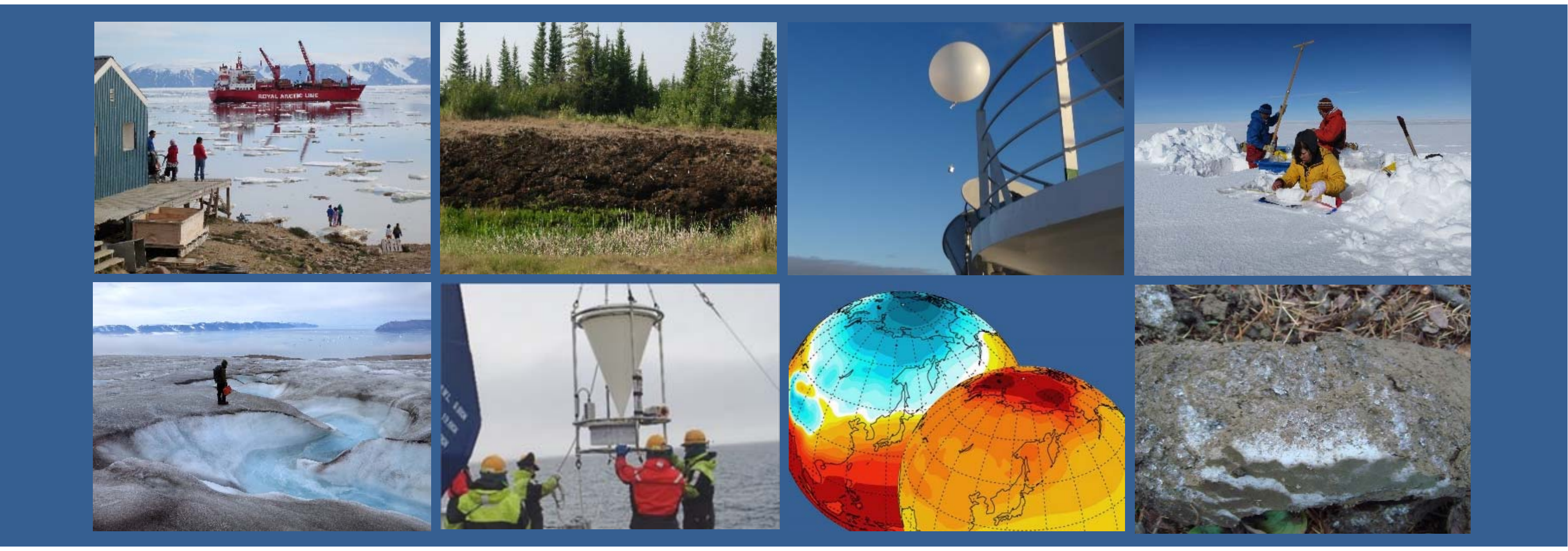
Long-term Plan
for Arctic Environmental Research

Japan Consortium for Arctic Environmental Research



Summary Edition

November 2014

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This booklet is the summary edition of "Long-term Plan for Arctic Environmental Research" published by Japan Consortium for Arctic Environmental Research (JCAR). For details, you should refer to the whole edition, which you can find at the following web site:
http://www.jcar.org/english/

Long-term Plan for Arctic Environmental Research
Summary Edition

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1. Introduction

(1) The purposes of the long-term plan report

In this plan, Arctic environment specialists aim to present research direction for the resolution of environmental issues to citizens concerned with environmental problems and researchers in various fields. The primary concern on the environment is global warming. In particular, it is said that the Arctic is experiencing warming more than twice as quickly as the global mean warming, and dramatic changes in snow and ice covers which have been observed are drawing our attention. It is accepted that despite global warming, some areas sometimes undergo cooling. This is due to atmospheric circulation variability where air temperature may go up and down from year to year with certain spatial patterns, while global warming has a time scale in the range of several decades to centuries. Therefore, after experiencing unusually cold winters, it is understandable that some doubt the existence of global warming and question which direction Japan will take.

Let us move onto the map (Fig.1). By studying the Arctic, it has become apparent that during summer, open water areas exist which were covered by sea ice in a whole year until some years ago. The region off the Siberian coast already experiences only seasonal ice cover. The future projections indicate that seasonal ice cover will expand across the entire Arctic Ocean around the middle of this century, although some models suggest this will be rather sooner at ten years from now. Whilst simulation models are necessary for future projections, some may question their reliability. An even more difficult question is when the Arctic Sea Route will become substantially available.

The distribution of vegetation, which is mainly controlled by climate, will increase under gradual warming in the middle and high latitude areas. As soil moisture is crucial, vegetation is dependent on precipitation and the length of snow cover. There are concerns that forest ecosystems are not easily transferable and hence may not be able to follow climate change. When anthropogenic influences such as deforestation and development are included, changes in the biodiversity and biota become difficult to estimate. Human beings keep an issue to preserve biodiversity, which provides the foundation of terrestrial ecosystem services [1] and determines the level of response to environmental change. Terrestrial vegetation supports wild animals, which are subsequently hunted for food by indigenous people in the Arctic area. Their traditional culture provided many treasures to global citizens. The situation is similar for the marine ecosystem where changes in marine biodiversity and biota are crucial to the ecosystem services which support residents around the oceans. Both agriculture and fisheries are influenced by the climate, however, there is one significant difference: i.e., agriculture can be managed to some extent by maintaining water resources and choice of crop species, whereas the fishery is dependent on the more complex natural environment, with issues regarding food chains and conflict among different species.

It should be noted how glaciers, ice sheets and permafrost are changing, which are unique features in the Arctic. The rapid degradation of the Greenland ice sheet during this century is well known, because it is crucial to future sea level rise. Shrinkage of mountain glaciers varies from place to place, but the global decrease rate is monitored only at certain degree. In contrast, the permafrost is more challenging to monitor, as it also has an environmental impact when its thawing affects vegetation and river flows, as well as the release of greenhouse gases from decomposing carbon-containing compounds. The recent increase in Siberian river discharges is attributable to an increase in precipitation, and possibly thaws permafrost along the rivers.

In light of the factors mentioned above, paleoenvironmental research uses analysis of past climate changes recorded in strata and ice sheets to verify simulation models for future predictions. An interesting, broader view includes the timing of the development of the semi-closed Arctic Basin, and its consequences on climate in the Arctic Ocean and coastal areas. The impact of the upper atmosphere on the stratosphere and troposphere, in accordance with variable solar activities, is another example. Not limiting to natural sciences, wider attention should be directed toward the humanities and social sciences: e.g., how to develop collaborative relationship between the indigenous residents and recent immigrants. We would expect readers to understand these concerns when reading through this report, and generate ideas for resolving them.

[1] Ecosystem services: Benefits that human being receives from ecosystems: i.e., main ones are food, mental and cultural benefits, and also mitigation of climate and water environment, extending further to oxygen supply and carbon dioxide absorption.

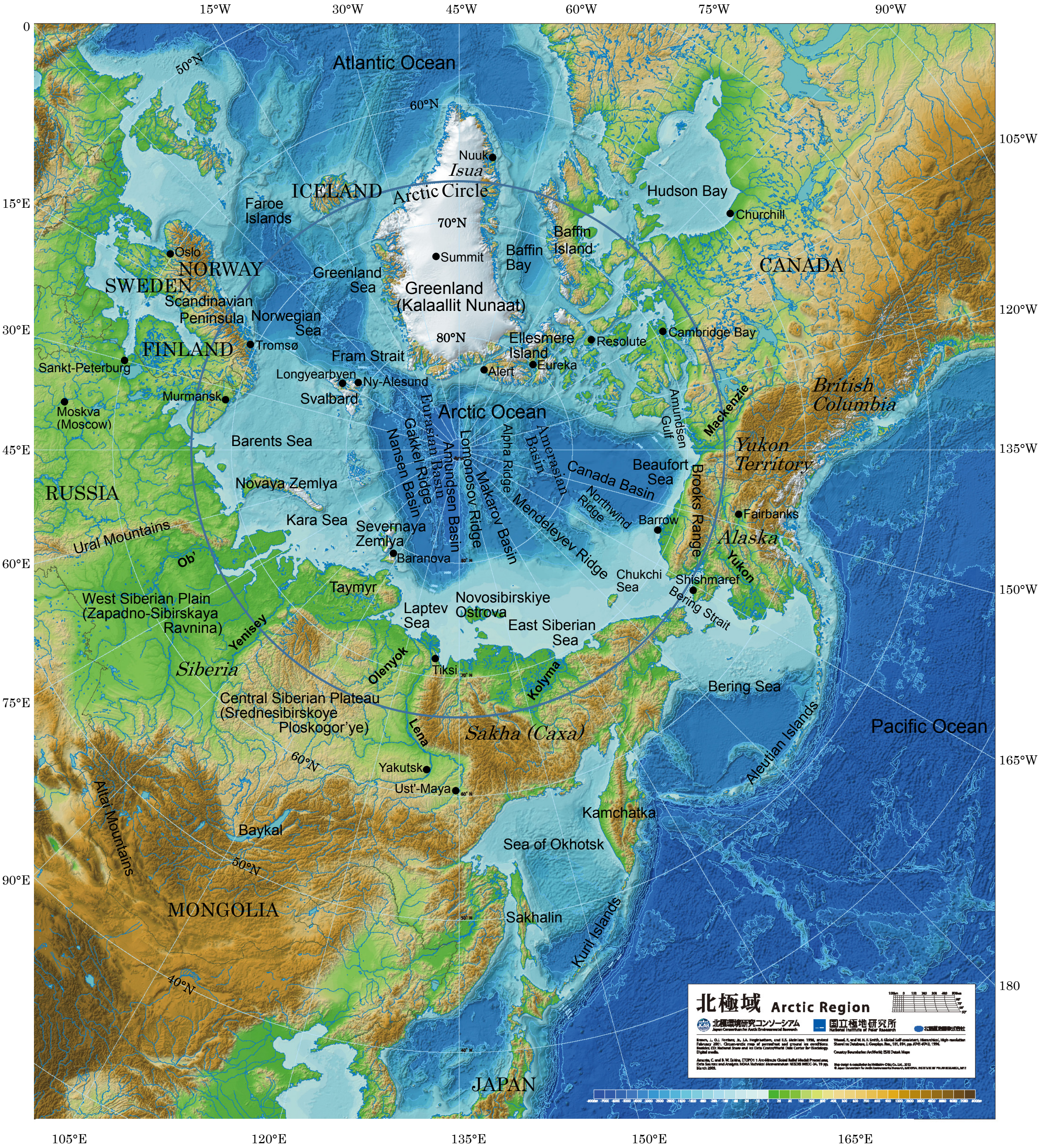

Figure 1: A map of Arctic region displaying the main geographical names which appear in the long term plan (full version). The original map can be downloaded from the JCAR website.

(2) The background and particulars of this report

The long-term plan was proposed in the Basic Policy Terms of the on-going GRENE Arctic Climate Change Research Program[2] and moreover in the prospectus and agreement of JCAR[3]. Up to now, no long-term plan has focused on Arctic environmental research in our country, hence, it is important to present analyses of the current status and future direction to be taken. It is no exaggeration to say that the fact that this long-term plan has been developed by JCAR has confirmed its existence. This plan reflects the hopes of the next generation of researchers, encouraging forward progress toward common goals by working together.

It is sensible to select enhanced warming and biodiversity as the two foci of Arctic environmental research, since international programs are already in place to establish the current status, make future projections, and provide proposals for management. The advantage of JCAR is that it consists of various disciplines, which will enlighten each other. Therefore, the plan is organized around the core subjects, which should be tackled in collaboration. Although environmental research has previously been carried out in the Arctic, global warming and biodiversity have not been directly focused on. Therefore, this research may not only enhance the activities of JCAR as a community, but also provide important, new information on global warming and biodiversity. Furthermore, this report includes guidelines to develop research infrastructure, construction of a platform for the research and capacity building.

(3) Contents of this report

Several themes have been chosen for each of the four objectives set here, starting with the changes and variations in the states to date, alongside a review of the research progress. We describe each theme, identifying gaps in the current understanding, and then suggest necessary research paths and systems for the next 10 to 20 years. The report is structured so that readers who are not familiar with science and researchers who are not involved in Arctic research, initially read the introduction about social concerns and then progress further into more specialized information with the deeper insights.

The four objectives are as follows. The first one, which is the background for formation of JCAR, is research on "Understanding of the abrupt-complex phenomenon and elucidation of the mechanisms and impacts associated with global warming enhanced in the Arctic, along with improvement of their future prediction". In this objective, seven themes have been selected such as amplification of warming in the Arctic. The second one, research to elucidate "Biodiversity in land and ocean, and also the effects of anthropogenic environmental change on ecosystem, not limited to global warming" is divided into terrestrial and marine themes. The third one covers "Broad and important research on the Arctic environment and its fundamental information" and includes three themes such as the geospace environment surrounding the earth. The fourth objective covers three categories of methods related to the previous themes, "Monitoring, modeling and integration of the two, enabling breakthroughs in environmental research".

Many of the environmental changes considered for these objectives contain complicated interactions among the atmosphere, ocean, cryosphere, land surface, geochemical cycle, and ecosystem. Hence, this approach activates inter-disciplinary research. In turn, this encourages a deeper understanding of each discipline and leads to exploration of unexplained phenomena. The forth objective encourages breakthrough research from the development of innovative methods of observation and modeling, not confined within the improvement of techniques.

2. Changes in the Arctic environment to date and in the near future

Let us consider the scientific questions for the academic experts as to how the Arctic environment has changed over time and will continue to change during this century. We also introduce progress in research, including the current direction, which has already been addressed. First, multi-disciplinary issues are described in association with the objectives of this long-term plan. Most of these issues are receiving attention from the ongoing GRENE program.

The various factors that cause warming over the global enhanced in the Arctic and are in turn affected by the

[2] GRENE Arctic Climate Change Research Project: project funded for 5 years starting in FY2011 by the Ministry of Education, Culture, Sports, Science and Technology-Japan (MEXT) within the framework of the GRENE (Green Network of Excellence) Program.

[3] JCAR: Japan Consortium for Arctic Environmental Research, a nationwide network-based organization for promoting arctic environmental research.

