Retreat history of West Antarctic Ice Sheet after the last glacial maximum: A critical review

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In the community of Antarctic paleoceanography, it has been long believed that the melting of West Antarctic Ice Sheet (WAIS) started just after the last glacial maximum (LGM), and occurred mainly in the deglaciation period (19-10 kyr BP), a timing of melting of Northern Hemisphere ice sheets such as Laurentide Ice Sheet. In contrast, some geological/geochemical evidences especially from Antarctic Continent have suggested that the melting occurred mainly in the Holocene and even in the latest Holocene. These two contrasting views can be at least partly ascribed to the lack of robust tools for the reconstruction of the ice sheet melting in the sedimentary record. Particularly, chronological framework in the sediments has been a key issue. Our recent evidence with compound-specific radiocarbon dating of the marine sediments suggested that the ice shelf edge in the Ross Sea retreated as large as 400 km during the last 5000 years, confirming above view. In this presentation, I critically review this problem, the timing of melting of WAIS after the LGM. I stress that the importance of precise sediment chronologies for the Antarctic paleoceanography.

Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution

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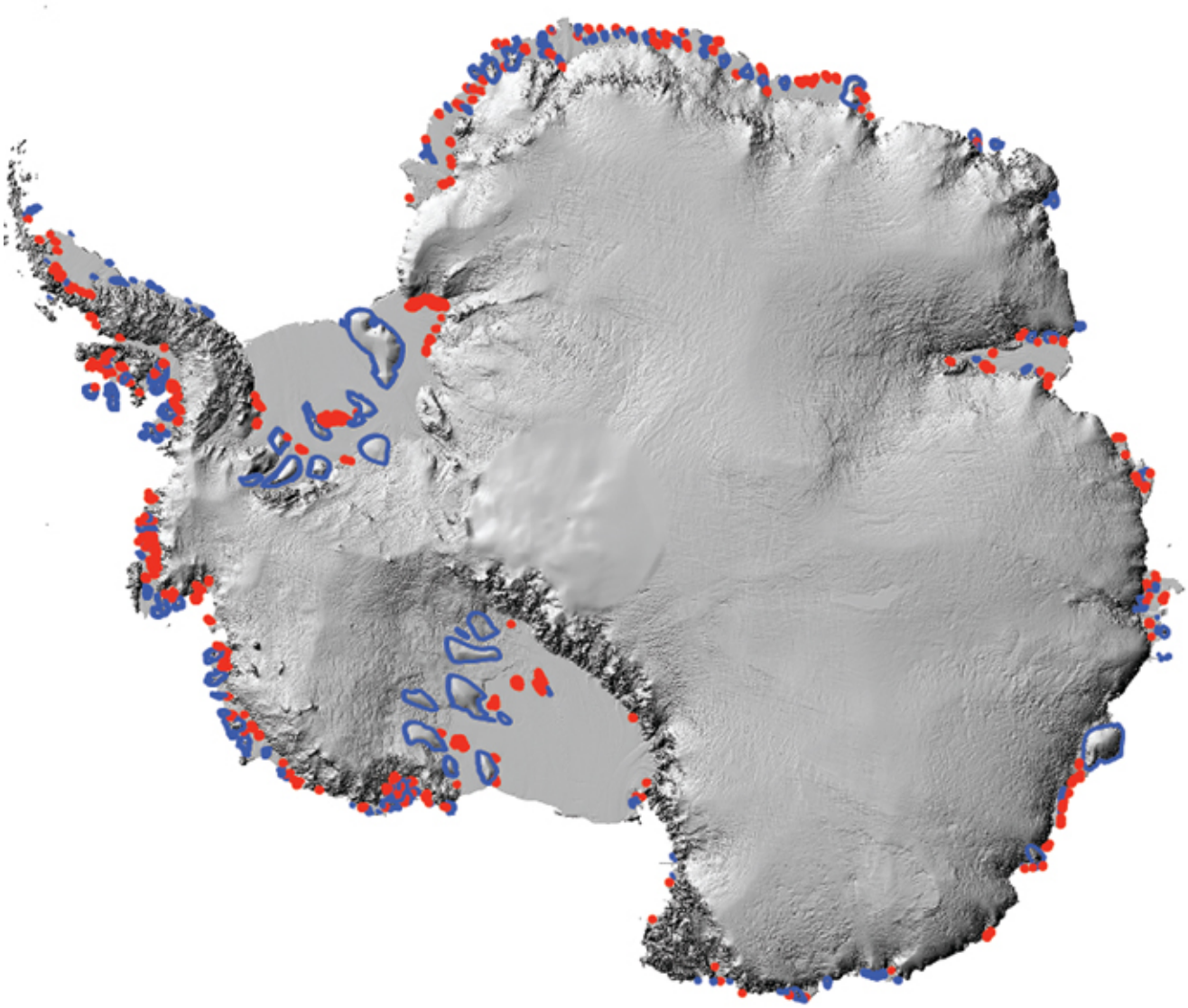
Locally grounded features in ice shelves, called ice rises and rumples, play a key role buttressing discharge from the Antarctic Ice Sheet and regulating its contribution to sea level. Ice rises typically rise several hundreds of meters above the surrounding ice shelf; shelf flow is diverted around them. On the other hand, shelf ice flows across ice rumples, which typically rise only a few tens of meters above the ice shelf. Ice rises contain rich histories of deglaciation and climate that extend back over timescales ranging from a few millennia to beyond the last glacial maximum. Numerical model results have shown that the buttressing effects of ice rises and rumples are significant, but details of processes and how they evolve remain poorly understood. Fundamental information about the conditions and processes that cause transitions between floating ice shelves, ice rises and ice rumples is needed in order to assess their impact on ice-sheet behavior. Targeted high-resolution observational data are needed to evaluate and improve prognostic numerical models and parameterizations of the effects of small-scale pinning points on grounding-zone dynamics.

