Arctic research
- its current status and future plans -

Executive Summary

Japan Consortium for Arctic Environmental Research

As of January 9, 2024

1 Natural sciences

1-1 Atmosphere (troposphere and stratosphere)

Weather and climate in the Arctic vary on various time scales. In particular, the Arctic experiences large changes in the recent decades. Our understanding of basic state of the Arctic atmosphere, its fundamental processes, and numerical representation are insufficient. In the future research, it is important to understand roles of atmosphere-ocean-land surface interactions (including the cryosphere component) and roles of troposphere-stratosphere interactions (including the chemistry component) in the atmospheric variabilities and changes. To evaluate the effect of climate forcers on the energy and moisture budget, it is necessary to understand teleconnection between inside and outside of the Arctic via atmospheric circulation and waves. As to the short-term variations such as extreme events, it is important to understand processes responsible for their emergence, predictability, and modulation by the long-term climate changes. To achieve these goals, it is essential to integrate multilateral approaches such as in-situ and satellite observations, climate modeling, and data assimilation.

Arctic clouds play an important role in the Arctic climate system by influencing radiation and precipitation processes depending on the amount of cloud water and ice. In the future research, we need further laboratory experiments and observations to understand the microphysical processes of mixed-phase clouds. We also need to study behaviors and radiation effects of clouds that are formed under various environmental conditions (such as surface conditions and meteorological fields) and are affected by various scale-interactions. An understanding of air-sea interactions and aerosol-cloud interactions within the warming Arctic climate system and their role in climate feedbacks needs to be assessed. Observations and models need to be compared and validated not only for statistical quantities but also for individual events to gain a better understanding of cloud and physical processes that contribute significant uncertainty to Arctic climate modeling.

In the Arctic, atmospheric substances, such as greenhouse gases (GHG), significantly affect the radiation budget and the ground-surface atmospheric environment. In the future GHG research we need to evaluate responses of emissions and sinks of carbon dioxide and methane, including their isotopic ratios, in the warming Arctic through observations, and analyses of permafrost and ice core. Contributions from these sources and sinks need to be also evaluated using atmospheric transport models. In aerosol studies, we need to evaluate the contribution of anthropogenic and natural sources within the Arctic (e.g., emissions from oceans and bare land-surface) associated with Arctic warming, along with transport from mid-latitude anthropogenic sources of aerosols that act as cloud condensation nuclei (CCN) and ice nucleating particles (INP).

Research priorities

- <u>Weather and climate:</u> Knowledge of basic state of the Arctic atmosphere needs to be enhanced. The understanding of processes connecting different time scales from weather to climate, interaction between the Arctic and outside the Arctic, and coupling between the troposphere and the stratosphere need to be studied through integrating observations, modeling, and data assimilation.
- <u>Cloud and physical processes:</u> Laboratory experiments and observations to understand the microphysical processes of mixed-phase clouds are required. Studies on behaviors and radiation effects of clouds formed under various conditions need to be conducted in terms of atmosphere-ocean and cloud-aerosol interactions within the warming Arctic climate system.
- <u>Greenhouse gases and aerosols:</u> Changes in emissions and sinks of carbon dioxide and methane due to Arctic warming need to be evaluated through observations and modeling studies including those on isotopic ratios of these compounds. Contributions of aerosols of anthropogenic and natural origin that act as cloud condensation nuclei (CCN) and ice nucleating particles (INP) need to be studied.

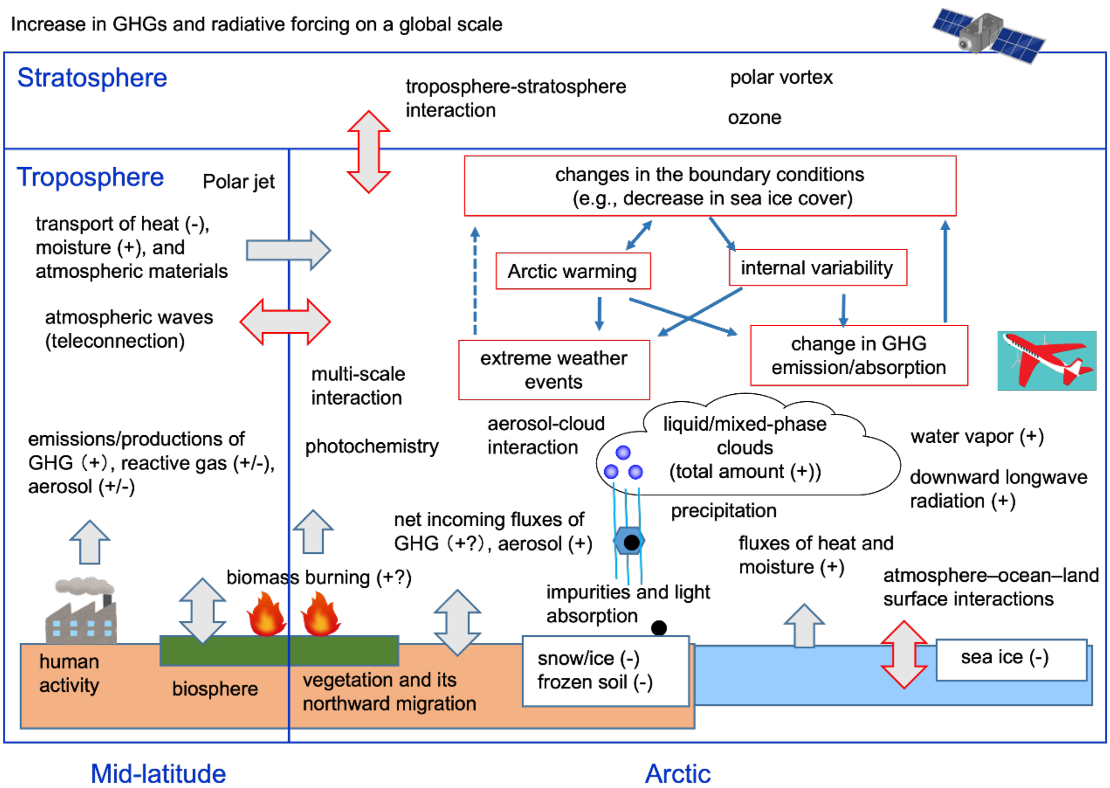

Figure caption : Atmospheric factors and processes involved in Arctic climate system. The "+" and "-" symbols in the figure indicate that an increases or decrease is expected in the future.

1-2 Geospace • Upper and middle atmosphere

Geospace is a term used to describe the space around the Earth that is part of the human activity domain, where many artificial satellites, the International Space Station, and planetary explorers fly. Recent studies are revealing that changes in solar activity and geospace are affecting the Earth's environment. In particular, a detailed understanding of the physical and chemical processes in the polar regions is required. Because various energies from solar and geospace flow into the polar middle and upper atmosphere. On the other hand, it has become clear that the middle and upper atmosphere also shows short- and long-term variations due to various factors such as energy and momentum transport by atmospheric waves excited in the lower atmosphere and the increase of greenhouse gasses. Thus, in order to understand the effects from geospace and the interactions between all atmospheres, the study of "vertical/latitudinal coupling processes of the atmosphere" is an important issue in Arctic middle and upper atmosphere and geospace research.

In addition, research on the geospace environment is becoming important as a practical science to improve the accuracy of space weather forecasts necessary for satellite operations and to reduce risks to social infrastructure (e.g., communications, power, and positioning) in the Arctic region as space applications develop.

In the past few years, much of the research on the middle and upper atmosphere and geospace has been led by Japan as an international joint research project, and new satellite observations ("Arase" : Exploration of energization and Radiation in Geospace) and large radar observations (EISCAT_3D radar) have been started. However, quantitative impact assessments of vertical coupling processes have not progressed much yet, and research projects are needed to be maintained in the future. In addition, it is necessary to further strengthen cooperation with mid- and low-latitudes and Antarctica in understanding atmospheric general circulation and global-scale variation mechanisms. Japan has the infrastructure (research base and network observations) to promote such research, e.g. the large atmospheric radar (PANSY) at Showa Station in Antarctica, and there are high international expectations for the development of this research.

1-3 Sea ice, ocean, and marine ecosystem

Sea ice decline is known as synonymous with Arctic climate change, however, various changes are also ongoing inside the ocean. Enhanced ocean circulation and increasing in warm oceanic currents from both Pacific and Atlantic origin waters pulsed the stock of oceanic heat, which caused further sea ice loss. Sea ice act as a "lid" that prohibits energy transfer from the atmosphere to the ocean, which used to make the Arctic a calm ocean, though the recent decrease in sea ice extent also accelerated wave activities. Such rough condition, in turn, can act as "ice-wave feedback" that wave physically breaks sea-ice into small pieces, which lead to further sea ice decline.

