 100 and the distance to the archipelago is about 200 km subsea production systems have to be used. There is no dangers from icebergs and ice loads in that region. Preventing of ice gouging is not required.

Chapter 11. Needs for HC transportation

In this chapter technologies relating to pipelines, tankers and oil/gas export alternatives are included.

1) Offshore pipelines include tools and technologies related to pipe-laying methodologies suitable for Arctic environments, pipeline design issues, route selection and pipelines protection strategies.

2) The main part of HC transportation is a processing facility. Similarly to the Sakhalin project it is better to build onshore processing facility on the exist infrastructure of archipelago Novaya Zemlya. This facility will receive oil and gas as well. It means gas and oil terminal are required.

3) For further transportation to the international market oil tankers and LNG carriers are needed. Oil tankers and gas export alternative technologies include tankers capable of operations in ice environments, whether having ice breaking capability or requiring icebreaker as a support. In case of transportation to the dormitory market, it is required to build a proper pipeline to the shore pipeline systems.

Table 10 Required parts of HC transportation

Transport to the market				
Onshore processing facility	LNG plant and storage tanks	Oil terminal	LNG carriers	Oil tankers
				
Receives oil and gas streams for onward transportation to the oil export terminal and LNG plant; capacity depends on received production volume	Liquefaction and purification facility; commercially viable to transport natural gas from one country to another	An industrial facility for the storage of oil transported to end users or further storage facilities.	Specially designed ships for LNG transport; tankers cost around US$200 million each	Ship designed for oil transport with Arctic category

Chapter 11.1. Oil and gas onshore terminal

At the transportation stage of Arctic development the great importance is given to seaports. In the Russian Arctic Basin and the Northern Sea Route about fifteen seaports have been built for half a century. In the Barents Sea these ports are Varandei, Murmansk, Naryan-Mar; in the Kara Sea they are Amderma, Dixon, Dudinka, Igarka. A significant development was received by the port of Arkhangelsk. The designed power included in the transport system of the country, provides the needs for the Russian North-Western and the Western sectors of the Arctic.

Ensuring of the petroleum and ore transportation requires the development of an integrated transport scheme in which all parameters and graphics operations are linked to production of fossils.

On the other hand, foreign companies show strong interest in obtaining rights and concessions to participate in development of fossils' fields, located on the South Island of New Earth and the Archipelago's shelf of the region. This creates a situation where due to the lack of an integrated transport system, economic development of the North-West is constrained. Thus, in the nearest time it necessitates to start developing transport strategies, and first of all to determine the construction site of the new port.

There is an option, which is suggested by the features of propagation of warm currents in the Barents Sea. A branch of the warm North Atlantic current, called the North Cape Current, nestles in the Barents Sea from the south-west, bathing the coast of Norway and the Kola peninsula (where the Murmansk). Then, the warm current runs parallel to the south coast, at a distance of several hundred kilometers away and "rests" in the Novaya Zemlya archipelago, and then turns to the north-east, washing the west coast of both islands of the archipelago to the 75th degree of north latitude.

The warm current could not get closer to the southern coast of the Barents Sea because of the number of outstanding barriers to the north - especially the Kanin Peninsula and the islands Kolguev and shallow areas. As a result of the winter in the Barents Sea, there is a unique ice conditions - the southern and the northern part of the area held down by ice, while in the central part of the sea goes ice-free corridor width of 400-500 kilometers, running from west to east from the coast of Norway to Novaya Zemlya.

Among of all, in the long term, Belushya Guba could become an important transport hub. Belushya Guba is called a cove in the south-eastern part of the Novaya Zemlya, on the shore of which the village of the same name is located.

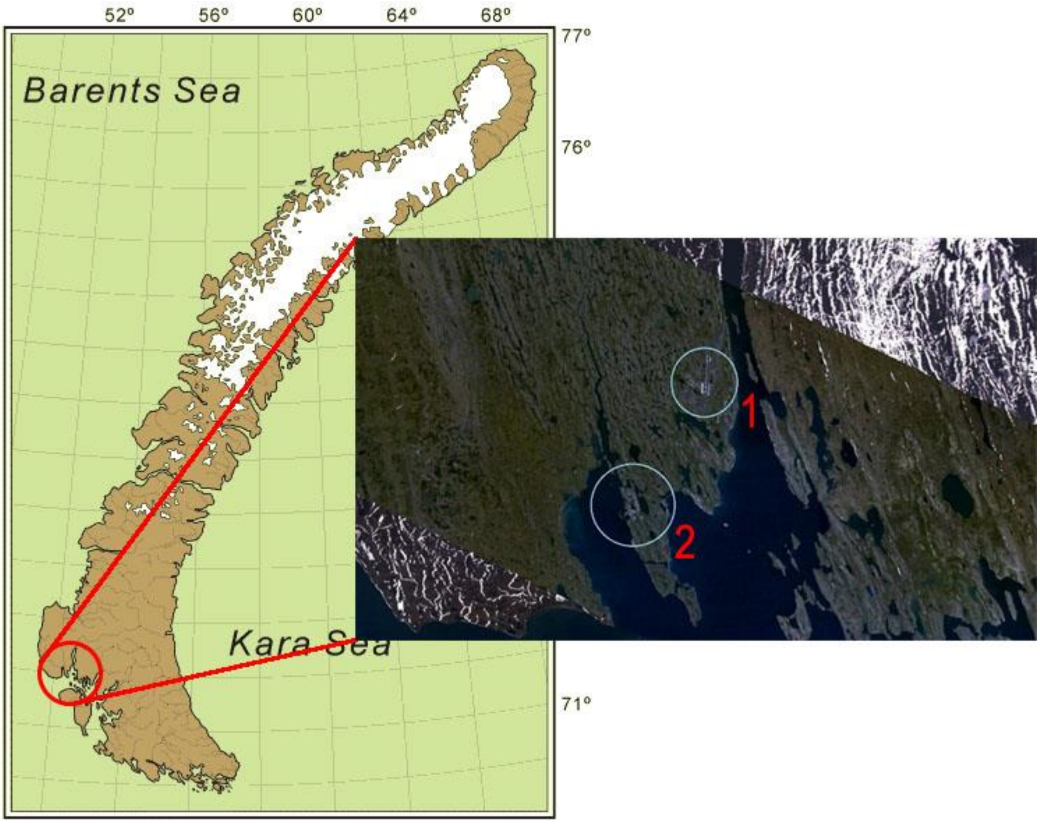
It should be the existing port Belushya Guba. (Map 19)

1) There, in the 130-150 km, is explored the rich ore-bearing deposits of base and precious of metals: manganese, lead, zinc and silver. Their total reserves are estimated at 3 billion tonnes.

2) On the shelf of the Barents and Kara Seas in a radius of 250-300 km from the bay Belushya Guba, a huge amounts of oil, condensate and gas deposits were revealed, total reserves of them exceed 30 billion tons of fuel equivalent, including - 1,5 billion tons of oil, 250 million tons of condensate and more than 15 trillion m3 of gas.

All these create a solid base for the power supply of the mining and petrochemical industries.

There is project, proposed by some authors [64] [63] [59] to build a major oil port, based on the shipment of oil from Western Siberia, Timan-Pechora and offshore, as well as the creation of the production of liquefied natural gas from fields on the Yamal Peninsula. Construction of the oil and gas port on the base of existed infrastructure at the Belushya Guba will reduce costs for long-distance exports of hydrocarbons to the international market, compared with transportation through pipelines.



Map 19 Location of the Belushya Guba (Source: Wikipedia, KolaTravel)

Where 1 – Rogachevo air base.

2 – Belushya Guba bay.

That is why the optimal location for the construction of a new port is the bay Belushya Guba. The advantage of this variant is in the successful geographical position in relation to the Northern Sea Route, favorable natural conditions, proximity to deposits of ores and hydrocarbons. Located in the zone of influence of the warm current, natural environment will ensure here a year-round swimming of all types and classes of vessels with a minimum of icebreaker escort. In the most severe winters band of fast ice is less than 1 km and the thickness of the ice is up to 1 m. The bay is well protected from the unrest and penetration of drifting ice. The depth at the inlet into bay is 30-50 m and in the bay area is 10-30 m.

Now there is already a port with two cargo and four extra berths. There are well-maintained village with the necessary infrastructure. Belushya Guba is also located near to Rogachevo airport capable of receiving the heaviest aircraft (runway length - 2500 meters), and some infrastructure facilities created to serve the "Object 700" - the nuclear test site. There is stone and sand surface, and in south-eastern and northern parts there is a large undeveloped area. All that makes it possible to handle construction in a certain order.

There can be built powers for handling bulk cargoes, mechanized complex for loading ore, container terminal for the supply and transit of goods, bunkering and accumulative distribution base for the supply of goods and the center of icebreaking.