Keywords: Antarctic Ice Sheet, ice shelf, ice rise



Development of a numerical ice-sheet/ice-shelf model IcIES and its performance on the MISMIP(+) experiments

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Ice sheet model for Integrated Earth-system Studies (IcIES) has been developed to simulate Greenland and Antarctic ice sheets as well as paleo-climate studies of past Northern Hemisphere ice sheets.
Experimental design for Marine Ice-Sheet and Ocean Model Intercomparison Projects (MISOMIP) has been launched (Asay-Davis 2015, GMDD).
Marine Ice-Sheet Intercomparison Projects third phase (MISMIP+) is one of the three subprojects of MISOMIP, which focuses on the comparison among `stand-alone' ice-sheet/ice-shelf models.
Seven sensitiivy experiments are proposed: each of them is a 100-year (optionaly 900-year) transient simulation under prescribed basal melting below ice shelf.
This study reports preliminary tests of MISMIP+ experiments using IcIES.

Keywords: Ice shelf, Numerical modeling

Research of Ocean-ice BOundary InTeraction and Change around Antarctica (ROBOTICA)

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Antarctica and surrounding Southern Ocean are changing. Acceleration of ice mass loss and warming of the coastal ocean in the West Antarctica are the problems of substantial impacts on the global climate system. In the East Antarctica, which has been considered to be stable and attracted relatively less attention, regional characteristics of interactions among climate subsystems have been recently revealed and evidences of variations on various time scales from decades to millennium have been accumulating. Off Wilks Land underneath the Totten Glacier Ice Shelf, whose ice discharge is accelerating, a potential pathway of warm water access has been discovered (Greenbaum et al., 2015). Along the East Antarctic coast, at the same time, sea ice formation and subsequent brine rejection in polynyas, including Cape Darnley Polynya as the head ofthe list, result in production of Dense Shelf Water and lead to the export of bottom water (Ohshima et al., 2013; Kitade et al., 2014). In the Lutzow-holm Bay off Enderby Land, oceanic temperature variability on decadal time scale was observed, and disintegration/stabilization of the landfast ice and Shirase Glacier Tongue seem to have a quasi-periodicity of one to two decades. In the deep past during the Pliocene when the surface temperature was higher by several degrees than that of the present climate, geological evidence was found for the substantial disintegration of Ice Sheet for the George V Land (Cook et al., 2013). Despite the growing awareness on the importance of ice-ocean interaction and long-term variabilities off the East Antarctic Coast, quantitative descriptions and understandings of the mechanisms are still insufficient. Given the global impact of the coastal variability through the bottom water export, investigations of the mechanisms and variabilities in the East Antarctica are indispensable.
As for the oceans and ice sheets, importance of repeated observations to describe their variabilities and changes, even at an interval of two to three decades, was stressed at least as early as IGY period. From 1976, year-round hydrographic observations have been conducted occasionally in Lutzow-holm Bay by Japanese parties, which provides one of the longest observational records. Together with the asset of long record of tide gauge near Syowa station, Lutzow-holm Bay is the important monitoring site for the description of temporal variability. However, a constant and sustained observation system is not yet established due to the logistic difficulties of sea ice. Even the bathymetric information, which is