The changes in the internal ocean have also modified the biogeochemical cycles. Increased inflow from the great rivers in addition to the Pacific and Atlantic Ocean, and pulsed atmosphere-ocean interaction and strengthening of stratification have changed both lateral input and vertical mixing of nutrients, which in turn increased the primary productivity in most areas in the Arctic Ocean. Losing the "lid" of the sea surface activated air-sea gas exchange; CO2 flux toward the ocean increased and releasing of methane from the ocean to the atmosphere rose. These physical and biogeochemical environmental changes caused subsequent impacts on marine ecosystems. Not only planktonic organisms that respond immediately to environmental changes, but also the higher trophic level organisms are facing the cascading changes. In particular, not a few sub-arctic species are beginning to expand their distribution into the Arctic. Signals of ocean acidification are also prominent, and there is concern about unknown effects on marine ecosystems. Establishing sustainable resource management and ocean governance is all the more essential in a race against time because of the rapid expansion of the distributional range of commercial fish species and potential fishing areas with the sea ice loss in the Arctic.

International and scientific concern for the Arctic climate changes has improved comprehension of environmental changes and subsequent biogeochemical cycles and marine ecosystems. However, our knowledge has large regional and seasonal biases. It is mainly because the Arctic sea ice has limited our challenges in collecting all kinds of observational data from basic oceanographic parameters to those requiring advanced analytical techniques (e.g. trace metals). The scarcity of observational data has acted as a barrier to capturing an overall picture of the Arctic marine environment. Proactive use of advanced technologies such as icebreakers, automated observation platforms, and biologging will help to fill data gaps, which will also contribute to improving the accuracy of ocean modeling and reducing uncertainty in future predictions.

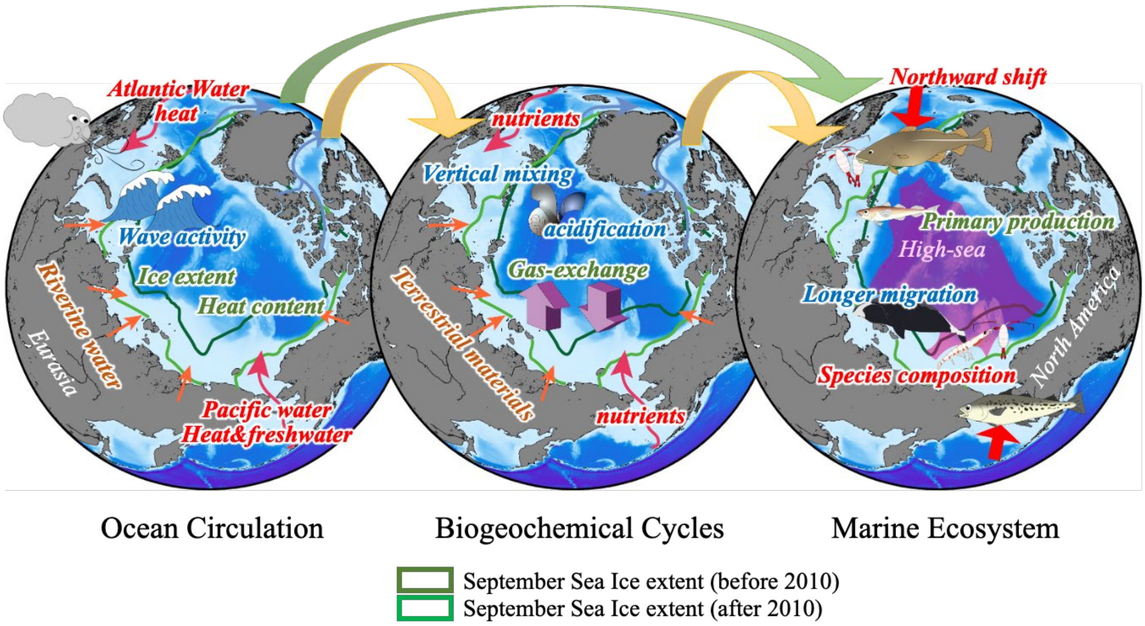

Figure . Schematic of the various changes recently reported in the Arctic Ocean. Physical changes in the ocean have a direct and cascading effect on biogeochemical cycles and marine ecosystems.

1-4 Land surface

The Arctic region (the Arctic Circle and its surroundings) is covered by evergreen coniferous forests, deciduous coniferous forests (larch forests), tundra, and boreal deserts and ice sheets, with most of the area being underlaid by permafrost. Permafrost has an active layer on the surface that thaws seasonally. The active layer is a place where plants tap water and nutrients through their roots during the thawing period, and where microbial communities work actively. When the permafrost thaws due to global warming, the impermeable soil becomes a layer that allows water to pass through, resulting in uneven subsidence of the ground and the formation of thermokarst lakes, as well as accelerating the decomposition of frozen soil organic matter. This releases greenhouse gases such as carbon dioxide and methane into the atmosphere. Furthermore, global warming is expected to increase plant productivity and expand areas suitable for the growth (i.e. higher latitudes and higher altitudes). In addition, it has been pointed out that it may change not only species diversity but also functional diversity.

In order to understand changes in the Arctic region, it is necessary to continue the long-term observations in Russia and Alaska, which have been proven so far, and to advance the understanding of changes and interactions between permafrost and ecosystems. Since most of the Arctic region is remote, remote sensing techniques are expected to be useful in monitoring ground deformation, phenology, and photosynthetic activity. It is also important to develop and improve the polar observation system in order to complement the information obtained from remote sensing data. Natural ecosystems and permafrost processes are mixed with events of various scales in space and time and it is necessary to understand phenomena using numerical models constructed on appropriate spatial and time scales. The terrestrial and marine ecosystems in the Arctic are closely related. It is necessary to consider interactions not only with terrestrial ecosystems but also with other ecosystems in the future. Ultimately, it will be necessary to create a database of the knowledge obtained from research on land areas and integrate it with social, cultural, and economic analysis.

Research Priorities

- It is necessary to continue and improve the polar observation system in terrestrial ecosystems (GHG fluxes, biogeochemistry, phenology, and biodiversity) and permafrost in order to complement the information obtained from remote sensing data.
- Natural ecosystems and permafrost processes are mixed with events of various scales in space and time and it is necessary to understand phenomena using land surface and ecosystem models constructed on appropriate spatial and time scales.
- It is necessary to create a database of the knowledge obtained from research on land areas and integrate it with social, cultural, and economic analysis.

1-5 Snow and ice

Snow and ice are key components to understand the Arctic environment. Although precipitation in the Arctic region has increased in the last century and is predicted to accelerate in this century, the ratio of snowfall in precipitation has decreased and will further decline in the 21st century. To better understand the changes in snow fall, the accuracy of models and observations of the precipitation are required to be improved. Satellite observation revealed that the area and period of the snow cover in spring and summer decreased and shortened, respectively. The future challenge is to improve the accuracy of the satellite observations. The melting process of snowpacks is closely related to air temperature, solar radiation, and surface albedo. The quantitative evaluation of the surface albedo regarding to the snow grain size and concentration of light-absorbing impurities is an issue for future works.

Mass loss of the Greenland ice sheet is a major component of the sea level rise in the 21st century. The mass loss is driven by increasingly negative surface mass balance and accelerated ice discharge into the ocean, thus investigation is required for interaction of the ice sheet with the ocean as well as warming climate. Rapid ice loss is also reported from mountain glaciers and ice caps distributed over the Arctic, including those along the coast of Greenland. These glacier changes pose risks of disasters due to the flooding of a glacial stream, glacial-lake outburst and landslide. To accurately understand the mass loss of glaciers and ice sheet in the Arctic and its global and social consequences, it is important to strengthen the synergy among long-term field observations, satellite remote sensing and numerical modelling.

Snow and ice in the Arctic region contain diverse impurities, derived from natural or anthropogenic sources via atmosphere. As the impurities on the surface has an effect of albedo reduction, quantifications of such impurities are important to estimate the melting rate of glaciers and snowpacks. Furthermore, cold-tolerant microbes growing on the snow and ice surface also have the effect of albedo reduction (bio-albedo effect). All of the impurities in snow and ice of glaciers are condensed or diluted, modified biogeochemically on, in, and below the glaciers, and transferred to the downstream by glacial-flow and running meltwater, and finally discharged out of glaciers. Our knowledges on such biogeochemical processes in snow and ice have significantly advanced recently, however, their quantitative and modeling studies are needed.

In the Arctic Ocean, which used to be covered by sea ice year-round, significant sea ice loss is observed along the coasts of northern Siberia and Alaska in the past 40 years. As a result, operation of vessels along the Northern Sea Route is now possible during summer. The rapid decrease of sea ice induced the remarkable changes of the Arctic Ocean including the increase of sea ice drifting speed, the expansion of the open water surface causing the significant waves, which have a positive feedback effect of sea ice loss. Real-time data obtained in high spatiotemporal resolutions are necessary for the accurate assessment of rapidly changing sea ice conditions. Changes in river ice and icing also need attention. River ice has a significant role of transportations of heat, water, and materials in the Arctic region.

Research priorities:

- Snow fall and melt

Advanced satellite remote sensing, in-situ observations and modelling are required for more accurate understanding and quantification of snow fall and melt.

- Glaciers and ice sheet

Long-term field observations, satellite remote sensing and numerical modelling are required to quantify and understand the mechanism of the mass loss of the Greenland ice sheet and glaciers in the Arctic.