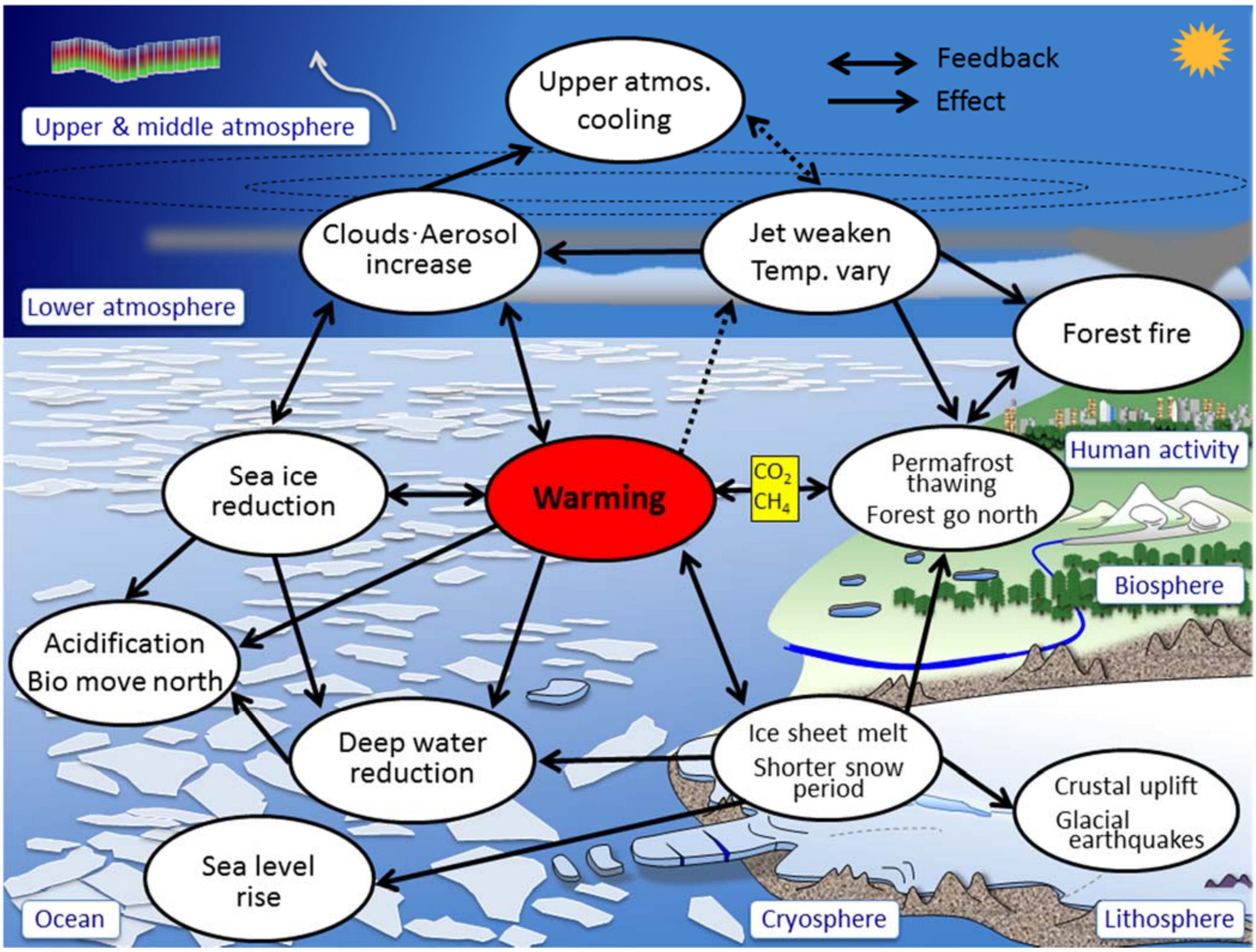

Figure 2: Crucial changes in the atmosphere, land, cryosphere and ocean, in response to current climate change, along with the effects (one way) and feedback (two ways). Note that while only major changes and interactions are displayed, other variations may exist. The solid arrows denote confirmed interactions, and the dotted ones denote more hypothetical ones. Also, the interactions between clouds and global warming can work both ways: e.g., the presented feedback is important in seasons other than summer, although clouds shield solar radiation and reduce sea ice melting in summer. In addition, forest fires occur without global warming, but are becoming more frequent.

phenomenon, are shown in Fig.2, where the warming is the pivotal point. For example, sea ice reduction and shortened and reduced snow cover occur as a result of global warming, and then contribute to a reduction in albedo (reflectance of solar radiation), making feedback to the Arctic amplification of the warming. Water vapor increases as a result of the air temperature rise, and hence, clouds and aerosols (air containing fine particles) increase. The effects of clouds are dependent on the season, while they increase the downward longwave radiation except for summer, contributing to warming at the earth surface. A future research topic will be to project quantitatively how much more rapidly the Arctic will warm up in comparison to the global average.

Greenhouse gases absorb longwave radiation from the earth's surface, causing the troposphere to warm up. In contrast, the stratosphere and upper atmosphere have been reported their cooling down. When temperature changes differ between the low- and high-latitudes, and between the lower troposphere and the upper atmosphere, various suggestions have been made regarding the feedback to the low-latitude atmosphere: e.g., how the jet stream around the Arctic changes, and whether meanders tend to grow more or not in the jet stream.

Global warming pushes the northern limit of forests northward, while permafrost tends to retreat, resulting in reduction of soil moisture and subsequent forest degradation in some areas. Once the warming affects atmospheric circulation through snow cover and the hydrologic cycle, feedback to the land surface should be considered, and hence, permafrost degradation and northward expansion of forests will vary by region. As a result of these changes, thawing permafrost may release greenhouse gases, while the growing forests will absorb carbon dioxide. Since soil moisture depends on precipitation, it is challenging to predict how vegetation will change. Improved prediction of ice sheet melting promote the correspondence of social infrastructure by estimating sea level rise, such as storm surges and lowland flooding.

The warming also affects the oceans. Cooling becomes weaker over the Greenland Sea, meaning that deep water formation under convection is reduced. Therefore, the driving force of the global conveyor belt[4] is weakened, or the deep water is reduced within the belt, resulting in a reduction of nutrient upwelling. In the Arctic Ocean and the surrounding seas, deep convection becomes weaker, impacting marine ecosystems. However, detailed investigations are necessary to judge the effects of changing conditions on both migratory species and the opposite ones. Acidification occurring primarily in the Arctic Ocean will have a large impact on the ecosystem. The partial pressure of carbon dioxide is determined by ocean temperature, inorganic carbon compound concentration and alkalinity, and increases under the global warming, although some unclear elements prevent prediction of the absorption of carbon dioxide in the ocean.

In order to retrieve useful information from the environmental variability of the past to enable predictions for the future, research activities have been focused on ice cores and marine bottom sediments, as well as exchanging knowledge with various other fields. A majority of this long-term plan is based on natural science, however, we also describe the social impacts of environmental change, and propose methods to respond to changing conditions with cooperation of the residents who rely on the Arctic area for their livelihood.

Next, we consider the on-going changes for individual elements of the Arctic environment and explore some academic questions. Around the atmosphere, increases in both longwave radiation from the sea surface and sensible and latent heat[5] fluxes due to sea ice reduction, will produce a significant change in the Arctic region. We need to improve the reliability of future prediction for the transition from stratus to stratocumulus by eliminating under- and over-estimation of cloud formation in a numerical model. Although increasing greenhouse gases modify the radiation balance, aerosols form cloud nuclei and enhance the cloud formation significantly in the Arctic, therefore we need to identify more appropriate processes. Atmospheric circulation patterns are modified by sea ice reduction and snow cover changes with spatial variability: e.g., the East Asian winter monsoon is modulated, giving anomalous weather around Japan. One of the necessary, but recently developing research topics, cover interactions of the Arctic area with interannual variability in the atmospheric circulation in the equatorial to mid-latitude areas.

As global warming occurs near the earth surface, the upper atmosphere becomes cooler. Monitoring the cooling provides us with an estimate of the global warming progress. The ozone layer, in the Arctic in addition to Antarctic, has been monitored, which highlights the need for continuous observations with regard to global warming. Since it has been suggested that solar activities affect the lower atmosphere, we should attempt to quantify the effects. Space plasma radiates along the magnetic field lines toward the polar region, producing various phenomena in the upper atmosphere such as aurora. Monitoring them from the ground helps us to examine the space plasma environment crucial to the safe and secure operation of satellites.

Let us consider the terrestrial cryosphere. As for ice sheets and glaciers, which melt and contribute to a rising sea level, we will investigate the dynamics and the energy/mass balance at the surface. Using observational data and modeling, we will be able to track the mass balance. Although the period of snow cover has been shortened over the high-latitude regions, snow depth and precipitation vary greatly in time and space. Therefore,

[4] Global conveyor belt: mainly driven by the North Atlantic Deep Water, but also involves other important driving mechanisms. In the Atlantic, the Pacific and the Indian oceans, heating and cooling work on the sea surface; salinity is reduced by precipitation and river inflow, and increased by evaporation. As a result, ocean circulation is induced along the meridional (north-south) plane, and hence, the North Atlantic Deep Water near the ocean floor in the North Atlantic flows southward in the Atlantic, eastward in the Southern Ocean, and northward in the Pacific, and then, rises to the surface layer in the North Pacific. It then goes through the Indian Ocean and returns to the Atlantic. This circulation pattern is called the Global Conveyor Belt.

[5] Sensible heat and latent heat: the cold and dry atmosphere takes heat from the ocean. Sensible heat flux is caused by a difference in temperature between the atmosphere and the ocean. Latent heat flux is induced by evaporation, and then, water vapor returns to the liquid phase and releases heat to the atmosphere.

the appropriate method is to combine continuous observations at stationary points and coverage with satellite data, where the northward shift and deterioration of forest zone are also monitored. It is examined quantitatively how much ice albedo is reduced by microbial effects, along with the effects of vegetation variability. We can easily imagine warming around the active layer in the upper part of permafrost, while the albedo and heat conduction are dependent on snow depth in early winter and will influence the loss near the southern edge. The net precipitation, which is precipitation minus evaporation, is thought to increase in time and contribute to river discharge into the Arctic Ocean. We should consider a complete picture of the hydrological cycle, by combining water vapor transport from the sea surface and mid-latitudes.

The terrestrial geochemical cycle remains as an uncertain component in identifying the global carbon fluxes. In the Arctic area, huge amount of organic matter in permafrost emits carbon dioxide and methane under global warming and large-scale forest fires. In addition to carbon, nutrients and trace metals also flow out to the ocean through rivers and due to coastal erosion, subsequently influencing the primary productivity of marine ecosystems. Contributions to monitoring of the environment are expected in Siberia, Alaska, Canada and Nordic countries.

Terrestrial vegetation supports wild animals, provides ecosystem services for human beings, and also has the capacity of feedback to climate change. It is well known that increased productivity of vegetation fixes more carbon dioxide, although the level of fixation is dependent on the abundance of nutrients. The other functions include reduction of albedo with the northward expansion of the forest zone, contribution to hydrologic cycle by soil moisture absorption and evapo-transpiration, and also arrangement of iron compounds for the marine ecosystem. Since reduced biodiversity yields vulnerability in environmental change, we should focus on exploring the biodiversity in the high latitude areas relatively behind mid- and low-latitudes.

Sea ice cover in the Arctic has noticeably reduced due to air temperature rise and ocean warming. Perennial sea ice has reduced all over the Arctic, shifting to a seasonal feature, which has happened most notably over the Siberian continental shelves. An increased flow of the warming Pacific Water into the Arctic Ocean is driving sea ice reduction. Based on historical records, our specialists should monitor oceanographic variability in the Pacific sector so that they may explore various components of sea ice and the processes. The inflow from the Atlantic region into the intermediate layer of the Arctic Ocean receives less brine rejection due to less ice formation in the Barents Sea, and hence, mixes with the Arctic surface water more easily. Thus, there is a need to investigate the processes associated with the seawater influx through the Barents Sea. Once we attempt a trial experiment to predict sea ice cover and movement with the navigability of the Arctic Sea Route in the near future, we will focus on a system to use satellite data and to develop numerical models.

Ocean geochemical cycles and the marine ecosystem will change, interacting closely with each other. Expansion of the seasonal ice-covered area tends to enhance the productivity, although it does not necessarily increase, for example, when circulation of nutrients is weakened under the freshened surface layer. The species that have lived in the adjacent seas continue to invade the Arctic Ocean, with the distinct possibility that the biota will be largely transformed. For the Arctic Ocean, which is under strong influences of river water spreading on the wide continental shelves, the research focuses on material exchange between the shelves and the basin, and the resultant responses of the ecosystem. As such, it is necessary to trace the effects of land-origin materials. In order to monitor the progress of ocean acidification, we should keep track the areas with under-saturated with calcium carbonate in the bottom layer of the shelf region and the surface layer of the basin. Our knowledge of the food-web and material fluxes from zooplankton to fish and birds is limited to early summer only, and hence, we have to build a platform to collect information during the other seasons.

Let us consider the phenomena over time scales longer than several hundred years. Paleoenvironmental data provide information on the interactions between temperature variability and geochemical cycles. Since the paleoclimate information is applicable to current environmental changes, the key issue is to develop and operate a research system under collaboration with various academic disciplines. Within the solid earth field, we focus on the effects of marine hydrothermal activities and seafloor geodetic on climate change through ocean circulation. As for the issues on the Greenland ice sheet, we propose to research the retreat of the grounding line under the ice sheet due to the sea level rise, and the response of the ice sheet to its own rapid melting, with a view of potential future problems.

As for the final issue, the social impacts of Arctic environmental change are described. In this plan, we list operation of the Arctic Sea Route, information transfer on earthquake and tsunami, impacts of terrestrial ecosystem changes, increasing forest fires, and changes in and maintenance of marine products. These aspects should not be considered just as information transfer to the Arctic residents, but be pursued in cooperation with them, as an understanding between the residents and the research community, and also on the basis of respect for other entire human beings.

