Managing climate risks associated with socio-economic development of the Russian Arctic

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Abstract. Every aspect of human activities in the Arctic faces a wide range of risks. By the beginning of the XXI century, mankind had recognized a new class of risks, namely the risks associated with anthropogenic climate change, which is more noticeable in the Arctic, where the rate of warming is twice as high as the world average. The global and especially Arctic climate is likely to continue to change, thereby significantly affecting future socio-economic development, biodiversity, ecosystems and human society. In this paper, we consider climate risks associated with socio-economic development of the Russian Arctic, and propose a modelling framework that allows stakeholders to identify and manage climate risks, assess the economic impacts of climate change in the Arctic, and assist in the development of climate change adaptation strategies.

1. Introduction
The rising interest in the Arctic is shown not only by littoral states (Canada, United States, Russia, Finland, Sweden, Norway, Iceland and Denmark), but also by other countries located at sufficiently large distance from the region. First, this is due to the vast resource potential and transport importance that the Arctic region possesses, and, second, to the lack of recognized and normatively formalized demarcation of international northern sea spaces and the Arctic shelf. Clearly, the Arctic resource potential has not increased recently; therefore, the main driver of the increased interest in polar regions is the depletion of the resource base (primarily hydrocarbon) of the continental part of our planet. For the Russian Federation (RF), which covers half the Arctic, the exploration and development of the Arctic region of Russia that is usually called as the Russian Arctic zone or Russian Arctic (RA) is one of the most priority areas of socio-economic development, and ensuring national security [1, 2].

Today, the economic diversification in the RA remains low. The gas sector dominates the economy of the RA, producing more than 80% of the Russia's natural gas. Followed by the mining sector, where the dominant role belongs to non-ferrous metallurgy (the Norilsk industrial hub with its copper-nickel industry) and gold mining. In the RA, about 98% of diamonds, 100% of rare metals, apatite, barite, antimony, more than 95% of platinum, over 90% of nickel and cobalt, more than 60% of copper are mined. Fishery takes third place in the economy of the RA, since more than a third of Russia's seafood is harvested here.

Every aspect of human activities in the Arctic faces a wide range of risks. By the beginning of XXI century, mankind had recognized a new class of risks, namely the risks associated with human-induced climate change [3, 4]. There is a scientific and political consensus that the Earth’s climate will most likely continue to change, thereby significantly affecting future socio-economic development,
biodiversity, ecosystems and human society. Scientific findings suggest that climate change will be more noticeable in the Arctic, where the pace of warming is two times higher than the global average [5, 6]. The effects of Arctic climate change include but not limited to rising air and water temperatures, loss of polar sea ice and continental snow cover, melting of permafrost, glaciers and the Greenland ice sheet, and rising sea level [3, 4]. All of those are the most important source of climate-related risks [7-9]. In this paper, we consider climate risks associated with the socio-economic development of the RA, and propose a modelling framework (the tool for proactive climate risk management) that allows stakeholders to identify and manage climate risks, assess the economic consequences of Arctic climate change, and provide assistance in developing climate change adaptation strategies. This framework combines both models of the physical climate system and socio-economic models that are integrated with an intellectual and knowledge-based system. From the viewpoint of climate risk management, the RA has essential features due to the two main reasons, which are, to some extent, related each other. The first reason is that global climate change is most pronounced in the Arctic, and the second reason is associated with the economic perspectives for the development of the Arctic provided by global warming.

2. Socio-economic activities in the Russian Arctic in the context of climate change

2.1. Definition of the Russian Arctic

RA is part of the Arctic, which is under the sovereignty and jurisdiction of the RF (Figure 1), including (a) land territories defined by the Decree of the RF's President No. 296 of May 2, 2014 (Murmansk Region, the Nenets, Yamalo-Nenets and Chukchi Autonomous Districts, municipalities of the Arkhangelsk Region, Krasnoyarsk District and the Republic of Sakha (Yakutia), (b) Franz Josef Land archipelagos, Severnaya Zemlya, Novaya Zemlya and other islands located in the Arctic Ocean in the west and in the east within the State Border of the RF, and on the north in accordance with international law, (c) internal sea waters, the territorial sea of the RF, the exclusive economic zone and the continental shelf of the RF adjacent to the above-mentioned territories on which the RF has sovereign rights and exercises its jurisdiction in accordance with the law.

