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Grant-in-Aid for Scientific Research on Innovative Areas

Giant reservoirs of heat/water/material: Global environmental changes driven by the Southern Ocean and the Antarctic Ice Sheet

Giant Reservoirs - Antarctic

News Letter vol.1-2

Circulation dynamics of heat, freshwater, and material originating from Antarctic Bottom Water (Bottom Water Group)

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1. Background and objective

The Antarctic Bottom Water (AABW), which accounts for 30–40% of the Earth's total seawater, is a giant reservoir of negative heat and material such as CO_2. Thus, the AABW is a key to the global climate system and long-term climate change as well. The IPCC Fifth Assessment Report suggests a significant decrease in AABW production, which may alter global thermohaline circulation as well. The IPCC report also indicates the possibility that the main factor of AABW change is increased freshwater flux resulting from the acceleration of ice shelf melting in West Antarctica. However, due to the difficulty of direct observations, the actual mechanism for AABW formation is unknown, despite AABW being an essential factor in the global climate system. For example, not even the exact locations of AABW formation have been identified. The main source of AABW is cold and saline dense water rejected by sea ice production in areas called coastal polynyas, where sea ice is actively produced. The first mapping of sea ice production in the Southern Ocean (Tamura et al. 2008) revealed that the Cape Darnley Polynya, about 1,200 km east of the Syowa Station, has the second-highest sea ice production volume in the Antarctic (Figure 1). The intensive observations during the International Polar Year in Japan newly identified the Cape Darnley Polynya as a fourth AABW formation area (Ohshima et al. 2013). With this discovery, research is underway to explore the possibility of bottom water formation in several polynyas of high ice production in East Antarctica. Observations on R/V Umitaka-maru (Kitade et al. 2014) showed that, even though it is a small amount, bottom water formation in the Vincennes Bay Polynya (Figure 1) that has the sixth-highest sea ice production volume. In contrast, the Amery Ice Shelf area situated east of Cape Darnley has sea ice production comparable to that of the Cape Darnley Polynya, but not as much AABW production as the Cape Darnley Polynya. This fact suggests that AABW formation is limited by freshening resulting from melting of the ice shelf. Thus, AABW formation is determined by the balance between the positive effect of sea ice production in the polynyas and the negative effect of ice shelf melting. As for East Antarctica, the quantification of the AABW has just begun.

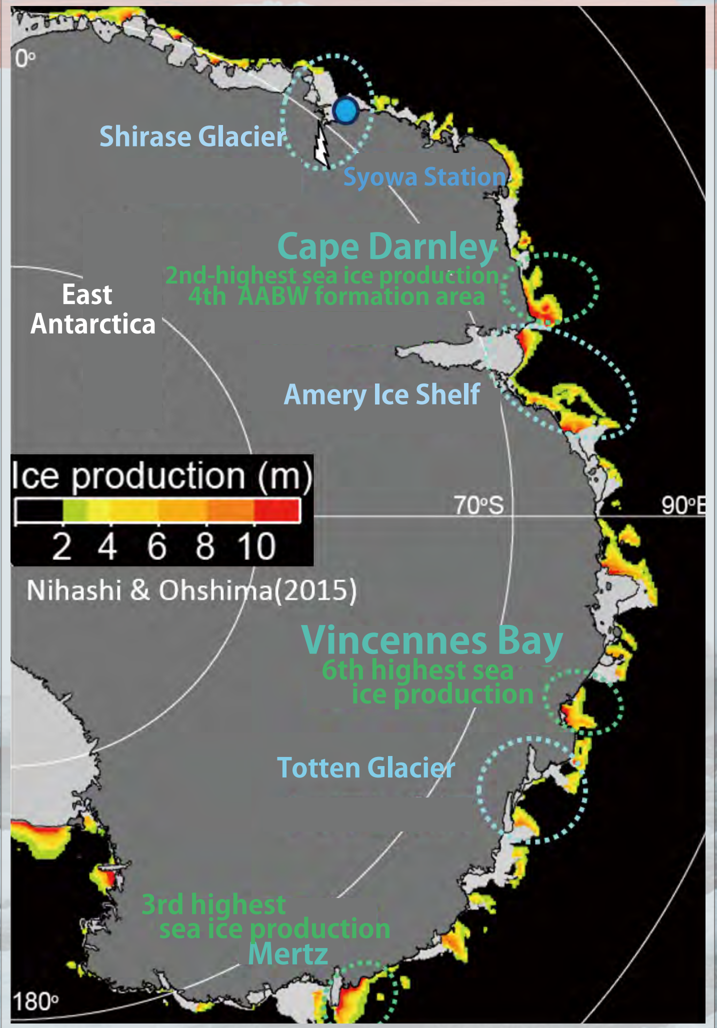

Figure 1. Mapping of annual cumulative sea ice production in East Antarctica and the area targeted for observation. Production is expressed as sea ice thickness in meters.

The Southern Ocean is a giant reservoir of material. Notably, the CO_2 and carbon balance in the Southern Ocean is presumed to have a close relation to the global CO_2 balance. The widely accepted assumption is that changes in the amount of CO_2 stored in the Southern Ocean determined past glacial-interglacial variations. To clarify this assumption, the large project "Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM)," led by the United States, conducts observations using about 200 biogeochemical floats. However, this project enables us to obtain data only from the open ocean. The Antarctic coastal area, where seawater sinks to the sea bottom, remains unexplored despite its importance for CO_2 balance.

2. Points to elucidate

First, in East Antarctica, we aim to quantify the formation, the exact area, and the spreading of bottom water. Especially, we will target areas offshore of Cape Darnley, the key AABW formation area in East Antarctica, for intensive observations. Second, mainly from the viewpoint of the balance between sea ice production and ice shelf melting, we will clarify the formation and spreading of bottom water in key areas of East Antarctica, such as the offshore areas of Vincennes Bay and the Totten Glacier (The Totten Glacier is predicted to have the highest melting rate by the ocean in East Antarctica – see Figure 1). Based on these understandings, we will assess the impact of the recent acceleration of ice shelf melting on bottom water formation. Finally, we aim to apply these evaluations to predict response of the thermohaline circulation, responding to further ice sheet melting. It is an important goal to clarify the CO_2・carbon exchange process through bottom water formation by direct observations with the Cape Darnley Polynya as a test site. In addition, it is also essential to advance the understanding of material circulation, such as CO_2 and nutrients originating from the bottom water, as well as evaluate the uptake rates of anthropogenic CO_2 in the bottom water.

3. Cruise observation plan

Regarding East Antarctica, during the research period, in addition to the yearly cruise observations of R/V Umitaka-maru and R/V Shirase, the observations with R/V Hakuho-maru and R/V Kaiyo-maru were planned for FY 2018, and observations with R/V Hakuho-maru and R/V Mirai were scheduled for FY 2019 (Figure 2). Thus, four research vessels gathered in East Antarctic for two consecutive years. We will take advantage of this ideal opportunity to conduct the following observations:

① Conduct mooring array observations on the AABW path (Figure 3) and estimate the flux of dense water and heat/salt/material from the surface to the bottom, especially by the new installation of remote access samplers and a novel pH sensor.

② Observe chemical tracers, such as CFC, SF_6, $\delta_{18}O$ to quantify the spreading process, mixing process, and residence time of the bottom water/ice shelf melt water.