- Glacial biogeochemistry

Quantification of organic and inorganic impurities in snow and ice, and evaluation of their impact on surface albedo and melting across Arctic glaciers are necessary. Long term observation and numerical modeling of microbial processes on glaciers are also important.

- Sea ice

Spatially and temporally high-resolution real-time data are required to assess the rapid change of sea ice.

1-6 Climate Prediction

Sea ice is one of the principal factors to characterize the Arctic climate. It is also important for the ecosystem and the existence of living organisms in the Arctic region and has direct impacts on human activities such as ship navigation and fishery. Furthermore, it is pointed out that the variabilities of Arctic sea ice trigger climate variabilities not only in the Arctic region but also in remote places. These make people have a special interest in sea ice prediction among various aspects of the Arctic climate. We need the effort to construct datasets for sea ice thickness, which is one of the most important issues for a more precise and longer prediction of sea ice. Changes in sea ice depend much on surface air temperatures and winds whereas actual weather is difficult to forecast beyond about one week. However, since drastic changes in sea ice are often dominated by extreme weather events such as intense low pressures, the reliability of sea ice prediction over seasonal and longer time scales would be significantly improved if long-term tendencies of extreme weather became predictable.

Climate variabilities include two fundamentally different causes: forced and internal. Forced variabilities are induced by factors existing out of the climate system. Global warming, which is induced by human activities, is a notable example. Internal variabilities are self-sustained by the interaction of the components in the climate system. The El Nino/La Nina phenomenon is a well-known example. For the time scales where internal variabilities dominate (typically shorter than a decade), longer and more precise prediction of the climate hinges especially on the acquisition of observational data, which are used to initialize prediction, and the development of methods to assimilate such data properly into prediction models. A better scientific understanding of the mechanisms controlling internal variabilities is also required to construct reliable prediction models. For the time scales where the influence of global warming dominates (typically longer than a few decades), the relative importance of initialization becomes low, while the reproducibility of prediction models becomes a much more severe constraint. The lack of reproducibility in current prediction models means our lack of scientific understanding of the fundamental mechanisms of the climate. Enhancement of basic research on the climate, including observation, is first required for better reliability of long-term climate prediction. On top of that, we need to continue our effort to scientifically understand elementary climate processes and precisely introduce them into prediction models.

Research priorities

- Sea ice prediction: Construction of datasets for sea ice thickness
- Seasonal-to-decadal climate prediction: Acquisition of observed data to initialize climate models and development of methods to assimilate such data into climate models
- Long-term climate prediction: Understanding of elementary climate processes and precise introduction of such processes into climate models

1-7 Climate Teleconnection

The Arctic climate is, of course, a part of the global climate, and both interact with each other through currents and waves in the atmosphere and the ocean. The Arctic region exhibits the fastest warming on the Earth, so the changes in the Arctic climate should significantly influence the extra-Arctic regions. In recent years, middle- and high-latitude regions in the Northern Hemisphere have been experiencing unprecedentedly cold winters despite the progress of global warming. In Japan, too, extreme (abnormal weather) events, such as cold waves and heavy snowfalls, are repeatedly reported. It has been discussed that such cold winter climate and weather are induced by the strong warming in the Arctic region. On the other hand, it is also pointed out that influences from the extra-Arctic regions are non-negligible in the enhanced warming and the consequent sea ice changes in the Arctic region. There remain many unknown aspects of the climate interaction between the Arctic and extra-Arctic regions. Scientifically understanding such teleconnection is one of the essential factors in understanding the current climate variability and predicting its future and is further important in investigating the cause of extreme events in and out of the Arctic region and obtaining their future perspective.

Large-scale, quasi-periodic variations of the climate are understood as “modes of climate variability”. They are self-sustained variability resulting from the interaction of the components of the climate, such as the atmosphere, the ocean, the land, and the cryosphere. They exhibit their own characteristic patterns of spatiotemporal variabilities, such as warming in one region and cooling in another region taking place in pairs, and the trend of warming and cooling reversing in time, for example. Such modes are the basic framework to understand climate teleconnections, but their mechanisms have not sufficiently been clarified yet. They are also pointed out to be modulated (i.e., periodicity and regionality are modified) under global warming. We need to simultaneously investigate the mechanisms, modulation, and future perspective for modes of climate variability. Furthermore, we need to advance our understanding and establish the prediction methods as to how global-scale climate teleconnections lead to the manifestation of specific extreme events. Numerical simulation is an indispensable tool to understand and predict climate variability, and we need to continuously develop numerical climate models as our basic research infrastructure. As for the manifestation of extreme events, on the other hand, numerical simulation is not necessarily the best way to provide forecast information. We also need to develop other handy ways to predict them, especially for practical purposes such as disaster prevention.

Research priorities:

- Mechanism of climate teleconnections between the Arctic and extra-Arctic regions
- Sustaining mechanism for modes of natural climate variability and their modulation under global warming
- Link between specific extreme events and global-scale climate teleconnections

1-8 Paleoclimate and Paleoenvironment

Ocean sediments are collected by coring and deep-sea drilling vessels and used to reconstruct the paleoenvironment. In the Arctic Ocean, studies have shown that 55 million years ago, the water temperature was 18°C, and the Arctic Ocean became the Arctic Ocean we know today, with perennial ice since 14 million years ago. Since the Arctic has been a human habitat, understanding how past climate changes have affected human life will be useful in predicting the future of the Arctic living environment. As long-term research topics, it is important to improve the reconstruction of the Northern Hemisphere ice sheet evolution and to reconstruct the past sea ice distribution in order to understand the Arctic climate system. Since changes in the Arctic region are occurring rapidly on land and at sea, there is a great need for paleoenvironmental analyses with high temporal resolution focused on the near past, and it is necessary to plan sampling in the estuaries of large rivers where high sedimentation rates can be expected.

Ice core studies have been conducted for last four decades using a number of ice cores drilled from Greenland Ice Sheet and other Arctic glaciers to reconstruct past climate and atmospheric conditions. Most of the ice core studies have been problem-finding type researches such as descriptions of climate changes and variations in the atmospheric greenhouse gas concentrations, but recently are shifting to the problem-solving type researches including estimation of carbon budgets and applications to removal of greenhouse gas in terrestrial and marine environments.

Future ice core studies are required to propose new processes and mechanisms using new analytical techniques and numerical simulations of the Earth environmental systems and/or to contribute certain geo-engineering studies.

It is essential to conduct numerical experiments to understand mechanisms of past climate and environmental changes and to examine proposed hypotheses. Proxy based reconstruction, on the other hand, play a vital role in evaluating climate models. International model-model and model-data comparison have been active through paleoclimate modeling, and the target period extends back to as much as several tens of million years ago. Polar amplification remains a common and important topic of study, and it is necessary to proceed research from process-oriented approach to system point of view. In addition to past warm periods, studies encapsulating long term environmental changes such as glacial-interglacial cycles are important. Furthermore, it is anticipated that modeling activity on material cycles accompanied by the development of earth system models expands.

Research priorities

- Ice core studies: reconstructing the atmospheric and climatic conditions using innovative analytical techniques and integrations of the data with numerical simulations of the Earth environmental systems to contribute geo-engineering studies.
- <u>Modeling</u>: To elucidate polar amplification mechanisms throughout the Earth's history from process level to climate system point of view by continuously supporting the international activities of model-model and model-data comparisons

1-9 Solid Earth

The solid Earth science in the Arctic region covers the full range of variability from the early Earth to the present, and includes processes from the interior to the surface of the solid Earth. The Arctic is an important region where an interdisciplinary approach through the coupling of geology, marine geophysics, and geodesy can capture a variety of processes at multiple time scales.

The geology of the Arctic region, as in other regions, consists of continental and oceanic crusts; but its position has changed due to plate movement. The geologic evidence in the Arctic also includes some of the oldest rocks on Earth and traces of early life; therefore, the Arctic area contains a unique interest in the study of the early Earth.

On the other hand, the seafloor in the Arctic is known to be the active site of important processes at the Earth's surface, such as seafloor spreading and plate subduction. Understanding these processes is crucial to understanding the relationship between the Earth's interior and the surface environment. The continuous geological record of the seafloor, approximately 200 million years, is crucial for elucidating such processes. However, the Arctic Ocean is generally covered by sea ice, making it a challenging area for marine geophysical surveys.

Ice sheet variations in the Arctic also play an important role in global climate change during the Quaternary. This ice sheet change causes viscoelastic deformation of the solid Earth over a wide range of time scales, which in turn causes not only local crustal deformation but also global-scale variations such as changes in the Earth's rotation. The Arctic is an ideal region where intense the causes of such processes, and geodetic observation make a significant contribution.

●<u>Geology</u>: From the early Earth and early life to the Paleozoic Caledonian orogeny, as well as basement rock specimens collected from beneath the Greenland ice sheet will be the main focus as Japan's strengths in geochronology and isotope geochemistry.

●<u>Marine geophysics</u>: Understanding Cretaceous igneous activity, continental breakup, and seafloor spreading processes is an important issue. Observation programs based on the new research vessels in the Arctic and the active use of underwater robot technologies for unmanned exploration and rock sampling are indispensable to clarify these issues.

