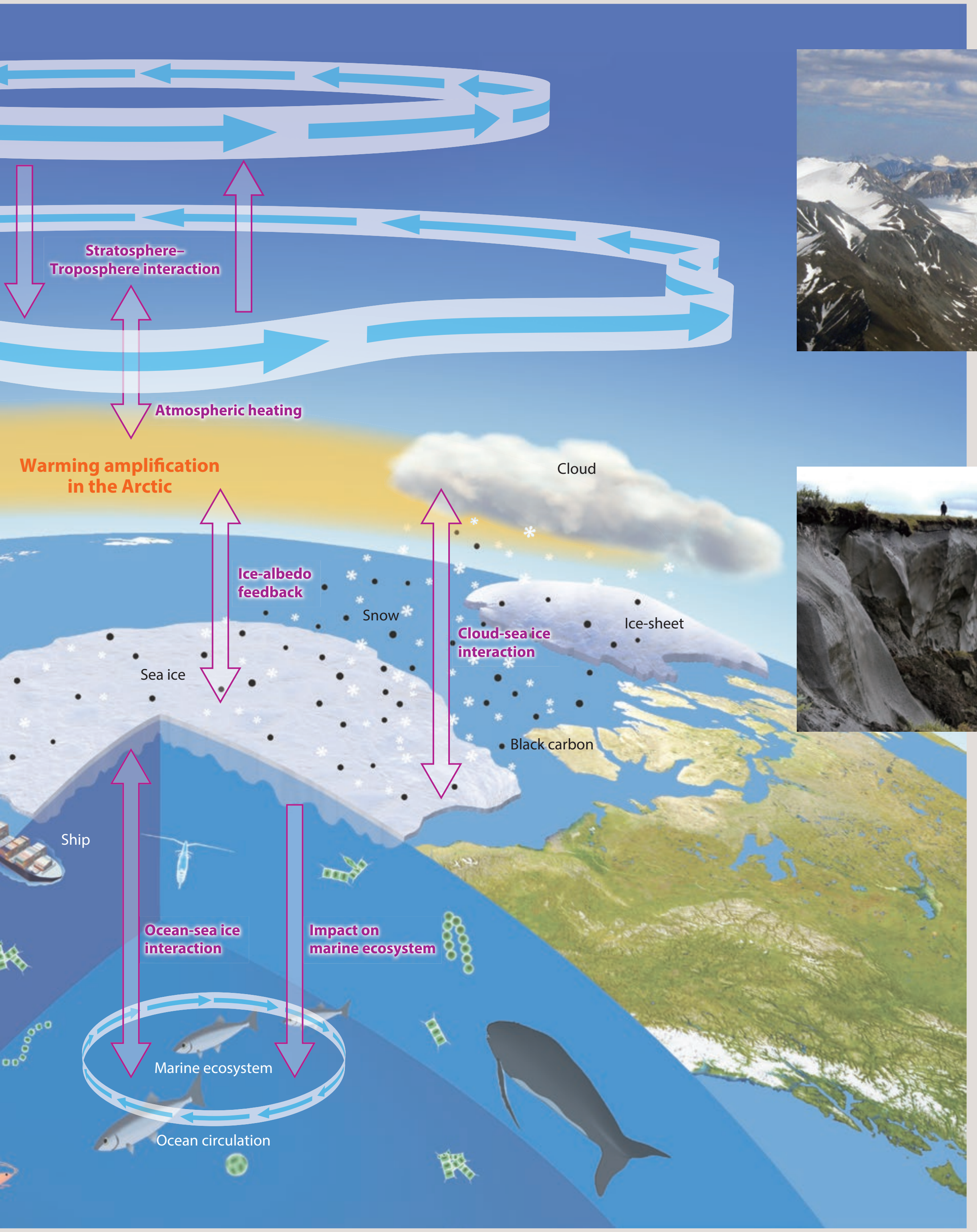
Earth!

trial biological activity will alter the amount of atmospheric carbon dioxide absorption by vegetation, and will affect global warming as feedback. Although it is far away from Japan, we cannot turn a blind eye to Arctic climate change, since we are affected by it, too.

In order to grasp these abrupt changes in the Arctic, to understand the mechanism, and to contribute to future climate change projection, we conducted the Green Network of Excellence Program (GRENE) Arctic Climate Change Research Project "Rapid Change of the Arctic Climate System and its Global Influences" for five years between 2011 and 2016. 39 institutes all over Japan have participated in the project, and more than 360 Japanese scientists tackled all aspects of the Arctic climate system. Comprehensive Arctic research incorporating multidisciplinary work and collaborations between observation and modeling have been realized.

Here we will report the scientific results achieved. In the project, four strategic research targets were presented and the outcomes for each target are described on the following pages. Finally, the mutual relationships between each target and a synthesis of "Rapid Change of the Arctic Climate System and its Global Influences" are shown in the flow diagram on the back page.