3. History of Arctic environmental research

International efforts focusing scientific studies on the Arctic were a response to the first International Polar Year (IPY; 1882 - 1883) in the late 19th century. Twelve countries participated in the IPY and 14 observatories were opened in the Arctic. In IPY, the main observations were meteorology, geomagnetism, and the aurora. Japan voluntarily participated in the IPY, with the advice of foreign experts, while the Ministry of Agriculture and Commerce, Geological Survey and the Navy Hydrographic Bureau started the geomagnetic observation. Complete oceanographic observations in the Arctic began with the Fram Expedition led by Nansen ten years later (1893-1896). It was still a time of global exploration, when each country was in competition to explore the Arctic Sea Route, discover unexplored land, and reach the North Pole.

Based on the success of the IPY, the second International Polar Year (IPY2; 1932 - 1933) was conducted 50 years later; 44 countries attended, including Japan for the first time. Japan did not have territorial waters in the Arctic, therefore they started geomagnetic observations at Sakhalin close to the Arctic, and the meteorological observations at the summit of Mt. Fuji, which has a climate that is similar to the Arctic. The major challenges of IPY2 were to observe the ionosphere in relation to "radio waves forecast" for long-distance shortwave communication. Japan also participated in this international project by establishing the observatory.

After World War II, the Arctic became the stage of the Cold War for the United States and the Soviet Union. The Arctic Ocean was surveyed by nuclear submarines, sea ice and ice islands were used as drifting stations, and resource exploration and cold region research engineering of the Greenland ice sheet and permafrost (which has strong implications for the military including the resource exploration) were performed.

Japanese scientists began to conduct research activities in the Arctic, from the late 1950s. The study of ice cores in the Greenland ice sheet by Ukichiro Nakaya (Hokkaido University), and meteorological and glaciological research on the ice islands called ALIS2 and T3 of the Arctic Ocean by researchers were all carried out as participations of the United States project. From the late 1960s, tracking observations of ice nuclei from over Japan to Alaska by Nagoya University, permafrost research in Siberia and Alaska and glacier survey in Alaska by Hokkaido University were performed by Japanese research groups. This was during the Cold War era and research observations in the Arctic were restricted. In particular, the door to the Arctic was closed and access to data was limited in the Soviet Union.

A major turning point in the Arctic research was in 1987 when General Secretary Gorbachev of the Soviet Union gave his speech at Murmansk. He called for a release of the Northern Sea Route and the promotion of scientific research in the Arctic. A momentum of international cooperation in the Arctic research grew in response to this, and in August 1990, Arctic countries met in Resolute, Canada, and installed the International Arctic Science Committee (IASC). The first meeting of the IASC Council was held in Oslo in January 1991, where membership examination of non-Arctic countries was carried out, and the six applicant countries, including Japan, were accepted.

This was also a turning point for Arctic research by Japan. In 1990, the Arctic Environment Research Center was established by the National Institute of Polar Research (NIPR). In 1991, along with the cooperation of the Norwegian Polar Institute, a research station was also set-up in Ny-Ålesund, Spitsbergen, Svalbard, which started observing atmosphere, snow and ice, ocean, terrestrial ecology and upper atmosphere physics. In addition, in 1990, the Japan Marine Science and Technology Center (JAMSTEC; currently, Marine-Earth Science and Technology Organization) in collaboration with Woods Hole Oceanographic Institution, used the oceanographic vessel of the University of Alaska and automatic sea ice observing station to perform marine observations of the Arctic Ocean.

NIPR conducted observations of greenhouse gases at Ny-Ålesund station, biological observations in the polynya (non-freezing open waters), ice core drilling on the Greenland ice sheet, the joint observation of the atmosphere by aircraft with the Alfred Wegener Institute for Polar and Marine Research of Germany, further aircraft observation of greenhouse gases, aerosols and clouds up to Svalbard across the Arctic Ocean from Japan, and carbon cycle study of tundra vegetation at Ellesmere Island in Canada and Svalbard. In contrast, JAMSTEC commended Arctic Ocean observations using the oceanographic research ship "Mirai" from 1998, with 10 voyages between 1998 and 2013 contributing to the international Arctic Ocean observation. From 1997, Nagoya University began water and energy cycle research in Siberia over snow cover on frozen ground, by installing the observation points such as Yakutsk and Tiksi, which also corresponded to WCRP [6] / GEWEX [7] research programs. Since 2001, the research project had been conducted by JAMSTEC, Hokkaido University, Nagoya University, and Research Institute for Humanity and Nature, and the research area has expanded around the Lena River basin.

In addition, from 1991, the National Institute for Environmental Studies (NIES), has continued sustainable observation of greenhouse gases in Siberia using the observation towers and aircrafts. Hokkaido University also began studying permafrost in Siberia and Alaska in the 1980s; Kitami Institute of Technology and Hokkaido University carried out glacier observation of Siberia in the 2000s, and the Forestry and Forest Products Research Institute has been completing a forest survey of Taiga band. Tohoku University and NIES have also continued observation of greenhouse gases by commercial airliner over Siberia. Furthermore, since 1999, JAXA (Japan Aerospace Exploration Agency) and JAMSTEC began joint research on the Arctic Research with the University of Alaska.

Observational research of the Arctic region by Japan had been carried out by group-based research, by institutions and projects, depending on the decentralized form; however, we recognize that domestic cooperation was essential to promote research, and consequently began Arctic research activities by constituting a committee by volunteers from 2006. To show our support, from 2008, the International Symposium on Arctic Research, which occurs every two years, and the Arctic session from 2008 at the Japan Geoscience Union General Assembly.

International research gained momentum around 2000 following sea ice decline in the Arctic Ocean. Between 2007 and 2008, on the 50th anniversary of the International Geophysical Year (IGY), with ICSU [8] and WMO [9] as the core, IPY2007-2008 for the Arctic and Antarctic was carried out with promotion of research activities on observation and data archiving. In order to strongly encourage research, expansion of the organization was discussed in the IASC, and the number of working groups increased since 2011. This gave Japanese researchers the opportunity to become more involved in IASC activities.

In 2011, the Ministry of Education, Culture, Sports, Science and Technology took up the "Arctic Climate Change" as a part of Green Network of Excellence (GRENE) program. Focusing on the "Rapid Change of the Arctic Climate System and its Global Influences", a five-year plan known as the GRENE Arctic Climate Change Project commenced. The GRENE Arctic project has the NIPR as a representative body and participating institution of JAMSTEC. It is a large-scale project with nearly 300 participating scientists participating from 36 universities and research institutes across the country.

JCAR was established in May 2011, as a part of the GRENE Arctic project. In addition to long-term planning on Arctic environmental research, JCAR has discussed the infrastructure of research and observation, promoted international cooperation and coordination, and development of human resources.

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6 WCRP: World Climate Research Program

7 GEWEX: Global Energy and Water Cycle Experiment; in 2013 and later, Global Energy and Water Exchanges Project

8 ICSU: The International Council of Science

9 WMO: The World Meteorological Organization

4. Abstracts of all themes

(1) Elucidation of abrupt environmental change in the Arctic associated with the on-going global warming

Global warming is the primary environmental change in this century, significantly impacting human society and ecosystems, causing great social concern. This is why we describe the themes in relation to global warming. The key processes are discussed, with the aim of clarifying feedback among the various elements of the Arctic environment. Feedback from ecosystem changes to global warming is also focused on.

Theme 1: Arctic amplification of global warming

In the Arctic, several elements in the atmosphere, ocean, cryosphere, land surface and ecosystems are interwoven in a complex with various feedback effects, resulting in a more rapid temperature rise than in other regions. This particular phenomenon is known as "Arctic warming amplification". However, our understanding of the quantitative contribution from the individual elements and physical processes is still insufficient. Therefore, using the following five questions, we proposed a long-term research strategy for the current and future situation.

Q1: How does horizontal and vertical heat transport from lower to upper atmospheric layers affect Arctic warming amplification?

Q2: Is the role of terrestrial snow cover, permafrost, vegetation and ice sheet important?

Q3: To what extent does the role of sea ice albedo and heat accumulation in the ocean vary seasonally?

Q4: Is it possible to quantify the role of clouds and aerosols?

Q5: Why is Arctic warming amplification occurring, and how uncertain are the predictions? How are radiative forcing and feedback processes changing in the Arctic?

In the context of atmospheric circulation, Q1 was discussed by dividing the role of the effects of heat transport from the mid-latitudes and the role of the upper atmosphere, how the horizontal and vertical heat transport in the lower layer to the upper layer of the atmosphere would affect the Arctic temperature amplification. Q2 is related to terrestrial snow cover, permafrost, vegetation and the ice sheet. We considered the effects of snow cover, permafrost, and ice sheet changes with water circulation changes, and the effects of soil and vegetation alterations on the atmosphere. Q3

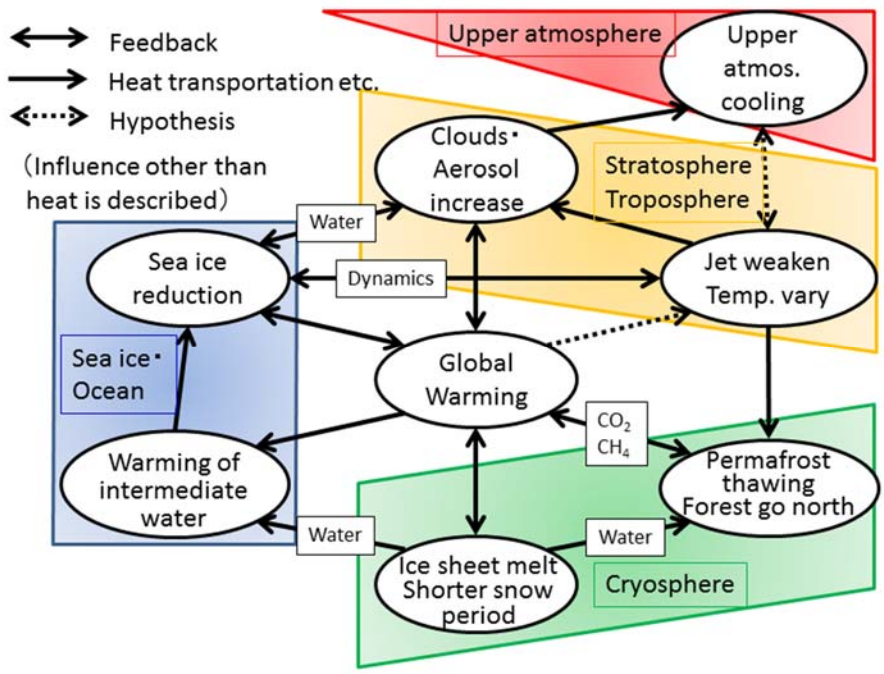

Figure 3: Potential feedback effects in the Arctic between each component. [Theme 1]

considered the role of sea ice albedo and heat accumulation in the ocean with seasonal fluctuations on the Arctic amplification. Q4 discussed the quantitative role of clouds and aerosols, considered to be extremely uncertain in Arctic warming amplification. Finally, as an overall summary, we questioned why Arctic warming amplification is occurring, how uncertain the predictions are, and what are the changes to the feedback processes and radiative forcing in the Arctic. We discussed the quantitative evaluation of the current state of research and the challenges. Through each question, we studied from the standpoint of process observation, long-term monitoring, process models and climate modeling.

Efforts for more than 10 years have focused on energy transport in the Arctic region, and continue to examine the interaction between elements from upper atmosphere to clouds, aerosols, snow cover, sea ice and ocean middle layer. In order to develop and use Earth System Models, not only is the cooperation of modelers in various fields required, but the planned acquisition of data for model validation is also needed. As a contribution from our country, we must work with the agency to continue sensor development and launch satellites in order to develop satellite observations from the sea ice to the upper atmosphere. In situ observations of the ocean are key to our contribution and should be repeated systematically.

Theme 2: Mechanisms and influence of sea ice decline

Recent rapid sea ice decline in the Arctic Ocean has increased social concerns on the possibility of the entire disappearance of Arctic sea ice in summer. This change is closely related to the development of a new commercial sea route and cold winters in Japan. It has therefore become an important issue, not only for research scientists, but also for social and economic communities. Theme 2 contains four questions listed below. First, mechanical factors on sea ice motion (Q1) and thermal factors on sea ice growth/melting (Q2) are described to explore mechanisms of sea ice reduction. Then, influences of sea ice retreat on atmospheric (Q3) and ocean (Q4) systems are discussed.

Q1: Do changes in wind pattern and sea ice fluidity promote sea ice reduction?

Q2: How does sea ice thermal reduction proceed?

Q3: How does sea ice reduction influence cloud and cyclones?

Q4: How does sea ice reduction influence the ocean fields?

Since the variation in Arctic sea ice is closely related to changes in wind pattern and sea ice fluidity, we should persistently examine the atmospheric pressure patterns most likely to exist under the future climate and efficiency of momentum transfer among air, sea ice and underlying ocean. It is problematic to attribute the sea ice decline mechanisms only to either motion/melting of sea ice or atmosphere/ocean warming. We should quantitatively examine various interactions such as the impact of ocean currents and weather conditions on heat balance at the ocean surface.