essential in any discipline of oceanography, is still insufficient. However, recent rapid progress in the techniques of remote autonomous observation and satellite communication are beginning to change this situation. Hence, under the project called ROBOTICA for the coming 9th six-year plan (2016-2023), we plan to utilize state-of-the-art unmanned observations such as under-ice oceanographic, seafloor and cryospheric observations using ROV/AUVs, geodetic network observations of ice/ocean motion and deformation using GPS/ GNSS, and oceanographic observations using tethered and moored profiling observation systems. Combinations with the conventional and robust observational techniques will enable us to acquire the detailedenvironmental information both in time and space. Implementation of this project can provide us a big step forward for realization of the dream of the sustained observation system around Antarctica. Application of the remote observation techniques to the new horizons such as Totten Glacier and Cape Darnley regions will enhance the understandings of the mechanisms of different ice-ocean interaction regimes.

Role of Southern Ocean in glacial atmospheric CO2 reduction

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Atmospheric carbon dioxide concentration ($pCO2^{atm}$) during glacial periods is known to be considerably lower than during interglacial periods. However, previous studies using an ocean general circulation model (OGCM) fail to reproduce this. Therefore, the detailed mechanism is still unclear.
Paleoclimate proxy data of the Last Glacial Maximum indicate high salinity and long water mass residence time in the deep Southern Ocean, suggesting that salinity stratification was enhanced and more carbon was stored there. The Southern Ocean has been recognized as a key region for carbon uptake during glacial periods. Here, we conducted numerical experiments using an OGCM to investigate the role of the Southern Ocean process in the variation of $pCO2^{atm}$; we evaluate the glacial response of ocean carbon cycles under the high salinity and long water mass age in the glacial Southern Ocean. We found that deep water formation in East Antarctica is required to explain high salinity in the South Atlantic. Contrary to previous estimates, saltier deep Southern Ocean resulted in increased $pCO2^{atm}$. This is because Antarctic Bottom Water flow increased and residence time of carbon decreased in the deep Pacific Ocean. On the other hand, weakening of vertical mixing contributed to the increase of the vertical gradient of dissolved inorganic carbon and decrease of $pCO2^{atm}$. However, we show that it is unable to explain the full magnitude of recorded reduction of glacial $pCO2^{atm}$ in our simulations which include the above-mentioned contribution of the Southern Ocean process in addition to SST and SSS changes, ocean circulation changes, and iron fertilization changes [*Kobayashi et al.*, 2015].
Carbonate compensation process acts to keep whole ocean alkalinity over the millennium timescale and affects the long-term variation of carbon cycle. Previous studies reported that it amplifies the variation of glacial–interglacial ocean carbon cycle. Our previous experiments assumed that particles such as particulate organic matter and calcium carbonate dissolved immediately when they reached ocean floor; therefore, the $pCO2^{atm}$ variation arises from carbonate compensation process was not included. As a next step, by using an OGCM coupled with a sediment model, we try to explicitly evaluate the role of carbonate compensation process. In the speech, we hope to report the results of numerical experiments performed by the newly developed sediment model.