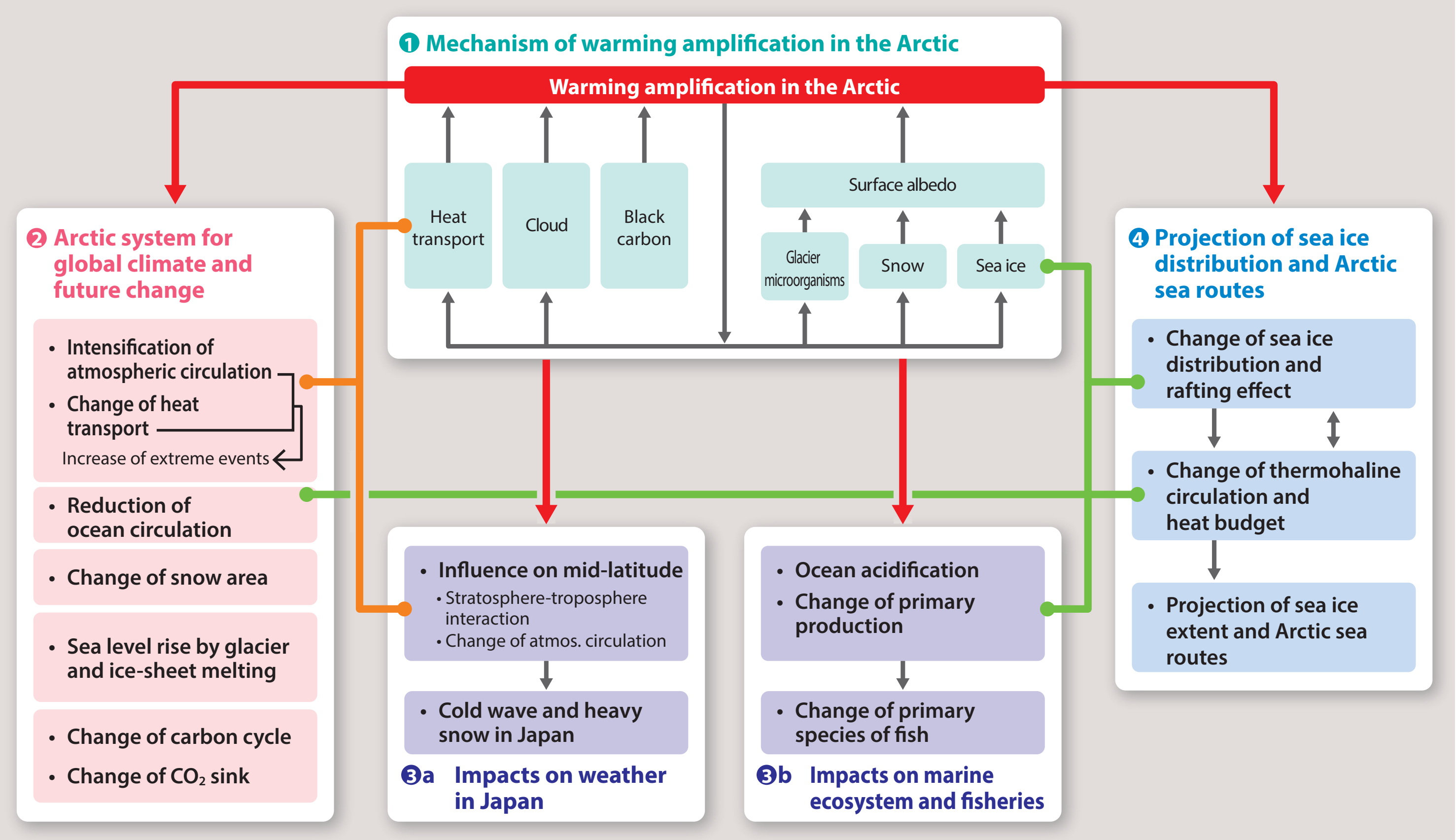
Retreating Suntar-Khayata Mountain Glacier in Siberia region

(Photo by Hiroyuki Enomoto, National Institute of Polar Research)