![Figure 1. Territories of the Russian Arctic zone.](image)

The RA's area is about 9.1 million km², which includes the continental part (~4.9 million km²), the ocean part (~4.0 million km²) and the islands (~0.2 million km²). Totally about 1.5 million people live in this region (about 1% of the country's population and about 40% of the world's Arctic population). Despite the small population living in the RA, about 10% of the country's gross domestic product (GDP) is generated here, and more than 20% of Russian exports are provided. RA has a unique transport network with ports located in close proximity to promising offshore oil and gas fields and to the markets of Europe and America. The Government of the RF, represented by the Ministry for the Development of the Russian Far East, plans launching the Arctic large-scale infrastructure and social projects in the next few years that will require enormous financial, human and technological resources.
2.2. Economic activities in the Russian Arctic
The historically developed structure of the RA economy is of a single-industry nature and is based on the operation of large vertically integrated corporations associated with the exploitation of natural resources. Oil reserves in the RA are estimated at 7.3 billion tons, condensate at 2.7 billion tons, and natural gas at about 55 trillion cubic meters. The Yamalo-Nenets Autonomous District has the greatest resources potential, accounting for about 43.5% of the total resources of the RA. In addition, the RA holds large quantities of minerals, including nickel, copper, iron ore, bauxite and phosphate, as well as deposits of platinum, gold, palladium and diamonds. The availability of hydrocarbons and minerals has a decisive influence on the perspectives for the economic development of the region. Aquatic biological resources are also of great strategic importance in the Arctic economic development. The state program "Socio-economic development of the Arctic zone of the RF for the period until 2025" is under implementation. This Program outlines the country’s major plans for the Arctic territories and sets out complex projects for the socio-economic development. The Program provides for the consistent formation of economic growth points related to the industrial development of the Arctic shelf and the development of technologies for more efficient use of the region’s richest resource base. Thus, economic activity in the Russian Arctic is not so diversified.

Arctic climate change (mainly the melting of sea ice) gives new impetus to the development of established sectors of the economy and opens new opportunities for shipping, fishing and Arctic tourism. However, climate change threatens traditional ways of life of local inhabitants involving them in mining, construction, administration, education, medical care and other economic activities. Albeit hunting, fishing, reindeer herding, and gathering continue to play a significant role in the life of indigenous people.

2.3. Economic aspects of climate change in the Russian Arctic
Numerous studies show that Arctic climate change is happening at an unprecedented rate, affecting the regional economy and population ([5, 10] and references herein). Moreover, via feedbacks in the Earth’s climate system and teleconnections between the Arctic and non-adjacent geographic regions, the Arctic climate change can, to some extent, affect the global climate [11, 12], causing economic consequences, that can go far beyond the Arctic [13-15]. Obviously, the Arctic "operates" as a refrigerator for the Earth’s climate system, since the amount of heat emitted by it exceeds the amount of heat absorbed, affecting thereby the climate in other regions of the globe. The study of the economic consequences of Arctic climate change is usually considered in relation to the economic activities that are characteristic of the Arctic region. Recent studies show that changes in the Arctic adversely affect not only the regional, but also the global economy (e.g. [11] and references herein). Despite that, the methodological basis for assessing the economic consequences of climate change in the Arctic and, in particular, the analysis of climate change in terms of costs and benefits, is very poorly developed, which does not allow an objective assessment of the political and economic costs associated with changes in the climate system. Analysis of the costs and benefits associated with Arctic warming includes, on the one hand, the development of regional and global macroeconomic models, integrated assessment models, models of economic entities and other specialized mathematical models, and, on the other hand, the development of greenhouse gas emission (GHG) scenarios. Thus, a better understanding of the economic consequences of Arctic climate change can be achieved using an integrated approach by combining the opinions of experts in the field of natural sciences, economics, and social sciences in collaboration with a wide range of stakeholders (politicians, businessmen, and the public).