Keywords: carbon cycle, glacial/interglacial, Southern Ocean, meridional overturning circulation , sediment model

Role of the Southern Ocean in the post-2002 global warming hiatus

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In spite of increasing atmospheric CO_2 concentration, the warming rate of the global-mean surface temperature slows down in the twenty-first century. Almost all of Coupled Model Intercomparison Project phase5 (CMIP5) climate model simulations fail to reproduce this global warming hiatus. Here, we discuss how the excess energy from top-of-atmosphere is stored in the ocean and quantify the influence of the ocean heat uptake on the surface temperature anomaly. Our numerical simulation, where wind stress anomaly in the equatorial Pacific Ocean is prescribed from reanalysis data, suggests that subsurface warming in the Pacific Ocean takes place at the beginning phase of global warming hiatus (1998-2002) as reported in a previous study. We newly clarify that this subsurface anomaly is transported into the Southern Ocean at the latter phase of hiatus (after 2002), which leads to Southern Ocean heating acceleration below subsurface. The historical observed data of ocean temperature also supports this scenario; warming trend of the Southern Ocean after 2002 is detected in data and its spatial pattern is consistent with our simulation. This result provides us with a clear evidence that the deeper parts of the Southern Ocean has a critical role in the post-2002 global warming hiatus.

Keywords: global warming hiatus, ocean heat uptake

Temporal and spatial variability of the ACC, fronts and eddies in the Indian Sector of the Southern Ocean derived from satellite radar altimetry

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In the Southern Ocean, the Antarctic Circumpolar Current (ACC) and fronts (e.g., Polar front) have been detected by using in-situ data, satellite data and numerical simulation (e.g., Gille, 1994; Belkin and Gordon, 1996; Feng et al. 2013). Except for numerical simulation, it is difficult to obtain temporal evolution of the ACC and fronts. In this study, the temporal and spatial variability of large-scale features such as the ACC and fronts are extracted from merged absolute dynamic topography (MADT) distributed by CNES/AVISO. To decompose MADT into those features, 2-D FFT and inverse FFT were applied. Results clearly show temporal variability of meandering of the ACC and fronts, and geostrophic velocity field in relation to the ACC variability. Using our method, mesoscale features without long-term trend was also derived, while the AVISO Sea level anomaly contains long-term and nonlinear trend.

Keywords: satellite radar altimetry, Antarctic circumpolar current, mesoscale eddy

Role of Weddell Sea ice variability in southern African climate

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A potential role of interannual sea ice variability in the Weddell Sea in the southern African climate is investigated through data analysis and coupled general circulation model (CGCM) experiments. The Weddell Sea ice undergoes a distinct interannual variability during the austral summer when the southern African rainfall experiences most of its annual rainfall. The sea ice concentration in the Weddell Sea shows a significantly negative correlation with the southern African rainfall during the season. It is found that the low sea ice concentration anomalies in the Weddell Sea are associated with anticyclonic circulation anomalies to the northeast in the South Atlantic which facilitate more moisture advection from the southern Indian Ocean toward the southern Africa. The composite analysis reveals that the low sea ice concentration anomalies in the Weddell Sea may be attributed to the atmospheric forcing such as the increased solar radiation related to the decreased albedo and the northwesterly wind anomalies. This low sea ice concentration anomalies, in turn, act to cause the skin temperature warmer than normal and reduce the meridional temperature gradient to the north. This is a favoring condition for sustaining the anticyclonic circulation anomalies there by increasing the atmospheric stability. The observed association between the sea ice concentration and atmospheric circulation anomalies is simulated in the CGCM experiment, and the local sea-ice impact on the atmospheric circulation anomalies is also demonstrated in a sensitivity experiment where the interannual sea surface temperature variability in the tropical Pacific is suppressed by the model climatology. These model experiments suggest that besides the remote influence by the tropical Pacific climate variability such as El Niñ o-Southern Oscillation, the sea ice variability in the Weddell Sea may contribute to the atmospheric variability in the South Atlantic, which may be important for the southern African climate.