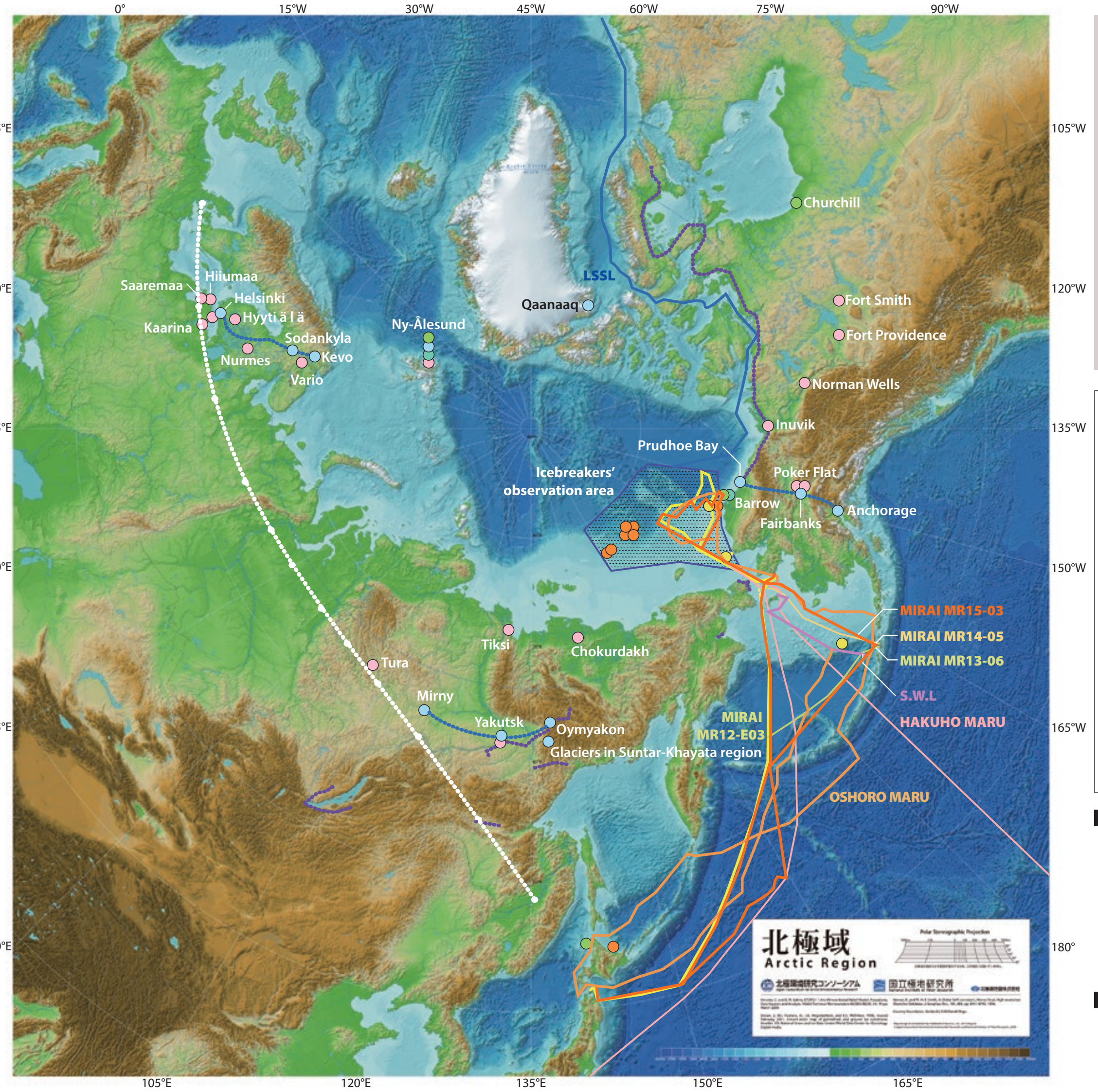
Degrading underground ice (yedoma) in the permafrost zone of the North Slope, Alaska

(Courtesy of Masao Uchida, National Institute for Environmental Studies; Go Iwahana, International Arctic Research Center)

Warming amplification in the Arctic and its global impact The key to Arctic climate change is Arctic warming amplification (AA). AA leads to the change in sea ice extent and then to the realization of the Arctic sea routes. It also affects the global climate, such as atmospheric circulation, cryosphere, and the carbon cycle. Moreover, AA will alter marine chemical components and the living environment for plankton, and hence have impacts on the major fish species and fisheries. AA will also influence the mid-latitude weather and climate, and bring cold and heavy snow to Japan in winter.



Map of GRENE-Arctic observation activities



Terrestrial ecosystem
Atmosphere
Cryosphere
Greenhouse gas
Marine ecosystem
Sea Ice and ocean environment
Snow survey lines
Permafrost survey lines
Airliner
Solid-lines (yellow, orange, pink, blue): Ship

About the project

Arctic Climate Change Research Project: Rapid Change of the Arctic Climate System and its Global Influences

"Green Network of Excellence" (GRENE) Program by Ministry of Education, Culture, Sports, Science & Technology, Japan (MEXT)

Core Institute: National Institute of Polar Research

Associated Institute: Japan Agency for Marine-Earth Science and Technology

Period: July 2011—March 2016

http://www.nipr.ac.jp/grene/

For further details: Final Report of GRENE Arctic Climate Change Research Project (Japanese edition only)

Editing/Publication
Inter-university Research Institute Corporation
Research Organization of Information and Systems
National Institute of Polar Research
10-3 Midori-cho, Tachikawa-shi,
Tokyo 190-8518, Japan
Telephone: +81-42-512-0922
http://www.nipr.ac.jp

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Front cover: Meltwater stream over a glacier surface darkened by glacier microorganisms in Greenland
(Photo by Shin Sugiyama, Hokkaido Univ.)