Arctic warming provides new economic opportunities for Russia. There are significant opportunities for the production of oil and gas, for the extraction of other minerals, for shipping, tourism, agriculture and fishing in high latitudes. At the same time, changes in the Arctic directly affect regional environmental conditions, the local population, ecosystems and communities, as well as indirectly (due to feedbacks and teleconnections) the climate of the rest of Russia. Changes in the Arctic via the “knock-on” effect can affect the Russian and world economies due to changes in the
prices of mineral and energy resources, changes in the structure of world trade and changes in other sectors of the economy [15]. In recent years, new trends have emerged in assessing the economic impact of climate change in the Arctic, as well as in analysing, assessing and managing climate risks. In 2018, P.M. Romer and W.D. Nordhaus were awarded the Nobel Prize in Economics “for integrating climate change into long-term macroeconomic analysis” and “for integrating technological innovations into long-run macroeconomic analysis”. The main contribution of Dr. Nordhaus was the development of the Dynamic Integrated Climate-Economy (DICE) model that links climate change and economics. Using this kind of models, one can consider climate change in terms of “costs” and “benefits”. Dr. Nordhaus introduced the parameter known as “social carbon price” or “social emission price”. This parameter allows for determining an economic damage caused by one ton of GHG emissions, and then calculate the corresponding tax that should be paid by economic entities that emit GHGs. Complex "climate-economy" models, such as developed at the Arctic and Antarctic Research Institute (AARI), allow us to aggregate the costs of climate change and costs of adaptation to climate change, and then estimate the overall "cost and benefits" of climate change. However, we have to accounting for the criticisms discussed in [16] regarding the use of the integrated assessment approach.

3. Key principles and approaches underlying the engineering of the climate risk management system

Climate risk management entity plays a critical role in risk assessment and management. According to the experts experienced in climate sciences, climate risks are clearly underestimated, since there is no unified “metric” that would allow us to assess the impact of an unusually wide range of effects of climate change on human society, biological, social, economic and technical systems (e.g., [17] and references herein). There is no “universal table” that lists the priorities for the well-being of present and future generations. Consequently, existing climate risk assessments are extremely unreliable. There is still a rather large uncertainty of climate change scenarios obtained by numerical modelling. The point here is not only the quality of climate models, but also the input data relating, for example, to the carbon cycle. According to experts, at some point, the currently observed climate trends may be disrupted, and events with catastrophic scales and consequences may occur. This requires the development of special approaches to assessing the risks of rare, but catastrophic in their consequences, natural phenomena, the frequency and intensity of which vary with climate change. In a probabilistic sense, such catastrophic natural phenomena are characterized by distributions with “heavy tails”, for which the probability of deviation from the mean values is much greater than with the normal distribution, and estimates of the mean sample values are unstable and unrepresentative, since the law of large numbers is not observed in this case. Damage from one such event can significantly exceed the total damage from similar hazardous events that occurred earlier. However, most of the climate research underestimates such risks and prefers conservative forecasts and "scientific restraint".

When assessing climate risks, we proceed from a holistic view on the problem [18] and consider in close interconnection the following issues: (a) estimated scenarios of GHG emissions; (b) corresponding changes in the climate system; (c) climatic risks for anthropogenic and natural systems (systemic risks); and an total cost of the effects of the expected climate change. The analysis of these four issues involves the use of different approaches. Assessment of global GHG emissions is based on an analysis of technological development policies of various countries and measures to control emissions. In the short term, political goals and plans that governments are implementing or plan to implement are analysed. In the long term, more attention is paid to the main technological problems associated with reducing emissions and assessing their complexity, as well as the barriers that must be overcome when introducing new technologies. What is important here is a creative approach to the problem, rather than blindly following known methods.

Changing the state of the climate system due to anthropogenic impact is a scientific problem, the solution of which will answer the question "what is the likelihood that certain climatic events will occur and whether this can be avoided.” Extreme climatic events (phenomena) are subject to analysis
along with the long-term trends, since ultimately these trends will lead to the fact that climatic
variables will reach some threshold values.

Analysis of systemic risks arising from the “interaction” between complex natural and man-made
systems, on the one hand, and a changing climate system, on the other hand, is essentially an
assessment of safety risks. In studies of the behaviour of complex natural and anthropogenic systems
in a changing climate, mathematical (computer) modelling using scenarios of anthropogenic impact on
the climate system, methods for analysing retrospective information, game theory, and other
mathematical apparatus play a significant role. The aggregate assessment of the cost of the
consequences of the alleged climate change is subjective and includes considering not only economic,
financial and special (climate-related) issues, but also of ethical, moral and legal issues.