Construction of multi-aim mechanized port in the bay Belushya Guba, in the center of and the absorption of cargo flows, will significantly allow to:

- reduce transport costs and faster return on capital investments;
- ensure good conditions for investment in the integrated development of large deposits;
- provide large-scale financial flows in the Russian economy and a good environment for the development of industry and the social sector of the North-West;
- attract new cargo flows to load the northern and Arctic ports.

Chapter 11.2. Features of the terminal

About 20-30 years ago, floating ice of 100-150 km wide has been formed along the west coast, but global warming has led to a reduction in ice area and recent years ships can float to the Novaya Zemlya almost freely.

Global warming makes it appropriate to consider the possibility of building on the Novaya Zemlya Archipelago Sea Port, LNG production and export center, and further pipeline Yamal – Novaya Zemlya.

For the terminal construction the main key parameters are as follows:

1. The distance from the fields to the port (pipelines).
2. Ice conditions in the waters surrounding the port.
3. The depth of the waters, allowing the use of large vessels.
4. The development of the territory, which affects the cost of construction.

On the archipelago Novaya Zemlya there is an extremely important advantage. From the first sight to the map it is sufficient to estimate the location of the Novaya Zemlya as a central base between the all fields. Creating a port here and the reference point of new development will greatly simplify implementation of future projects on the shelf of the Barents and Kara Seas.

Another advantage was hold at the beginning of 21st century, two authors carried out an economic assessment of that supposed terminal. The results of their analysis is shown below in the Table 11. [59]

Table 11 Results of economic assessment [59]

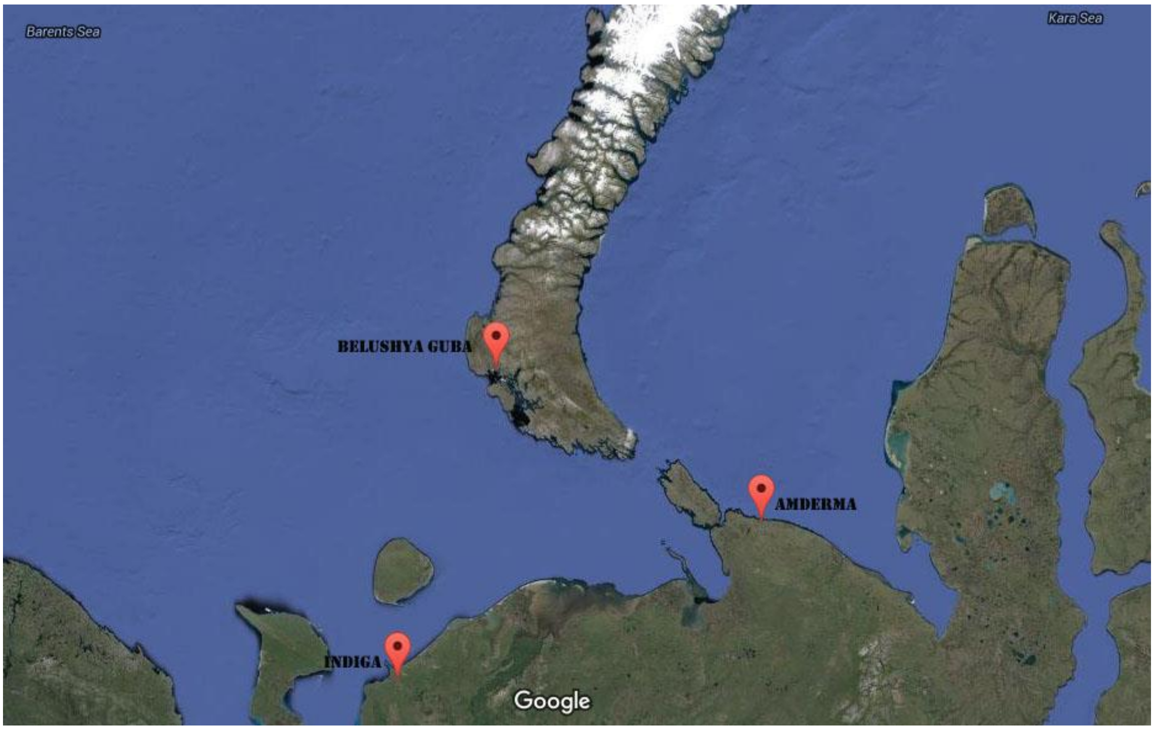
№	Parameter	Value
1	Influence of ice conditions on the route to the tariff for maritime transport	marginally
2	The unit cost of LNG per thousand cubic meters, mln. $	1.1-1.2
3	The gas rate, $ per thousand cubic meters (including delivery)	25
4	The tariff for maritime transport in the UK, $ per thousand cubic meters. (calculation for vessels with a capacity of 200 thousand cubic meters)	8
5	The tariff for maritime transport to the US East coast, $ per thousand cubic meters. (calculation for vessels with a capacity of 200 thousand cubic meters)	16
6	Liquefaction cost, 40 $ per thousand cubic meters (In terms of reduction of costs in the region with cold climate) and regasification of 12 $ per thousand cubic meters	52
7	To the US East coast, $ per thousand cubic meters (excluding export duties)	93
8	To the Kingdom, $ per thousand cubic meters (excluding export duties)	85

At the end, the results of their calculation were "The minimum rates for transportation is achieved by a combination of pipelines (pipelines bypassing ice-covered areas of the Kara and Barents Seas) and transport of LNG and oil with a minimum ice strengthening." [59]

Yet in 2010 year, news was announced that Russia plans to build railways to two northern settlements that can be used as bases for traffic along the Northern Sea Route from Europe to Asia. Russian Railways has included railways to Indiga and Amderma (Map 20) in its development plans for the period to 2030. [2]

As reported by BarentsObserver, the Russian Railways in its development plan for the period until year 2030. Several companies see Amderma as the best suited base alternative for the offshore oil and gas activities in the region. The town has existing infrastructure, housing and an airport capable of handling big-size aircrafts. [2]

That will help much to the terminal construction, especially in the supply of equipment.



Map 20 Planned railway to two northern settlements (Source: GoogleMaps)

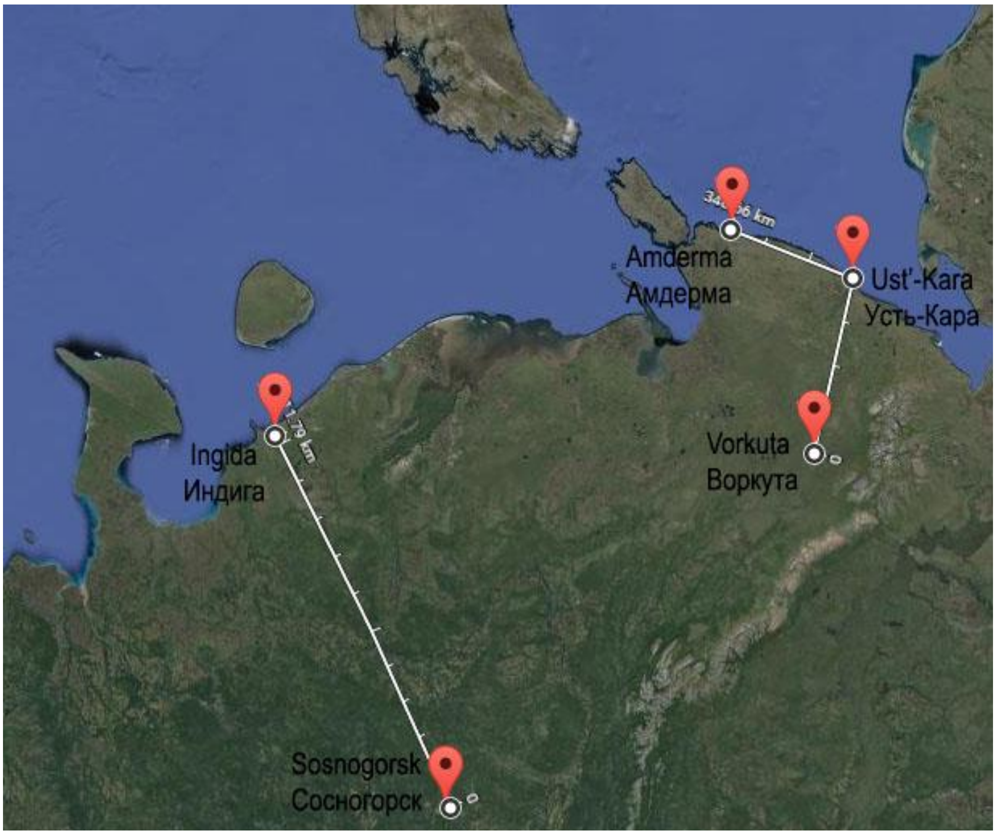
Distances from these two ports to the Belushya Guba are shown in the Table 12:

Table 12 The distances between villages and Belushya Guba

Amderma – Belushya Guba	390 km
Indiga – Belushya Guba	419 km

The company already considers a possibility of the construction of railway lines Vorkuta-Amderma through Ust-Kara and Sosnogorsk-Indigo in the Nenets Autonomous Okrug. (Map 21)

According to announcements, the branch Vorkuta-Amderma through Ust-Kara is promising due to the activation of navigation on the Northern Sea Route and the development of new deposits on the shelf of the Pechora and Kara Seas. The branch Sosnogorsk-Indigo is necessary for the development of gas condensate fields in the area.