Arctic Climate Change Research Project
Rapid Change of the Arctic Climate System and its Global Influences

GRENE Arctic Climate Change Research Project

Summary of outcomes, 2011–2016

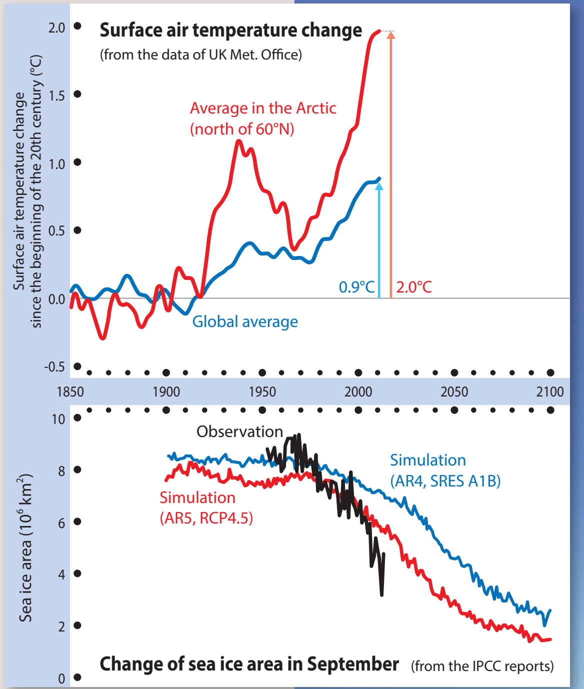
The Arctic, the fastest-warming place on

What is happening now in the Arctic, under global warming?

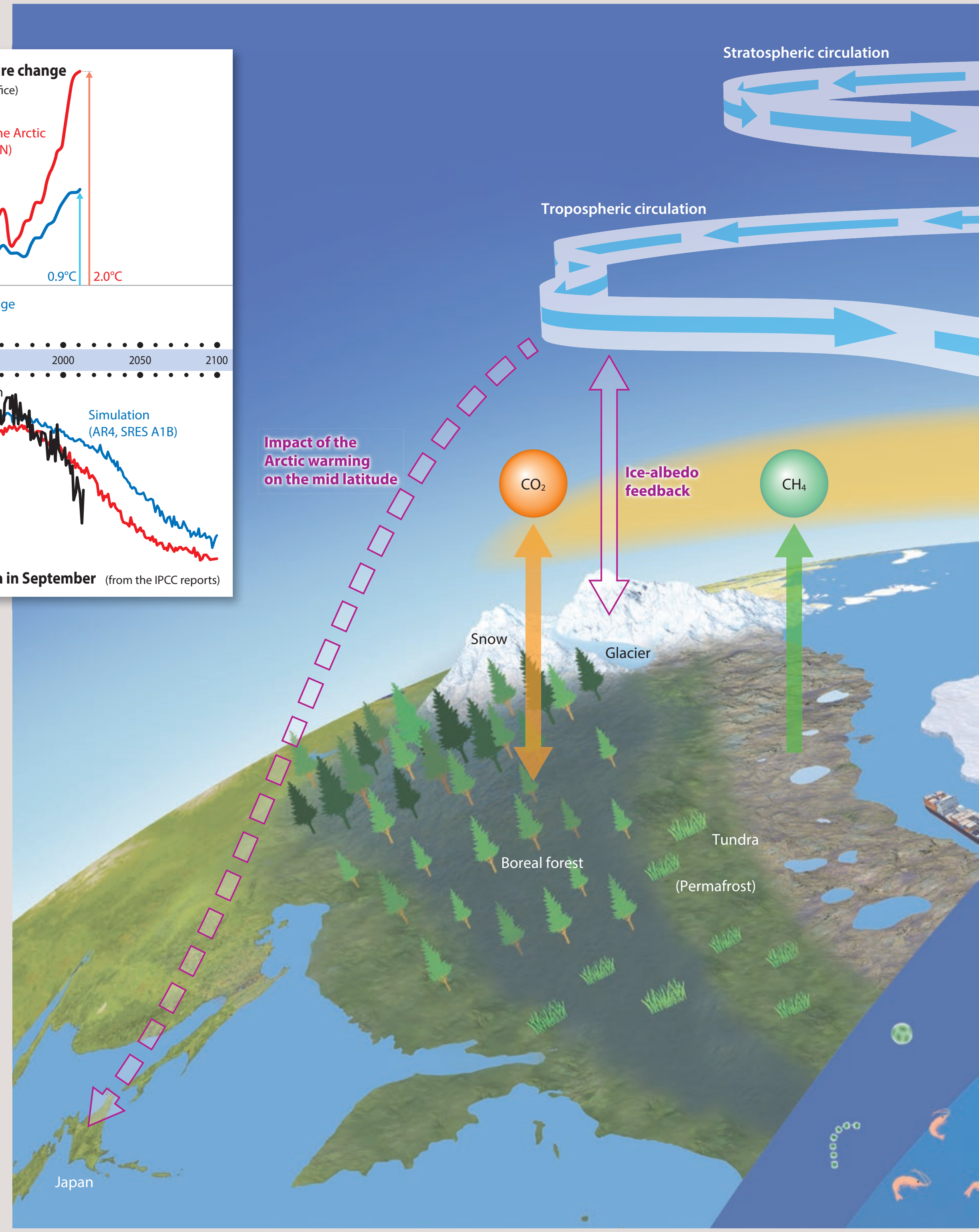
In warming due to anthropogenic increases in carbon dioxide concentration, the surface temperature in the Arctic is increasing with a speed that is more than double the global average. We call this "Arctic warming amplification," and an understanding of its mechanism is urgently needed.

Reduction of sea ice extent in the Arctic Ocean is continuing, and an abrupt decrease since the 2000s is especially noticeable. Owing to this change, potential for regular ship navigation through the Arctic Ocean have increased, and they have become broadly known as "Arctic sea routes." The reduction of the sea ice extent and the warming of the ocean are expected to lead to changes not only in the physical and chemical ocean environment, but also to changes of marine ecosystems.