③ Re-observe the spots where CFC and $\delta_{18}O$ data were obtained during the last 10-30 years, estimate the interannual variability of bottom water formation in East Antarctica, and evaluate the influence of recent glacial melting acceleration.

④ Estimate anthropogenic CO_2 in seawater from total carbon dioxide/alkalinity and CFC/SF_6, re-evaluate the uptake rate of anthropogenic CO_2 caused by bottom water, and quantitatively assess acidification due to anthropogenic CO_2 uptake.

⑤ In collaboration with the Ice sheet group, estimate the amount of ice sheet melting by the effect of the ocean, as well as clarify its melting process in the sea areas around the Shirase and Totten Glaciers using Remotely Operated Vehicle (ROV) which are being introduced and operated by the Exploration group.

⑥ In collaboration with the Paleo-oceanography group, collect sediment cores from the seabed and install sediment traps in mooring systems near the path of AABW to reveal the history of AABW formation.

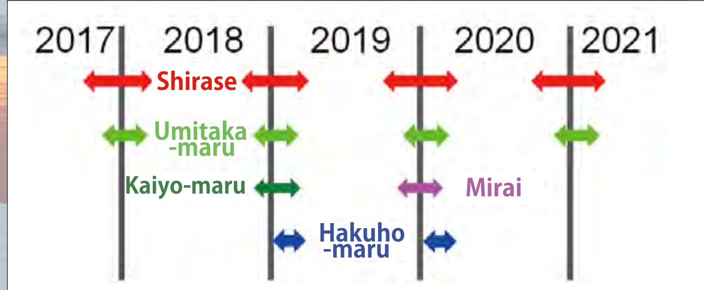

Figure 2. Antarctic cruise expeditions scheduled for 2017–2021.

Figure 3. Overview of mooring systems installed in the AABW formation area off Cape Darnley.

Paleoclimate dynamics of the Southern Ocean (Paleo-oceanography group)

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1. Academic background and objective

The Southern Ocean is the ocean encircling Antarctica, a giant reservoir of material such as negative heat and CO_2, and a key to global climate change. The Antarctic Circumpolar Current (ACC) (Figure 1) that characterizes the Southern Ocean is the world's largest surface circulation. The ACC flow in the Drake Passage reaches up to 135 Sv (10^6 m^3/s) at maximum, which is more than four times larger than the Kuroshio flow. Variations of ACC, sea ice distribution (Figure 2), surface water temperature, and salinity are considered to affect the ocean circulation of the Southern Ocean, the intensity of CO_2 emissions from the deep water to the atmosphere, and the Antarctic ice sheet. These variations are also considered to drive global climate change through the carbon cycle and sea level fluctuations. Up to the present, we have surveyed the Conrad Rise and Del Caño Rise (the sea areas marked CR and DCR, respectively, in Figure 3) in the Indian Ocean sector of the Southern Ocean, and reconstructed fluctuations of ACC, the Polar Front (PF), and the sea ice distribution from the last glacial period through the present. As a result, the following three points have been clarified:

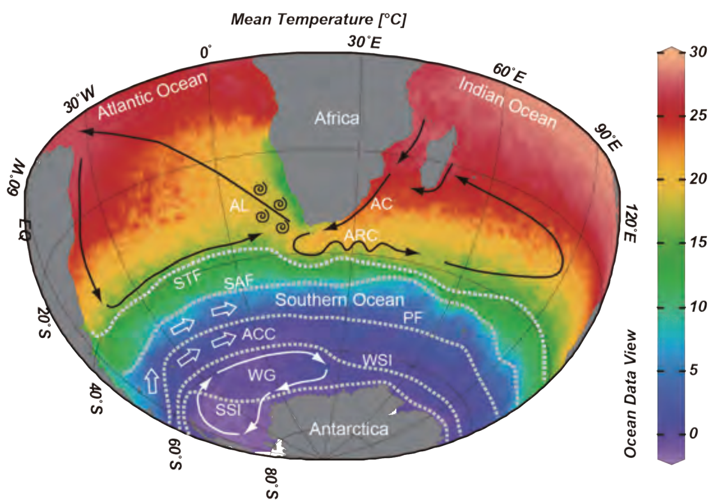


Figure 1. Conceptual diagram of ocean circulation and the Agulhas current system in the Southern Hemisphere. The background color shows the distribution of the annual average water temperature on the surface of the ocean. Arrows (black and white) indicate the main surface circulation pattern. The Southern Ocean is divided into several zones by the ACC, a wind-driven circulation, and each zone is characterized by different water temperatures and salinities. Key to abbreviations: Agulhas Current (AC), Agulhas Leakage (AL, indicated by vortex), Agulhas Return Current (ARC), Subtropical Front (STF), Subantarctic Front (SAF), Polar Front (PF), Antarctic Circumpolar Current (ACC), winter sea ice limit (WSI), summer sea ice limit (SSI), Weddell Gyre (WG).

(1) The winter sea ice distribution fluctuated significantly, in synchronization with the glacial-interglacial variations. During the last glacial period, the winter sea ice distribution not only moved northward by more than 10 degrees but also repeatedly expanded and decreased on a thousand-year timescale.

(2) The ice melting hotspot presently located in the northeastern part of the Weddell Gyre is most likely to have extended eastward to the vicinity of Del Caño Rise during the glacial period.

(3) The ACC is most likely to have moved northward greatly in the early Pleistocene epoch, when the current climate mode was established (about 1.5–2 million years ago), as assumed from the spatio-temporal distribution of the sediment waves (giant dune-like submarine topography) newly discovered in the Conrad Rise.

These results suggest the possibility that the Southern Ocean may have played an important role in the climate variability of the glacial-interglacial cycle and long-term climate revolution. Thus, two hypotheses have been proposed: (1) the Weddell Gyre extended eastward during the glacial period and (2) the ACC of the early Pleistocene epoch moved northward. However, the paleoenvironmental indicators (proxies) are neither sufficiently verified nor accurate enough due to a lack of basic data on the Southern Ocean. In addition, due to an overwhelming lack of spatio-temporal paleo-oceanographic information, the entire picture of north-south shifting, such as the winter sea ice edge and the frontal zone (STF, SAF, and PF in Figure 1), during climate variations on various timescales remains unclear. Thus, the roles of ACC and the Southern Ocean as forces driving global climate variability have not been clarified. Therefore, we plan interdisciplinary research and will promote international collaborative investigations by strengthening in situ observations and cooperation with other groups in this project for the following three objectives:

Figure 2. Southern Ocean sea ice

A) Improve the accuracy of paleoenvironmental indicators (proxies) in the Southern Ocean

Clarify latitude distribution, seasonal variations of various proxies (microfossils, chemical composition, and isotope ratios), and develop and test new proxies by examining the interactions with the surface water temperature, salinity, and sea ice distribution.