●<u>Geodesy</u>: Monitoring ice sheet mass balance in global warming urgently requires satellite-based analysis of regional crustal deformation, development of an absolute gravimeter network, and development of high-resolution numerical modelings to reconstruct these observables.

In order to strategically promote solid earth science research in the Arctic, Japanese researchers can play a leading role and support the research community in this decade. In addition, since the themes listed here can be expected to make a significant contribution from the Japanese research community, the research system for these issues should be established over the next decade.

2 Engineering

2-1 Built Environment Engineering

In the Arctic, harsh cold temperatures make it impossible to live without buildings and energy inputs to buildings. The severe climate also damages structures, so the design of structures must be durable. However, with rapid climate change, the design conditions such as melting of the ground supporting the foundation structure and increase in snowfall are changing the design conditions, and it is necessary to review the design of the structures. In addition, some situations are occurring that make it impossible to use the structures.

While global warming is progressing. the Arctic region is the area where the effects of global warming are most pronounced. However, it is not easy to achieve carbon neutrality in the Arctic region, where energy consumption for daily life is high, renewable energy is low, and snow cover is abundant, making the use of renewable energy sources difficult. On the other hand, carbon neutrality is not only a global trend that cannot be avoided, but also has the effect of increasing local energy security and self-reliance, and how to maintain and develop buildings, cities, and infrastructure in the Arctic region in the future is an urgent issue. The question of how to maintain and develop buildings, cities, and infrastructure in the Arctic region in the future is an urgent one. Against this backdrop, the following topics are discussed in the Land Engineering section of this report.

1) Ideas for research and practice on sustainable development: The essay explores strategies for achieving sustainable development in urban areas of the Arctic region. It emphasizes the significance of reducing energy consumption through building insulation, downsizing, and the adoption of renewable energy sources like geothermal heat.
2) Research and development for materials supporting carbon neutrality: The report examines the need for materials that can safely support buildings and infrastructure in cold climates while also promoting carbon neutrality. It provides insights into frost damage and cold-weather construction in relation to concrete and highlights the potential of wood in contributing to carbon neutrality.
3) Challenges of waste disposal: Given the Arctic's cold climate, waste disposal presents unique challenges. The essay addresses the issues associated with waste management in the region and emphasizes the importance of implementing proper waste disposal methods to prevent environmental pollution.
4) Research on the impact of rapid global warming on the ground: Rapid global warming in the Arctic has led to the thawing of permafrost, resulting in structural damage. This section focuses on understanding the impact of this rapid warming on the ground and presents remedial measures to mitigate the effects on infrastructure.
5) Introducing renewable energy in the Arctic: The essay acknowledges the difficulties of introducing renewable energy in the Arctic region due to high energy consumption, limited renewable resources, and the abundance of snow cover. However, it explores potential ideas and strategies to promote carbon neutrality in the region through the adoption of renewable energy sources.
6) Overview of disasters and disaster prevention: This section provides an overview of possible disasters in the Arctic region and discusses the challenges and strategies for disaster prevention in this unique environment.

2-2 Ocean and coastal engineering

Arctic sea route is broadly divided into the Northwest Passage along the coasts of Alaska and Canada, and the Northeast Passage along the coasts of Russia. The Northeast Passage is an east-west route between Asia and Europe and 20-40% shorter than the Suez Canal route. Although its potential as an international shipping route was recognized for a long time, its use has increased in recent years as global climate change has led to a marked reduction in the extent of sea ice, particularly in summer, and the development of oil and gas along its coasts. However, a balance between safety, environment and economics is a prerequisite for ensuring the sustainability of Arctic shipping routes and coastal development. The presence and uncertainty of sea ice increases environmental risks such as accidents and oil pollution by ships and resource development platforms and makes it difficult to ensure the timeliness required for shipping. From the perspective of environmental protection, underwater noise from ships is likely to be a major issue in the future, and it is desirable to develop methods of its mitigation, measurement and evaluation methods and the accumulation of the field observation data. Along with the enhancement of engineering knowledge, it is important from the perspective of international shipping to study the feasibility of Arctic shipping routes based on practical needs more precisely. In recent years, accelerated coastal erosion in the Arctic region is having a serious impact on Arctic society and infrastructure. To ensure the safety of the population, specific technical development of countermeasure methods should be carried out including erosion control.

Research priorities.

1) Arctic sea route

- Improvement of sea ice forecasting accuracy and real-time ice condition information, and development of numerical models that represent physical phenomena in more detail, based on field observations and model tests.
- Enhancement of field observation data by the newly built Japanese arctic research vessel and AUVs suitable for wide-area exploration of the Arctic Sea.
- Establishment of future scenarios of international shipping through inter-disciplinary research with experts in international politics and legislation surrounding the Arctic region, and implementation of various simulations based on these scenarios.

2) Coastal erosion

- Assessment of wave environment and coastal landform changes through inter-disciplinary research with meteorological and climatological research fields, and coastal erosion countermeasures based on future projections.

2-3 Sky engineering

This section deals with engineering related to tropospheric observations (Tropospheric Engineering) and satellite remote sensing (Space Engineering). The subsection "Tropospheric Engineering" describes issues to be addressed with regard to small unmanned rotorcraft (so-called drones), the future use of which is expected to be promoted. In order to realize these goals, it is necessary not only for atmospheric researchers and drone engineers to cooperate with each other, but also with engineers of mechanical engineering experimental facilities such as wind tunnels and researchers of Computational Fluid Dynamics (CFD). Drones are expected to be a promising observation tool for implementing such collaboration. The subsection "Space Engineering" describes satellite remote sensing technology. It describes the characteristics of various sensors onboard satellites, including optical sensors, microwave radiometers, microwave scatterometers, and synthetic aperture radar (SAR). Also, the importance of launching a successor satellite before the end of the satellite's life and continuously acquiring data was discussed. Especially for SAR data, it is expected that more free and open data will provided in the future. Especially for SAR data, free and open data provision is expected to increase in the future.

Research priorities

(1) Improvements of safety and operability of the drones, and training of piloting technicians for observation.
(2) Development of various sensors suitable for drones with small payloads.
(3) Development of measurement and data analysis methods that eliminate or correct the effects of drones themselves.
(4) Automation of SAR image analysis, which has been converted into physical quantities by the eyes of experts, through the introduction of artificial intelligence (AI) technology.

2-4 Information engineering

Information engineering in the Arctic is an issue that should be considered on a global scale, not just in the Arctic, and there are two major perspectives. One is that it is an information service for people and places who live and conduct research in the Arctic region, and the other is that people and companies outside the Arctic region can use the geographical and climatic conditions of the Arctic region.

Many areas in the Arctic region have low population density, low economic activity, and undeveloped remote access environments. As a result, compared to mid and low latitudes, the region is behind in terms of information services for the people living in this region. These factors cause problems such as lack of real-time observation data and transmission/reception of large-volume data, which are necessary for weather and climate forecasting research at high latitudes, including the Arctic region, and contribute to the inability to improve the accuracy of global forecasts.

On the other hand, the Arctic Ocean is the shortest route connecting the economic zones of Asia, North America, and Europe due to its geographical conditions, and the Arctic Sea route is the focus of attention and has been used as an air route for a long time. However, recent global warming has led to the discovery of new applications for the Arctic Ocean in the field of information engineering, and the possibility of laying submarine fiber optic cables connecting the west coast of North America, Europe, and Asia via the Arctic Ocean has emerged.

There is also growing focus on locating data centers with high power consumption in regions with cold climatic conditions, where submarine cables are landed. It is well known that most of the power consumed by data centers is by the air conditioning systems that cool the ICT equipment. The cold climate conditions of the Arctic region mean that data centers can reduce their power consumption.

Furthermore, it is essential to enhance the network environment through the development of low earth orbit satellite systems. Its network will also be connected to the optic fiber cable backhaul infrastructure, which will lead to improved information services in the less densely populated Arctic region. The innovation and infrastructure will also be essential for commercial and research activities by ships and other vessels in the Arctic Ocean.

Research priorities

- Construction of a submarine cable linking Asia, North America, and Europe via the Arctic Ocean
- Development of a low earth orbit satellite system and its linkage with the optical fiber network to improve information services.
- Construction of data centers in the Arctic region that meet the climate conditions of cold temperatures, considering energy consumption.

3 Humanities

3-1 Human History in the Arctic

As the earliest evidence of human expansion into the Arctic region, *Homo sapiens* were found to have been active at 70°30' N latitude during the late Pleistocene era over 32,500 to 29,200 years ago (Yana Rhinoceros Horn Site (RHS), lower Yana River area). They hunted a wide variety of animals using tools made of [stone, bone, antlers and tusks], crafted ornaments, and made use of hearths in daily life. The combination of stone tools that were discovered is similar to those found at sub-Arctic sites (near Lake Baikal) dating back 39,000 to 28,000 years ago, except for the absence of blades and microblades. Corresponding with environmental changes, activities ceased in the Arctic Circle by the Last Glacial Maximum (LGM) 26,000-19,000 years ago and then reappeared during the warm period that began 15,000 years ago.　The keys to the arctic adaptation in LGM were the dog domestication, projectile hunting tools, hide-working and sewing skills for making complex fur clothing, as well as patterns of foraging movement and settlement for systematic resource acquisition and utilization.