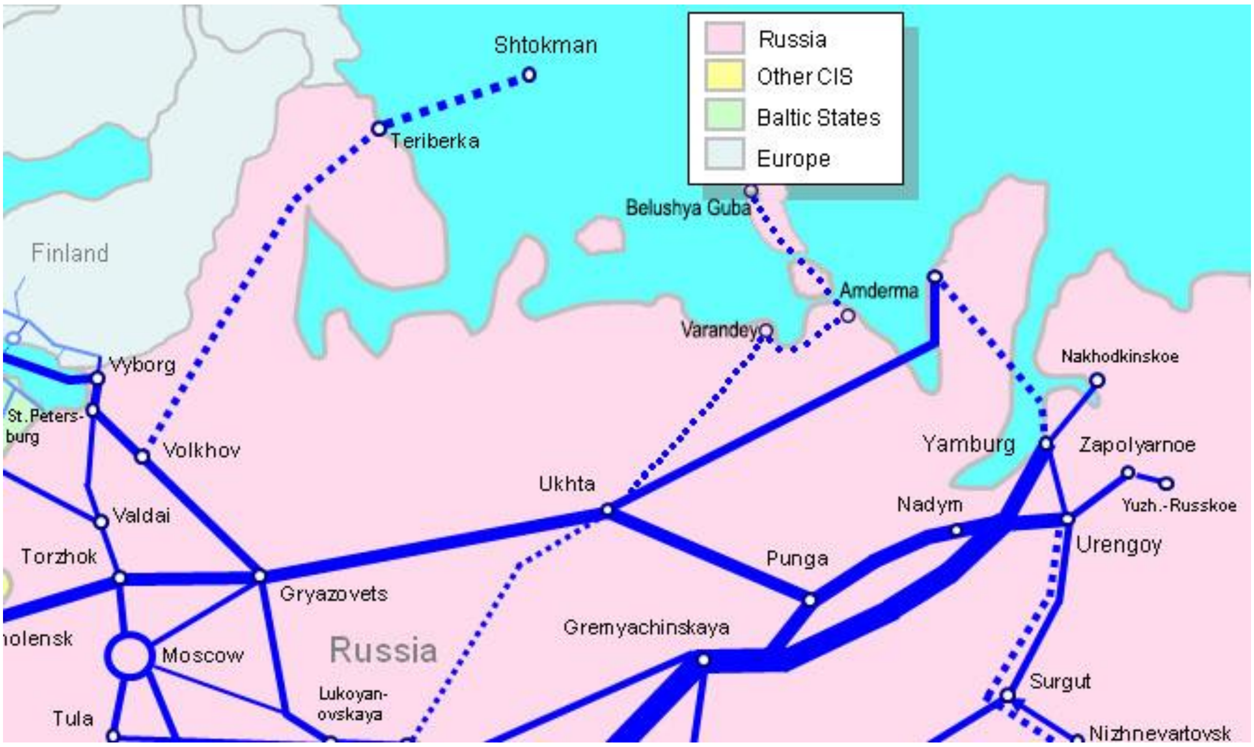


Map 21 Planned railway lines (Source: GoogleMaps)

Chapter 11.3. Transport schemes to the markets

Perspective domestic supply routes for transportation of hydrocarbons (Map 22):

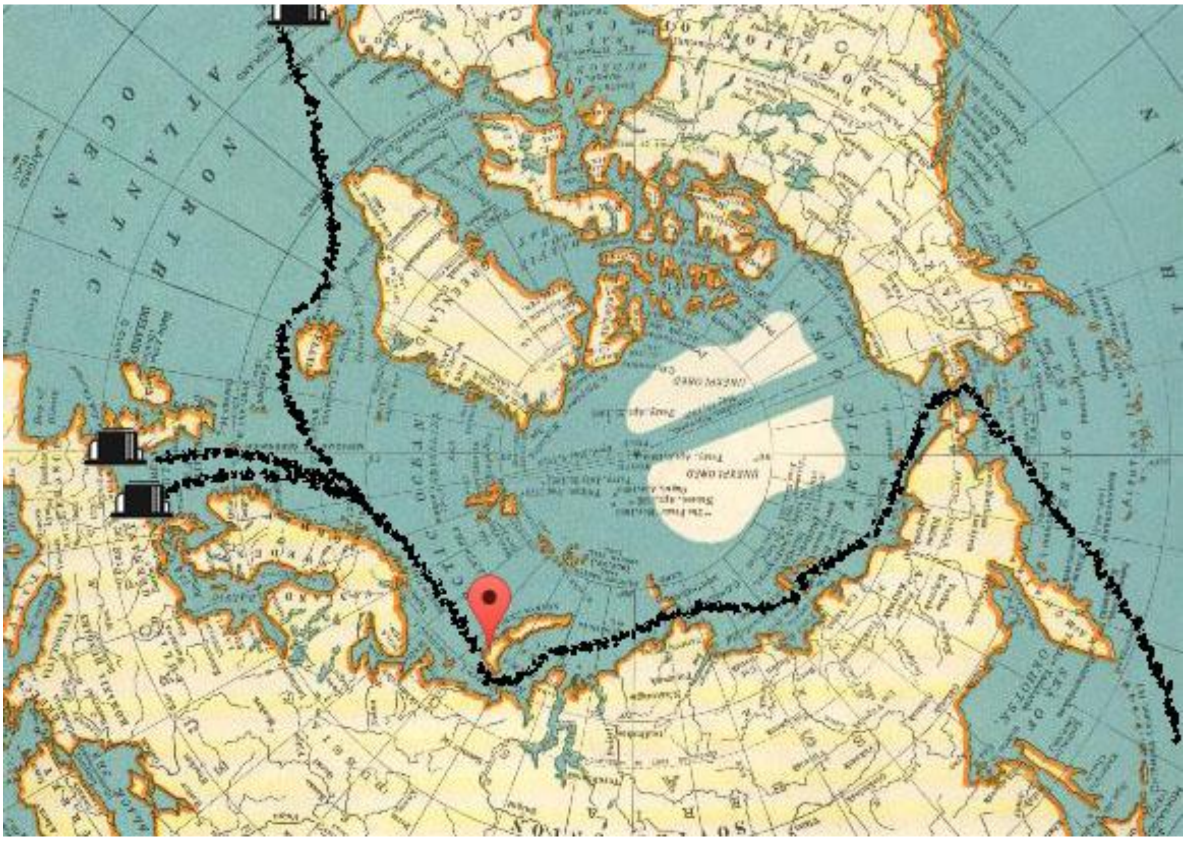
Delivery of petroleum to the domestic market pipeline will require the construction of new pipelines, for example, Varandey - Amderma - Belushya Guba (600 km) and further connection to Yamal line in Ukhta, but allows to expand the geography of supplies.



Map 22 Project pipeline to the Belushya Guba (Source: EEGAS [12])

Perspective international supply routes for transportation of LNG and oil products (Map 23):

1. Rotterdam (Netherlands) – Nowadays this port receives an oil from the Prirazlomnoye field. Moreover, in the port of Rotterdam, import and export of LNG for use in Europe takes place on a large scale.
2. Isle of Grain (United Kingdom) - Grain LNG is a national LNG facility at the Isle of Grain, near London in Kent.
3. St. John's port (Canada) – Today, Saint John Port is an important industrial center for Canada. In the 20th Century there was built a huge industrial development in the city that processed oil, forest products, and ships. Canaport LNG Situated in Saint John is the first liquefied natural gas (LNG) receiving and regasification terminal.
4. Yokohama (Japan) – Because of huge LNG receiving terminals Japan is perspective supply route.
5. Qingdao (China) – There is an agreement with the Yamal LNG to deliver gas to China. For that case, China's company has started up its first LNG terminal in Qingdao.



Map 23 Russian perspective gas and oil supply routes (Source: Arctic circle region)

As a result, the construction of the seaport at the Novaya Zemlya Archipelago has the following advantages:

1. Reduction of the length of pipeline from the fields to the port of shipment;

2. Access to a very promising global LNG market;

3. The exceptional flexibility of supply – transportation of LNG to almost any part of the world;

4. Exclusion of transit through the territory of foreign states;

5. Creation a framework for the development of the Shtokman and other offshore fields.

Supply route to the Asian market goes through the Northern Sea Route that passes through the Barents Sea, the Kara Sea, the Laptev Sea, the East Siberian Sea and the Sea of Chukotsk to the Bering Strait. The most important users of the route are the Russian companies Norilsk Nickel, Gazprom, Lukoil, Rosneft and Rosshelf.