B) Verify the hypothesis that the Weddell Gyre extended eastward during the glacial period

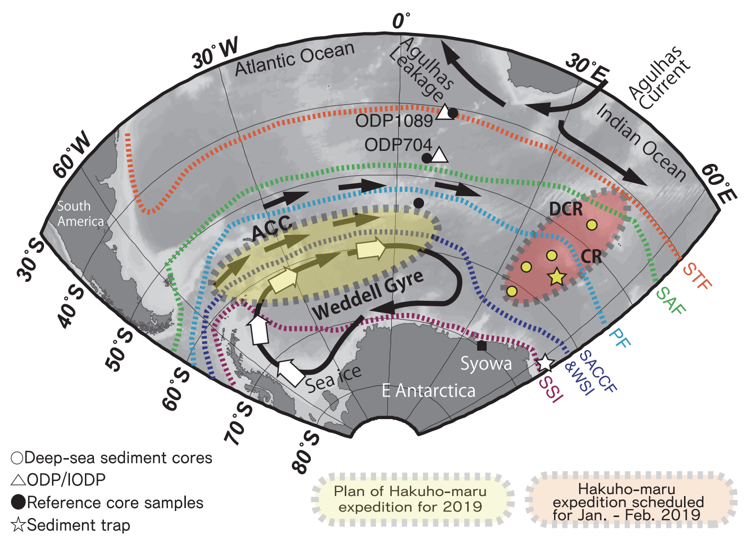
Reconstruct paleoceanographic variability of the Southern Ocean during the Quaternary glacial-interglacial cycle, including the super-warm periods (e.g., 127,000 and 41,000 years ago), which is an analogy for the global warming in the near future. Understand the actual state of north-west and east-west shifting of the ACC, Weddell Gyre, Polar Front, winter sea ice distribution, and ocean stratification. Elucidate the role of the Southern Ocean in the glacial-interglacial variability.

C) Verify the hypothesis that ACC of the early Pleistocene moved northward

Restore the dynamics of the ACC, Weddell Gyre, and sea ice advection on a long-term timescale from the late Pliocene (3 million years ago) through the Quaternary epoch. Elucidate the role of the Southern Ocean in the long-term climate and the mechanism of its interactions.

2. Research cruise and research plan

Presently we have been analyzing samples from deep-sea sediment cores, surface sea water, and plankton obtained from the Conrad Rise and Del Caño Rise in the Indian Ocean sector of the Southern Ocean during the research cruise of R/V Hakuho-maru (FYs 2010 and 2016). We collected deep-sea sediment cores and recover sediment traps from Conrad Rise and Del Caño Rise in FY 2018 (Figure 3). Furthermore, we planned the next research cruise in the Scotia Sea and Weddell Sea in FY 2019 and aim to advance the project "Giant Reservoirs – Antarctic" by enrichment with data obtained through in situ observations and deep-sea sediment core samples.



DCR: Del Caño Rise, CR:Conrad Rise, ACC: Antarctic Circumpolar Current, STF: Subtropical Front, SAF:Subantarctic Front, PF:Polar Front, SACCF: Southern Antarctic Circumpolar Current Front, WSI: winter sea ice limit, SSI:summer sea ice limit

Figure 3. Outline of seafloor topography, surface circulation, fronts, and sea ice distribution in the sea area targeted by this research.

Ecosystem dynamics in the Antarctic sea ice zone (Ecosystem group)

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Tokyo University of Marine Science and Technology

1. Sea ice and ecosystem

Elucidating the role of sea ice in the Southern Ocean is central to understanding this ecosystem. In winter, sea ice covers a sea area of 20 million m2, which is larger than the land mass of Antarctica and accounts for 10% of the world's oceans. In contrast, in summer, more than 80% of this sea ice melts and the ocean surface appears. These seasonal changes that are repeated every year in the extent of sea ice play a critical role in the organisms in the Southern Ocean. Although the precise mechanisms of sea ice melting are not fully understood, the process of melting is known to be associated with ice edge blooms i.e., explosive growth of phytoplankton. The blooms form the basis of a food chain, and several species have evolved adapting their life histories in response to the timing of the blooms.

Sea ice plays another important role in the marine ecosystem. Pockets frequently form inside sea ice, and ice algae (microalgae), mainly diatoms, flourish in these pockets. These diatoms become trapped in the ice from the seawater during the sea ice production in the sea areas referred to as coastal polynyas near the Antarctic continent, and is then carried northward together with sea ice by wind and ocean currents. Water/air temperatures are higher near the ice edge (i.e., the northern edge of the sea ice area). As the sea ice melts, the ice algae are released into the seawater. Since sea ice is produced continuously in the coastal polynyas from autumn to winter, ice algae are considered to be supplied continuously to these ice edge areas. Although the living of ice algae frozen inside the sea ice as it moves northward remains unknown, some species have been found to survive in sea ice and presumed even to proliferate. Although conditions inside the ice appear to be harsh, algae trapped in the surface layer are exposed to abundant light energy and are likely to photosynthesize advantageously.

Sea ice begins to melt from the northern side, and the ice edge recedes southward, releasing ice algae as the ice melts. This release of algae is brought into the ocean as primary production that differs from algal blooms. In addition to microalgae, sea ice has been found to contain fauna, such as protozoa and copepods. This assemblage of different organisms is generally referred to as sea ice biota (SIB), including algae and animals. Little is currently known about the living of SIB after it is released into the sea e.i., how SIB is input into the marine ecosystem, whether or not SIB only sinks, and how much SIB is released remain to be clarified.

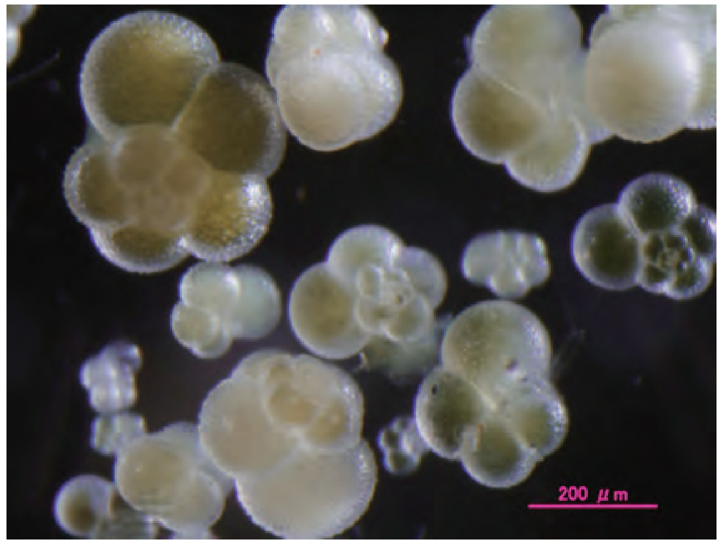

Figure 1. Foraminifera found in sea ice. Althogh the foraminifera appear at high densities, their feeding ecology remains poorly known. (photo by Motoha Ojima).

2. Antarctic krill and myctophids

Euphausia superba (krill) is a central component of the food chain/ food web of the Southern Ocean. Krill is believed to accounts for approximately 400 million tons of biomass and is the most important prey of large predators, such as seabirds (including penguins), seals, and whales. Consequently, elucidating the ecology of this species is the shortest way to understanding the Southern Ocean ecosystem. Considerable effort and resources have therefore been devoted to research on the krill, and monitoring this species is of primary importance. On the other hand, accumulated data and information have shown that krill is not abundant in some ocean areas, such as the East Antarctic sea area (the Indian sector, southern Australian waters) targeted in our project. In these areas, myctophid fish play a significant role in transferring energy of lower-level production to higher-level predators. Although research on myctophids has been actively conducted in the Southern Ocean in recent years, little data on myctophids are lacking at present compared to on krill. The most productive areas in the Southern Ocean are off the Western Antarctic Peninsula and the Scotia Sea, where the krill biomass is concentrated. Because research historically focuses on areas of high production, the ecology of the Southern Ocean has long been considered to be a krill-centered ecosystem. However, research resources do not seem sufficiently utilized in investigations on other key species.