4. Climate risks associated with socio-economic development in the Russian Arctic

Risk is an inherent part of almost any human activity. Depending on the context, there are many
definitions of risk in use. The ISO 31000: 2018 defines the risk as the “effect of uncertainty on
objectives”. Here uncertainties include events that may or may not occur, as well we uncertainties
caused by uncertainty or a lack of information. Practically, risk is understood as the amount of loss
that may arise due to any event during a certain period of time. Climatic risks arise as a result of a
wide range of natural hazards that can occur suddenly. However, some of them can evolve slowly.
Typically, climate risk is associated with strong events, the incidence of which is low. According to
the latest reports of Munich Re, the German reinsurance group, which is the leading company in the
world, the number of natural disasters, including those related to weather, has had a positive trend over
the past few decades. For example, since 1980 the number of severe floods has nearly tripled, and
storms almost doubled, which, at least in part, Munich Re insurance experts attribute to the impact of
climate change. The analysis provided by the second largest reinsurer in the world, the Swiss Re, is
consistent with the analysis of Munich Re.

Climate change directly affects social and natural systems. Risks resulting from exposure to the
physical climate system represent direct climate risks. This applies to extreme values of climate and
weather variables and extreme natural events. Thus, the direct risks of climate change are associated
with industries and human activities, which are highly dependent on environmental conditions.
However, climate change is also a source of indirect risks such, for example, as legal and regulatory
risks, litigation and reputational risks, competitive and production risks. These risks do not arise
directly from changes to climate system and related climate or weather variables, but from a range of
consequences caused by climate change. These consequences may affect the organization’s capacity to
achieve its objectives.

Climate risks for society, the economy and ecosystems require the development of effective
methods for their identification and management. A variety of climatological, oceanographic and
meteorological information is required as input to the climate risk assessment process. Since climate
remains an extremely complex area of scientific research, the main method of studying it is computer
modelling. Thus, the climate change projection data used in assessing climate risk are the results of
climate modelling driven by various scenarios of GHG and aerosol emissions. To quantify risk,
various methods are available for use in different industries.

Within our framework, the two main approaches are used to assess climate risk: the natural hazard-
based technique and the vulnerability-based method. Here, the term “hazard” refers to climate-related
physical events or trends in their physical effects. Risk, in a statistical sense, is defined as the product
of the probability of occurrence of an adverse climate event over some period of time and the severity
associated with such an event: $R = \int_\Omega P_e \times S_e (P_l, S_l) dt$. Here $R$ is the total risk, $\Omega = [t_0, t_e]$ is the
time interval of interest; $P_e$ is the probability of the event; $S_e$ is a function for severity of the event
defined as $S_e (P_l, S_l) = \sum_{loss} P_d \times S_d$, where $P_d$ is the probability of loss (damage) of a certain type,
and $S_d$ is its severity. Severity of impact of climate extremes depends on two determining components:
- system vulnerability and exposure to threats. Vulnerability depends on the nature, magnitude and rate
of climate change to which the system is exposed, as well as its sensitivity to climate change and its
adaptive capabilities. Both vulnerability and exposure should be assessed when managing climate risk. To this end, for each hazard caused by climate change, some “standard” indicator values are introduced that characterize this hazard. For example, for floods, such a standard indicator is a certain predetermined level of increase in water, and for stormy weather, some fixed wind speed on the Earth's surface. Then, assuming that the vulnerability remains unchanged, we analyse the impact of climate change on the frequency variations of standard indicators and, ultimately, on climate risk. In addition, some criteria should be introduced that characterize the vulnerability of the system to climate change. For example, such a criterion for the coastal flood is a certain critical value of the increase in water level \( h \) as a result of global warming. In this case, the risk is defined as the probability of an event corresponding to a water level exceeding the critical value, i.e. \( R = P(h > h_c) \). Thus, using the concept of systems vulnerability to climate change, we can assess climate risks based on a statistical analysis of the hazards caused by climate change.

5. Generic algorithm for climate risk assessment for the socio-economic development in the Russian Arctic

The climate risk management system developed at the AARI [9] includes: (a) mathematical models of social, economic and environmental systems, (b) an adaptive intelligent computer system that allows one to process the results of global and regional modelling of climate change for various global warming scenarios, and to extract the information required for risk analysis, (c) automated methods for analysing and assessing risks, and (d) mathematical models used in developing climate risk hedging strategies, and in formulating national climate change adaptation policy (Figure 3).