Looking at the land area, many glaciers distributed around the Arctic are retreating. The Greenland ice sheet, the largest ice mass in the northern hemisphere, is also melting markedly, and the flow-out or collapse from its terminal glacier is serious. This will be a concern in terms of the world sea level rise. Moreover, the duration of the snow season is decreasing. In such ways, snow and ice have been showing great changes, and thus great impacts on atmospheric circulation and terrestrial biology are foreseen. Changes in terres-



(Upper) The mean surface air temperature in the Arctic has clearly increased twice as rapidly as that of the global mean, both in the last 100 years and in the last 40 years.
(Lower) The Arctic sea ice extent in September has decreased faster than what has been simulated by climate models. Moreover, the decrease is projected to continue through the 21st century.



Strategic Research Targets 2 | Understanding the Arctic system for global climate and future change

Arctic change is advancing with potential global influence.

The land and ocean in the Arctic have an important role in the uptake of CO_2 from the atmosphere, which has been demonstrated by observations of atmospheric CO_2 concentration. An increase in terrestrial uptake for the most recent 10 years was also suggested by the observed data.

Net uptake (or release) of CO_2 by the land is a balance between net primary production of vegetation and soil respiration. It had been generally believed that the productivity of vegetation in cold regions such as the Arctic and sub-Arctic increased with warming. However, tree ring analyses for circum-arctic forest ecosystems revealed that not all regions in the Arctic and sub-Arctic show increases in tree growth. Tree growth is decreasing in some regions such as eastern Siberia, the Alaska Interior, and Canada. Moreover, soil respiration is expected to increase with temperature, which has been shown by ecosystem model simulations, which suggests that CO_2 uptake by the Arctic may not continue in the future.

The GRENE-Arctic project has also revealed that snow duration is getting shorter and that reduction of sea ice extent may lead to extreme events such as heavy snowfall in mid-latitude regions due to changes in the atmospheric circulation pattern. These may also affect the Arctic and sub-Arctic ecosystems, resulting in changes in the CO_2 budget.

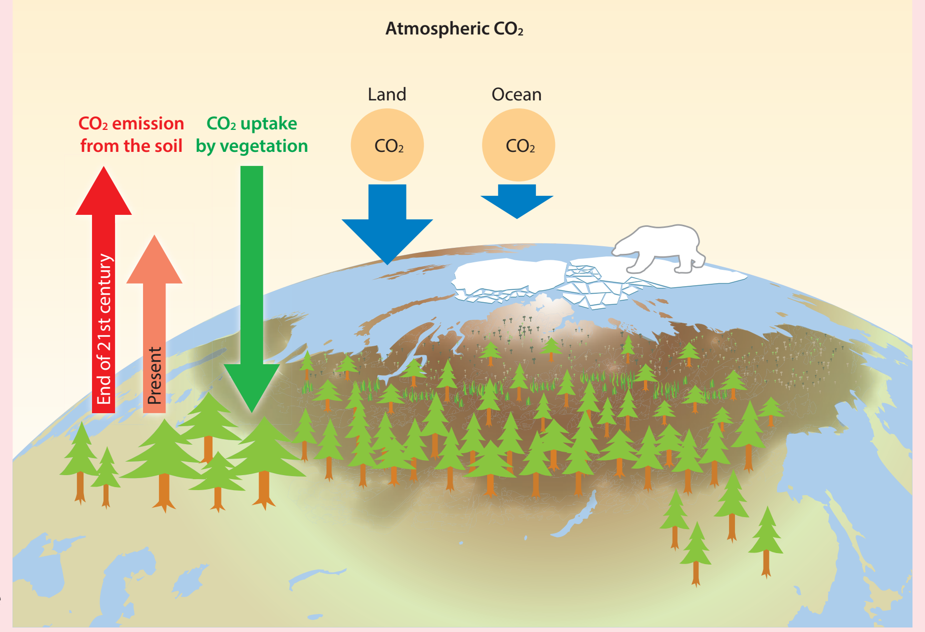
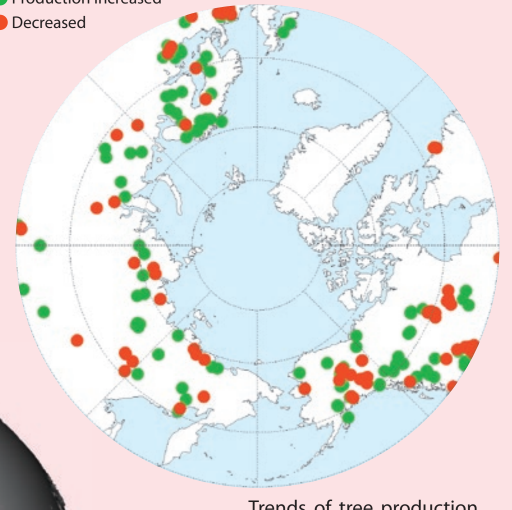