Figure 2. Myctophid fish, Electrona antarctica. This abundant prey species is dominant in the high latitudes of the Southern Ocean. The adult fish, which feed on Antarctic krill, are in turn predated upon by a variety of larger predators.

3. Research objective

Atmospheric CO_2 dissolves in the surface layers of the ocean where it is converted to organic matter in the form of phytoplankton by photosynthesis. As organisms increase in size in the food chain, e.g., from phytophagous zooplankton to zoophagous plankton/fish, their fecal pellets also increase in size. Since larger particles sink faster in the sea, the process of trophic level advancement (being eaten in sequence) accelerates the effect of carbon segregation (organic matter) by the deep sea. This process, called the biological pump, is essential for stabilizing the atmospheric CO_2 concentration. Since the biological pump is dependent on biological processes, ecosystem changes are likely to affect the function directly.

We aim to clarify the lower production processes originating from sea ice by way of SIB, as well as the structure of the myctophid-centered trophic pathway. This research will contribute to predictions of ecosystem change resulting from fluctuations of sea ice volume and sea ice area. Understanding these cold environments where CO_2 dissolves easily and the functions of the biological carbon pump in the Southern Ocean that has the vast seasonal sea ice area is considered indispensable for improving the accuracy of predicting global environmental change.

Figure 3. The distribution of Humpback whales has extended southward in recent years. The prey of Humpback whales and the reasons for their southward expansion remain unknown.

Variations and interactions of climate and the Antarctic Ice Sheet (Ice sheet group)

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National Institute of Polar Research

1. Background

The Antarctic ice sheet is the largest freshwater reservoir on earth, and the speed and quantity of its changes in response to climate change have been scientifically and societally a significant issue. Since the Antarctic ice sheet margin is mostly terminating into the ocean, the collapse of glacier tongue and basal melting of ice shelf trigger the mass loss. Therefore, various processes such as ice-shelf basal melting and warm water intrusion must be quantitatively understood. However, comprehensive observations of glacier terminus, ice shelves, and ocean under sea ice are challenging to conduct, which hinders research progress. Since global warming increases snowfall, ice sheet mass also increases in some areas in East Antarctica. However, the estimate of surface mass balance over vast East Antarctica has a large uncertainty, which affects the evaluation of the mass balance of the entire Antarctic ice sheet. Accurate understanding of variations and mechanisms of ice-sheet mass balance is indispensable to project the timing and speed of the ice sheet fluctuations caused by global warming. It is also indispensable to look into the past variations over the long term to understand the behavior of the whole Antarctic ice sheet. Because high-resolution climate models can now be run over ten-thousand-year timescales, high-quality paleoenvironmental data are required as the input and validation data. The analyses of the Dome Fuji ice core have provided the paleo-environmental data such as temperature and atmospheric composition over the glacial-interglacial cycles (Figure1). Increasing the length, accuracy and resolution of the paleo-environmental data is imperative.

The data shown in Figure 1 illustrates that the atmospheric CO_2 concentration, Antarctic temperature, and sea level changed nearly synchronously, but the causal relationships have not been understood well and remain an important problem. Improvement of analytical techniques on microparticles and impurities in ice cores has also brought the potential to reconstruct the past atmospheric chemical environment.

2. Research aim

We conduct the research on the variations and interactions between the Antarctic ice sheet and climate, focusing on the following points (Figure 2);

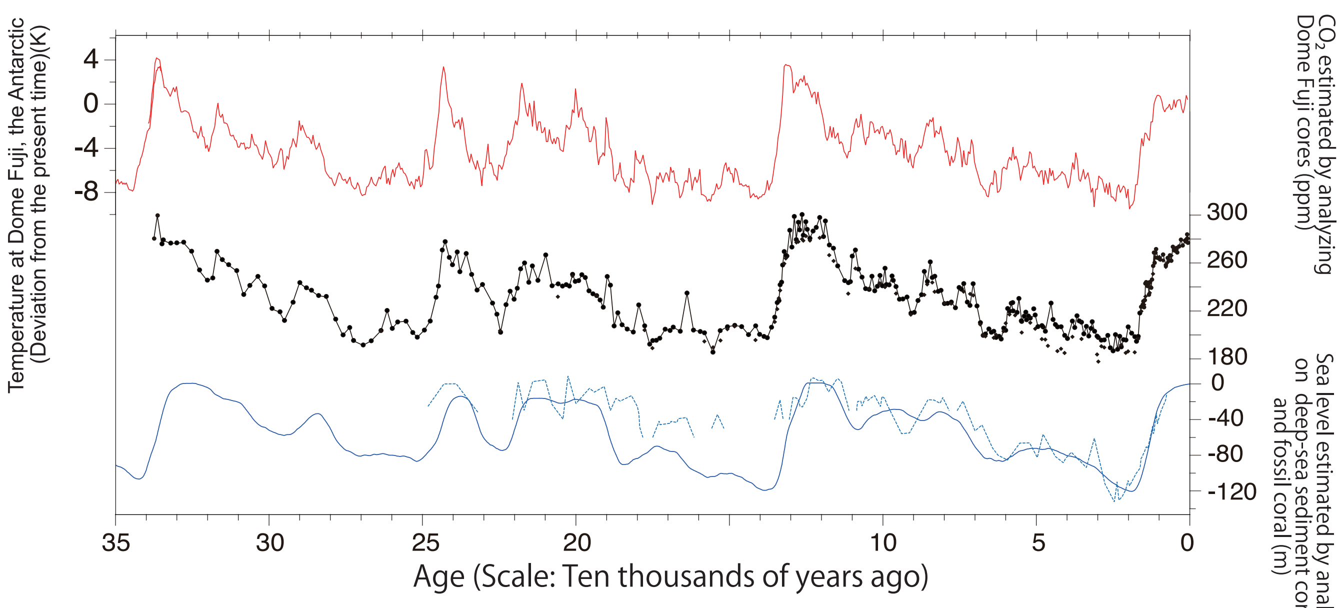

Figure 1. Temperature index and CO_2 concentration for the past 340000 years based on analysis on Dome Fuji cores. The fugure also shows sea level estimated by deep-sea sediment cores.

(1) Interactions between climate and ice sheet on long timescales

Focusing on "super-interglacial periods" such as the last interglacial period and the interglacial period about four hundred thousand years ago, we reconstruct the atmospheric composition and climate variations by analyzing the second Dome Fuji deep ice core. Utilizing these reconstructions as input and validation data for climate and ice-sheet models, we aim to better understand the variations and interactions of the climate and ice sheet. We also aim to establish an accurate paleoclimatic timescale by utilizing the dating accuracy of the Dome Fuji core, and discuss paleoclimatic and paleo-oceanographic data from around the world on the same timescale.

(2) Interactions of the ice sheet and ocean, and mass balance on large spatial scales

We aim to reveal the current surface mass balance and ice flow by glaciological observations from the margins to the inland areas, together with the analyses of satellite data. Also, we observe the sea under the ice by ice shelf drilling (Figure 3) and underwater vehicles. Through quantifying the contribution of ice shelf basal melting to ice sheet fluctuations, as well as studying the physical and chemical characteristics of seawater and ocean circulation, we advance the understanding of ice sheet–ocean interactions.