Northern Sea Route normally navigable without icebreakers for two to four months each year.

Chapter 12. Oil spills in the arctic region

The oil spills can be happened in different cases. The results will be different from the small leakage to the big loss of oil during blowout. These big accidents are

- Uncontrolled blow-out of oil;
- Damage to the oil storage tank;
- Damage to the oil or gas tanker during the transportation

Such events are rare and the occurrence of such accidents during the project lifetime is unlikely. However, amongst of all, there are accidents that are most likely to happen:

- Oil and gas leaks during drilling;

Basically “zero discharge” principle is used to preventing small oil spills and leaks. Such example is the Prirazlomnaya offshore platform that located in the Arctic region. Platform’s drainage systems ensure collection of all oil-containing water, polluted rainwater and snow for further treatment and injection. [49]

- Leakage on wellhead equipment;

To prevent oil spills during drilling operation blowout preventors with equipped saety and hydraulic valves are used.

According to the Decree of the Government of Russian Federation, safety zone around an offshore hydro technical structure is 500 meters. All accidents are divided on three tier’s programs. They are usually accepted in OSR Plan [49]:

- Tier 1: spill volume below 500 t. Response operations will be carried out using company’s means and forces;
- Tier 2: spill volume between 500 and 5000 t.. If unable to respond to the spill using company’s own means, engaging outside regional forces and means;
- Tier 3: spill volume over 5000 t. Such spill would be considered catastrophic and would require resources on a national level.

After cleaning up a large oil spill, a lot of time is spent on damage assessment and compensations to the parties involved, or those affected by the spill. (Figure 9)

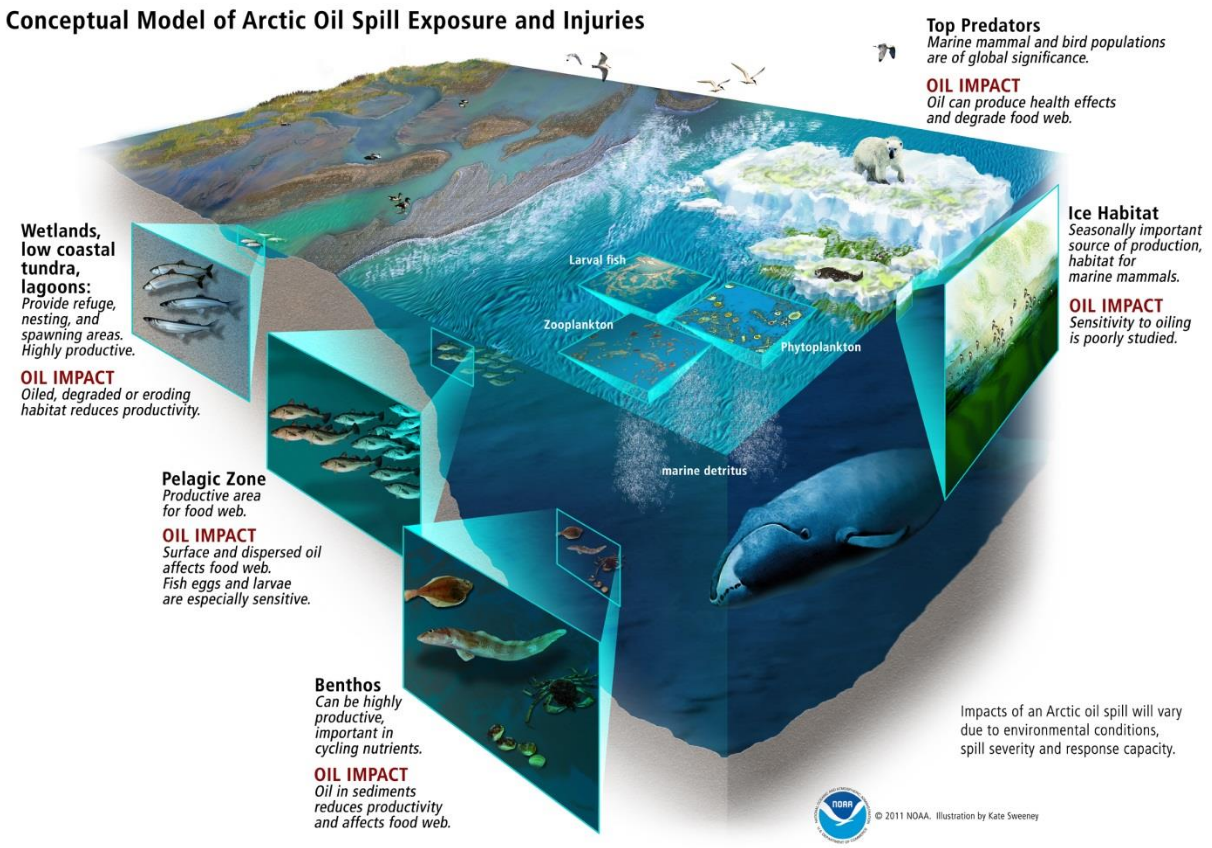


Figure 9 Conceptual model of Arctic oil spill exposure and injuries (Source: NOAA [3])

To make conclusions all we need is to pay an attention on BP's catastrophe in the Gulf of Mexico. Realizing the consequences, we will understand how challenging Arctic development could be. The oil industry cannot guarantee yet the safety of Arctic development.

PIPELINE ROUTE SELECTION

PART 4

For the Barents-Kara region selection of pipeline route is a challenge that has to be considered from the modern point of view. Such uncertainties as weather condition, seabed relief, soil structure and mechanical properties can affect pipeline route.

The solution offers significant benefits that will help to avoid accident not only during the construction but also during the development. (Figure 10)

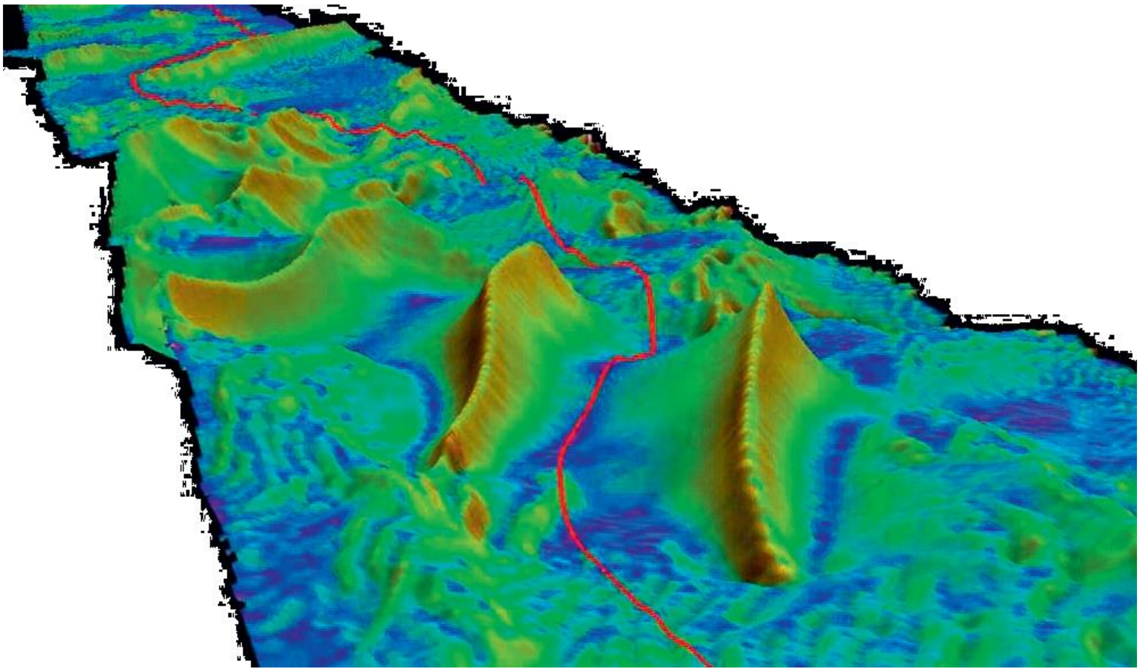


Figure 10 Software for accurate modeling of subsea environments (Source: Wood Group Renewables)

Chapter 13. Data requirement

The typical key data required for pipeline route selection (Figure 11):

- Maps;
- Satellite integrity;
- Air photos;
- High quality digital imagery of the terrain;
- Topographic map;
- Geotechnical survey.