In the field of biological anthropology, ancient genome analysis has unearthed the phylogeny and migration of human populations. The oldest *Homo sapiens* in Asia were the Ust'-Ishim humans living in western Siberia 45,000 years ago. After this, humans migrated eastward along two routes to the north and south along the Himalayas. The first Arctic humans (Yana RHS site) are from a lineage that took the northern route. The human remains from the Sub-Arctic (Mal'ta site) appear to be a population derived from the northern route, but there is an added West Eurasian genetic influence compared to the Yana RHS site. They mixed with humans of southern route origin to form the Ancient Paleo Siberian (APS).

In the Early Neolithic era, the APS population changed significantly when the area around Lake Baikal was genetically influenced by the northern East Asian population. East Asia diverged genetically between south and north during the Neolithic period, and the southward migration of the northern population 5,000 years ago led to the formation of the modern East Asian human population. This led to the formation of a population with little north-south genetic gradient, part of which migrated to the Japanese archipelago during the Yayoi period and mixed with the Jomon people to form the genetic characteristics of the modern Japanese.　In addition to Jomon influence, genetic elements of Kamchatka and Amur River natives have been confirmed in the genomes of people belonging to the Okhotsk culture who lived in coastal areas of the Sea of Okhotsk in Hokkaido 1500-800 years ago. Thus, the human history of the Arctic is one of repeated migrations and population formations throughout Eastern Eurasia and within the micro-regions therein.

Research Priorities:

- Why were *Homo sapiens*, and not Neanderthals or Denisovans, able to penetrate the Arctic Circle?, and it is the task of the collaboration of archaeology and biological anthropology with interdisciplinary approach.

- It is important for us to construct a paleontological database, and to synthesize topographical, geological, and vegetation information, analyses of satellite derived archaeological site distribution data, and ethnographic information by the evolutionary ecological theory.

- It enables to explain the actual conditions by era and region which should be connect with the human history of East Asia.

3-2 Ethnic Culture and Identity

Japanese field-based anthropological research on the indigenous peoples in the Eurasian and American Arctic is comprehensive, aligning with Western anthropological theory while uncovering unique ethnographic insights. Japanese research on the ethnic culture and identity of indigenous peoples in the North American and Greenlandic Arctic regions investigate topics such as subsistence activities (hunting, fishing, and gathering), food sharing and distribution, human-animal relationships, rituals, religion, song and dance, and indigenous knowledge. In particular, the research explores hybrid economic systems blending subsistence and market (wage-earning) activities. Studies also examine the migration of Arctic indigenous people to cities and towns in the USA, Canada, and Denmark due to economic globalization and their lifestyles in cities. Investigating the diverse impacts of social media usage on their societies is another vital research topic. In contrast, primary research on indigenous Arctic peoples of the Eurasian continent includes studies on residential patterns and ways of life, subsistence culture centering on reindeer herding, clothing, food, housing, their worldview, and spiritual culture. Many research studies have focused on reindeer herding, complex subsistence systems, and shamanism, among others. Some scholars explore the dynamic of culture and permafrost related to Climate Change. However, little research has investigated fishing, despite it being a critical food acquisition activity for these people. Studies in both regions reveal commonalities, including the food cultures characterized by high protein and high fat intake, reciprocal relationships between humans and animals, and animistic worldviews. The limited number of younger researchers specializing in Arctic indigenous research underscores the urgent need for worldwide recruitment and training.

Research priorities include:

- Evaluating the Arctic commercial fishery and gas-oil industry's influence on the traditional fishery culture of the Eurasian Arctic.
- Conducting interdisciplinary anthropological studies on health science and environmental policy, local health, and other issues related to waste management.

- Analyzing the transformation and re-interpretation of traditional culture in the context of social media and youth culture.
- Examining indigenous and local societal changes, tourism, and migration in East Asia
- Investigating indigenous well-being and ethnicity related to war, conflicts, and collaboration.

3-3 Indigenous languages

Indigenous languages within and surrounding the Arctic region display significant relationships in terms of language genealogy and language contact. Indigenous languages in Northeast Siberia, South Siberia, and West Siberia exhibit close connections to languages in North America, Central Asia and Mongolia, and Northern Europe, respectively. Researchers in Japan have been actively engaged in field research in Siberia since the 1990s, making substantial contributions to the advancement of research. Nevertheless, not all languages have been comprehensively covered. Additionally, the unstable employment of researchers studying indigenous languages has led to a shortage of young researchers and, consequently, to the inability to continue further research in this field. Another major issue is the rapid decline of indigenous languages resulting from the shift from indigenous languages to a dominant language.

It is necessary to recognize that the decline of indigenous languages is not only an issue for the communities that speak them but also a crisis for all of humanity. Engaging in the documentation, preservation, and succession of indigenous languages as a stable, long-term project is essential.

The research priorities listed below have been highlighted for more than 20 years and are still unresolved. Immediate action is needed to address these issues.

Research priorities:

- Research and information sharing of unpublished materials

In addition to field research, there is an urgent need to survey and share unpublished materials stored in research institutions and researchers' private archives in Russia and Japan.

- Establish international research collaboration

It is essential to collaborate with Russian researchers to investigate Russian materials.

- Construction of a digital archive

Since most of the audio and video materials collected in the past have not been made public, opening these materials to the public as a digital archive to facilitate access is necessary.

- Cooperation with indigenous communities

It is important to collaborate with community members, train researchers from indigenous communities, and establish a system for language succession.

- Development of researchers

Developing researchers and providing them with stable employment is a critical issue to ensure long-term continued research.

4 Social sciences

4-1 Politics

The first section has discussed trends in the field of international relations with emphasis on states as the main agency by examining Hønneland's (2013) first and second waves in literature. This paper argues that there is no third wave of research replacing the second wave yet. Potential research lies in two directions. The first budding research is the so-called global Arctic. Another research is the impact of the Russo-Ukrainian war on Arctic international relations. Both researches are promising although it is unsure to be enough powerful to replace the second wave.

The second section focuses on the nexus of indigenous peoples and governance and reviews previous research that focused on this nexus. Indigenous peoples have been subject to both state inclusion and exclusion since the 18th century when colonialism reached the Arctic. Considering this history, especially in the post-Cold War world, the symmetry between indigenous peoples and the state, referred to as recognition, renewal, and reconciliation, has become the subject of debate. However, limited empirical research exists on the policy implementation stage. Although overly simple, the most fundamental task is overcoming this status quo through empirical research using primary sources. How can we then unravel our fixed-thinking attitudes? For example, in searching for possible alternatives between indigenous knowledge and scientific knowledge, the question is "how can we look beyond the master–servant relationship and view them relationally?"

The third provides discussions of transnational agencies. It has recently been argued that the international engagement of and the role played by the subnational governments, private enterprises, indigenous organizations, academia and epistemic communities, and NGOs in the Arctic governance are not properly covered in research literature. While this argument is partly based on an incomplete analysis of the existing research, there certainly is a need and room for further studies also reflecting the changes caused by the Russian invasion of Ukraine. Current research is characterized by an uneven but constantly widening geographical coverage; interest in non-state actors' role in the Arctic Council; interest in relationship between national and subnational authorities in Arctic matters; studies on international scientific cooperation that is not emphasizing science diplomacy or Arctic governance; studies on Arctic economy and business which only rarely focuses on Arctic governance or the interaction between private sector and policy-makers.

Section 1

- First, that the second wave of research groups, both empirical and critical approaches, should maintain its sophistication through sound debates between both approaches.
- Second, that the global Arctic should explore more effective approaches by further building on case studies.
- Third, to elucidate the impact of the Russian-Ukrainian war on governance, security and geopolitics in the Arctic.

Section 2

- Empirical research to reveal the extent of the "actual presence" of indigenous peoples forgotten in the dynamics of national history.
- Research to extract descriptive inferences, that is, established facts accumulated by reading extensively, responding to, and writing about primary sources.
- Research identifying missing variable bias through the critical reading of history and documents, contrasting what was written in history and documents with what was not (as cases of deviation, etc.), while taking into account the history of knowledge and power.
- When we focus on something that is not A = B,C,D..., juxtaposing B,C,D... against A rather than taking up B,C,D..., and brainstorming how we can accept them as valid options alongside A.

Section 3

- Research analyzing the impacts of the Russian invasion of Ukraine into the structures and functions of the organizations and forums supporting interregional collaboration in the circumpolar north.
- Research analyzing the issue areas that will gain greater importance or lose their significance in collaboration between the Arctic and northern regions and other non-state actors.
- Research that focuses on the relationships and interaction between companies and different levels of government to elaborate the drivers and practices of Arctic governance.
- Research analyzing the possibilities, challenges, and achievements in the rebuilding of the international epistemic communities and scientific collaboration shaken by the ongoing war.