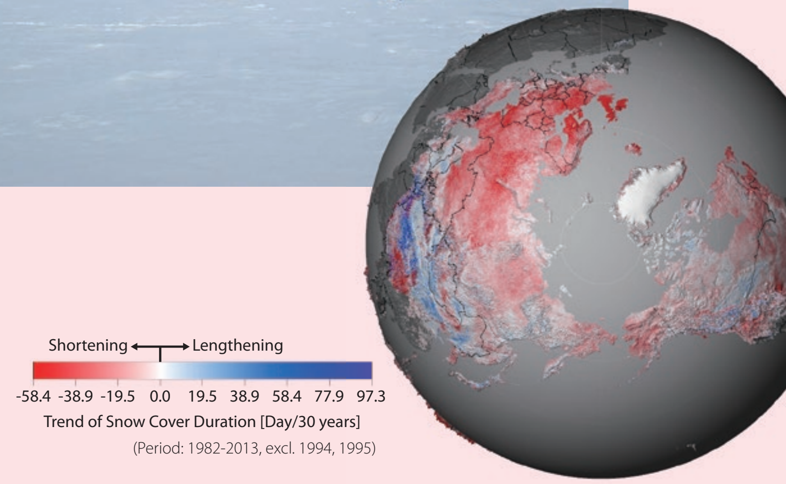
Image of CO_2 exchange in the Arctic

Snow sampling site near Denali National Park, Alaska

(Photo by Yoshimi Tsukagawa, National Institute of Polar Research)



Trends of tree production in the second half of the 20th century inferred from tree ring analyses



Changes in snow cover duration during the past 30 years. The red area indicates shortening of the snow-covered period, while the blue area indicates lengthening. There has been a significant reduction of snow cover duration in Europe.

Strategic Research Targets 1 | Understanding the mechanism of warming amplification in the Arctic

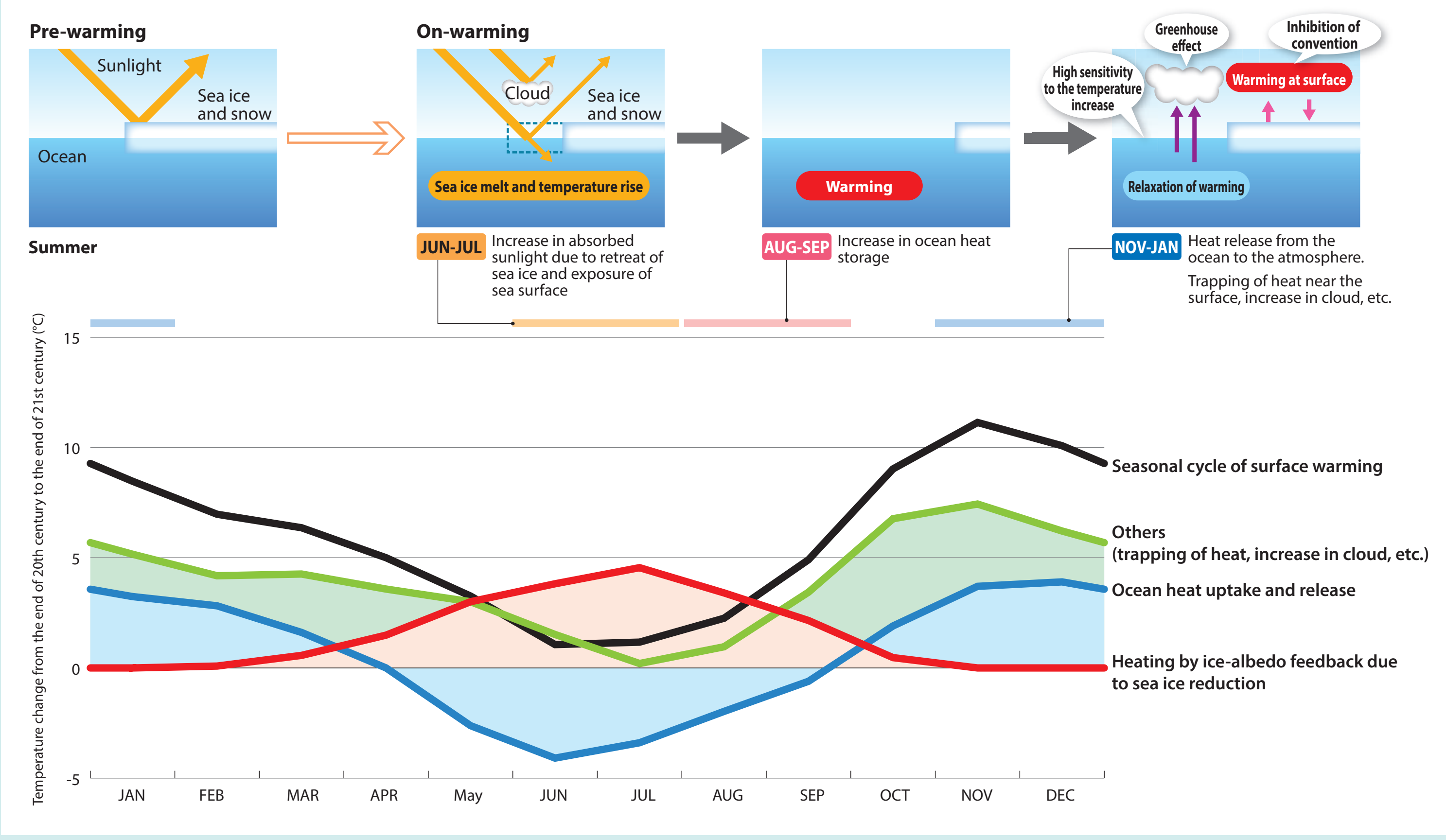
Quantification of relative contribution to Arctic warming amplification factors and their seasonality.