Keywords: Weddell Sea ice, Interannual variability, Atmosphere ocean sea-ice interaction

Development of a thin ice thickness algorithm of AMSR2 for Antarctic coastal polynyas

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A coastal polynya is newly-forming thin sea-ice areas formed by divergent ice motion driven by prevailing winds and/or ocean currents. In coastal polynyas, huge amounts of heat flux from the ocean to the atmosphere occur because the heat insulation effect of sea-ice is greatly reduced in the case of thin ice, and accordingly sea ice is formed actively. Dense water formed in Antarctic coastal polynyas with the intense sea-ice production is a major source of Antarctic Bottom Water, which is a key player in the global climate system.

In Antarctic coastal polynya areas, algorithms that detect the polynya areas and estimate the thin ice thickness from passive microwave satellite (SSM/I or AMSR-E) data have been developed to estimate the ice and dense water production. The spatial (grid) resolution of AMSR-E, which was launched in May 2002 onboard NASA's Aqua satellite, is four times higher than that of SSM/I in the pixel density. This advantage of AMSR-E is critical for the monitoring of the coastal polynyas because of their fairly small areal extent (i.e., from 10 to 100km at most). Although AMSR-E failed in October 2011, AMSR2 (Advanced Microwave Scanning Radiometer 2), the successor to AMSR-E, was launched in May 2012 onboard the GCOM-W (Shizuku) satellite. The spatial resolution of AMSR2 is improved about 17% from AMSR-E (about 5 km at 89 GHz). In this study, we present a thin ice thickness algorithm for AMSR2 data.

The thin ice algorithm has been developed based on a relationship between polarization ratios (PR) of AMSR2 brightness temperatures (TBs) and thermal ice thickness, as in previous algorithms of AMSR-E. We used AMSR2 TBs at 89 GHz and 36.5 GHz. The thermal ice thickness is based on heat flux calculation using sea-ice surface temperatures derived from satellite thermal infrared images. As the first step of the AMSR2 algorithm development, we used 14 clear-sky MODIS images acquired in the Ross Ice Shelf polynya area. The AMSR2 PR is negatively correlated with the thermal ice thickness. The AMSR2 PR vs. ice thickness relationship is similar to that of AMSR-E. We plan to develop the AMSR2 algorithm also using clear-sky MODIS images acquired in other Antarctic coastal polynya areas, such as the Ronne Ice Shelf and Cape Darnley polynyas.

Keywords: Antarctic Ocean, Coastal polynya, AMSR2

Estimation of thin ice thickness discriminating polynya type from AMSR-E passive microwave data