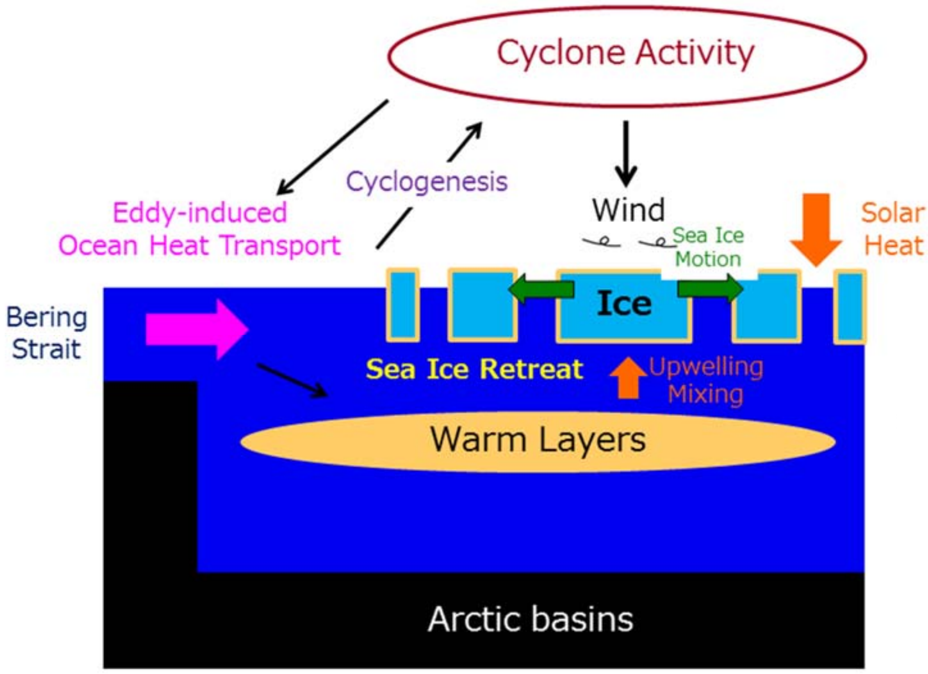

Figure 4: Schematic image of sea ice variations. Sea ice forms from sea water cooled to its freezing point and melts due to solar and ocean heat. Due to the wind, the most part of sea ice is exported toward the North Atlantic. [Theme 2]

International cooperation is essential for academic research on the Arctic Ocean environment, especially using field observations, which is too challenging to be adequately conducted by only one country. The Japanese research group has obtained many achievements from ship-based field campaigns in the Pacific side of Arctic Ocean. To continue our international contribution in the Pacific Arctic region, comprehensive year-long (including freezing period) measurements are big challenges to fill in blank data. Over recent years, several non-Western countries have already built their own icebreakers. Now we need further efforts to maintain and strengthen the scientific contribution of Japan. Satellite remote sensing represented by the microwave radiometer can play a leading role in Arctic environmental research by Japan in the distance from the Arctic. The improvement of numerical models is expected to provide more quantitative information on air-sea ice-ocean interactions and water mass transport across the multiple basins. The findings obtained by such efforts will result in the understanding of not only physical oceanographic properties but also polar marine ecosystems.

Over the next decades, we aim to clarify and quantify the processes on ocean heat transport covering ocean interior from bottom of sea ice to intermediate water layers and on air-sea ice-ocean interactions related to cloud and cyclones. With regard to the characteristics of sea ice itself, the detailed processes of melt pond formation and collision among sea ice floes should be analyzed. For these analyses, operations of an icebreaker and all weather-type satellite microwave sensors are essential. We should also develop next-generation sea ice-ocean models explicitly resolving individual ice floe and dense water plumes so that reliable information can be provided for vessels sailing through the Arctic Sea Route.

Theme 3: Biogeochemical cycles and ecosystem changes

Biogeochemical cycle across the atmosphere, land, and ocean is closely related to greenhouse gas dynamics such as CO_2 and methane, aerosols that affect cloud formation and solar radiation, and nutrients that sustain marine ecosystems. In the Arctic regions, sea ice, ice sheets, snow cover, and permafrost play a major role in biogeochemistry and complicate the processes further. Here, we highlight the following four questions that describe important aspects of changing biogeochemistry, which is the other side of the same coin with the perspective of environmental changes.

Q1: How are concentrations of greenhouse gases and aerosols in the atmosphere changing?

Q2: How are biogeochemical cycles that related to terrestrial ecosystems changing?

Q3: What is needed for quantitative elucidation of the geochemical material transport from land to sea?

Q4: How are biogeochemical cycles that related to marine ecosystems changing?

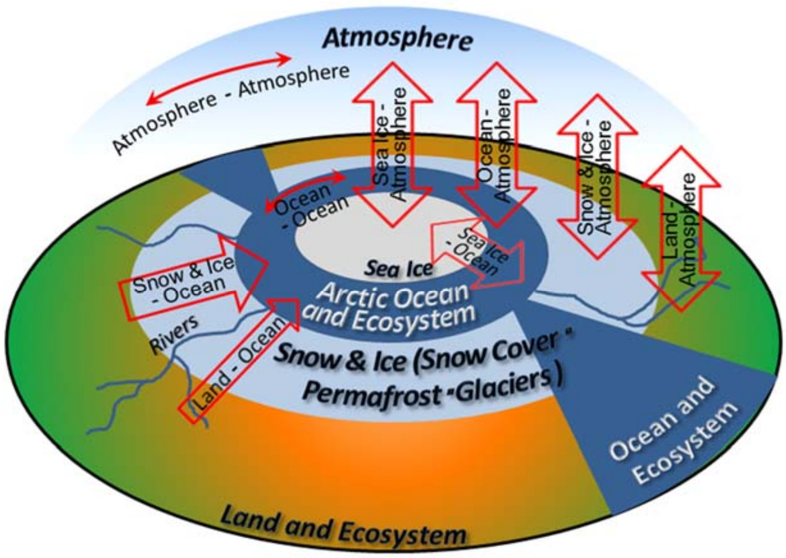

Figure 5: Schematic diagram of biogeochemical cycle in the Arctic. [Theme 3]

As for the atmosphere, since observational data are currently very poor in Siberia, deployment of new observation sites to implement year-round observations of atmospheric trace gases is important in Siberia. The use of satellite data and aerosol observation over the ocean using marine vessels on a regular basis are also necessary. For terrestrial ecosystems, the implementation of long-term study sites that allow centennial-scale continuous data acquisition of vegetation change such as species composition and structure change is important. Also, satellite observations that record signals of vegetation change, development of vegetation dynamics models that perform reliable predictions on long-term ecosystem changes, and understanding the geographical distribution and its accumulation and decomposition mechanisms of soil organic carbon (SOC) are crucial for the scientific progress. For the geochemical transport from land to ocean, we need to develop an extensive observation network around rivers and coastal areas in the Arctic to monitor fluxes of pollutants, carbon, nutrients, and trace metals etc. that are released by coastal/soil erosion and thawing of ice sheet and permafrost. For marine ecosystems, obtaining the observation data with no spatial and seasonal gap is important. For example, it is necessary to obtain the data by ice camps and year-round observation by sediment trap and mooring system to understand the seasonal variation of biogeochemistry and ecosystems. Furthermore, by comparing and integrating these data with the numerical models and incubating/feeding experiments, it is possible to evaluate quantitatively the relationship between biogeochemical cycle and ecosystem along with the effects of ocean acidification.

Theme 4: Ice sheet, glaciers, permafrost, snowfall, snow cover and hydrological cycle

Change to glaciers and ice sheets in the Arctic region affects the regional climate and hydrological cycle, and furthermore, has effects on the global-scale environment including sea level and albedo. Strong collaboration between in-situ/ satellite observation and modeling is important in order to clarify the variation mechanism and to improve projections into the future. Moreover, understanding of phenomena such as interaction between calving glaciers and the oceans, and the influence of cryosphere biology and ice quakes also need to be advanced.

Change in the surface layer of permafrost (active layer) is strongly related to snow cover and soil moisture, in addition to warming in the area. When the active layer reaches the level of permafrost ice and melting proceeds, irreversible thermokarst occurs, and resulting in feedback

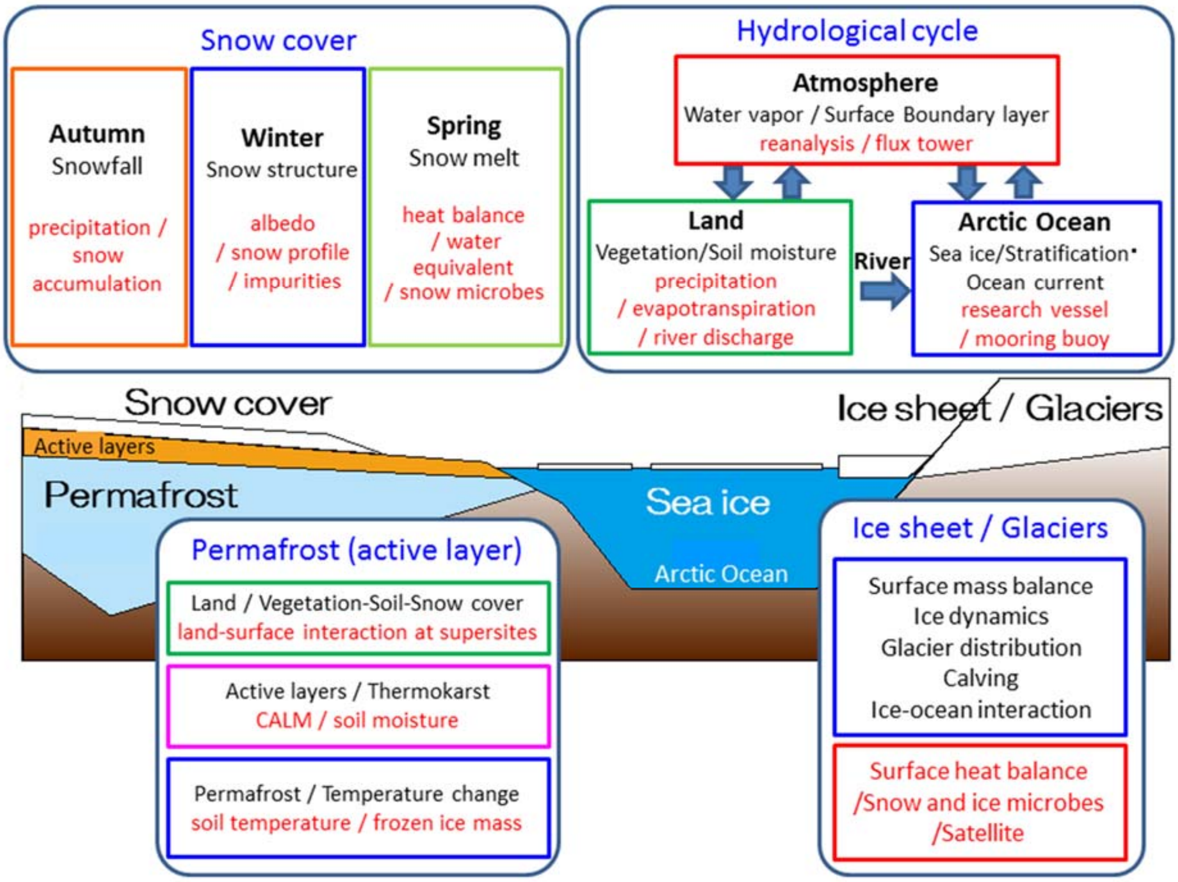

Figure 6: Schematic diagram of the research on ice sheet/glacier, permafrost and snowfall/snow cover variation and hydrological cycle. [Theme 4]

to the climate system through ecological and hydrological processes. In order to clarify these changes, research schemes based on integration of existing permafrost-observation networks, observation of land-surface processes, and support of satellite data and modeling, will all be needed.

Snow cover in the northern hemisphere is decreasing, especially in spring. However, existing information on quantitative and qualitative conditions is insufficient. Integrated research schemes, consisting of combined in situ observation and satellite observation need to be developed. Specific objectives should include improvement of the accuracy of observations of winter precipitation, snow quality and impurities/biological components, as well as improvement of the snow-cover model.

Study of the hydrological cycle in the Arctic region, including land, atmosphere and ocean, is proceeding in each research field, but the current understanding of the interrelationship between the fields is inadequate. Continuation of land and satellite observations, and synthetic study done under collaboration of terrestrial, climate, hydrological, and ocean modeling is necessary. With more data and insights, may come chances to clarify the influences of frozen ground, snow cover, vegetation, rivers, and meteorological conditions on the hydrological processes in the pan-Arctic terrestrial region, and on the sea-ice formation and material cycle in the Arctic Ocean.

In this theme, the following four scientific key questions will be focused on.

Q1: Will the change in ice sheet and glaciers accelerate?

Q2: How will the permafrost change interlink with climate change?

Q3: How is the snowfall and snow cover of the Arctic Region changing?

Q4: How will the hydrological processes in the Arctic change?

Theme 5: Interactions between the Arctic and the entire earth

In this theme, we discuss the interactions between the Arctic region and global-scale processes recognized by climate system research. In comparison with previous interests, greater attention is now given to Arctic-global interactions, exploring the potential significant effect of atmospheric and ocean circulations in the Arctic on the other regions. One of the examples actively discussed considers the impact of the sea ice decrease on the East Asian monsoon in winter, which may contribute to the improvement of seasonal prediction of abnormal weather. There are many suggestions from various points of view that the Arctic-global interactions may need to be explored well to facilitate our understanding of climate change over the time scale of several years to several tens of years, including global warming.

The elements composing the climate system are described first: i.e., the Arctic-global interactions in each of the tropospheric and stratospheric atmosphere, the ocean, land and the upper atmosphere. The central research of the troposphere and stratosphere covers dynamical processes of various teleconnection patterns related to the westerlies and polar vortex surrounding the Arctic, and also in the climate variability mode such as Pacific Decadal Oscillation. The results of these studies will give a basic understanding on the interactions between the atmosphere and the other systems (ocean, land and upper atmosphere), and also on the climate change expected to occur in this century.

The important research topics in the oceanographic field include water exchange between the Atlantic and the Pacific, deep water formation and the general circulation in the mid-latitudes, all of which require the arrangement of observational infrastructures such as a research vessel and high-resolution numerical models with model verification. In the terrestrial field, considerable attention has been paid to quantitative estimates of the effects of snow cover variability on energy and water balances over large areas, and also the effects of variability in biogeochemical cycles of soil, vegetation and permafrost, in the form of carbon flux and so on. The most active research until now was conducted by field observations and process modeling. However, further basic research is necessary to provide quantitative estimates of the effects of terrestrial processes on climate variability at large scales, including the establishment of an assessment method for the terrestrial processes. With regard to the upper atmosphere, the most important issues would be its variability in the mid- and low-latitudes caused by an energy injection into the polar region from the Sun through the near Earth space, the cooling associated with increasing greenhouse gases, and also the effects of the polar upper atmosphere on the lower atmosphere. A deeper understanding of the roles of the upper atmosphere on the climate system is expected by using ground-based observation networks, satellite observations with multiple sensors on a global scale, and numerical modeling with the inclusion of photochemistry.