Figure 11 is a simplified representation of how data is combined.

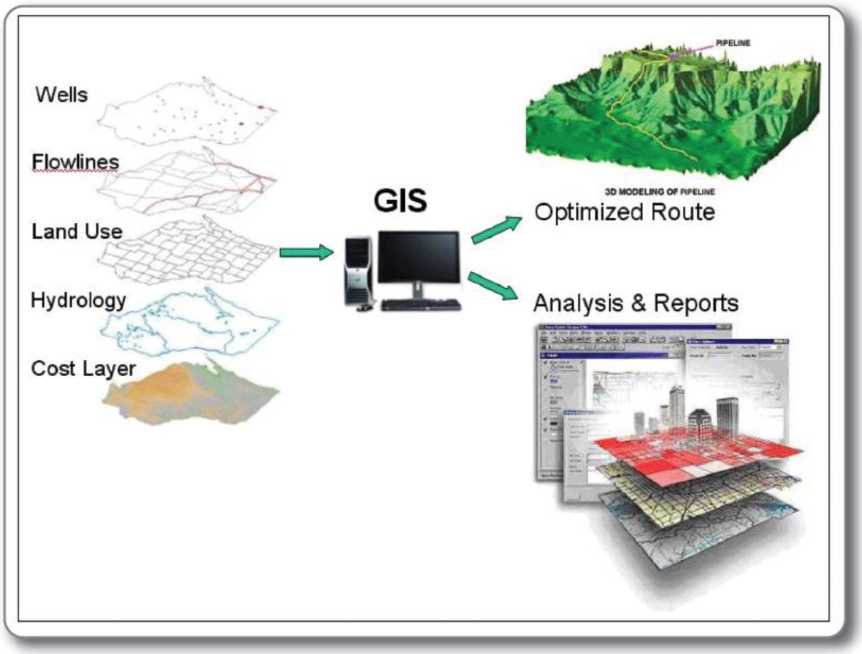


Figure 11 Process to optimize pipeline route (Source: An IPLOCA document [39])

Geographic Information Systems are scientific and technological tools that enable the integration of data from different sources into a centralized database from which the data is modelled and analyze. GIS-based tools and processes have been extensively used to address the challenges of optimizing pipeline route selection and route networks based on the collection, processing and analysis of spatial data. [39]

Traditional manual pipeline routing uses data, such as field's locations, seabed topography, environmental conditions, wildlife presence, seabed conditions, infrastructure features, map of private territories and of nature reserves. (Table 13)

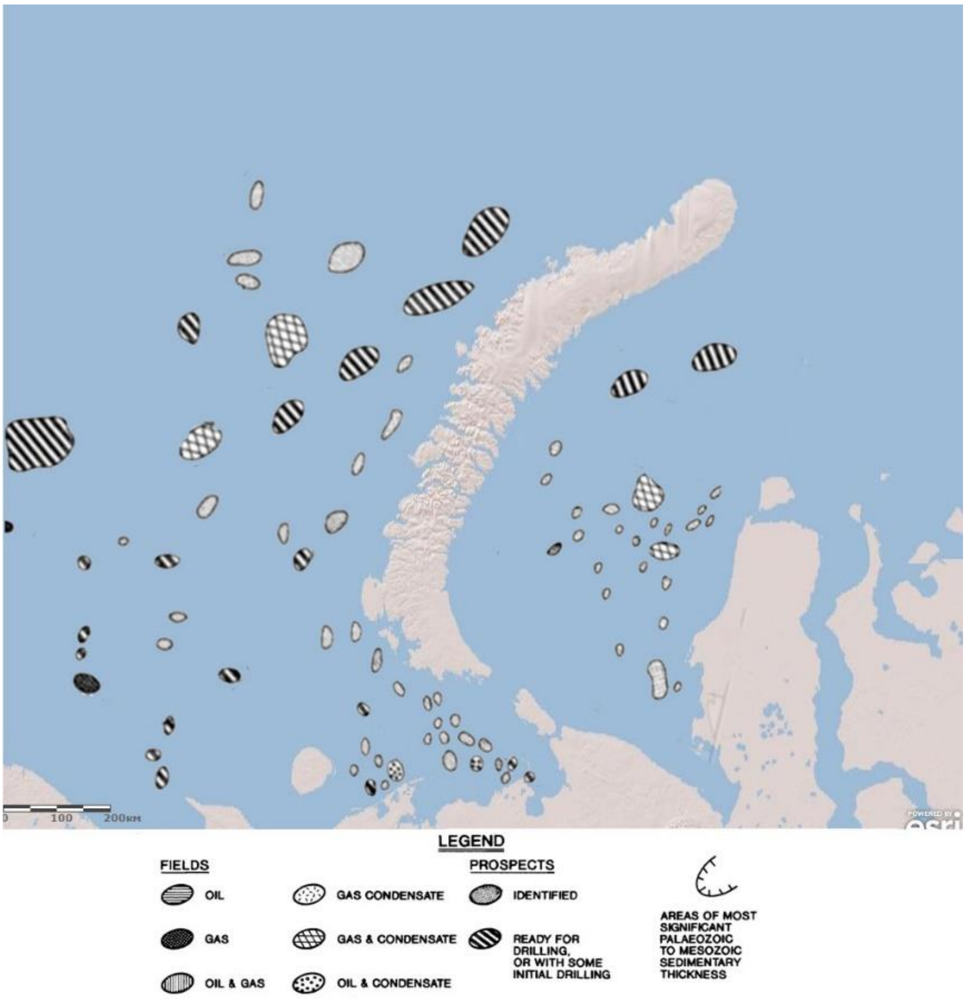
Table 13 Rules for the key data

Factor / Feature	Rule
Field's location	• Avoid unprofitable fields and satellites
Seabed topography	• Avoid steep slopes • Use flat terrain where possible
Environmental conditions	• Avoid place of icebergs and ice ridges appearance • Avoid high wave and wind conditions
Wildlife presence Nature reserves	• Avoid habitats of animals • Avoid highly-sensitive areas
Seabed conditions	• Avoid surface/sub-surface rock • Stable soils are important

Chapter 14. Use of ArcGIS™ software for the evaluation of optimal pipeline route

The objective of this chapter is to determine the least cost path from the chosen field to the central point. The least cost path is the product of the GIS analysis. It represents the path of least resistance from the origin point to the destination.

1) The first step of calculation is to define a base required for pipeline evaluation. This base is all maps and pictures that limit a pipeline routing. For example of evaluation I will choose 2 fields: from the Barents Sea it is Shtokmanovskoye field; from the Kara Sea it is Pobeda field. (Map 24)



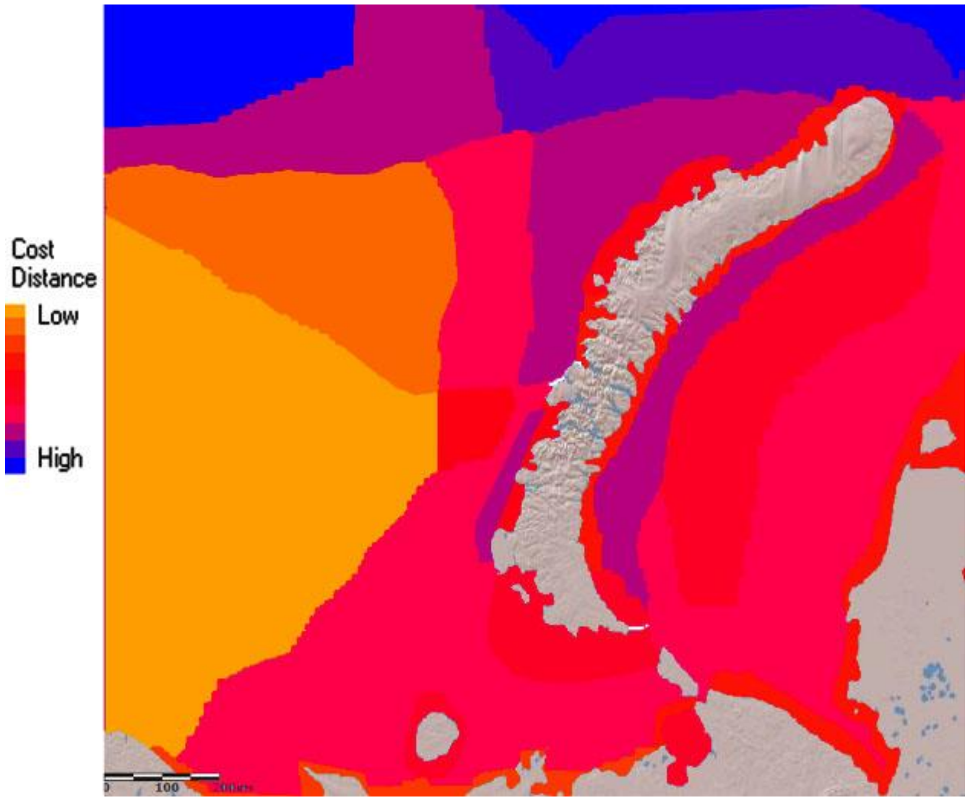
Map 24 Required map of all oil and gas fields and structures

2) The second step of calculation is to create a discrete cost map. It shows all cells from the cheapest to most expensive. (Map 25)

Satellite images, maps, photos, existing GIS data, traditional geotechnical and topographical surveys are all sources of data that should be gathered and incorporated into the project GIS.