3.Research methods

We develop and improve the ice-core analytical methods. Analyses of shallow ice cores, firn air and snow will allow us to better understand the recording processes of climate signals and gases into the ice sheet. Then, we analyze the Dome Fuji ice core to reconstruct long-term Antarctic and global environmental changes, and also investigate the published data from marine sediment cores. We contribute to the numerical simulations of climate, ice sheet and ocean by the Model group by providing input and validation data from the ice core. We also collaborate with the Paleo-oceanography group to integrate the age scales of paleoclimatic data from around the globe, compare them with various model results, and advance model validation and our understanding of variations and interactions of climate and the ice sheet.

We also conduct in-situ observations on the Langhovde Glacier and its ice shelf. We collaborate with the Exploration group and the Bottom Water Group to observe surface mass balance, ice flow, ice shelf basal melting, seawater characteristics, ocean circulation, and organisms and geology in the seafloor, through comprehensive observations in the coastal area using hot water drilling and unmanned vehicles. We also investigate the seasonal and interannual variations of ice and sea by long-term operations of observational instruments. Moreover, we estimate the surface mass balance, ice flow velocity, grounding line, and sea ice concentration over the past decades by analyzing satellite data and past in-situ observational data.

In collaboration with the Model group, we advance our understandings of ice sheet-ocean interactions and surface mass balance variations, by providing boundary conditions for the models and comparing the simulation results with the in-situ observational data. We also collaborate with the Solid Earth group to improve the estimation of ice sheet mass balance, by using our glaciological data as boundary conditions for GIA models.

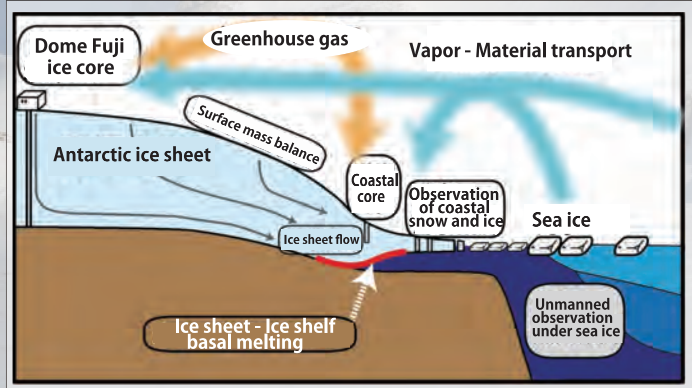

Figure 2. Research area and main environmental elements in this project. The black flames show main observation and investigation items.

Figure 3. Observation of glacier terminus by using hot water drilling system

Interaction of the solid Earth and the Antarctic ice sheet (Solid Earth group)

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1. Background and objective

The Antarctic ice sheet is closely associated with global environmental changes through sea level rise and ocean water circulation. A greater understanding of ice sheet fluctuations is indispensable for environmental prediction in the future. In East Antarctica, the ice sheet was considered to be barely affected by the ocean, since most of the bedrock there was previously believed to be above sea level. In addition, global warming was considered to have little effect on the ice sheet on a timescale of merely a hundred years, since almost the entirety of Antarctica remains at temperatures below freezing year-round.

However, in recent years, aerial radar surveys on the ice sheet and geological drilling surveys on the surrounding ocean floor have revealed that the bedrock of the Pacific section of East Antarctic is mostly below sea level. These results also suggested that massive melting of the East Antarctic ice sheet raised the sea level about 5 to 2.5 million years ago (the Pliocene epoch), when the atmospheric CO_2 concentration was considered to be approximately 400 ppm, which is the same as in the present. Consequently, there is a growing concern regarding the possibility of significant melting and decrease of the East Antarctic ice sheet at the current CO_2 concentration. Since the East Antarctic ice sheet accounts for more than 90% of the entire Antarctic ice sheet, it will be a serious problem if the melting accelerates.

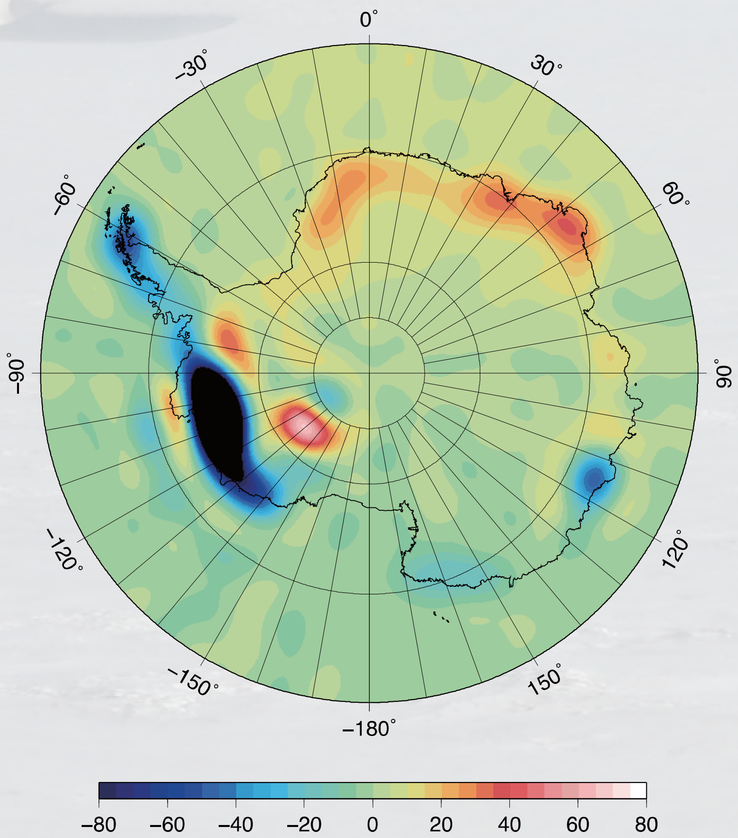

Figure 1. Mass change rate based on GRACE satellite gravity data (water equivalent conversion mm/y)

On the other hand, although the melting of the West Antarctic ice sheet is progressing, both recent climate models and Satellite Gravimetry/Satellite Altimetry Synthetic data reveal that the ice sheet also tends to increase due to increased snowfall in the part of East Antarctica (Figure 1). Thus, presently it has not been determined whether or not the melting of the East Antarctic ice sheet will progress in the future. Additionally, even if the ice sheet melting is progressing up to now, its timing, mechanism, and melting rate have not been sufficiently clarified, which is scientifically and socially important issue.

While it is essential to accurately observe and monitor the current ice sheet mass balance for prediction of ice sheet fluctuations in the future, one of the primary obstacles in this observation is the uncertainty in the GIA (Glacial Isostatic Adjustment). GIA is the ongoing movement toward a state of isostasy, which is the equilibrium between gravity and buoyancy resulting from the viscoelastic response of the solid Earth to changes in the ice sheet load. Despite the fact that the equilibrium between gravity and buoyancy is static, the viscoelastic characteristics of the solid Earth cause a time delay in reaching the state of (gravitational) equilibrium. Therefore, for accurate GIA modeling, information on the viscoelastic structure of the entire Earth is required together with information on the ice sheet load fluctuations, i.e., the history of ice sheet melting, from past to present.

However, the uncertainty in the GIA models is prominent especially in Antarctica as in situ data necessary to constrain GIA models are lacking and is also the major factor to inaccuracy in satellite gravity observations that are indispensable for estimating current ice sheet fluctuations.