Following these approaches, we describe the interactions among the systems introduced above, such as the atmosphere, being remained challenging issues continuously. The troposphere plays an important role in the interactions, due to its location among the others. It can interact with the upper side, the stratosphere and the upper atmosphere, as well as the lower side, the ocean and land. One of the examples referred to at the beginning of this theme was the effect of the sea ice decrease on the East Asian monsoon in winter, which could be led to the feedback from the atmosphere to sea ice.

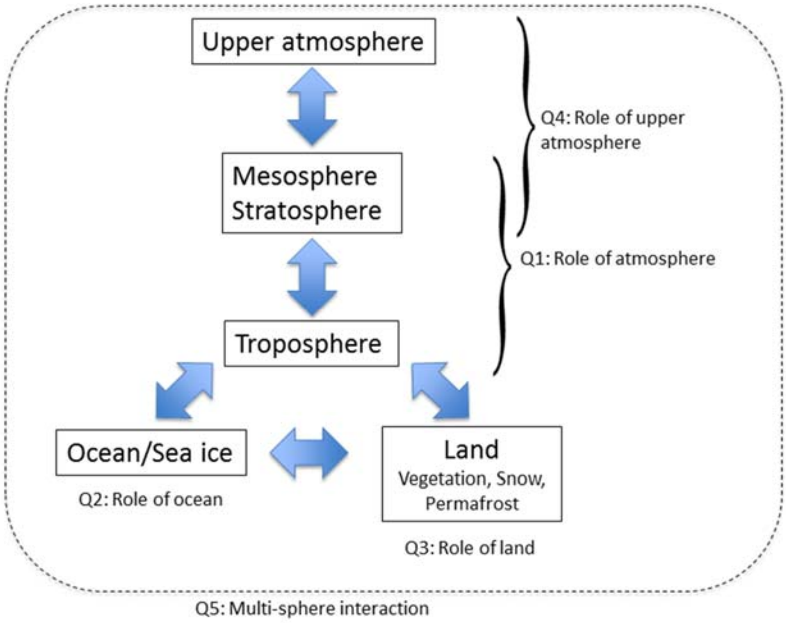

Figure 7: The interactions between spheres: i.e., the atmosphere, the ocean, land and the upper atmosphere. The mesosphere is the layer defined to be part of the upper atmosphere and immediately above the stratosphere. [Theme 5]

The effects of the Arctic variability appear in the mid-latitude area, such as the Far East, where climate variability is significant. The research community in Japan is supposed to play a major role in this subject. In fact, the researchers in Japan have made a pronounced contribution to understanding the effects of Arctic sea ice on atmospheric circulation. We are expected to advance our knowledge of the Arctic climate system within the global climate system, on the basis of this research achievement. As a result, more sophisticated and accurate prediction will not be limited to the Arctic climate, but also possible for the global climate.

This theme is formed with the five key academic questions as follows:

Q1: Roles of the atmosphere: Is its variability intensified or weakened for example, the Arctic Oscillation?

Q2: Roles of the ocean: Is the water exchange between the Atlantic and the Pacific intensified? Is the deep water formation reduced? Is general circulation modified in the mid-latitudes?

Q3: Roles of land: How does the variability in vegetation and permafrost have effects on carbon flux and the geochemical cycle? How does the variability in snow cover and vegetation have effects on energy and water balances at large scales?

Q4: Roles of the polar upper atmosphere: What effects does the upper atmosphere in the polar region have on the lower atmosphere and the whole region of the upper atmosphere?

Q5: Interactions among multiple spheres: Which one is the most influential on Arctic-global interactions, among the upper atmosphere, the atmosphere, snow and vegetation on land, or the ocean?

Theme 6: Predicting future environmental conditions of the Arctic based on paleoenvironmental records

The effects and feedbacks resulting from warming of the Arctic region on ice sheet, sea-ice, permafrost, land vegetation and aerosols continue to receive attention (see Fig. 8). However, by studying only the modern and recent past records, it is not possible to understand the entirety of the Arctic climate system which has time scales of variability over ten thousand years. During the past tens of millions of years, there have been periods when there were no continental ice sheets and atmospheric CO_2 concentrations were much higher than today, and when there were glacial-interglacial cycles in which Arctic temperature and ice sheets underwent large variations due to Earth's orbital cycles. By examining such records, it is possible to understand the Arctic climate system and test numerical models. Here, we list five questions for reconstructing Arctic paleoenvironment and for understanding its mechanisms by linking data and numerical modeling.

Q1: How different are the past Arctic amplifications from that of today, and what are their causes?

Q2: How did the Greenland and continental ice sheets change, and what caused them?

Q3: What were the environmental conditions of the Arctic Ocean, especially in terms of sea-ice and biological productivity?

Q4: How different were the terrestrial Arctic paleoenvironmental conditions from that of today, and how were they related with atmospheric composition and climate?

Q5: Were the natural variability on timescales from years to centuries in the Arctic different from today?

Research methods include collection and analyses of ice cores and marine sediment cores as well as geomorphological and geological surveys of land and sea-floor. Regarding the modeling, the approach is to develop a coupled Earth system model including climate, ice sheets, vegetation and solid Earth, and to conduct numerous, long numerical simulations. While it is particularly important to reconstruct and understand environmental conditions during previous warm periods, it is also important to investigate instability and variability of the climate system by studying abrupt climate changes which occurred repeatedly during glacial periods and deglaciations, and natural climate variations on timescales from years to centuries.

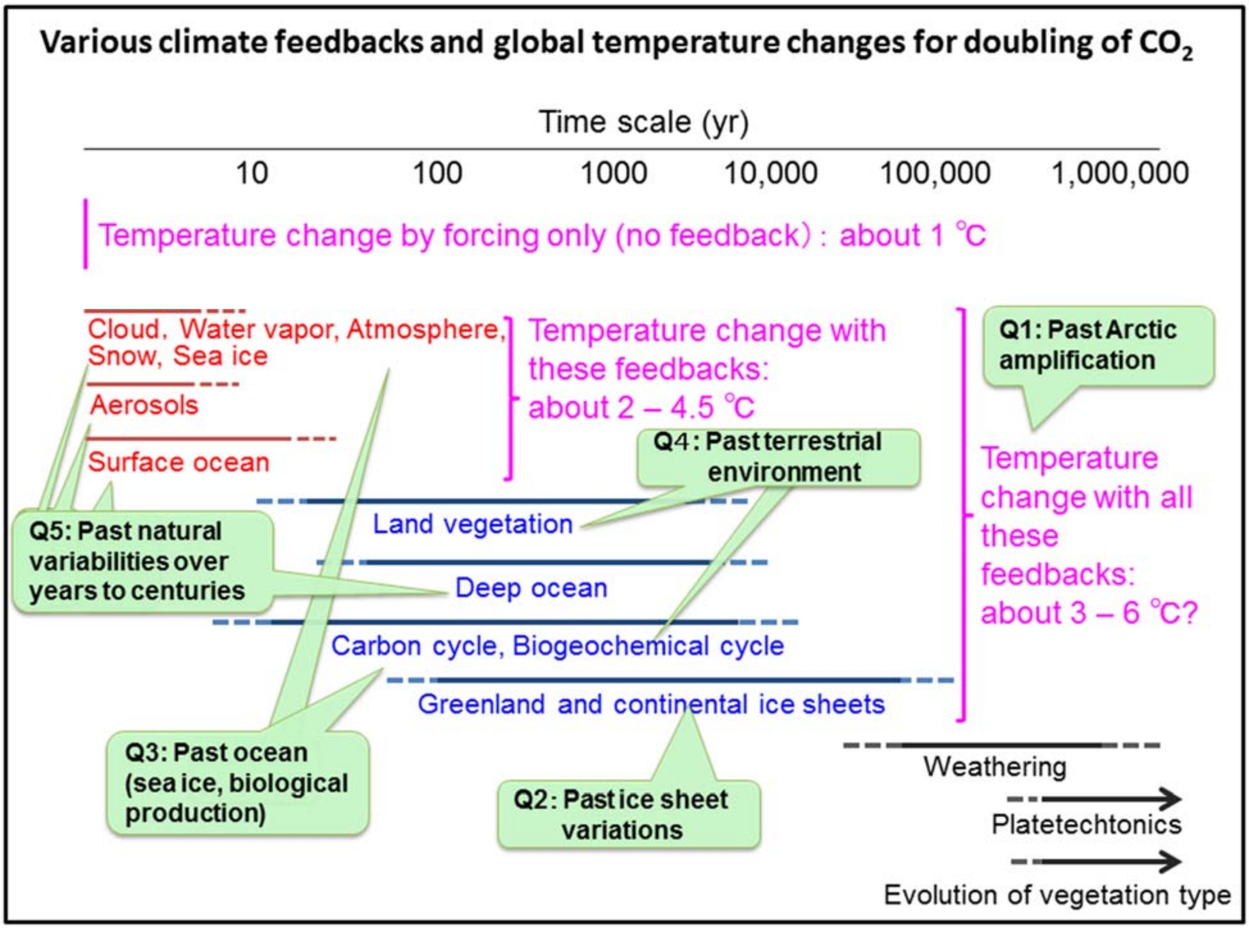

Figure 8: Climate feedbacks and resulting global temperature changes under doubling CO_2. The timescales of each climate component, as well as the relationship between the questions in the text and climate components, are also shown. [Theme 6]

Theme 7: Effects of the Arctic environment on human society

The five academic questions in this theme are as follows:

Q1: How do the impacts of climate change, including global warming, appear?

Q2: What apparent effects in the terrestrial environment change due to global warming?

Q3: What apparent effects in the marine environment change due to global warming?

Q4: How do the impact of solar activity and the Arctic upper atmosphere appear on the human societies?

Q5: How do the human societies in the Arctic respond to these impacts?

In the Arctic area, the natural environment is rapidly changing, for example, sea ice reduction, permafrost thawing, and changes in terrestrial vegetation and wild animals, caused by proceeding global warming along with development from the last century. As implied by the increasing interannual variability, unusual weather episodes that we have never experienced are likely to occur more probably. Fluctuations in climate and weather differ according to the region; therefore, the prior selection of suitable varieties is necessary for effective agricultural production. Vegetation and wild animals are seriously impacted by environmental change, including forest fires, which causes significant problems for residents with a livelihood in hunting. Disturbances caused by solar activities create communication failures in the polar region. As such, it is necessary to intend to preserve the environment and living conditions by taking measures and advantage to reduce the emission of greenhouse gases; for example, carbon credit.

As the sea ice retreats, seasonal ice cover basically expands in the Arctic Ocean. Since the Arctic Ocean is a semi-enclosed basin influenced by river water, the deep basin and bottom sediments, the variability in nutrient distribution is complicated. In addition, it is the first place in the world to suffer marine acidification. As for fishery resources suitable for the Arctic Ocean, we should be concerned with resource management, keeping in mind the serious impact on the residents who rely on fishing and hunting sea creatures. In order to safely operate the Arctic sea routes, effective prediction of sea ice conditions is essential. In addition to pollution associated with accidents such as groundings, livelihoods may be modified by shipping, therefore development should be conducted with consideration of the impact on residents.

By using examples from the alarm system in Japan for earthquakes and tsunami, we propose a method to cope with environmental problems that will be acceptable to residents with a livelihood in the Arctic. The important point is cooperation with indigenous peoples, who account for the majority of the population in the region, and not forcing them to accept the methods in the developed nations. We will present research on the impact on human societies and the countermeasures taken, including information on humanities and social sciences, and propose measures to be taken at each level of international relations, and the national and local governments. The basis of the long-term plan is to develop cooperation between the natural sciences and the humanities and social sciences across the Arctic area, which will extend beyond the existing environmental research community.

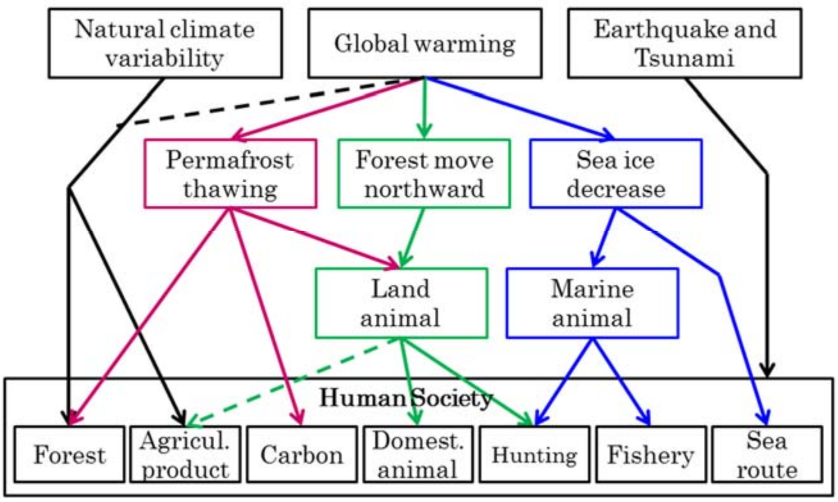

Figure 9: The impact of Arctic environmental changes on the human society. [Theme 7]

(2) Elucidation of environmental change concerning biodiversity

Ecosystems are affected by global warming and other various environmental changes caused by both natural and human factors. Here we describe the mechanisms in ecosystems and effects on that, and note current status and changes in biodiversity.

Theme 8: Effects on terrestrial ecosystems and biodiversity

Arctic terrestrial ecosystems and its biodiversity are now exposed to significant changes due to strong impact of human activities such as global warming. Compared with other ecosystems of the world such as temperate and tropical, the expected environmental changes in the Arctic terrestrial regions are particularly strong (IPCC AR5), and we have to predict the future conditions by promoting research and organizing the knowledge about the effects of the environmental changes. Nevertheless, research on Arctic terrestrial ecosystems is significantly delayed, when compared with other ecosystems, and a strong emphasis on this topic is urgently needed.