The most valuable sources of data are

- Topography map of the seas;
- Wind map
- Current map
- Wave map
- Ice concentration map
- Map of iceberg frequency
- Map of ice gouging

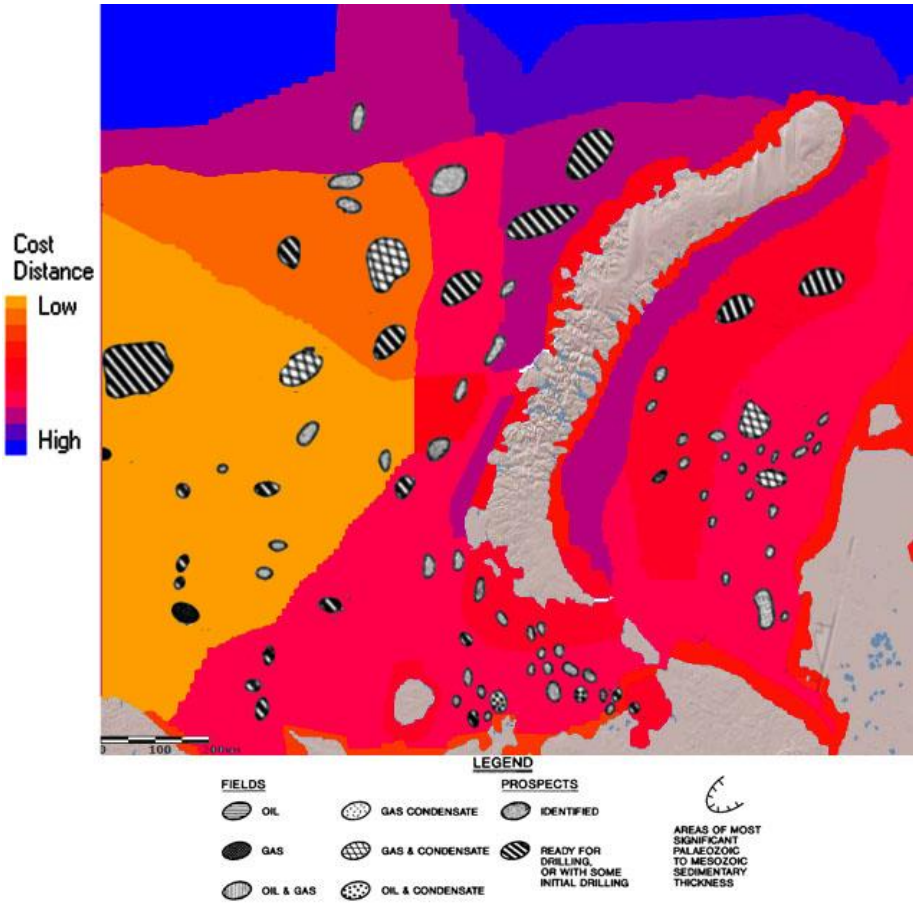


Map 25 Discrete cost map (from the cheapest to most expensive 0-10)

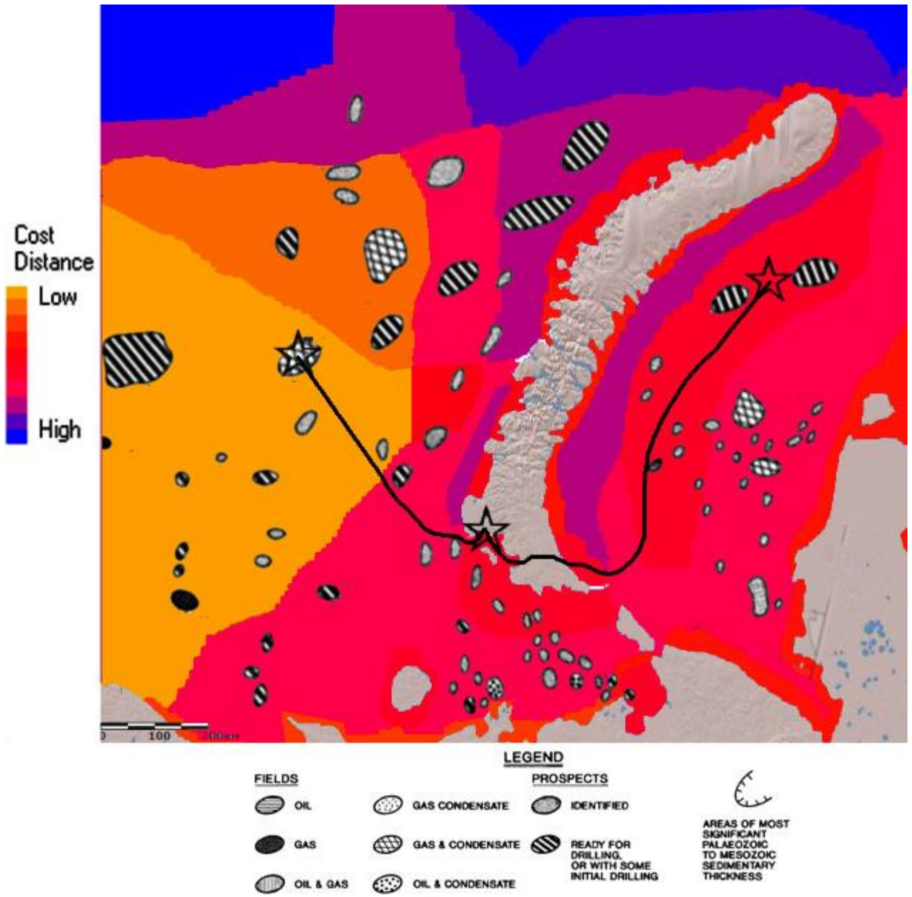
3) The third step is to carry out the cost distance analysis that will show optimal pipeline route. When the discrete cost map is already determined, the initial route is modified to provide the optimum route through the area. (Map 26, Map 27)

At the end, we can find the route between any two points A and B. Optimization criterion for optimal route is a minimum cumulative sum of cells through whole discrete cost map.

This cumulative sum is calculated by modified algorithm that utilizes the node/link cell representation used in graph theory.



Map 26 Surface of accumulated cost projected on the map of fields and structures



Map 27 Surface of cost distance between fields and center

Finally, we receive a data of distance of optimal pipeline routing. That method of evaluation is used for onshore pipeline route as well.

Comparing to direct distance received data is much higher. However, the risks is minimal. (Table 14)

Table 14 Difference in direct/cost distances from the fields to the central point

Field	Direct distance	Cost distance
Pobeda	550	800
Shtokmanovskoye	300	370

ECONOMICAL ASPECTS OF THE PROJECT

PART 5

To sum up all data received I have carried out short economic analysis that will define advantages of the project.

The feasibilities of construction of infrastructure based on the Belushya Guba bay:

1. Impact of the construction of subsea production systems for field development - **small**, compared with the construction of large offshore structures.

2. The impact of cooperation with other companies in the process of construction of the technological complex - **high**, reducing capital and operating costs.

3. Impact of the use of the bay lots of tankers, transports - **significant,** the width of the bay allows to expand the number of berths; frequent movement of vessels will reduce the formation of fast ice.

The feasibility of using tankers for the transport of:

1. Effect of ice on transportation costs - **minimal**, the only serious problem is the band of fast ice, whose thickness can be up to 1 m, but the width is less than 1 km. The presence of the port and the active movement of vessels - a reliable means of combating the formation of stable ice cover.

2. Effect of auxiliary vessels, icebreakers on transportation costs - **small**, for the problem with fast ice tankers enough to have ice strengthening category Arc4. (Appendix A, Table 15)

3. Influence of the terminal placed on the mooring facilities – **minimal**, possible to use standard shipping and berthing facilities, designed to operate in ice.

CONCLUSIONS

PART 6

In conclusion, the best solution is complex development from Archipelago Novaya Zemlya. The project offers a new concept that proposes to use the Novaya Zemlya archipelago as a central base for development of the whole regions. That might improve economics of field development due to less overall investments in common infrastructure.