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In Antarctic coastal polynyas, high production of sea ice occurs due to huge heat loss to atmosphere, resulting in the formation of dense water, precursor of Antarctic Bottom Water. Detection of thin ice area and estimation of ice thickness are inevitable for the calculation of sea-ice production. Several studies have developed algorithms for estimation of the thin ice thickness from brightness temperature (TB) of satellite passive microwave sensor [e.g., Martin et al., 2004; Nihashi and Ohshima, 2015]. In these algorithms, ice thickness of less than 20 cm is empirically estimated by utilizing negative correlation between the ice thickness and a ratio of the horizontally to vertically polarized TBs (PR).
Thin ice (polynya) areas are classified roughly into two types. One is frazil ice type: a mixture of open water and grease ice/pancake areas. This type is formed under strong wind condition. The other is nilas or thin consolidated ice type: nearly uniform thin ice covered area. This type is formed under relatively calm condition. It has been speculated that difference in polynya type causes reduced accuracy of the ice thickness algorithm because the two type polynyas likely show quite different microwave characteristics. In this study, we examined the PR-thickness relationship on these two types separately, and developed the thin ice algorithm discriminating the polynya type.
We used 36 GHz and 89 GHz TBs data of Advanced Microwave Scanning Radiometer for EOS (AMSR-E, the resolution of 12.5 and 6.25 km, respectively), MODerate resolution imaging Spectroradiometer (MODIS, the resolution of 1 km) data and the Advanced Synthetic Aperture Radar (ASAR, the resolution of 150 m) data, obtained from the major three polynya around the Antarctica (Ross Ice Shelf polynya (RISP), Ronne Ice Shelf polynya (RONP) and Cape Darnley polynya (CDP)). We estimated sea ice thickness for the AMSR-E footprint using MODIS and ERA-interim atmospheric data. After thin ice areas are divided into the two types from the ASAR data, we examined the AMSR PR-MODIS ice thickness relationship for each polynya type. The result shows the clear difference of PR-thickness relationship between the two polynya types. The exponential fitted curves for frazil and nilas types are similar to those of Martin et al. [2004] and Nihashi and Ohshima [2015], respectively. We considered that the difference of PR-thickness relationship is caused by the presence or absence of open water fraction. Because the ratio of open water in sea-ice region is largely reflected in gradient ratio (GR) of 36 and 89 GHz vertically polarized TBs, the two types can be clearly discriminated by the PR-GR plane. Based on these, we have developed a new thin ice algorithm in which polynyas are classified into the two types by a quadratic discriminant method. Sea ice thickness is estimated from the fitted exponential curve of PR-thickness relationship for each polynya type. Using this algorithm, daily polynya type and ice thickness for the three polynyas have been estimated during April-November in 2003-2010. Sea-ice production has been also estimated by heat flux calculation using the ice thickness and ERA-interim atmospheric data.
It is found that the occurrence frequencies of the two polynya types are largely different among the three polynyas. In the CDP, frazil type is more predominant, compared with other two polynyas. In previous algorithms, ice thickness was overestimated because the PR-thickness relationship is similar to that of the nilas type. Therefore, sea-ice production in the CDP with high occurrence frequency of frazil type is calculated to be about twice as that of previous studies.

Keywords: coastal polynya, ice thickness, sea-ice production, AMSR-E

Temporal and spatial variation of dissolved inorganic carbonates in the summer of Antarctic seasonal sea ice zone

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To clarify the variations of carbonate system in the Southern Ocean, multi-ship observations and line observation which closes ice edge were performed since JARE-51st (2009/10 austral summer) on-board Icebreaker “SHIRASE” and T/V Umitaka-Maru of TUMSAT (Tokyo University of Marine Science and Technology). Although seasonal changes of pCO_2 are attributed to thermodynamics and biological activity , Analysis of DIC vertical profiles reveal that biological uptake and entrainment of sub-surface water played major role and air-sea CO_2 exchange can contribute a little.

Keywords: Dissolved inorganic carbonates, Southern Ocean, Seasonal sea ice zone

Integrated multidisciplinary study in Antarctica and next six-year Japanese Antarctic Research Project phase IX