Additionally, due to the ice sheet fluctuations, GIA causes a significant change in the solid Earth equivalent to the density ratio between the ice sheet and the solid Earth in isostasy. For example, the melting of a 3000 m ice sheet triggers elevation changes of approximately 1000 m. Thus, it is indispensable to consider the effects of elevation changes and sea bottom topography changes due to GIA, in order to quantitatively restore the past sea level changes and ice sheet mass fluctuations, as well as improve the accuracy of this restoration. It is therefore important to improve the accuracy of the GIA model itself.

2. Research Plan

In the Solid Earth group, we have been conducting research activities on the interaction between the solid Earth and the ice sheet with GIA as a key focus in order to solve our problems such as ice sheet fluctuations and predictions of global environmental changes in addition to pursuing a theme of purely academic importance: We aim to explore the viscoelastic structure of the Earth's deep interior through GIA.

First, in order to obtain in situ observation data in the Antarctic, which is overwhelmingly lacking, individually, we plan to conduct the following surveys: (1) Absolute gravity measurements and GNSS observations of the crustal deformation at research stations run by several countries, and in the coastal and inland mountain areas of East Antarctica; (2) In situ observations of the ice sheet and sea level changes by GNSS buoys and satellite data; (3) Mapping of the glacial landforms and the sediment distribution via Unmanned Aerial Vehicle (UAV) in the inland mountain areas of East Antarctica, and surface exposure dating based on field sampling.

In 2017, as the first step of these observations, we conducted absolute gravity measurements (Figure 2), GNSS observations, geomorphological surveys, and sampling for surface exposure dating (Figure 3) at several outcrops in the Lützow-Holm Bay region and around Syowa Station. Additionally, since few measurements of absolute gravity, in particular field measurements, have been conducted in the Antarctic, we also carried out field measurements during the 2017 expedition.

The main goal of the Solid Earth group is to investigate and construct GIA models that best fit the in situ observation data in East Antarctica. To achieve this, we combine various data and survey techniques, such as geodetic observations of crustal movement, gravity changes, ice sheet flow, sea level changes, the reconstruction of coastal uplift, ice sheet fluctuation from the geomorphological surveys, and various satellite data analyses by collaborating Publicly Offered Research.

Furthermore, we aim to precisely reconstruct the history of the ice sheet fluctuations from millions of years ago to the present day, in collaboration with other research projects such as ice sheet-climate modelings. Ultimately, our goal is to elucidate the response mechanism of the East Antarctic ice sheet to global climate change.

Figure 2. Field measurements of absolute gravity in the Antarctic (Botnnuten). (Photo by Hiroshi Ikeda)

Figure 3. Sampling for surface exposure dating in the Lützow-Holm Bay area.

Challenges for unexplored frontiers (Exploration group)

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National Institute of Polar Research

1. Academic background and objective

The Antarctic environment system, which consists of the Antarctic atmosphere, ice sheet, and ocean, plays an important role in global climate formation through changes in sea level, deep ocean circulation, and atmospheric CO2. Therefore, it is indispensable to understand the behaviors of the Antarctic environmental system for future predictions. Recent results indicate the possibility that the Antarctic ice sheet and the Southern Ocean have begun rapidly changing while interacting with each other. Because these indications appear in the coastal areas of the Southern Ocean and the Antarctic ice sheet margins in the forms of glacier flow acceleration, the collapse of ice shelves, and fluctuations in bottom water production, observations in these areas are required.

However, little is known concerning the seafloor topography under sea ice and ice shelves in the coastal areas of the Southern Ocean; the oceanographic structure, such as the water temperature and salinity and their temporal changes; and the surface and bed topography in coastal areas. This lack of data significantly hinders understanding changes in the Antarctic ice sheet and the Southern Ocean. As a specific example, regarding data on the seafloor topography and the bed topography under the Antarctic ice sheet that are indispensable for quantitative comprehension of the ice shelf basal melting and bottom water formation, geophysical survey results obtained by aerial vehicles and research vessels from each country were compiled in a database for Antarctic bed topography (BEDMAP2), which is an international project. Although the BEDMAP2 project made some positive progress, it has yet to obtain detailed data on the areas under sea ice and the coastal areas.

Additionally, although these surveys have detected long-term variations in the oceanographic structure, such as water temperature and salinity, it remains hard to conduct continuous observations indispensable to understanding the dynamics in the coastal areas of the Southern Ocean covered by ice. Furthermore, observations of elevation changes at the glacier terminus suggest that the ocean accelerates the ice sheet basal melting in summer. Extensive observations of ice thickness and surface topography over a vast area are required to quantify the amount of basal melting. Presently, for both ice and topography observations, thick sea ice considerably obstructs access to the sea ice and ice shelf areas and the coastal crevasse zones. By introducing new in situ observation methods, dynamic observations in the coastal and sea areas are strongly needed both by Japan and foreign countries engaged in Antarctic research.

In the recent oceanographic observations, the development of underwater robot technologies, such as Autonomous Underwater Vehicle (AUV) and Remotely Operated Vehicle (ROV), has promoted their practical application to extensive underwater observations. Therefore, we aim to expand observations to unexplored areas under the sea ice and ice shelves by introducing AUVs and other unmanned observation technologies in the coastal area of the Southern Ocean and the marginal areas of the ice sheet, which are the areas indispensable to understanding the changes in the Antarctic ice sheet and the Southern Ocean.

However, because the sea area covered by ice is still a difficult place to conduct surveys with underwater such as AUV, it is imperative to establish an operation method. Wth a new observation method established, we expect to make significant progress in understanding the actual state by multidisciplinary in situ observation, such as elucidating the dynamics of climate change and ecosystem change originating from the sea ice areas of the Antarctic coast. Additionally, concerning observations in the coastal areas where numerous crevasses exist, the introduction of various types of unmanned aerial vehicles (UAVs), which have rapidly developed in recent years, enables us to obtain accurate data on surface shapes over vast areas. Consequently, we have planned the project "Challenges for Unexplored Frontiers," which will bring breakthroughs in interdisciplinary research by establishing unmanned observation methods and obtaining data in unexplored areas.

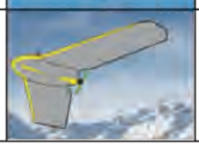
Model	Image	Feature / Investigation area	Observation item	Introduction
AUV Autonomous Underwater Vehicles		**Underwater** Sea ice edge / Under sea ice Automatic navigation	Seafloor topography survey under sea ice Water temperature/ Salinity Video recording	FY 2019 (Test dive under sea ice)
UAV(Rotor) Unmanned Aerial Vehicle		**Aerial** Semi-automatic navigation Large loading capacity Outcrop / Glacier / Ice sheet	Topography / Snow and ice Measurement by laser	FY 2017 (Introduced)
UAV (Fixed-wing) Unmanned Aerial Vehicle		**Aerial** Automatic navigation Vast area Outcrop / Glacier / Ice sheet	Topography / Snow and ice Aerial photography	FY 2017 (Introduced)

Chart 1. Unmanned vehicles to be introduced in this project.