Starting with a comparison of sea-state parameters and metocean conditions of the Barents and Kara Seas, the thesis discussed the challenges for the development of potential hydrocarbon fields in the Barents Sea Area. Such challenges are based on observations and features that were made in the project. These special features are as follows:

- Sea ice, icebergs, icing and wind chill are new elements that may increase both frequency of accidents and the consequences thereof. Data on ice and iceberg are insufficient.
- Ice cover, icebergs and short ice-free period in the western Kara Sea limits technical solutions and development schemes that can be applied here.
- Large annual variations in temperature relative to ice coverage.
- Less reliable weather-, ice- and iceberg forecasts combined with small scale, very local atmospheric phenomena.
- An uneven seabed, which makes building of infrastructure harder.
- One of the largest concentrations of sea birds in the world.
- Management of living marine resources in the Barents-Kara region.

In the next step, based on the high levels of offshore activity in these regions, four scenarios were considered for this region:

– oil and natural gas development on the continental slope (>100m) in Kara Sea;

– oil and natural gas development on the continental slope (>100 m) in central part of Barents Sea;

– oil and natural gas development on the continental slope (>100 m) in North-Eastern part of Barents Sea;

– on-shelf (< 100 m) oil and natural gas development in Pechora Sea.

A short analysis of the different technologies was conducted for each of these scenarios, and the main categories of technology required for these development scenarios were summarized.

Finally, using all data received the evaluation of optimal pipeline routing was conducted. The special program ArcGIS helped to economically build a cost distance. By the way, the program is also used for onshore route building as well.

Finally, construction of port in the bay Belushya Guba, in the center of cargo flows, will significantly allow to:

- reduce transport costs and faster return on capital investments;
- ensure good conditions for investment in the integrated development of large deposits;
- provide large-scale financial flows in the Russian economy and a good environment for the development of industry and the social sector of the North-West;
- attract new cargo flows to load the northern and Arctic ports.

Use of all of these techniques and challenges allow to:

• Reduce the high capital and operating costs of large offshore structures.

• Dramatically reduce the environmental impact on the marine and coastal areas.

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APPENDIXES

Appendix A

Table 15 Classification of vessels in the Russian maritime register of shipping [22]

The first four means a group of icebreakers.

Rules of 2005 y.	New rules	Description
LL9	Icebreaker 9	Icebreaker category notation (intended for icebreaking operations: in the arctic seas in winter and spring with ice up to 4,0 m thick and in summer and autumn with no restrictions, and capable of forcing the way continuously running in compact ice field up to 2,5 m thick. The total shaft power is not less than 48 mW)
LL8	Icebreaker 8	Icebreaker category notation (intended for icebreaking operations: on coastal routes of the arctic seas in winter and spring with ice up to 3,0 m thick and in summer and autumn with no restrictions, and capable of forcing the way continuously running in compact ice field up to 2,0 m thick. The total shaft power is not less than 22 mW)
LL7	Icebreaker 7	Icebreaker category notation (intended for icebreaking operations: on coastal routes of the arctic seas in winter and spring with ice up to 2,0 m thick and 2,5 m thick in summer and autumn; in the non-arctic freezing seas and mouths of rivers flowing into the arctic seas with ice up to 2,0 m thick, and capable of forcing the way continuously running in compact ice field up to 1,5 m thick. The total shaft power is not less than 11 mW)
LL6	Icebreaker 6	Icebreaker category notation (intended for icebreaking operations in harbour and roadstead water areas as well as in the non-arctic freezing seas with ice up to 1,5 m thick, and capable of forcing the way continuously running in compact ice field up to 1,0 m thick)

The next group was created from the Arctic categories that applies to vessel intended for sailing in the Arctic Seas (Arctic vessels).

Rules of 2005 y.	New rules	Description
LU9	Arc 9	Ice strengthening notation of the ship (independent navigation in young open arctic ice up to 0,6 m thick in winter and spring, and up to 0,8 m thick in summer and autumn. Navigation in a navigable passage astern an icebreaker in young arctic ice up to 0,7 m thick in winter and spring, and up to 1,0 m thick in summer and autumn)
LU8	Arc 8	Ice strengthening notation of the ship (independent navigation in young open arctic ice up to 0,6 m thick in winter and spring, and up to 0,8 m thick in summer and autumn. Navigation in a navigable passage astern an icebreaker in young arctic ice up to 0,7 m thick in winter and spring, and up to 1,0 m thick in summer and autumn)
LU7	Arc 7	Ice strengthening notation of the ship (independent navigation in young open arctic ice up to 0,6 m thick in winter and spring, and up

		to 0,8 m thick in summer and autumn. Navigation in a navigable passage astern an icebreaker in young arctic ice up to 0,7 m thick in winter and spring, and up to 1,0 m thick in summer and autumn)
LU6	Arc 6	Ice strengthening notation of the ship (independent navigation in young open arctic ice up to 0,6 m thick in winter and spring, and up to 0,8 m thick in summer and autumn. Navigation in a navigable passage astern an icebreaker in young arctic ice up to 0,7 m thick in winter and spring, and up to 1,0 m thick in summer and autumn)
LU5	Arc 5	Ice strengthening notation of the ship (independent navigation in young open arctic ice up to 0,6 m thick in winter and spring, and up to 0,8 m thick in summer and autumn. Navigation in a navigable passage astern an icebreaker in young arctic ice up to 0,7 m thick in winter and spring, and up to 1,0 m thick in summer and autumn)
LU4	Arc 4	Ice strengthening notation of the ship (independent navigation in young open arctic ice up to 0,6 m thick in winter and spring, and up to 0,8 m thick in summer and autumn. Navigation in a navigable passage astern an icebreaker in young arctic ice up to 0,7 m thick in winter and spring, and up to 1,0 m thick in summer and autumn)

The last one is non-Arctic vessels (Ice 1 – 3) applies to vessel intended for sailing in freezing Arctic Seas.

Appendix B

Besides the most popular oil and gas fields the Barents-Kara region has a huge amount of unexplored and undrilled yet fields.

Table 16 Field discoveries of the Barents Sea

Field name	Petroleum type	Location	Discovered	Water depth
Murmanskoye	Gas	Southern	1983	68-123
Severo-Klidinskoye	Gas	South-Western	1985	230-280
Pomorskoye	Gas condensate	Pechora Sea	1985	20-30
Severo-Gulyaevskoye	Oil and gas condensate	Pechora Sea	1986	10-30
Shtokmanovskoye	Gas condensate	Central	1988	279-380
Prirazlomnoye	Oil	Pechora Sea	1989	17-19
Ludlovskoye	Gas	Central	1990	200-240
Ledovoye	Gas condensate	North-Eastern	1992	200-280
Varandey-more	Oil	Pechora Sea	1995	14-18
Medynskoye	Oil	Pechora Sea	1997	12-22
Dolginskoye	Oil	Pechora Sea	1999	15-62

Table 17 Field discoveries of the Kara Sea

Field name	Petroleum type	Location	Discovered	Water depth
Rusanovskoye	Gas condensate	South-Western	1989	50-100
Leningradskoye	Gas condensate	South-Western	1990	80-165
Pobeda	Oil and gas condensate	Central	2014	70-90