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The changes in the Antarctic ice sheet and the Southern Ocean most likely indicate the precursor and driving force of the global environmental changes, and these changes are essential for future projection of the Earth system. The six-year Japanese Antarctic Research Project phase IX centered on main scientific theme of “Investigation of changes in the Earth system from Antarctica” will be commenced from 2016/2017 austral summer season with the three subthemes. The three subthemes are followings, “Investigation of the whole global atmospheric system through precise observation of the Antarctic atmosphere”, “Investigation of the interaction of atmosphere, ice sheets, sea ice, and ocean from integrated research in areas bordering ice sheets and sea ice” and “Reconstruction of the Antarctic paleoclimate to elucidate changes in the Earth system.” Integrated multidisciplinary study are required to promote these subthemes under the main scientific theme in order to elucidate changes in the Antarctic subsystem and its effect to the Earth system. Especially, multidisciplinary study is key to understand the interactions around the boundary between ice sheet and ocean, namely ice shelf and sea ice areas, in the context of the Southern Ocean and the Antarctic ice sheet, which correspond to the second subtheme.
We will present the outline of the six-year Japanese Antarctic Research Project phase IX briefly and the necessity of integrated multidisciplinary study in Antarctica is discussed.

Keywords: Antarctica, ice sheet, ocean

Interaction of the solid Earth and the Antarctic ice sheet

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The Antarctic ice sheet, which relates to the global climate changes through the sea level rise and ocean circulation, is an essential element of the Earth system for predicting the future environment changes. Thus many studies of the ice sheet changes have been conducted by means of geomorphological, geological, geodetic surveys, as well as satellite gravimetry and satellite altimetry. However these studies thus far conducted have been affected by the large uncertainties of GlA (Glacial Isostatic Adjustment), which is the rheological response of the solid Earth to the ice mass loading. Therefore the precise estimation of the GIA effects is an urgent and an important task for these studies. The effects of GIA, on the other hand, include valuable information about the rheological properties of the solid Earth. Thus the observational studies of the GIA effects should greatly contribute to investigate the inner structure of the Earth. GIA, as a keyword to investigate the interaction between the solid Earth and the ice sheet changes, is an important research target not only for a practical requirement of predicting global changes but also for a more pure scientific interest to know the structures of the deep Earth's interior.
In view of these points, we plan to conduct geomorphological, geological and geodetic surveys in the inland mountain areas and the coastal areas in East Antarctica, where the in-situ data for constraining GIA models are very few. In addition, we will conduct precise monitoring of the land movements at Syowa Station using space geodetic observations such as SLR (Satellite Laser Ranging) and VLBI (Very Long Baseline Interferometer) as well as sea bottom geomorphological surveys on continental shelves using new technology of ROV (Remotely operated Vehicle) and AUV (Autonomous Underwater Vehicle). Combining these observations with the analyses of the sea bottom cores obtained by the bowling surveys on the continental shelves, various satellite data analyses and numerical modeling, we will precisely estimate the response of the solid Earth due to the GIA effects and corresponding sea level changes. These procedures lead us to a precise GIA model and constructing a reliable ice melting history after LGM (the Last Glacial Maximum) and the viscoelastic structure of the Earth's interior.
We will present the outline of this research project.

Keywords: GIA, Antarctic ice sheet, Sea level rise

Summary of marine geological survey in the Indian sector of the Southern Ocean: Preliminary reports of KH-16-1 cruise

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Marin geological survey in the Indian sector of the Southern Ocean have been done during the KH-16-1 expedition by R/V Hakuho-maru. Multichannel seismic (MCS) reflection survey was conducted in the Del Cano Rise and the Conrad Rise to prepare the future IODP proposal. It is interpreted that sediment waves in the Conrad Rise were originally formed by the Antarctic Circumpoar Current (Oiwane et al., 2014). Sediment waves were also observed under the seafloor on the Del Cano Rise, suggesting main axis of the ACC was occasionally fluctuated to north during past glacial stages.