By analyzing future climate change projection datasets simulated by a number of climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), we quantify the role of various factors contributing to the Arctic warming amplification and clarify their seasonality.

Increases in surface air temperature over the Arctic regions are smallest in summer but largest in winter. Over the Arctic Ocean in summer, ice-albedo feedback due to sea ice retreat has the largest tendency to warm the surface. However, the surface warming is smallest because of the large heat uptake by the open ocean. In autumn and winter, the heat stored in the Arctic Ocean in summer is released into the atmosphere. Moreover, there are a number of other factors that contribute to warming the surface: strong vertical stability in the atmosphere traps warming close to the surface; increased low-level clouds enhance the greenhouse effect by trapping more longwave radiation; surface warming sensitivity is larger in colder regions than in warmer regions due to the effect of the Stefan-Boltzmann law; and so on. As a consequence, the largest surface warming occurs in winter. Over the Arctic land, the ice-albedo feedback has a peak in the early summer. Its additional heat warms the land surface, though part of this enhances surface evaporation and reduces surface warming. In winter, on the other hand, the land has no heat storage to release into the atmosphere. Therefore, the amplitude of seasonal variation for surface warming is smaller over the Arctic land than over the Arctic Ocean.

This study clarifies the seasonality and the relative contributions of various factors that were separately investigated, and also provides a comprehensive understanding of the mechanism of Arctic warming amplification.

Ice-albedo feedback:
As the temperature rises over the Arctic, snow and ice with high reflectance retreat, and the land and the ocean surfaces with low reflectance are exposed. The absorption of sunlight then increases, leading to a further increase in temperature and hence to a further increase in snow and ice retreat.



The seasonal cycle of warming amplification over the Arctic Ocean and its contributing factors. The black line shows the seasonal cycle of temperature increases from the end of the 20th century to the end of the 21st century averaged over the Arctic Ocean under the moderate warming scenario of RCP4.5. The contributions from the major factors contributing to the Arctic amplification are shown by the colored lines (red, blue and green).

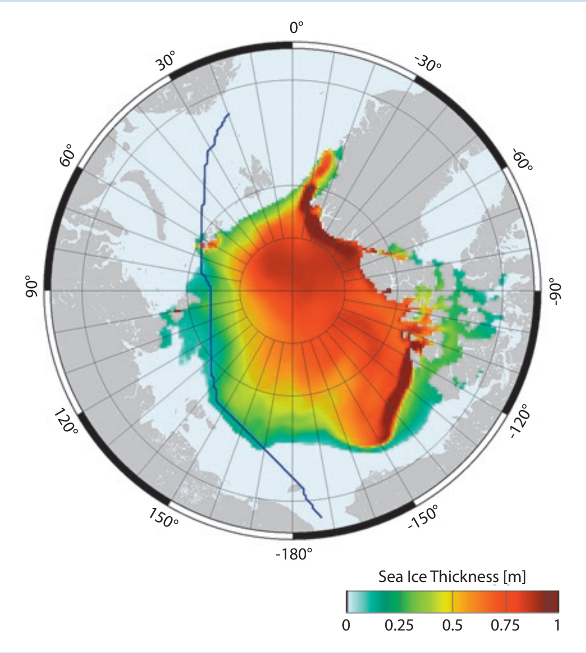
Strategic Research Targets 4 | Projection of sea ice distribution and Arctic sea routes

The Arctic sea routes: Feasible for sustainable use.

We have proposed empirical method to estimate timing of disappearance of sea ice, and proposed a simple model using just sea ice motion to evaluate volume transportation of upper ocean circulation, so called "Beaufort Gyre", that delivers the heat into the central Arctic Ocean and affects fate of sea ice. Analyses using in-situ and satellite observation data have clarified that volume transportation of the oceanic Beaufort Gyre is determined by past sea ice motion from about four years previously. We have also constructed methods to derive the timing of the disappearance of sea ice associated with rafting of sea ice from satellite-derived high-accuracy sea ice motion data. We also conducted a study using a high-resolution numerical Arctic Ocean model to reveal the structure of the heat transport system from the Atlantic to the Arctic, and the impact of meso-scale eddies on the advance/retreat of sea ice cover.

Another important theme of ours is seasonal-scale sea ice prediction, which is necessary for a decision of whether or not to take the Arctic route. We have improved the statistical method of the prediction using satellite remote-sensing data. In 2015, our prediction provided a good forecast of the timing of summer ice retreat and the spatial pattern of the minimum ice cover. Our activity regarding the Arctic sea route included many other themes, such as the optimal routing of ships, engineering studies on ship/ice interaction, ship icing, economic evaluations, and a proposal of scenarios for the use of Arctic sea routes. With these multidisciplinary efforts, studies for realizing the sustainable use of Arctic sea routes have advanced greatly during the GRENE Arctic Research Project.