Appendix C

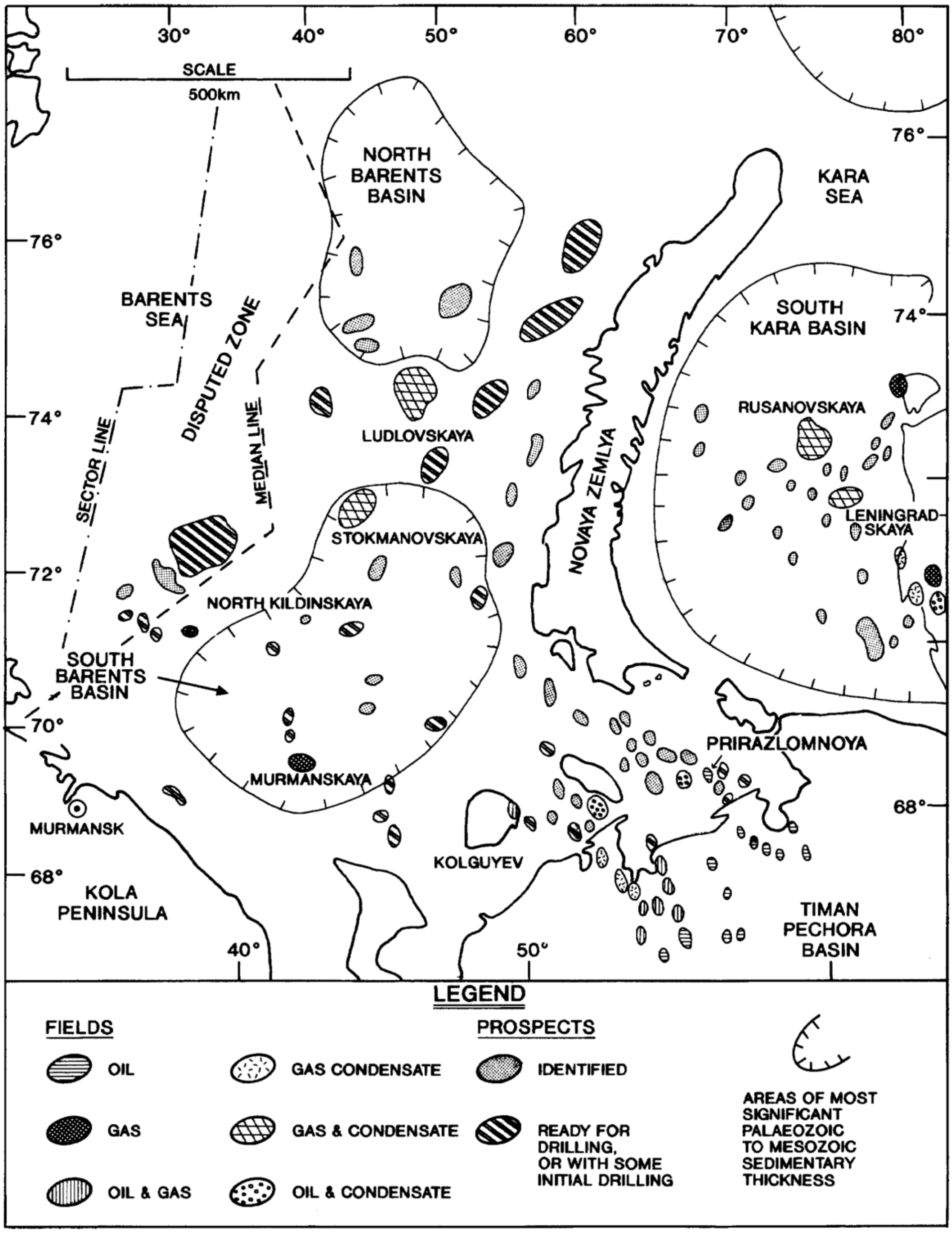

Figure 12 All exist structures and fields in the Barents-Kara region (Source: unknown)

Appendix D

All calculations of ice gouging depth for the Kara Sea are implemented in this appendix [31].

Table 18 Environmental data

Parameter	Unit	Value
Water density	$\rho_w, \frac{kg}{m3}$	1050
Current speed	$u_c, \frac{m}{s}$	1.5
Current drag coefficient	C_{dw}	0.8
Air density	$\rho_a, \frac{kg}{m3}$	1.3
Wind speed	$u_w, \frac{m}{s}$	5
Wind drag coefficient	C_{da}	0.8
Wind skin friction coefficient	C_{sa}	0.001

Table 19 Ice data

Parameter	Unit	Value
Level ice thickness	h_i, m	2
Ridge sail height	h_s, m	5
Consolidated layer thickness	h, m	2.5
Keel angle	a_k, rad	0.5
Sail angle	a_s, rad	0.35
Keel breadth	B, m	25
Ridge block size	T_b, m	0.4
Ice density	$\rho_i, \frac{kg}{m3}$	925
Ice speed	$u_i, \frac{m}{s}$	1
Elasticity modulus	E_i, MPa	8000
Poisson ratio	v_i	0.34
Ice rubble internal friction angle	ϕ_i, rad	0.33
Keel rubble cohesion	c_i, kPa	15
Ridge sail porosity	η_s	0.1

Table 20 Soil data

Parameter	Unit	Value (clay)	Value (sand)
Wall friction angle	ϕ_w, rad	0.349	0.443
Internal friction angle	ϕ, rad	0.401	0.523
Friction between ice and soil	μ	0.4	0.5
Soil density	$\rho_s, \frac{kg}{m3}$	1600	1500

Under assumption that brine volume is small and all pores are occupied either by water or by air, the density of porous keel part of the ridge therefore will be outlined as:

$$\rho_{iw} = \eta_k \cdot \rho_w + (1 - \eta_k) \cdot \rho_i$$

The upper sail part, located above the sea level has a density:

$$\rho_{ia} = \eta_s \cdot \rho_a + (1 - \eta_s) \cdot \rho_i$$

Keel draught

$$h_k = 3.95 \cdot h_s$$

Keel width at water line

$$w_k = 3.91 \cdot h_k$$

Keel width at bottom line

$$w_b = w_k - 2 \cdot h_k \cdot \cot \alpha_k$$

Current projection area

$$A_w = (h_k - \frac{\rho_i}{\rho_w} \cdot h_i) \cdot B$$

Wind projection areas

$$A_{a1} = (h_s - \frac{\rho_w - \rho_i}{\rho_w} \cdot h_i) \cdot B$$

$$A_{a2} = w_k \cdot B$$

Table 21 Ridge features

Parameter	Unit	Value
Ridge keel macro porosity	η_k	0.23
Average keel density	$\rho_{iw}, \frac{kg}{m^3}$	953.75

Average sail density	$\rho_{ia}, \frac{kg}{m^3}$	832.63
Wind projection area	A_{a1}, m^2	119
Wind projection area	A_{a2}, m^2	1930.56
Current projection area	A_w, m^2	449.7
Keel draught	h_k, m	19.75
Keel width at the sealevel	w_k, m	77.2
Keel width at the bottom	w_b, m	4.92

Wind drag force

$$F_{dw} = \frac{1}{2} \cdot \rho_a \cdot C_{da} \cdot A_{a1} \cdot {u_a}^2 + C_{sa} \cdot \rho_a \cdot A_{a2} \cdot {u_a}^2$$

Current drag force

$$F_{dc} = \frac{1}{2} \cdot \rho_w \cdot C_{dw} \cdot A_w \cdot {u_c}^2$$

Ridge weight

$$W = \rho_{iw} \cdot B \cdot g \cdot [\frac{\rho_{ia}}{\rho_{iw}} \cdot \left(h_s - \frac{\rho_w - \rho_i}{\rho_w} \cdot h_i\right) \cdot \cot \alpha_s + \frac{\rho_i}{\rho_{iw}} \cdot h \cdot w_k + \frac{1}{2} \cdot (w_k + w_b) \cdot \left(h_k - \frac{\rho_i}{\rho_w} \cdot h\right)]$$

Buoyancy

$$F_b = \rho_w \cdot B \cdot g \cdot [\frac{1}{2} \cdot (w_k + w_b) \cdot \left(h_k - \frac{\rho_i}{\rho_w} \cdot h\right) + \frac{\rho_i}{\rho_w} \cdot h \cdot w_k]$$

Ice force

$$F_i = 0.43 \cdot 4.059 \cdot B^{0.622} \cdot {h_i}^{0.628}$$

Passive friction force

Passive earth pressure coefficient

$$K_p = \frac{\cos \phi^2}{\cos \phi_w \cdot (1 - \sqrt{\frac{\sin(\phi + \phi_w) \cdot \sin \phi}{\cos \phi_w}})^2}$$

Front resistance

$$P_f(d) = \frac{1}{2} \cdot K_p \cdot \rho_s \cdot g \cdot (d + 0.635 \cdot d^2) \cdot B$$

Side resistance

$$P_s(d) = \frac{1}{6} \cdot K_p \cdot \rho_s \cdot g \cdot d^2 \cdot w_b \cdot (w_b + \frac{d \cdot \cot \alpha_k}{2})$$

Horizontal passive friction force

$$F_{cx}(d) = \mu \cdot P_f(d) \cdot \cos\phi_w \cdot \cos\alpha_k + \mu \cdot P_s(d) \cdot \cos\phi_w$$

Vertical passive friction force

$$F_{cy}(d) = \mu \cdot P_f(d) \cdot \cos\phi_w \cdot \sin\alpha_k$$

Active friction force

Seabed reaction

$$N(d) = F_{cy}(d)$$

$$F_a(d) = \mu \cdot N(d)$$

And finally the equation will depend only on d. It will be easily to calculate

$$F_{da} + F_{dw} + F_i - F_a(d) - F_{cx}(d) = 0$$

Table 22 Forces action

Force component	Unit	Value	
		Sand	Clay
Drag force due to wind	F_{dw}, N	1610	
Drag force due to current	F_{dc}, N	424968	
Ridge weight	W, N	2.2 10^8	
Buoyancy	F_b, N	2.25 10^8	
Force due to drifting ice	F_i, N	19.97 10^6	
Passive earth pressure coefficient	K_p	7.83	4.12
Specific horizontal Coulomb friction	F_{cx}, N	17.95 10^6	18.53 10^6
Specific vertical Coulomb friction	F_{cy}, N	6.1 10^6	6.2 10^6

Table 23 Gouge depth

Force component	Unit	Value	
		Sand	Clay
Gouge width	B, m	20	20
Gouge depth	d, m	3	4.5