Managing climate risks for the socio-economic development of the RA, we consider that (a) climate change is likely to be more rapid in the Arctic compared to other regions on Earth, (b) climate change in the rest of Russia depends on changes in the Arctic due to teleconnections and feedbacks in the Earth’s climate system, and (c) climate change initiates socio-economic transformation, opening up new business opportunities. The vast territory of RA includes several natural zones, and its natural and climatic conditions are extreme and vary significantly when moving from west to east. The local population is characterized by a low density and focal type of territorial development. Given the heterogeneous climatic conditions in the territory of the RA and the focal nature of its development, the assessment of climate risks involves climate zoning (division of the continental and marine parts of the Arctic into regions with the same climatic conditions), as well as functional zoning (division of the territory of the RA into areas with similar types of economic activities). Instead of functional zoning, we use the existing division of the RF into territorial units of the upper level (regions, territories, autonomous and urban districts).

Diverse geographical, weather, climatic and ice conditions in various parts of the RA, the focal nature of its development and the prospects for diversification of the regional economy determine an extremely heterogeneous picture of the identified climatic risks for Arctic natural and anthropogenic
systems. Combining maps of climate and functional zoning, we have developed information databases for each territorial unit, which include:

- characteristics of natural-geographical, climatic, meteorological and hydrological conditions;
- retrospective and actual climate information, as well as climate projections;
- environmental information, including environmental indicators characterizing the state of ecosystems;
- socio-economic information (retrospective, actual and predictive estimates), including a register of the main types of socio-economic activity and a register of systems whose operation may depend on weather and climate conditions.

Based on the complex information contained in the databases, for each socio-economic system (SES) located in a specific territorial unit, a risk environment is formed that is a verbal (qualitative) description of the external (in relation to the SES) environment, environmental restrictions on SES, as well as SES responses to adverse environmental conditions. To develop a risk environment, we apply a SWOT analysis, which allows us to classify the factors of internal and external environment for SES into four main categories: **Strengths**, **Weaknesses**, **Opportunities** and **Threats**. Factors related to strengths and weaknesses are controlled factors (we can control them), and factors related to categories of opportunity and threats are environmental factors, and we cannot control them. The results of the SWOT analysis are preliminary, since they are descriptive in nature without specific recommendations. The SWOT analysis is supplemented by a PEST analysis to identify the **Political**, **Economic**, **Social** and **Technological** external environment that affects SES.

After the formation of the risk environment, the identification of climate risks is performed by assessing the vulnerability of the SES to each hazardous climate event and/or trigger (the critical value of climate indicator). Climatic risks are identified using expert assessments, the analogy method (previous experience), a brainstorming session, the Delphi method, the nominal group method, the root cause identification, etc. Risks are assessed using specific criteria, which are mainly subjective. Vulnerability of SES is evaluated for each hazardous climatic event, considering the likelihood of its occurrence. According to the “vulnerability” parameter, screening is carried out to screen out climate events that are not of great importance for a given SES. Remaining events are ranked by the degree of their negative impact on the SES. Ultimately, for each SES, a final register of climate risks is formed, which lists the identified risks, indicates the main causes of their occurrence and marks the category of risks.

Vulnerability assessment for each SES is performed on the basis of mathematical modelling, justifying key performance indicators (KPI) for each SES (territorial unit, economic entity (enterprise, plant), the entire population or individual social group, ecosystem) and using mathematical relationships between these indicators and climate variables. The main indicator based on which the operational effectiveness of SES is assessed is the gross regional product, GRP, (here, the system is understood as a territorial unit). For individual enterprises, gross profit is used as the main indicator of efficiency. Thus, the impact of climate change on SES implies the presence of a mathematical relationship between KPIs and variables that affect the system.