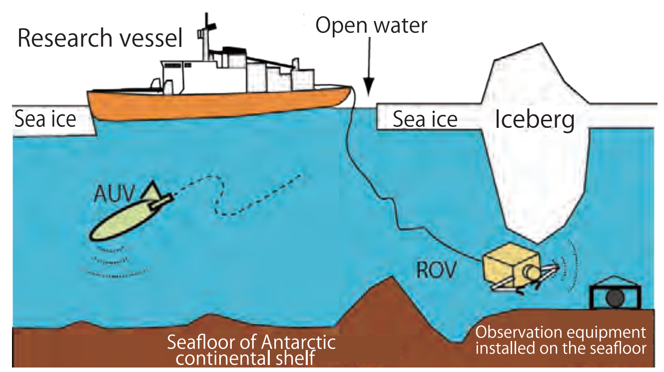


Figure 1. Investigation under sea ice by unmanned vehicles.

2. Research Plan

In this project, we plan to introduce unmanned investigation technology over a vast area and data transmission technology via satellite communication to explore the spatio-temporal frontiers of oceanographic observations in the Antarctic sea ice areas in addition to observations of the snow, ice, and topography in the areas of the Antarctic coastal ice sheets and outcrops, which have not been explored.

With the practical applications of the unmanned underwater survey method by AUV beneath sea ice and also of the observation method by UAV (the measurement of the surface topography) in the coastal areas of the East Antarctic, we will construct a basic infrastructure of observational research to reveal the dynamics of Antarctic bottom water formation areas, the role of the ocean in ice sheet melting in the East Antarctic, the topographies of the seafloor and the land where remains the evidence indicating the past ice sheet ranges, and the ecosystem. In addition, we aim to deploy unmanned fixed point continuous observation systems such as a repeating floating and sinking type water temperature-salinity meters in the sea ice areas. We also aim to comprehend temporal changes of the oceanographic structure in near real-time by automatically transmitting the observation data via satellite communication.

The construction of the observation system will enable us to conduct planar in situ observations in Antarctic coastal areas and coastal sea ice areas, as well as establish an observation network in mostly unexplored areas. Furthermore, observation data obtained in the unexplored areas will significantly advance each research plan in the overall project "Giant Reservoirs – Antarctic" as well as enable us to create new interdisciplinary research, strengthen systematic cooperation within the project, and bring breakthroughs in the science of the entire project.

The objective of this project is to install a system of unmanned and ocean bottom fixed-point continuous observation devices in the sea ice areas of the Antarctic coast, to maintain year-round observation, design and introduce AUV aimed at three-dimensional observations over vast areas of sea ice, and use UAVs to realize three-dimensional measurements of the surface topography of the polar region. We will test the unmanned survey technology and the unmanned fixed point continuous observation system to be constructed in this project first in cold Japanese areas, such as Hokkaido and the Sea of Okhotsk, prior to its introduction in the Antarctic. We will introduce the system and technology from the sea ice area to the coastal area in the Antarctic in collaboration with the other groups of this project, as well as other domestic and foreign Antarctic observation programs. Additionally, we aim to operate several unmanned vehicles, to introduce various observation sensors to be loaded on the vehicles, and to establish practical observation methods for observations of oceanographic structure, ecosystem, water sampling, and ocean floor topography.

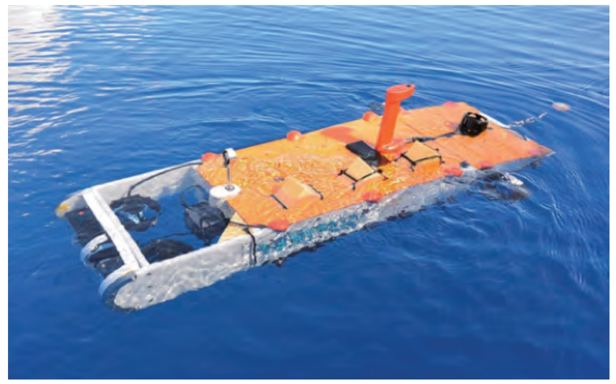


Figure 2. Highly Agile Terrain Tracker for Ocean Research and Investigation (HATTORI), a small and light-weight cruise-type AUV from the Institute of Industrial Science, University of Tokyo. We are currently using this model to design an AUV for observation under sea ice.

Integrative modeling of the Antarctic ice sheet, ocean, and climate (Model group)

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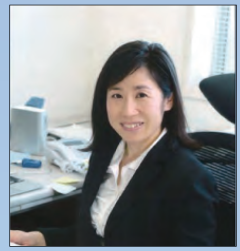

1. Academic Background and objective

Due to global warming, ice sheet fluctuations and their impacts on ocean circulation and sea level have been growing concerns. Although the Antarctic ice sheet is a giant freshwater reservoir, its response to climate change was thought to be much slower than the Greenland ice sheet, which is under the warmer climate. However, recent studies have revealed unexpected variations of the Antarctic ice sheet in the present and past, such as ice mass loss over the past decades observed by satellites, and reduced ice sheet in the past interglacial periods deduced from ice cores and geological records. In particular, it is very surprising that the Antarctic ice sheet was smaller in the last interglacial period (130,000 years ago) when the Antarctic temperature was only 2 °C higher than the present. However, the ice mass loss has not been scientifically understood nor reproduced by numerical models, which poses a serious concern for future projections.

In addition to the interactions between atmosphere, ice sheet, and solid Earth, which are important for the Northern Hemisphere ice-sheet changes over the glacial cycles, the interaction with the ocean is critically important for the Antarctic ice sheet. Because most of the Antarctic ice sheet terminates in the ocean with bedrock below sea level, warm ocean water can melt the ice from below (Figure 1 (b)) and cause rapid retreat of the grounding line and acceleration of ice flow.

In the current ice sheet models, if a small ice sheet is used as the initial condition, the small ice sheet size can be maintained in a warm period ("C" in Figure 1 (a)), but the models have not adequately reproduced the transient response of the large initial ice sheet ("B" in Figure 1(a)) to warming.

On the other hand, global warming is known to enhance hydrological cycles and thus promote ice accumulation. The importance of quantitative projections of the effects of ice sheet melting and precipitation increase on the ice sheet mass changes have been defined as an internationally urgent issue. Consequently, the ice-sheet model simulations have been added to the model intercomparison projects linked to the IPCC Sixth Assessment Report.