4-2 Economy

The macroeconomic structure of the Arctic region consists of three sectors: large-scale resource development, mainly oil and gas; a traditional economy based on small-scale traditional family businesses in hunting, breeding, fishing, and gathering; and the public service sector, including public administration, national defense, utilities, education, public health, and social security. Large-scale resource development is the driving force behind the economic development of the Arctic region, and the main challenge is how to retain the profits generated by this development within the region.

Oil and gas development is the most important type of resource development in the Arctic region, and studies have shown that their reserves are extremely large. The focal point is the Russian Arctic region. Oil and gas development in the Russian Arctic has been accelerated due to the maturation and decline of the Western Siberian oil fields, the existing major production area in Russia, and the utilization of the Arctic Ocean shipping routes. However, the economic sanctions against Russia since 2014, the West's move to reducing its dependence on Russia after 2022, and the current trend toward decarbonization have put the brakes on such development.

Tourism and fisheries are another two industries that characterize the Arctic economy, despite their relatively small scale. First, as for tourism, summer cruising in the region had been growing steadily since the 2000s before the Covid-19 pandemic. The recovery trend after the end of the pandemic remains to be seen. Second, the fishing industry is one of the key industries supporting local employment in some Arctic regions such as Alaska. While the fisheries in the region mainly consist of capture fisheries such as those for pollocks, the importance of aquaculture fisheries, such as of those for Atlantic salmon, is gradually gaining importance. Climate change is expected to significantly affect this industry in the future.

In the Arctic region, the standard of living is highest in its North American section, followed by its Nordic and Russian parts, in that order. It is not that the standard of living in those respective Arctic areas is necessarily lower than their national average. In fact, in some regions, the living conditions are higher than the national average. A reason for this is the significance of the resource extraction industry in the Arctic economy, but a further detailed analysis requires future development of statistical datasets.

The Arctic region has been relatively strongly affected by climate change, and its economic impact, such as that through infrastructure damage caused by permafrost degradation, is notable. Other major environmental issues faced by the region include the black carbon problem and ecosystem change.

Research priorities

Economic research

There are needs for economic research that takes into account long-term trends affecting the region as a whole, such as the changing regional security environment, the global move toward decarbonization, a warming climate, and declining birthrates and aging populations. To this end, the utilization of regional frameworks for cross-national cooperation, such as the Arctic Council, can be effective.

4-3 International Law

The rapid changes occurring in the natural environment and human society in the Arctic have led to the formation of new international law on the Arctic. Among the various issues related to the Arctic, the protection and conservation of the Arctic environment and biodiversity, sustainable use of the Arctic and its resources, and ensuring respect for the rights of the peoples of the Arctic, including Indigenous Peoples, are among the issues that have been actively discussed from the perspective of international law. With regard to the protection of the environment and the conservation of biodiversity, the implementation of global conventions such as the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity in the Arctic, as well as cooperation on this issue among the countries concerned, have become important issues. Regarding the sustainable use of the Arctic and its resources, there is attention on the regulation of the Northern Sea Route and cooperation for the conservation of living resources under the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean, and the sustainability of resource development on land and its impact on Indigenous Peoples. The rights of the peoples of the Arctic have been discussed in the Arctic States by referring to and applying international human rights treaties. In addition, international cooperation in the field of science has become an important cross-sectoral theme, as measures to address issues in the Arctic need to be formulated based on scientific knowledge.

As a long-term research strategy, research on the above major topics of international law in the Arctic should continue to be conducted, taking into account new developments. Most recent developments include the application of the Agreement on the Conservation and Sustainable Use of Marine Biodiversity in Areas beyond National Jurisdiction (BBNJ Agreement), adopted in June 2023, to the Central Arctic Ocean, and the implications of a currently-negotiated treaty to regulate plastic pollution for the Arctic. It will be important to continue to deepen the analysis of the state of international law in different areas, taking into account the formation of new rules of international law. At the same time, however, taking a more integrated approach to issues that have hitherto been discussed as separate issues is extremely important. It is more necessary than ever to consider the interrelationships between treaties that have been formed separately, to take an integrated approach to the protection of the terrestrial and marine environment, and to conduct cross-sectoral research from perspectives that are of importance in the Arctic region, such as scientific cooperation and the rights of indigenous peoples.

Research priorities

- To consider the implications of new developments in international law that contribute to the conservation and sustainable use of the Arctic and its resources, including the recent BBNJ agreement and the global plastic treaty that is currently being negotiated
- To pursue a more integrated approach to the protection of the environment and conservation of biodiversity under international law that cuts across different treaty regimes and issue areas that have hitherto been discussed separately

5 Cross-cutting subjects

5-1 Indigenous Peoples' Rights and Movements

Indigenous peoples of the Arctic have become an integral part of policy decisions related to the Arctic. For example, the six Arctic indigenous peoples'organizations are permanent participants at the Arctic Council, a forum that seeks to promote cooperation, coordination, and interaction among Arctic states on common Arctic issues, and have a significant influence on the Council's activities. In this section, the authors review the current Japanese and global state of research on rights and movements, who have become nonnegligible actors in the Arctic, and further outline future research agenda.

First, the role played by Arctic indigenous peoples' organizations, particularly the Sami Council and the Inuit Circumpolar Council (ICC), in the drafting of the United Nations Declaration on the Rights of Indigenous Peoples (hereinafter the UN Declaration), and in the establishment and practice of international organizations related to indigenous peoples, is examined.

Second, the authors primarily indicate that studies have been conducted in the field of cultural anthropology on how indigenous peoples, being most vulnerable to the effects of climate change, have adapted to environmental changes by changing their cultures and means of living, etc. Furthermore, the research in the field of international law examines the significance of the human rights approach to climate change in the context of the Paris Agreement and the related UN meetings, advocated by indigenous peoples in the Arctic, and the role played by it.

Third, authors examine the process by which the Ainu people were officially recognized as indigenous, and the " Ainu Policy Promotion Act" was enacted in Japan and how the UN

Declaration is respected in the international forest certification system. They also introduce the developments regarding the recognition of the Ainu people as an indigenous minority in the Russian Federation.

Research priorities:

- In future studies, while paying attention to how the UN Declaration will be institutionalized and implemented in the Arctic, it is necessary to review the possibilities and challenges of UN activities by indigenous peoples to date, and to study other Arctic indigenous groups besides the Sami and Inuit, that have not been focused on till date.
- Future studies should clarify the Arctic's uniqueness, through comparative research with indigenous peoples' organizations around the world. They should also focus on the distinction between local communities and indigenous peoples in the United Nations Framework Convention on Climate Change (UNFCCC) regime.
- For future studies, it is essential to build and expand research networks that can collaborate with the Ainu, for making research fair to indigenous peoples.

5-2 Natural Resource Development and Adaptation to Disasters

In the Arctic region, human activities adapt to the various constraints of the cold environment, from subsistence use of the natural environment to the development of mining resources. However, the foundation of these activities is being shaken from the ground up by catastrophic events associated with climatic and environmental changes progressing throughout the Arctic region. Adaptation of resource development and livelihoods to environmental changes is in the phase of shifting awareness and activity patterns that will lead to social implementation, requiring further accumulation of integrated knowledge through interdisciplinary collaboration based on clarification of actual conditions and future projections. This section proposes the current status of research and future long-term research strategies for the following four high priority and noteworthy events.

(1) Changes in ground-bearing capacity for urban and settlement structures in permafrost zones

Warming and thawing of permafrost, which is widely distributed in the Arctic region, reduces the ground-bearing capacity of cities and infrastructure and causes significant damage due to heterogeneous subsidence of the terrain, making sustainable development difficult. Detecting topographic displacement by synthetic aperture radar satellites is effective in assessing the vast area, and analysis on the circum-Arctic scale is necessary in conjunction with future projections of permafrost thawing.

(2) Coastal erosion and flooding

Coastal erosion in the Arctic Ocean and along the coasts of rivers is progressing significantly due to sea ice reduction and permafrost thawing, and the actual situation is being clarified on the circum-Arctic scale. On the other hand, understanding of flood occurrence and damage is not fully understood, and localized information on local communities is lacking. In the future, in addition to wide-area assessments based on meteorological and oceanographic observations and satellite data analysis, detailed collaborative research on the impacts on local communities about their livelihoods will be necessary.

(3) Use of ice on rivers and lakes and its sustainability

Rivers, lakes, and seawater surfaces that freeze in winter are used in various ways by human activities. Ice roads are a vital winter transportation infrastructure, but engineering knowledge of their vulnerability to climate change remains limited. In addition, changing traditional subsistence activities, such as winter under-ice fishing, is an essential socio-cultural issue. These are considered research issues that should be treated as applications and practices of climate adaptation.

(4) Risks of environmental pollution and disasters associated with economic development

Environmental pollution accompanies resource development in the Arctic region and has the potential for a wide range of impacts due to accidental incidents. Combined pollution and disasters can significantly impact the very survival and livelihoods of the inhabitants, including indigenous peoples, who use the surrounding natural environment. There are still few examples of studies on environmental pollution and disaster risk, and integrated studies are needed on the relationship between environmental conservation and possible disasters in economic development and accident response.