In Topic 8, Arctic terrestrial ecosystems, biodiversity that is an important component of the ecosystem, and impacts from changes in ecosystems and biodiversity on the climate change and regional communities are considered. Because Arctic terrestrial ecosystems are now facing serious changes that caused by human activities, such as agriculture and forestry and exotic species other than climate change, we have to highlight the importance of field observations and experiments, remote sensing, and simulation studies that integrate spot field observations and predict future ecosystem conditions in large scale. Studies and observations on biodiversity of the Arctic terrestrial regions are not progressed sufficiently due to the vastness of the region, but further expansion of the investigation, networking of the field studies, and studies on ecosystem and biodiversity under the environmental changes are required. Changes in the ecosystem will have strong impacts on animals such as mammals and birds. In addition, since the effect of the Arctic terrestrial ecosystems that accumulate large amounts of soil organic carbon in the vast wetlands on the global carbon cycle is large, it is essential to enhance both field and simulation studies that are essential to make appropriate predictions using explicit reproduction of ecosystem processes.

Here we have three study questions:

Q1: What environmental changes will occur in the Arctic terrestrial ecosystems due to anthropogenic factors?

Q2: How is the biodiversity affected?

Q3: What are the impacts on climate and animals due to the changes in the Arctic terrestrial ecosystems?

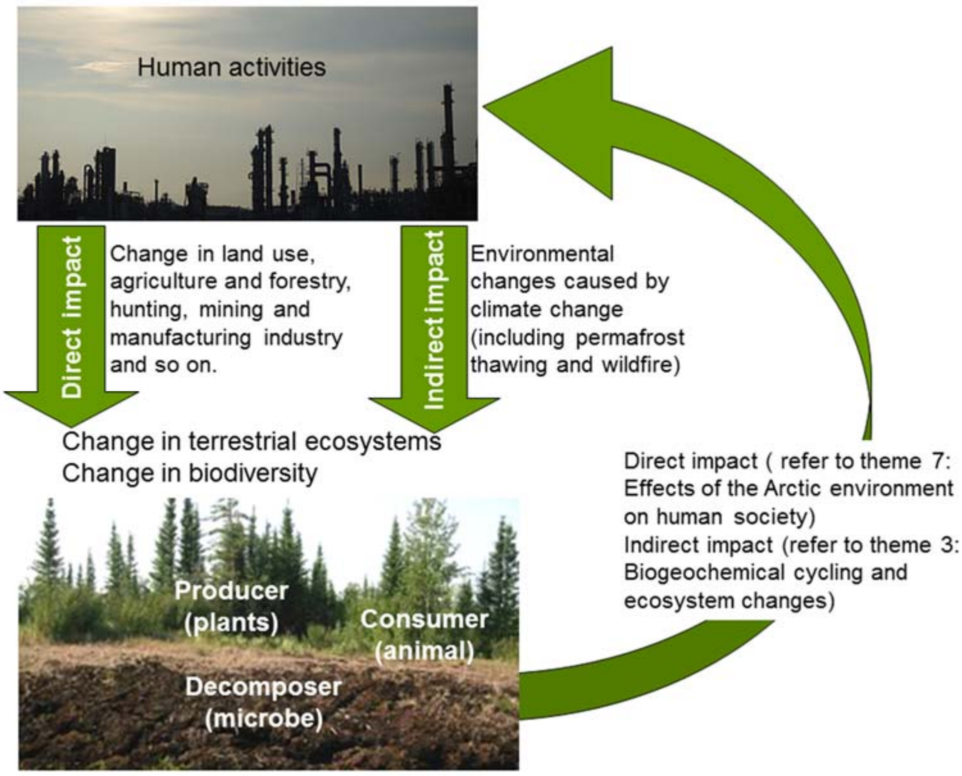

Figure 10: The interactions between the spheres Arctic terrestrial ecosystems, its biodiversity and human society. [Theme 8]

Theme 9: Influence on marine ecosystem and biodiversity

Because the surface of the Arctic Ocean is extensively covered by sea-ice, inhabiting marine biota thrive by adjusting to the unique environment formed according to the characteristics of the ecosystem. However, the Arctic sea-ice ecosystem has been disappearing due to the rapid decrease of sea-ice cover caused by the recent warming. We now list the following four questions and describe our long term view for future research by focusing on the changes occurring from perennial to seasonal sea-ice formation, which affect the marine ecosystem and biological diversity in the Arctic ocean.

Q1: Are the ecosystem and biodiversity of the Arctic Ocean significantly affected by the substance in the atmosphere and from the terrestrial areas?

Q2: How do the biota of the Arctic Ocean transport and change in quality of substance?

Q3: How the food chain and changes in ecosystem and biodiversity are related in the Arctic Ocean?

Q4: How does ocean acidification and denitrification in the Arctic Ocean influence the ecosystem and biodiversity?

The dramatic environmental changes in the Arctic Ocean are of concern because, not only is biological production in the Arctic Ocean altered, but also the disappearance of biota and entry of new biota may occur, as well as additional influences on material transport, biodiversity via food chain and competitive relationships. The change in species diversity significantly affects productivity and decomposition of the ecosystem. Therefore, quantitative interpretation of the environments surrounding the sea-ice ecosystem of the Arctic Ocean and each of the processes and mechanisms in the ecosystem is important for assessing the influence on future sea-ice ecosystem and biodiversity of the Arctic Ocean.

However, most of the knowledge that has been obtained thus far is tempo-spatially fragmentary because that it is based on the limited data from open waters during summer season when research vessels can safely cruise around in the Arctic Ocean. Furthermore, the sea-ice ecosystem has aspects where almost no information is available due to the complex relationships among physical, chemical, and biological processes. Therefore, our long-term goal is to clarify the influence of the Arctic Ocean on the ecosystem and biodiversity, not only by conducting multidirectional observations in extensive areas with the use of ice breakers and mooring systems, but also by conducting interdisciplinary research that links process experiments and numerical modeling.

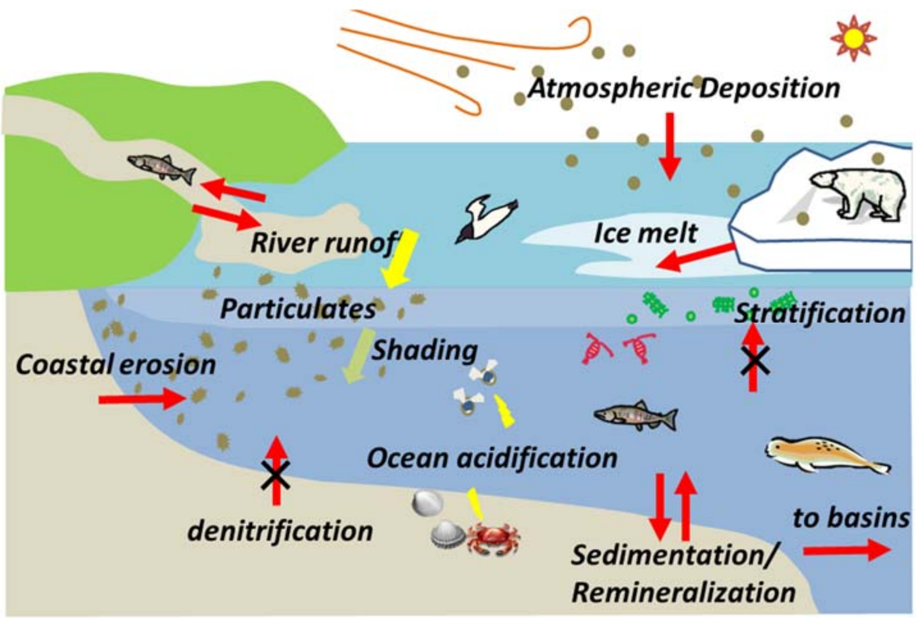

Figure 11: Influence of material flow from land and the atmosphere and the various types of processes in the ocean involving living things. [Theme 9]

(3) Broad and important subjects on the Arctic environment

Important environmental research that is not included in the focus of the previous two areas are also underway for the Arctic. We selected activities which were highlighted as research themes by the JCAR community. Following advances in research, this work will potentially provide further information relating to the former two focal points. In addition, it includes the research areas that describe the basic information on the focal points.

Theme 10: Geospace environment

Due to the precipitation of charged particles and the propagation of electromagnetic waves from geospace (space around the Earth that is part of the active region for humans), it has been noted that in recent years the upper and lower atmosphere of the Arctic region is subject to change. In particular, minor constituent variations in the middle/upper atmosphere and its impact on the ozone concentration and stratosphere-troposphere coupling such as the downward propagation of the Arctic Oscillation — effect of the upper atmosphere on the lower atmosphere attracted the interest in the recent. It has also become clear that the atmospheric waves excited in the lower atmosphere have a great influence on the thermal and dynamical structure of the middle/upper atmosphere. In addition, the results also suggest a significant increase in the cooling of the middle/upper atmosphere with increasing greenhouse gases. It is believed that understanding the various coupling process between the lower atmosphere and the upper atmosphere is important in order to appreciate the full extent of the Arctic environment. However, little progress has been made with a quantitative impact assessment.

Electromagnetic and particle energies entering from the Solar wind and magnetosphere to the polar upper atmosphere cause fluctuations in the upper atmosphere at the low/middle latitudes (including large-scale fluctuations such as magnetic storms). In addition, atmospheric waves generated from the lower atmosphere may contribute to driving the global scale atmospheric circulation. However, the full extent of such changes on a global scale is still unknown. As one of the important information infrastructure businesses that support the human society, it is necessary to monitor the polar upper atmosphere in order to provide effective, reliable detection and prediction of ionospheric disturbance phenomenon. It is expected that in the next few years, geospace exploration, including the middle/upper atmosphere, will be achieved using new satellite/rocket observations and large atmospheric radar observations. In conjunction with these enhanced observations, there is a need to develop a research framework to evaluate and predict the influence of geospace on the upper atmosphere and lower atmosphere. Questions about the impact of the geospace environment on the Arctic environment and the connection between the geospace and Arctic environments are summarized as follows:

Q1: What are the effects of geospace on the upper atmosphere and lower atmosphere?

Q2: What are the effects of the upper atmosphere on the lower/middle atmosphere?

Q3: What are the effects of the lower/middle atmosphere change on the upper atmosphere?

Q4: How important is the energy flow from the polar region into the middle/low latitudes through the upper atmosphere?

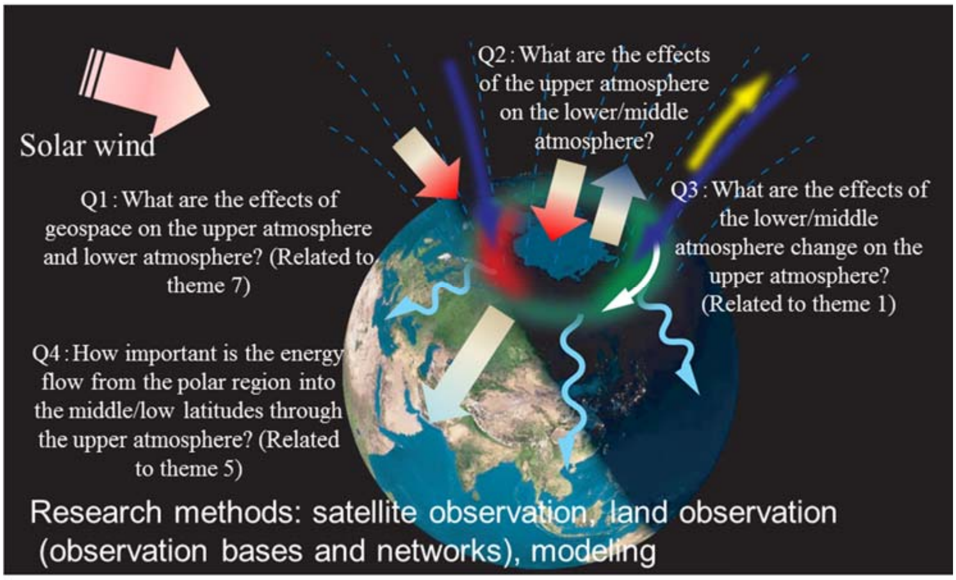

Figure 12: Relationship of four Key Questions of theme 10.

Theme 11: Interaction of surface environment change with solid earth

The spreading and subduction of oceanic floor occur by thermal convection of solid earth's interior, and causes phenomena such as the formation of new marine and collision of the continents. The change in the configuration of the ocean and the continents at the earth's surface due to thermal convection of the earth's interior is an important factor that causes the shift of environmental changes such as the atmospheric and oceanic circulations and the ice sheet. On the other hand, changes in the volume and geographical location of the ice sheet and seawater due to climate change lead not only to sea level change, but also to the deformation of solid earth, such as the crustal movement and mantle flow. It has been thought that the climate and solid earth interact with each other over a range of time and space scales, however, the mechanisms are not clear, which prevents us understanding the whole earth system. In particular, the Arctic region where interactions, such as crustal deformation due to ice sheet mass change, occur over various time scales, and the formation and fragmentation of the continent with the time scale of several billions of years, is key to solving the problem. In this chapter, we have set the following four questions for the research plans on the solid earth changes in order to understand the interaction between solid earth and surface environmental change with various time and space scales.

Q1: What is the interaction between the currently active hydrothermal system of Arctic mid-ocean ridges and the marine environment?

Q2: How is the solid earth deformed by an ice sheet change?

Q3: In the process of the Arctic Ocean formation, how did the interaction of the atmosphere - ice sheet - ocean change?

Q4: How did the development process of the Arctic Ocean and surrounding continents affect the surface environment change on the time scales from tens of millions of years to several billions of years?

Question 1 focuses on the hydrothermal system of the Gakkel ridge, which is one of the currently active mid-ocean ridges under multi-year sea ice and has not been well researched. The aim of the research regarding Q1 is to clarify the causes, the local ecosystem, and the effect of oceanic circulation on the hydrothermal system of the Gakkel ridge.