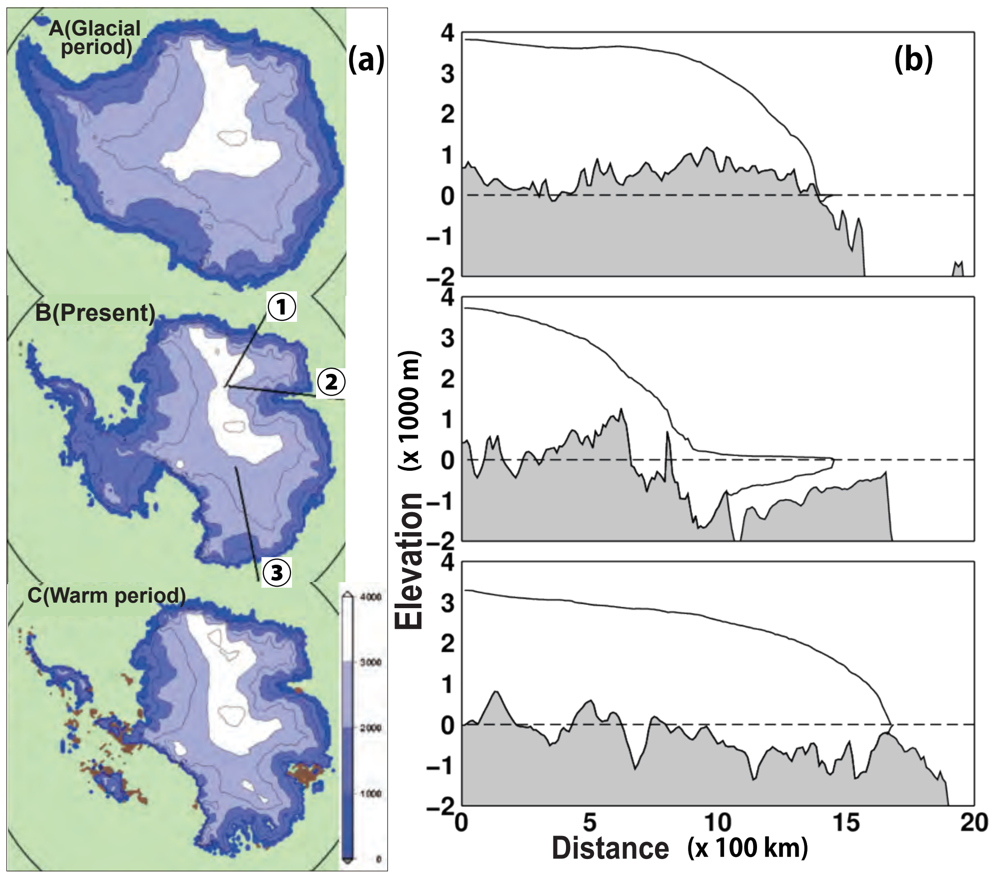

Figure 1. Cross sections of the ocean and ice sheet in and around Antarctica. (a)Altitude distribution by model calculation of Antarctic ice sheet (A: Glacial period, B: Present, C: Warm period). (b) Cross sections of the lines ①,②,③ in "B:Present" (altitude distribution). Since in ② and ③, the grounding line is below or on the sea level, irreversible retreat resulting from ocean-ice sheet interactions are likely to occur.

Under these circumstances, we aim to reveal the past and present states of the Antarctic ice sheet, the Southern Ocean and polar climate as well as the mechanisms of their variations, by using numerical models of atmosphere, ocean and ice sheet. Through the improved understandings, we also aim to contribute to the future projections. For these objectives, we incorporate the observational findings from other groups and conduct various numerical experiments by fully utilizing our expertise on the models of different complexities and scales.

Our final goal is the universal and integrated understanding of the role of the Antarctic ice sheet and the Southern Ocean within the climate system at different time scales (Figure 2). Specifically, we endeavor to address the following subjects;

A) Drastically improve the Antarctic ice sheet models based on collaborative research of observations and high-resolution models, focusing on the roles of the ice sheet - ocean interaction and ice sheet – solid Earth interaction. Advance our climate model based on better understanding of processes in the atmosphereand ocean, evaluate the reproducibility of the surface temperature of the Southern Ocean and sea ice field in the climate models, and clarify the tipping points of the Antarctic ice sheet and the Southern Ocean.

B) Reveal the causes for the climate variations and ice sheet retreat in the warm periods over the past millions of years, as well as the mechanisms of the Southern Ocean and sea ice variabilities over glacial-interglacial cycles, by numerical experiments using climate and Antarctic ice sheet models and comparison of the model results with paleoclimatic data.

C) Based on numerical experiments on climate changes over the past decades to centuries, clarify the causes of observed changes of the Antarctic ice sheet and the Southern Ocean as well as those recorded in ice cores. Furthermore, conduct long-term simulations to contribute to the future projections of the Antarctic environments through the international model intercomparison projects.

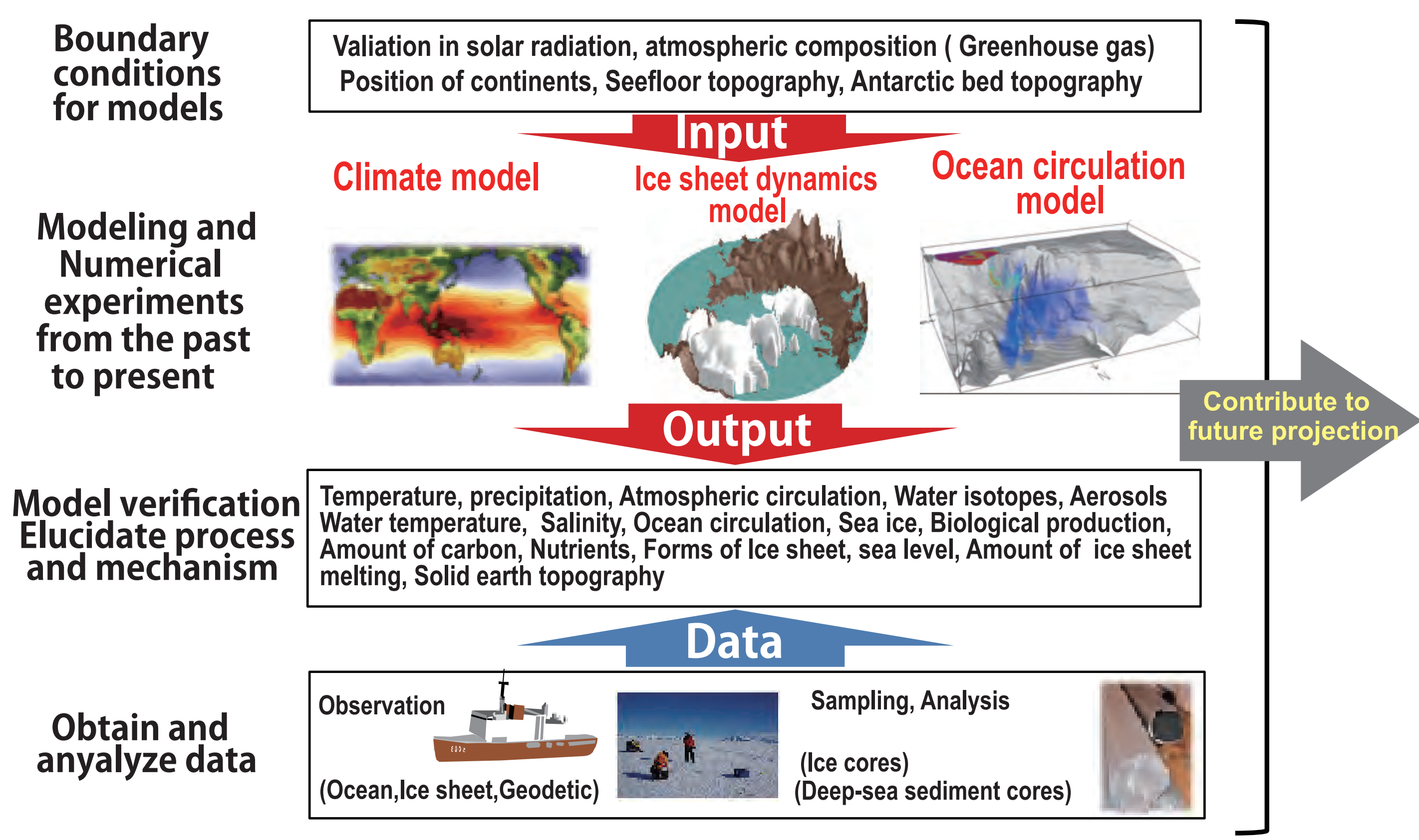

Figure 2. Overview: Subjects concerning our research and plans