Research Priorities

- A combined satellite remote sensing and field verification study of changes in the ground-bearing capacity of urban and settlement structures in the permafrost zone
- Study on coastal erosion and riverine flooding by estimating erosion rates and flood impacts around settlements
- Engineering assessment and social anthropological research on the use and sustainability of river and lake ice concerning the duration and intensity of its availability
- Research on the risk of environmental pollution and disasters associated with economic development, including assessment of disaster occurrence and pollution spread and its impact on indigenous peoples' use of natural resources

5-3 Living environment and security — Changes in the Arctic environment for people living there —

Rapid warming and environmental changes in the Arctic region are demanding changes in the lives of people who have long lived in the region by adapting and utilizing the environment. These drastic changes are also creating various social problems in the region. The "Living Environment and Security" section discussed the challenges of Arctic environmental change from the perspective of the people living in the Arctic.

The "Food" section discussed issues related to food in the Arctic region, including issues related to fisheries, livestock and agriculture as industries, as well as those related to "food sovereignty", as the unique systems and cultures of Arctic residents and indigenous peoples. The distribution and abundance of fish species and marine mammals in the oceans, as well as those in terrestrial vegetation and riverine fisheries, have undergone drastic changes in recent years, with direct implications for the food industry and the diets of indigenous people. The multifaceted study and analysis of possible countermeasures is of great importance as a future cross-disciplinary research topic.

"Water Resources and Water Use" analyzed the state of water resources in the Arctic environment, and describes the different forms of water use and the impact of environmental change on them. It was pointed out that the annual precipitation in the Arctic region is similar to that in the semi-arid region, and was also mentioned that water resources are mainly secured by snowfall and river water (ice) in the cold season. From a social anthropological perspective, there are different patterns of water use adapted to each region of the Arctic. The impact of recent warming and permafrost degradation on water resources is an important research issue from a hydro-climatological perspective, and comparisons in terms of indigenous knowledge, history and culture are crucial for the sustainability of water resources and water use under climate change.

In "Pollutants and health effects", the authors reviewed pollution issues specific to the Arctic region and summarized some of the most pressing issues, including plastics. Although international regulatory efforts are underway in some areas, the lack of observational data is still a problem, and much research is needed, including an assessment of human health risks. It is suggested that pollution and health issues to be included in the future research topics in combination with various environmental studies. It is necessary to design research studies that meet the needs of the region, including methods for releasing and sharing data.

5-4 Summary and Implications

Chapter 5 brings together several cross-disciplinary discussions on Arctic research. The Arctic is at the forefront of environmental change due to rapidly rising temperatures; it is also a region where approximately four million people, including indigenous peoples, live. Inevitably, the various impacts of changes in the natural environment on human society are the subject of research. Historically speaking, Japanese Arctic research has focused on themes that delve into each subdivided research field. In addition, the fact that Japan's first national project on the Arctic began as a study on global warming led to a heavier focus on Science, Technology, Engineering and Mathematics (STEM)-oriented research themes. In recent years, however, Japan's Arctic scientific community has recruited, promoted, and encouraged cross-disciplinary research. The results of these efforts are gradually emerging, as documented in this chapter.

With regards to the future of Japan's Arctic research, three types of efforts are required. The first is to continue ongoing efforts to gather information and examine the impacts of various internal (domestic) and external changes. Examples include the role of UN activities and international norms on indigenous rights and movements, climate change, UNFCCC and their impacts on indigenous organisations, the Ainu Policy Promotion Act of 2019 as well as the UN Declaration on the Rights of Indigenous Peoples.

The second necessary effort is to fulfil information and knowledge gaps. There are people with Ainu ethnic identity in Russia but our knowledge of them is limited. We can consider building research networks that enable cooperation with Ainu people in Japan and abroad. Our knowledge of winter roads engineering has not kept pace with the development of transport infrastructure with regards to ice roads in the Arctic. In collecting data, the authors call for closer cooperation with residents and careful consideration in selecting target areas of study. This is particularly the case with the ground bearing capacity of structures in cities and settlements in the permafrost zone.

The third type of effort required is to further improve the transdisciplinary, comprehensive aspect of Japan's Arctic research. The practice of trans-disciplinarity is essential in understanding environmental security, including pollution, food, and other scarce resources like water in the Arctic. Overall, all discussions expressed concerns about recent changes in the international political situation, which has distorted international research exchanges and may have long-term consequences. Last but not least, the significance of gender should be mainstreamed throughout the Japanese Arctic research.

6 Research infrastructure and capacity building

6-1 Icebreaker observation

In the Arctic region , where the impact on the climate system is significant, the spatio-temporal in-situ data are essential for advancing the Arctic research. Currently, Japanese Arctic Ocean observations are conducted either by its own ice-strengthened ships or by icebreakers of other countries, each of which has its own limitations in terms of timing, area, personnel, budget, etc. In particular, the use of icebreakers of other countries has been limited by the political trends of each country and always entails the risk of interference with the observation program of the home country, as well as other problems that cannot be ignored, such as restrictions on the use of data. In addition, icebreakers of other countries may not be research vessels, such as vessels belonging to the coast guard, and they may not have adequate facilities such as observation equipment and laboratories, and their research missions are not given high priority. Even if an icebreaker is used for research purposes, it may not have personnel with advanced observation skills on board. In addition, the costs involved in transporting (importing and exporting) observation equipment and samples to and from icebreakers in other countries, as well as dealing with accidents and problems, are a heavy burden for research in fields that require on-site analysis and experimentation. These have been a major disincentive to research and data acquisition in Japan.

In order to advance Arctic research aimed at understanding the global climate system and improving the accuracy of future projections for the Arctic region, it is essential to carry out the observational research by making maximum use of Arctic research vessels with icebreaking capabilities, responding flexibly to the rapidly changing Arctic Ocean atmosphere-sea ice-ocean system and acquiring in situ data and samples that capture ongoing changes. In order to develop Japanese own Arctic research in the future, it is necessary to establish a system that can deploy in-situ observations (including on ice), manned observation stations, and unmanned observations (AUVs, drones, etc.) using icebreaker as platforms, and to expand observation research throughout the Arctic Ocean including organic collaboration with other countries.

6-2 Satellite observation

In only half a century of satellite-based earth observation, it has played an important role in making humans aware of the fragility of the global environment, for example, by detecting the shrinkage of the Arctic sea ice extent and snow cover in the northern hemisphere. Earth observation satellites are already an indispensable and important research infrastructure for efficiently and continuously monitoring environmental changes in the Arctic region, which is vulnerable to the effects of global warming. In particular, observations using microwave radiometers began in the 1970s, and the AMSR series developed by Japan has been leading the world's sea ice observations since 2002. The medium resolution optical radiometer has been in operation since the 1970s and has contributed to the observation of a wide range of geophysical parameters on the ground surface (snow and ice, vegetation, ocean areas) and in the atmosphere (clouds and aerosols). Japan has also launched the SGLI in recent years.

Active radar observation has been effective in understanding quantitative changes in glaciers, ice sheets, sea ice, vegetation, etc. The PALSAR series, Japan's leading L-band synthetic aperture radar, has contributed to observations of flow rates in glaciers and ice sheets, land subsidence caused by permafrost thawing, etc. The PALSAR series has also been used in the field of ice sheet observation. The PALSAR series, the leading L-band synthetic aperture radar, contributes to observations of flow velocity in glaciers and ice sheets, land subsidence due to permafrost thawing, etc. Observation of clouds and aerosols, which are important for the Earth's radiation budget, requires radar and lidar for vertical profiles and optical radiometers for areal profiles. The EarthCARE satellite, which is scheduled to be launched in FY2023 jointly by Japan and Europe, will be equipped with the cloud radar developed by Japan and the lidar and optical radiometer developed by Europe at the same time, and is expected to contribute to the elucidation of the three-dimensional structure of clouds and aerosols.

In Japan, satellite observation data is already being used for a wide range of research on the Arctic environment, and further improvements in sensor performance, such as higher sensitivity, higher resolution, and more wavelengths, are desired in collaboration with the development plans of space agencies around the world. On the other hand, in order to extract long-term variation trends from satellite observation data and to be able to discuss the existence of climate and environmental changes with statistical significance, it is very important to continue to develop satellite sensors with the same design concept, such as maintaining the same observation wavelength and frequency band of the sensor and adopting the same satellite orbit (observation altitude and time). It is very important to continue to develop satellite sensors with the same design concept, such as maintaining the same wavelength and frequency band and adopting the same satellite orbit (observation altitude and time).

6-3 Aircraft observation

Aircraft observation is an effective means of Arctic researches in a wide range of fields of earth science. In atmospheric science, in particular, it is the only means that enables direct three-dimensional observations (internal diagnostics) of atmospheric elements. In research fields of snow and ice, oceans, land, and vegetation, remote-sensing from aircraft is also effective means of observation. Japan has some of the best observation technologies in measuring atmospheric greenhouse gases, aerosols, and cloud/precipitation. However, unlike Europe and the United States, Japan has not been able to conduct systematic and continuous aircraft observations in the Arctic because it does not have an aircraft dedicated to earth observation. In order to conduct future Arctic research, it is highly desirable to introduce an aircraft dedicated to earth observation that can conduct Japan's own Arctic observation projects, and to establish a system to operate the aircraft for joint use. The establishment of an observation system is necessary as soon as possible because of the rapid Arctic warming and the accompanying major environmental changes in many areas.