Question 2 applies to the observational study on the current crustal deformation with the load change of ice sheet, which is a unique phenomenon of polar regions with a spatial scale of several thousand kilo-meters and a time scale of tens of thousands years. This study, in the

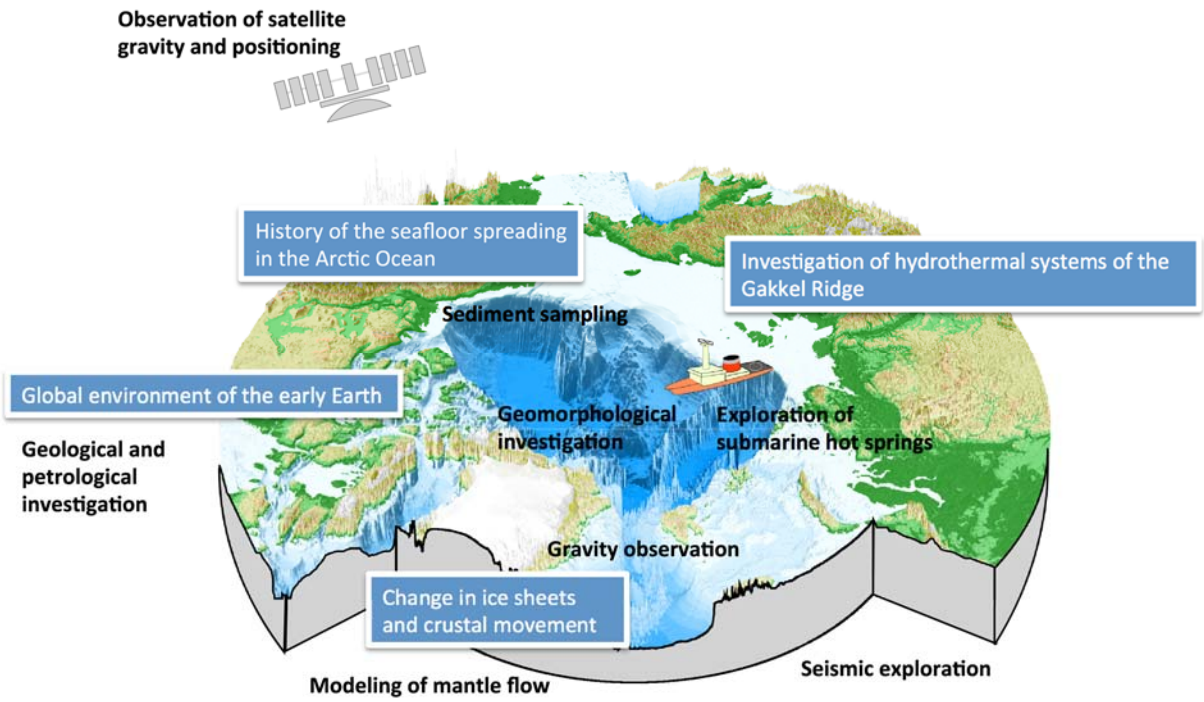

Figure 13: Important research theme on the interaction of the solid earth with the outer layer environment change. [Theme 11]

areas of Greenland ice sheet, northern Canada and their marginal ocean, aims to clarify the mechanisms of ice sheet changes and viscosity structure of earth's interior by geomorphological, geological and geodetic investigations together with modeling study.

Question 3 applies to establishing the formation history of the Arctic Ocean on a scale with hundreds of millions of years and the changes of atmosphere - ice sheet - ocean interaction. Most of the Arctic Ocean floor remains uninvestigated due to sea ice cover. The objectives of this study are to (i) determine the history of the Arctic Ocean seafloor via geophysical and geological investigations, (ii) clarify the changes in the atmosphere - ice sheet - ocean interaction by investigating the reconstruction of the paleoclimate and paleoenvironment by the sediment collection, and (iii) estimate the time for ice sheet expansion in Arctic Ocean formation and the expansion associated with the tectonic history of the Arctic Ocean.

The last question Q4 is on a change of the solid earth on the several billions of years scale, and aims principally to analyze the earth's surface environment change on the scale of 3-4 billion by the earth crust study with mainly the geological investigations in the continent around the Arctic region. The promotion of the research on the history of global environment change on the long geological time scale from the early days of the earth formation to now by a geological investigation in the Canadian Arctic and west coast of Greenland, where exists a stratum of approximately 3-4 billion years old, is suggested.

Theme 12: Basic understanding on formation and transition process of permafrost

Permafrost regions occupy approximately 25% of the land area. It is one of the major factors affecting the Arctic environment through the complicated feedback of heat and materials with atmosphere and vegetation, etc. It is a potential GHG source due to the surface thawing. However, there is a lack of detailed scientific understanding on the present state and dynamics of changing permafrost distribution. Therefore, there is considerable uncertainty regarding the future projection of permafrost variation. The main reason for this situation is that the spatial heterogeneity of the permafrost is large, the observational sites are limited in terms of representing the whole region, and observation from satellites is challenging. It is therefore necessary to develop new observation techniques and to improve the existing methodology, as well as to expand the observation sites and to carry out multi-point measurements. It is becoming increasingly important to improve the knowledge of detailed permafrost distribution and the heterogeneity of its composition, and to increase the information regarding the change of ground temperature, the amount and the state of ice and

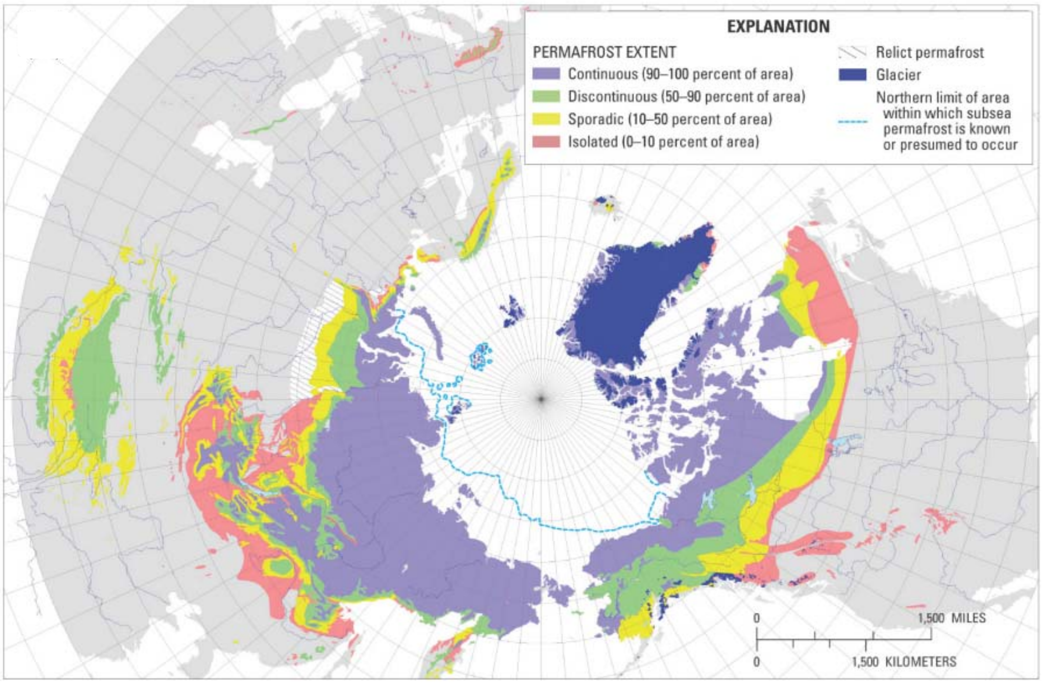

Figure 14: Distribution of permafrost in the northern hemisphere. Partially revised USGS Professional Paper 1386-A. [Theme 12]

organic carbon storage. Permafrost study should focus on modeling and quantifying the process of changing permafrost based on distributional information. We need to integrate our scientific knowledge and techniques with the modeling in order to understand the behavior of the permafrost land system and the variation of arctic environment system.

In this theme, the following four questions will be discussed.

Q1: Permafrost distribution: how is the permafrost in the arctic distributed, both horizontally (in terms of space) and vertically (in terms of depth)?
Q2: Permafrost composition: what material does the permafrost consist of, and how heterogeneous is it?
Q3: Warming and thawing of the permafrost: what is the process, and on what scale does it happen?
Q4: Permafrost-Atmosphere-Snow-Vegetation system: what is its structure and behavior?

(4) Development of methods enabling breakthroughs in environmental research

The pioneering breakthrough research is triggered by innovative deployment of observation and modeling technique. Process research and monitoring of mutual enlightenment, system modeling and data assimilation is important. Identify the current gap, as well as efficiently conducting research and leading to the need for research infrastructure. Overcome the handicap by the complexity and difficulty of the data acquisition of the Arctic, and contribute to the global scale study.

Theme A: Sustainable seamless monitoring

Research monitoring of the Arctic environment has been carried out as two elements, remote sensing, including the satellite and in situ observation. Environmental change in the Arctic is important with regard to global scale influences; however, because of the severity of the Arctic environment, in situ field observations are hampered by the sparseness of observing stations and subsequent large areas with no data. Although, due to recent progress, satellite monitoring has generated new information, there are still many factors that need to be observed in situ. The most important point of monitoring is to collect continuous, representative data. International cooperation is essential to enable this; therefore, Japan is also required to play a role.

As a matter of convenience, if the subject of monitoring is classified into the oceanic, cryospheric, atmospheric and terrestrial area, then the long-term priority issues that Japan should tackle are as follows. For the ocean area, the monitorings of sea ice change, marine ecosystem and material cycle through the year, with our own icebreaker and satellites are needed. In the cryosphere, determining the mass balance and related various quantities of the Greenland ice sheet and the mountain glaciers of the Arctic Circle, coastal erosion and thermokarst associated with thawing and borehole management of permafrost is essential. In the atmosphere, precise long-term observation and understanding of the spatial variation of atmospheric minor constituents involved in the climate, cloud and precipitation is essential. For the terrestrial monitoring, maintenance and development of observing stations (super site) overall to perform monitoring of vegetation change, terrestrial ecosystems and meteorological and

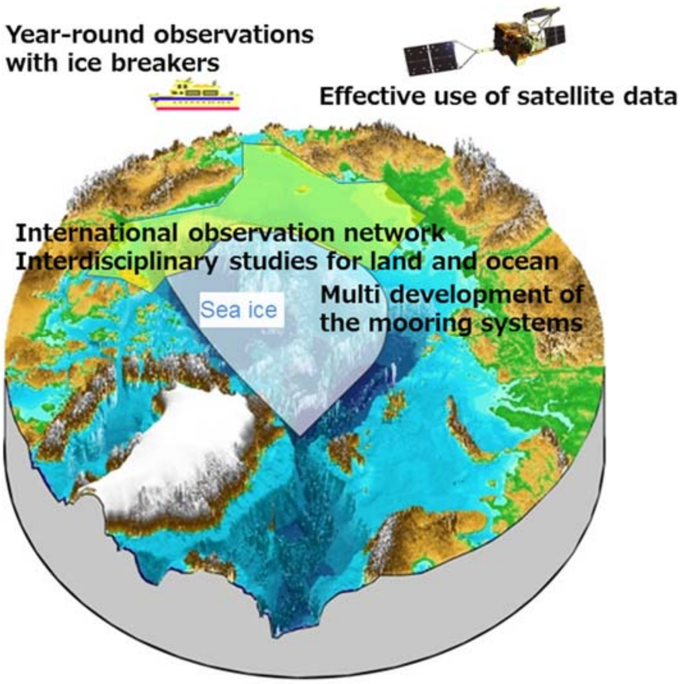

Figure 15: Elements necessary for the monitoring of marine ecology in the future (conceptual diagram). [Theme A]

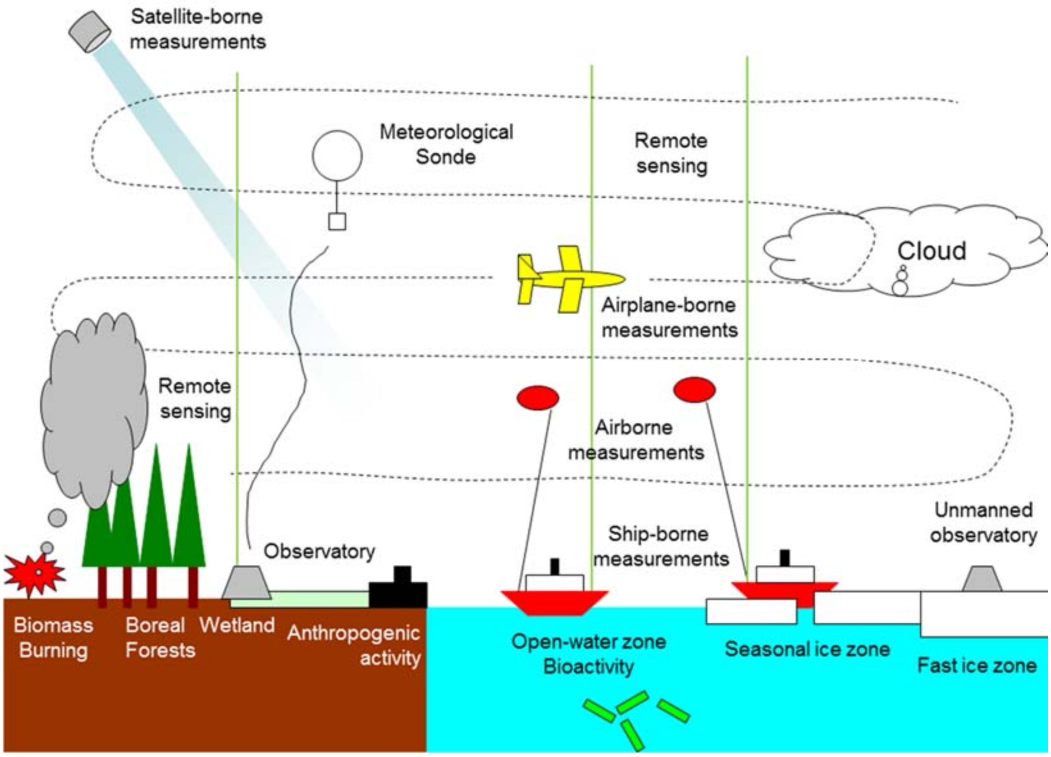

Figure 16: Elements necessary for the monitoring of atmospheric minor constituents in the future (conceptual diagram). [Theme A]

hydrological observations, including heat, water and carbon fluxes in the terrestrial sphere are needed. With respect to these issues, monitoring conducted by both in situ observations and remote sensing is required.

Here, we describe the monitoring initiative by classifying areas into oceanic, cryospheric, atmospheric and terrestrial.