Among the influencing variables are climatic triggers, the list of which was previously determined qualitatively. Let $Q$ be GRP. If $x = (x_1, x_2, ..., x_n)$ is a vector of dependent variables that affect the efficiency of the territorial economy, then $Q = f(x_1, x_2, ..., x_n)$. Model development comes down to the determination of the function $f$. To study socio-economic systems, production functions are used that associate $Q$ with the variables $x_1, x_2, ..., x_n$: $Q_{ti} = F_{ti} (x_1, x_2, ..., x_n)$. Here, $i$ is the serial number of the branch of the regional economy (or enterprise), $t$ is time, and $F$ is the given (known) function of the variables affecting $Q$. The production functions used in economic analysis connect the key indicator of the effectiveness of socio-economic system $Q$ with the main production parameters, such as capital, technology, human resources, etc., as well as with climate variables (extreme temperature, quantities of precipitation, wind speed, etc.). There is a certain set of production functions traditionally used in economic analysis, including a trans-logarithmic function:
\[ F_{lt} = \beta_0 + rt + \sum_{n=1}^{N} \beta_n \ln x_{in} + \frac{1}{2} \sum_{n=1}^{N} \sum_{m=1}^{N} \beta_{nm} \ln x_n \ln x_m + \epsilon_{lt}, \]  

(1)

where \( r \) is the interest rate, \( \beta_0, \beta_1, \ldots, \beta_n \) are unknown coefficients to be determined, \( \epsilon_{lt} \) is the approximation error (usually random). The coefficients \( \beta_0, \beta_1, \ldots, \beta_n \) are found using retrospective climate and economic information contained in the adaptive database.

The sensitivity of GRP to climatic variables (triggers) is estimated using the sensitivity functions. If \( x_n \) is a certain trigger, then the absolute and relative sensitivity functions are defined as follows:

\[ S_n = \frac{\partial Q}{\partial x_n}, \quad S_n^R = \ln Q / \ln x_n. \]

Function \( S_n \) shows how the output variable \( Q \) changes with an infinitesimal change in the input parameter \( x_n \). In turn, function \( S_n^R \) identifies the relative importance of the parameter \( x_n \) and shows how the dependent variable \( Q \), in relative terms, changes when the parameter \( x_n \) changes by 1%. If \( \delta x_n \) is a small variation in the parameter \( x_n \) caused by climate change, then the change in the dependent variable \( \delta Q \) caused by the variation \( \delta x_n \) is estimated as \( \delta Q(\delta x_n) \approx \delta x_n S_n \). The variation \( \delta Q \) is used to assess system vulnerability and climate risk. However, only knowledge of variations in KPI is insufficient to assess climate risk. Probabilistic characteristics of random triggers are also required. For example, for the coastal zone of such a territorial unit as the Murmansk region, one of the most important indicators of climate change is the time dynamics of sea level rise (SLR). To obtain the probabilistic characteristics of SLR, considered as a random process, we can apply the diffusion stochastic model \[ h_t = \alpha h_t dt + \sigma h_t dW_t \]

(2)

where \( h_t \) is the SLR (in centimetres) at time \( t \) relative to a certain initial (base) level \( h_0 \) at the geographical point of interest, \( \alpha \) is a parameter that describes the sea level trend obtained from climate change projections (for various emission scenarios), \( \sigma \) is the SLR volatility, and \( dW_t \) is the increment of the Wiener process. Eq. (2) describes a random process called geometric Brownian motion, i.e. such a random process whose logarithm is a Wiener process.

Thus, the SLR is defined by the deterministic factor represented by the parameter \( \alpha \), which describes the tendency of the SLR ensemble mean \( \langle h_t \rangle \), and random factors that are aggregated by the second term in Eq. (2), in which the quantity \( \sigma \) determines the degree of uncertainty in our knowledge of SLR for a given forecast lead time. A stochastic model of the form (2) with several stochastic equations is used in assessing climate risks caused by melting of Arctic ice and other climatic events, as well as in simulating various climatic variables (e.g. surface temperature). To predict sea level at a given geographical point, the following information is required: initial sea level \( h_0 \), deterministic trend (parameter \( \alpha \)) and sea level volatility (parameter \( \sigma \)). Model (2) must be calibrated using climate data. Calibration is conducted in such a way that the model parameters are a 95% percentile. Solving Eq. (2) numerically, we obtain the evolution of sea level and its statistical characteristics (first and second central moments, and the median), which are then used in the process of assessing climate risk. Note that SLR is accompanied by an increase in the frequency of floods in coastal zones. To calculate the frequency of hazardous events, special models are used with predicted sea level as an input. The development of models for calculating the frequency of rare but catastrophic natural events is based on the theory of extreme events. The probability of such events, including coastal floods caused by global warming, is estimated using the generalized Pareto distribution, which is a family of continuous probability distributions applied to model the “tails” of other distributions. The cumulative distribution function describing the probability that the sea level \( h \) will exceed a given threshold \( h_c \) is written as

\[ H_{h_c;\xi;\lambda}(h) = \begin{cases} 
1 - \exp \left[ -\frac{h - h_c}{\lambda} \right] & \text{at } \xi = 0 \\
1 - \exp \left[ 1 + \xi \frac{h - h_c}{\lambda} \right]^2 & \text{at } \xi \neq 0
\end{cases} \]