On the other hand, it is expected that unmanned aircraft, including drones, will be used more frequently in future observations of the Arctic region due to their high mobility, economic efficiency, and safety. Currently, the weight of onboard equipment and the observation area are limited. However, it is necessary to push forward the advancement of unmanned aircraft themselves and the development of measuring instruments to realize various earth observations.

Research priorities

Because Japan does not have an aircraft dedicated to earth observation, it is highly desirable to introduce such an aircraft and conduct Japan's own Arctic observation projects. It is also necessary to develop technologies to use unmanned aircrafts and measuring instruments to enhance various earth observations in the Arctic.

6-4 Overseas Observation and Research Centers

After the long Cold War between the U.S. and the Soviet Union, the Arctic was liberated in the 1908s, and the International Arctic Science Committee was established in 1990. In Japan, too, the National Institute of Polar Research established a Japanese Arctic observation base in Ny-Olson, Svalbard in 1991, and other institutions such as JAMSTEC, Hokkaido University, and Nagoya University established observation and research bases in Yakutsk and Fairbanks. Later, the Japanese Arctic research projects GRENE and ArCS have also been actively establishing and expanding overseas observation and research bases.

It is essential for Japanese researchers who do not have a territory in the Arctic to have a relationship with local researchers and institutions so that they can cooperate with each other for local observations and observation bases. For the sake of research efficiency and user convenience, it is desirable that major Japanese Arctic research institutions that have joint research and use projects conclude agreements with local researchers and institutions on research cooperation and bases in advance. If long-term continuous observation is an important element of the project, it is necessary that the agreement be concluded by a Japanese institution that possesses a system that can be maintained over a long period of time. Also, due to the nature of the agreement, it is desirable that mutual access with researchers from the partner country or institution is possible.

In addition, it is necessary to collaborate with the local community from the research planning stage, while taking into consideration the local community. In the Arctic region, where many people live, there is a need for researchers to deepen their expertise based on their academic interests, as well as to accumulate diverse expertise on social issues and conduct observations and surveys with consideration for the local community. The formation of overseas observation centers in the future will require collaboration not only among researchers and research institutions, but also in consideration of the local communities.

(Summary of long-term issues)

-The major Japanese Arctic research institutions should have prior agreements with local researchers and institutions for research cooperation and bases.

-The institutions that enter into such agreements should have a mechanism to maintain them over the long term.

-The agreement should allow mutual access to researchers in the partner country or at the partner institution.

-The formation of overseas observation and research centers requires cooperation that takes into consideration not only the researchers and research institutions, but also the local community.

6-5 Human Resource Development

Medium- to long-term activities are needed to foster young researchers who will be responsible for Arctic research and have an international perspective. To this end, outreach to high school and undergraduate students who have not decided the future research field, and the development and clarification of career paths after obtaining degrees are required, while keeping in mind the need to resolve the current serious gender imbalance. In addition, the program is expected to contribute to the development of young indigenous researchers internationally.

6-6 Research Promotion System

Arctic research requires the sharpening of specialized fields and interdisciplinary collaboration. In addition, there is a need not only to explore scientific truths but also to connect with society, such as social fields such as industry and resource development, and government agencies and local governments that carry out policy activities. International movements in Arctic research are diverse and change rapidly, and international cooperation is frequently called for. To respond quickly and appropriately to these global trends, researchers should strengthen their activities, build cooperative systems, obtain information on international trends, and participate in domestic and international decision-making; an approach to promote them is necessary.

(Current Status)

Since 2011, Japan has promoted the flagship research projects. They call on scientists to have intent and participate in the holistic project. In addition, there have been many opportunities to examine issues that transcend the specialties of each field in the last decade. As for opportunities to connect with international research activities, we have been promoting activities such as holding and participating in ASSW in Japan in 2015, participating in IASC activities, and hosting the internationally recognized ISAR-7. The government's policy review and involvement in the Arctic have also been promoted with the participation of observers in the Arctic Council. The National Institute of Polar Research, JAMSTEC, which is the core of Japan's Arctic project, Hokkaido University, and many other universities in Japan maintain the research promotion system, provide opportunities to use observation stations and research vessels and provide opportunities to think about requests and ideas. The Arctic project maintenance system depends on each organization's budget and operating costs, and the expectations and burdens on them are high.

(Long-term strategy)

Short-term, focused, and mobile research practice by relatively small groups will be the substance of the academic activities. Group formation and exercises should be promoted while inviting new researchers, which will grow into a large community with high motivation.

On the other hand, the national government's involvement in international Arctic activities, discussion and promotion of strengthening research capabilities of the entire country, and investment of resources will involve calls for cooperation and long-term maintenance under the core concept study group organization. Cooperative institutions can have that function. Regarding understanding and participation in international trends, moving from individual involvement to group contact, participation, and support is necessary. SAON is that model, so increase its awareness, domestic engagement, and support. Initiating exchanges with governments should be structured more robustly. Create more diverse and long-term opportunities to connect with stakeholders and society.

6-7 Research equipment by field, etc.

6-7-1 Atmosphere

Complementary atmospheric observations by combining ground-based, shipboard, unmanned and manned aircraft, and satellite are required. In order to make diverse analyses and cross-disciplinary studies, it is effective to gather a variety of measuring instruments at super observation sites such as Ny-Alesund in Norway and Utqiagvik (Barrow) in Alaska.

6-7-2 Middle and upper atmosphere

It is important to establish a global radar network that includes Japan's own large atmospheric radar plus the EISCAT_3D radar, which will provide an extremely strong research base for global atmospheric environment research.

In addition to single satellite remote sensing, it is essential to conduct simultaneous combined observations by multiple satellites and direct observations of areas where satellites cannot fly, using small observation rockets and balloons.

It is important to develop and maintain instruments for observing atmospheric gravity waves and ionospheric variations in the Arctic region, and to concentrate these instruments at observation sites such as EISCAT radar sites, which are equipped with large instruments capable of high-precision measurements.

It is important to conduct comprehensive monitoring of the middle and upper atmosphere by establishing a joint research system with domestic and foreign research institutes.

In order to link satellite and ground-based observations with simulation research, it is necessary to further refine models, introduce detailed coupling processes, and develop data assimilation.

It is also important to construct an environment and develop analysis methods, such as the use of machine learning, which has been making remarkable progress in recent years.

6-7-3 Snow and Ice

Continuous efforts should be made to innovate the field observation methods themselves and to improve their quality control methods.

In particular, it is important to seek new collaboration with engineering researchers and promote research and development for upgrading and automating portable observation instruments.

It is essential to deepen domestic and international collaboration to build as tight an observation network as possible, linking specific fixed-point and regional observations.

6-7-4 Terrestrial ecosystem and material cycles

Long-term and wide-area monitoring of ecosystem material cycles using micrometeorological methods and remote sensing methods (UAVs, aircraft observations, earth observation satellites) exist as representative long-term and wide-area observation methods for terrestrial ecosystems in the Arctic region. For the eddy correlation method, which is a representative micrometeorological method, it is important to disclose and share observation data. Although UAVs and aircraft observations are widely used, correct operation in accordance with the laws and regulations of each country is required. For satellite observations, it is important to promote analysis of wide-area environmental changes through the combined use of data from various satellites, including optical sensors and microwave sensors.

6-7-5 Ocean

It is crucial for enhancing our understanding of the Earth system to particularly refine the atmosphere-sea ice-ocean model through continuous and wide-ranging observations. To achieve higher-resolution observation data, the following developments of observation systems or approaches are highly anticipated: 1) advanced onboard instruments capable of withstanding extreme low-temperature conditions in polar regions, 2) autonomous and controlled observation capabilities of underwater robots (AUVs and ROVs) to leverage their respective advantages, 3) networked mooring systems and drifting buoy systems, 5) a large-scale seafloor coring system enabling the reconstruction of paleoclimate over thousands to tens of thousands of years, and 6) a comprehensive sea ice monitoring approach utilizing buoys, satellites, manned/unmanned aircraft to track sea ice mass balance and morphological changes. Furthermore, collaboration with private vessels and the establishment of coastal observation stations are also anticipated, particularly in conjunction with the utilization of the Arctic Ocean route.

6-7-6 Numerical modeling

The research infrastructure for numerical modeling first includes hardware aspects such as computers, storage, and networks. In addition to securing sufficient computing resources on state-of-the-art large computers, preparing a set of practical servers, large-capacity storage, and high-speed networks that can hold and publish data and contribute to the analysis of experimental results and model development is necessary. On the other hand, on the software side, in addition to numerical models, it is essential to maintain and grow a community of researchers who develop and use them. Depending on the scale of the model and the community, it is necessary to set up an appropriate organization, such as a model center, and to pursue methods of releasing models, such as open source, in a manner that upholds modeling diversity. In addition, the Arctic community must stably employ human resources who are well-versed in the latest computer science and computer management techniques.