Q1: Oceanic monitoring
Q2: Cryospheric monitoring
Q3: Atmospheric monitoring
Q4: Terrestrial monitoring

Theme B: Earth system-modeling for inter-disciplinary research

If we try to understand the Arctic area, in which various complex processes interact with each other, we need an earth system model to deal with the entire system. Here, the current state and challenges of modeling are discussed, from the aspect of individual fields, such as the atmosphere, ocean and land, and also system modeling of integrated fields. The key questions are as follows:

Q1: What are the development challenges for earth system modeling?
Q2: What are the development challenges for atmospheric modeling?
Q3: What are the development challenges for ocean-sea ice modeling?
Q4: What are the development challenges for land-cryosphere modeling?

For research using the earth system model, we can be more efficient by selecting the one suitable for the time scale of the subject concerned. If the models are used to predict outcomes for several years or less, they must be precise and reliable. Hence, we need to achieve a higher resolution in regional models. The models for studying the longer time scales need to provide a secure representation of paleoenvironmental experiments and future projection. For this purpose, it is desirable to develop models that replicate the heat and water balances and represent the geochemical cycles, ecosystems, snow and ice processes accurately. Of primary importance for both cases is the correct selection of parameters, and also the evaluation of the effect caused by an error generated in one of the other elements.

Each field, which forms the earth system model, has its own subject. The central subject for the atmospheric

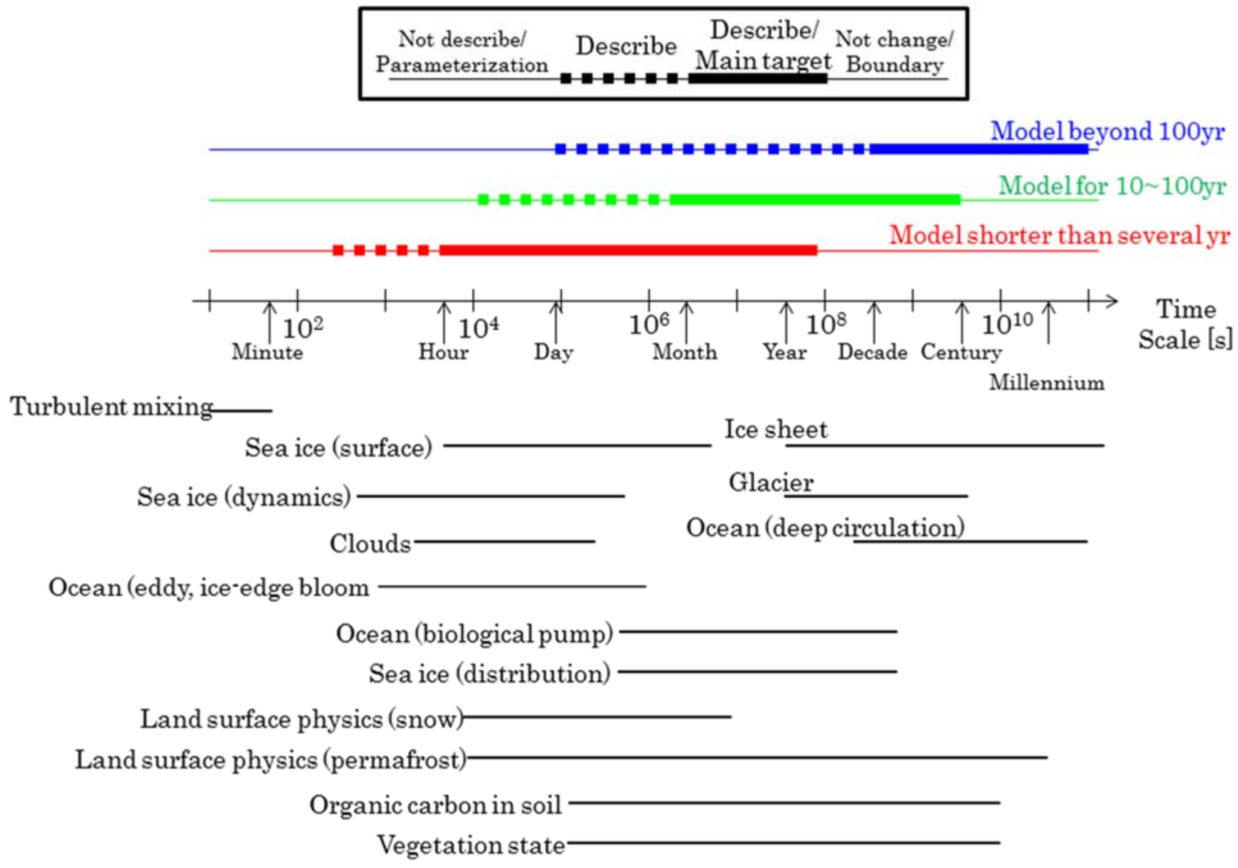

Figure 17: The time scales of the representative models (upper part) and the time scales of major processes in relation with the Arctic area. [Theme B]

models is verification of a non-hydrostatic, high-resolution model which explicitly describes the behaviors of clouds, and also a hydrostatic normal-resolution model with the cloud parameterization by using cloud data. The subjects for the ocean models are improvement of water mass formation modified by the inflows to the Arctic Ocean and vertical mixing, and also parameterization of the ecosystem processes. The sea ice models have the subject to improve dynamic and thermodynamic processes at the pack ice scale and also mixed-layer processes under sea ice cover. The subjects for the land surface models include verification by use of paleoenvironmental indices, application of data assimilation techniques, improvement of duplication of interactions with the other elements, and then, development of the framework within the system model for long-term integration or off-line experiments. Our preference would be to use the earth system model as a basis for linking various fields of the Arctic area, through the initiatives described for the individual fields.

Theme C: Data assimilation to connect monitoring and modeling

Here, we describe the techniques of data assimilation and the application to the Arctic environmental research, along with a survey of the present status. It has been confirmed that advanced techniques are in place for the operational forecast and the reanalysis system to be applied to the atmosphere-sea ice-ocean system. In the fields where data assimilation techniques have not been applied extensively, such as state estimation of the ice sheet, some applied examples are introduced. The current situation, as described above, has been built on the knowledge that long-term monitoring is important, the reinforcement by the improvement of observation techniques and the recognition of rapid climate change. On this basis, the future direction is proposed to combine observational techniques, and networks as well as numerical modeling techniques. For practical reasons, data assimilation research for the Arctic has to be selected according to the handicaps of the area: i.e., atmospheric measurements have limited coverage, sea ice thickness is not measured in-situ, and remote sensing data are not available for the sea water. The long-term future direction is likely to be challenging for data assimilation to the multi-disciplinary system and aiming at the operational objective to implement forecast of the Arctic Ocean state for the safe sea routes. Considering the limited resources for Arctic research in Japan, an appropriate path is presented here, with regard to data assimilation research proposal. This report has touched on the necessary terminology for data assimilation literature and information on the discussed technology.

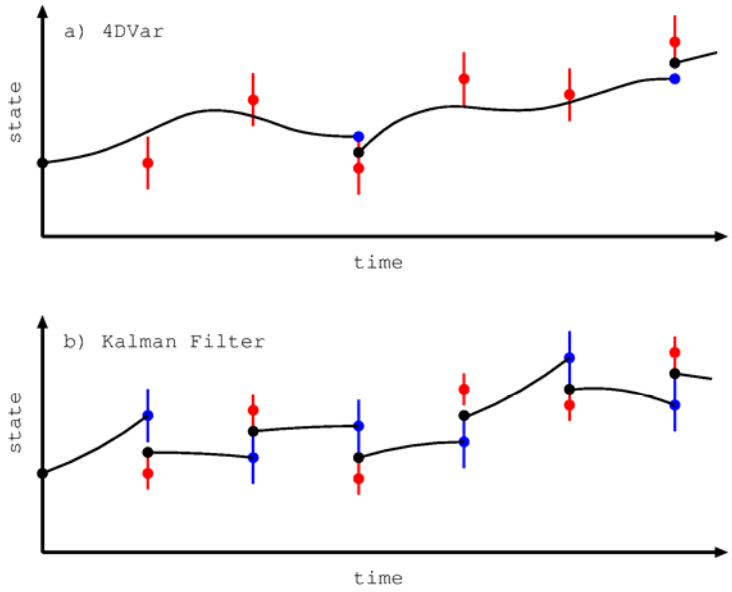

Figure 18: 4-dimensional variational (4DVar) method and Kalman filter method. Red circles denote observed data, black circles and lines denote analysis values, and blue circles denote model prediction values. State variables can be temperature, velocity and others. [Theme C]

5. Improvement of research foundation

Various organizations, systems, and facilities are needed to pursue the research themes described previously, but they are cited individually. We have reorganized them here, since there are many common items among the themes, and should be grouped together as a proposal on community infrastructure.

Research vessels

Japan does not possess an ice breaking research vessel, which can operate in the Arctic Ocean, and they were therefore obliged to use foreign vessels to do observations. In these cases, observations were limited and developing a sound observation plan was challenging. This is a crucial matter that needs to be overcome. A new research ice breaker is the way to overcome this situation. This would allow us to both lead and vastly improve the observation ability of the Arctic Ocean. The equipment particularly needed includes a : moon pool, multi-purpose winch, automatic launcher for radio sonde, ROV (remotely operated vehicle), chemical-biological-geological laboratory (including cold rooms), long-time navigation capable and multi-sensor equipped AUV (autonomous underwater vehicle), sampling capable ROVF, long and large diameter piston corer, multi-beam bathymeter for ocean bottom survey, sub-bottom profiler for strata probing.

Satellite

It is necessary to improve the observation of sea ice distribution by using a micro-wave radiometer installed satellite, which would double the present spatial resolution of AMSR2 (89GHz and 3～5km). An integrated observation system of Synthetic Aperture Radar (SAR) and Laser/Radar altimeter is also very effective for detecting the mass change of the ice sheet/glacier, sea ice and snow cover. There is also a need to develop a satellite for measuring gravity.

Japan previously depended upon the USA for visible sensor monitoring of the terrestrial and marine ecosystem, but now has plans to launch GCOM-C1/SGLI.

Aircraft

Aircrafts are needed to provide a platform for using the electromagnetic induction probe (EM) in addition allowing the direct measurement of the atmospheric composition and cloud particles. In the past, commercial aircraft were used for such Arctic observations, but since the development of observation instruments, the most effective plan is to possess a purpose-built aircraft. On the other hand, the usage of un-manned aircraft may also be a possibility.

Oversea research and observation base

From the standpoint of international cooperation and sustaining/process observation, the priority will be to improve/develop the Arctic observation site and network, including the supersites, and steadily collect the various environmental parameters within it. Regions and Countries where geographical position is important for Arctic Research, such as Svalbard, Russia, Alaska, and Canada, an observation/research base will need to be developed and founded on Bi-lateral Cooperation. Existence of such a base is also important for human resource development, especially young scientists. There is also a need for the Institute to maintain and manage the overseas research base in cooperation with foreign countries, including the necessary domestic arrangements.

Data archive

The important element in this is stability and flexibility. The system needs to be user friendly and must accept various format data. A Data Center is needed, where reproduction of data, digitization and authorization of DOI for identification will be performed. Development of a Center will be only possible with the cooperation of an international data center, and use of other databases.

Human resource development

From the stand point of training of young researcher, JCAR needs to cooperate with the activities of APECS[10], and cooperate with Japanese Universities to strengthen the partnership with UArctic [11], UNIS [12] and other Universities in the Arctic. Programs needed are, intern system, summer school and development of career path, and continuation of the GRENE Fellowship for Japanese Early Career Scientists and Graduate Students. It is also advisable to start an invitation program for young researchers in the indigenous community.

Research promotion system in Japan

The most important thing is to develop a domestic system for strong Arctic Environment Research under the cooperation of the research institutes, universities, JCAR, and various academic societies. To achieve this, firstly, there is a need to strengthen the Core Agency, so that the domestic promotion and implementation system can advance using the initiative of this Institute. Secondly, the main Institutes need to take responsibility for the various research infrastructures and scientific research areas under the cooperative relations. On the other hand, the existence of JCAR, which can gather various scientists to discuss / propose new scientific issues and directions is needed, due to understand the nature of the Arctic Change which requires much discussion between the various scientific disciplines. Lastly, good international coordination and cooperation is needed in Japan, due to the internationality of the Arctic Change issues, and also due to the fact that Japanese scientists will perform observations in foreign countries.

Instruments
(Atmosphere, Upper-Atmosphere, Cryosphere, Land and Ocean)

There is a great need for instruments. One example is the development of a large radar network with EISCAT-3D [13], MU radar at Shigaraki, Japan, Equatorial Atmospheric radar in Indonesia, etc. for the distributed monitoring of upper-atmosphere. As an example of chemical analysis, continuous development of a high-resolution stable isotope analyzer for aerosols and gas, and a high resolution ice-core melt analyzer, is required in the area of glaciology. For the terrestrial vegetation, a Hyper Spectral Camera [14], which will reveal the composition of the tree, is necessary. Development of an observation platform, such as ROV and AUV, is also important to be able to observe the sea ice from below.

Numerical model

In addition to hardware such as massive calculation resources and large storage, there is a need to secure human resources to develop models and run the hardware. Furthermore, a system which will dispose research technicians to prepare data and develop source codes is needed.

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[10] APECS: Association of Polar Early Career Scientists

[11] UArctic: The University of the Arctic is a cooperative network of universities, colleges, research institutes and other organizations concerned with education and research in and about the North. From Japan, Hokkaido University has been appointed as an associate member of UArctic since 2011.

[12] UNIS: The University Centre in Svalbard is the world's northernmost higher education institution, located in Longyearbyen at 78º N. UNIS offers high quality courses at the undergraduate, graduate and postgraduate level in Arctic Biology, Arctic Geology, Arctic Geophysics and Arctic Technology. National Institute of Polar Research manages an office in it.

[13] EISCAT-3D: European Incoherent Scatter radar.

[14] Hyper Spectral Camera: Much as the human eye sees visible light in three bands (red, green, and blue), spectral imaging divides the spectrum into many more bands. This technique of dividing images into bands can be extended beyond the visible.

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- Numbers and alphabets in parentheses indicate the section that the author is assigned to. 1-12 and A-C means the name of the themes. F means Improvement of Research foundation.
- "*" or "+" beside the numbers and alphabets signify the lead author or the second lead author of the theme.
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