(3)
at \( h > h_{\ast} \). Here \( \xi \) is the shape parameter, and \( \lambda \) is the distribution scale parameter. If the parameter \( \xi < 0 \), then the sea level is bounded from above by the maximum possible value \( h_{\text{max}} = h - \lambda / \xi \), and we assume that \( H_{\xi,\lambda}(h) = 1 \) when \( h > h_{\text{max}} \). It should be noted that the calibration of models (2) and (3) and, therefore, the reliability of the results obtained is determined by the reliability of the available climate data (retrospective and projected, calculated for various global warming scenarios).

To assess the economic losses caused by hazardous events, we define (polynomial) damage functions (simplified relations between climate variables and total economic losses). For SLR damage function is of the form:

\[
D_t(h_t) = \varphi_1 h_t + \varphi_2 h_t^2 + \cdots + \varphi_n h_t^n
\]

where \( \varphi_1, \ldots, \varphi_n \) are unknown coefficients estimated via model calibration, the implementation of which is fraught with significant difficulties due to the lack of representative socio-economic data for a sufficiently long period of time for cities, towns and economic entities located in the RA.

To assess the economic losses caused by SLR (and other climate variables that affect socio-economic systems), we apply two measures of risk: Value at Risk (\( \text{VaR} \)) and Expected Shortfall (\( \text{ES} \)). \( \text{VaR} \) characterizes economic losses that with a given confidence (e.g., 95%) will not be exceeded, while \( \text{ES} (5\%) \) characterizes economic losses caused by five percent of the worst climate events. Input data for damage assessment include: predicted SLR at a given point for specified time (e.g., 2050 or/and 2100) using stochastic model (2), projected estimates of the socio-economic development of the city (region), and the likelihood of coastal floods of varying intensity. Since the system is currently being configured and tested, we present here some results for the city of St. Petersburg, which is located at the North-West Federal District of the RF and is the second largest city in the country. For the RCP8.5 emission scenario, the values of \( \text{VaR} (95\%) \) and \( \text{ES} (5\%) \), calculated for 2050/2100, areo US$ 2.3/8.1 and 3.0/10.0 billion, respectively (for these calculations, some input data were taken from [20]). Adaptation measures to minimize the economic losses caused by the SLR include the construction of dams, the relocation of production facilities deeper into the continental part, the development of plans for the restoration of the coastline, the development of a hydrologic monitoring system, the cessation of construction near the coastline, etc. Possible adaptation measures are evaluated in monetary terms and then compared with estimated losses calculated in accordance with the methodology presented above. By comparing the costs of adaptation measures with the expected losses caused by SLR, we can estimate the costs and benefits of climate risk management.

6. Concluding remarks
In conclusion, let us once again draw attention to the following. Due to feedbacks and telecommunications in climate system, the economic costs of the RF due to climate change can balance the (expected) economic benefits of economic activity in the Arctic, which has become possible due to the warming of the Arctic. Therefore, the question remains open whether changes in the Arctic can lead to positive economic consequences both in the territory of the Russian Arctic and in the rest of the RF. Let’s make this comment a little clearer. On the one hand, the warming of the Arctic provides new economic opportunities in the Russian Arctic related to oil, gas and minerals sectors, shipping, tourism, agriculture and fisheries. On the other hand, changes in the Arctic have a direct impact on its climate, local population, ecosystems and communities, as well as the indirect impact (due to feedbacks and telecommunications) on the climate of the rest of the RF and on the global climate. In addition, changes in the Arctic due to the “knock-on” effect can lead to secondary consequences for the Russian and world economies due to changes in the prices of mineral and energy resources, changes in the structure of world trade and changes in other sectors of the economy. Nevertheless, comprehensive research in this direction is practically not carried out.

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