Predicted (green line, forecasted at the end of May) and observed (white area) ice area on September 11, 2015



An example of optimal routing based on the predicted sea ice thickness on 24 October, 2011 with the prediction system for Arctic sea routes

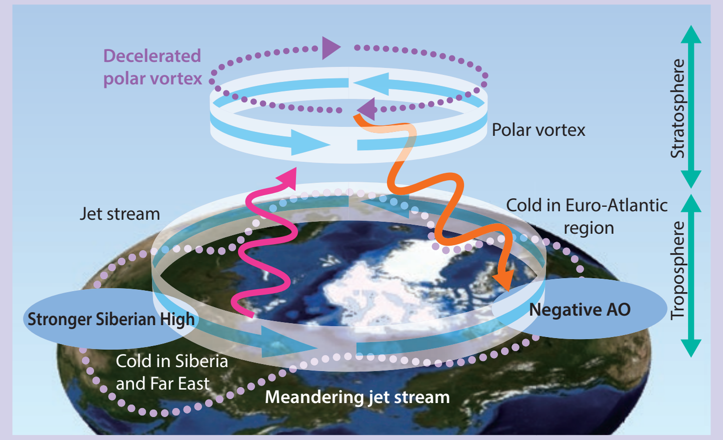
Icebreaker navigating the thin ice area

(Photo by Kazutaka Tateyama, Kitami Institute of Technology)

Strategic Research Targets 3a | Evaluation of the impacts of Arctic change on weather and climate in Japan

Climate change in the Arctic brings cold spells and snowstorms over Japan.

Arctic–mid-latitude climate linkage refers to possible impacts of Arctic climate change on mid-latitude climate and weather, which have recently been intensively studied. Severe weather in the northern mid-latitudes is often associated with meandering jet stream and the negative phase of the Arctic Oscillation (AO). Both observations and model simulations provide evidence that reductions in Arctic sea ice, or an increase in the Eurasian snow cover, tend to cause a negative AO phase, which is often preceded by weakening of the stratospheric polar vortex. This evidence hints at a stratospheric involvement in the Arctic–mid-latitude climate linkage. By artificially suppressing the stratospheric wave–mean flow interactions in numerical experiments, tropospheric signals of the Arctic–mid-latitude climate linkage can be significantly reduced, and thus we confirm that the stratosphere plays a crucial role in the Arctic–mid-latitude linkage. The results also imply that realistic representations of both Arctic surface boundary conditions and stratospheric processes are critical for improving predictions of weather and climate in the mid-latitudes.



Mechanism of the impacts of Arctic change on weather and climate in Japan

Fallen tree by a snowstorm (Photo by Shuhei Takahashi, Okhotsk Sea Ice Museum of Hokkaido)

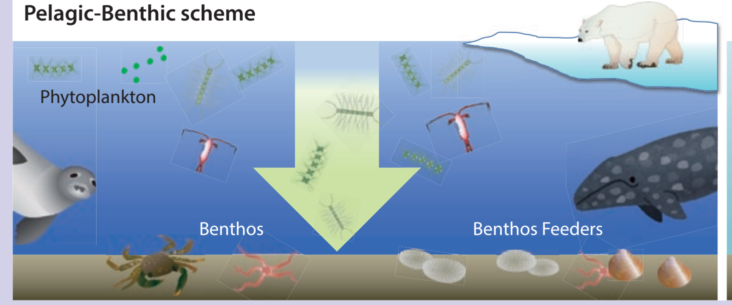
Strategic Research Targets 3b | Evaluation of the impacts of Arctic change on marine ecosystems and fisheries

Changes and shifts in the Arctic marine ecosystem have been evident.

The Arctic Ocean has experienced significant warming, freshening, and ocean acidification mainly caused by rapid reduction of sea ice. In the project Ecosystem Studies on the Arctic Ocean with Declining Sea Ice (ECOARCS), we investigated the impact of sea ice decreases on marine ecosystems. Our results show several forms of scientific evidence for changes in the marine ecosystem: the dominance of larger phytoplankton due to faster sea ice retreat in spring in the shelf region of the Arctic Ocean and Bering Sea; and a northward shift in the geographic distribution of the zooplankton community, benthos, fish, and marine mammals. On the other hand, we found that the North Pacific species of zooplankton transported into the Chukchi Sea (Arctic Ocean) is unlikely to establish stable Arctic populations in the near future due to large differences in geographic and life conditions. Currently, a bloom of phytoplankton at the ice edge in spring to summer sinks down to the seafloor and becomes food for the benthos (Pelagic-Benthic scheme, Figure below left). However, warming due to faster sea ice retreat may increase the population of zooplankton and fish, which feed on phytoplankton at the ice edge (Pelagic-Pelagic scheme, Figure below right).

The Arctic region will warm more rapidly than the global mean, and the resultant changes in Arctic environments could serve as an indication of global climate change, and should ring alarm bells not only for scientists, but also for the public. That is why we need to continue to monitor Arctic environmental changes and responses of marine ecosystems to assess how they can or cannot adapt to these changes.

Pelagic-Benthic scheme



Pelagic-Pelagic scheme