Keywords: Southern Ocean of the Indian sector, ACC, Multichannel seismic reflection survey, KH-16-1 cruise, Del Cano Rise, Conrad Rise

Transitions of redox state and nutrient status in the Southern Ocean since the last glacial: Evidence from speciation analyses of C, Fe, and P in sediments at the Conrad Rise

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The Southern Ocean, a high-nutrient, low-chlorophyll region, has played an important role in regulating global climate system. The Southern Ocean became suboxic during the last glacial period (~40 to 19 kyr ago) and changed to oxic toward Holocene. In order to elucidate changes in the redox state and nutrient status of the seawater caused by sea ice, we performed C, Fe and P speciation analyses of the marine sediments (COR-1bPC) recovered in 2010 at the Conrad Rise in the Southern Ocean (KH10-7 cruise).
Thirty-seven samples were quantified for five P-bearing species (P_{abs}, P_{Fe}, P_{auth}, P_{det} & P_{org}) by modified SEDEX method of Ruttenberg (1992) and four Fe-bearing species (Fe_{HCl}, Fe_{carb}, Fe_{ox} & Fe_{mag}) by the method of Poulton et al. (2005). The abundance and the stable isotope compositions of organic carbon were measured using EA-irMS at Center for Advanced Marine Core Research, Kochi University. Average content of P_{det}, which represent the continent flux, in the dark colored (last glacial) sediments was 0.004 wt.%. Conversely, that in the light colored (interglacial) sediment was 0.002 wt.%. The $\delta^{13}C_{org}$ values in last glacial period (avg. = −23.63 ‰) was isotopically lighter than those in the interglacial period (avg. = −21.73 ‰
). These results suggest that the Conrad Rise (54.2 °S) was covered by sea ice during the last glacial period. Suppression by sea ice of atmosphere-ocean interactions would have decreased dissolved oxygen concentration and gradually created suboxic condition. Fluctuating contents of P_{Fe} and Fe_{ox} indicate occurrence of short-term oxidation events during the last glacial period. In the deglacial period, abundance of C_{org} decreased but that of all P-bearing phases, Fe_{HCl}, and Fe_{ox} abruptly increased to the maximum value. This suggests that melting of the sea ice would have increased P and Fe nutrient supply to the surface ocean and dissolved oxygen supply to the deep ocean, leading to enhanced decomposition of organic matter and drastic changes into oxic conditions. Such environmental changes would have been due to southward migration of Antarctic Circumpolar Current (ACC). Speciation analysis of C, Fe and P in sediments is a powerful tool toward reconstruction of redox and nutrient states in the ocean.

The impact of Drake and Tasmanian Passages on Antarctic regions and deep ocean temperature

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Through the Cenozoic, the climate has long term cooling trend. At Eocene/Oligocene boundary, the opening of the Drake and Tasmanian Passages caused the development of Antarctic Circumpolar Current and led to the thermal isolation of Antarctica (Kennett, 1977), and previous modeling studies investigated the effect of the opening those passages (Sijp and England, 2004, 2011, Zhang et al., 2010). In addition to the passages, the effect of the land-sea configuration change was investigated (Sijp et al., 2014, Lunt et al., 2015). And CO2 is considered as the important forcing of the Cenozoic cooling (Hansen et al., 2013). In long-term climate change, the relative importance of various forcings wasn't understood well. It is suggested that the different conditions about land-sea configuration, CO2 concentration, and the existence of Antarctic ice sheet in these previous studies affect the amplitude of the Antarctic regions at the closing the passages.
Here we investigate the Antarctic regions and deep ocean temperature change between the opening and closing Drake and Tasmanian Passage under with Antarctic ice sheet and without that. Our result says that the closing passages cause the temperature increase at Antarctic regions through the strong deep water formation at Southern Ocean and strong southward heat transport. The deep ocean temperature is mainly affected by the absence of the Antarctic ice sheet. Our results suggest that the absence of Antarctic ice sheet largely affect the temperature change of the deep ocean and at the Antarctic regions by closing Drake and Tasmanian Passages.

Keywords: Passage, Cenozoic, Paleoclimate

Numerical experiments using ice sheet models on the ice-ocean inteaction and stability of Antarctic Ice Sheet

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Ice-ocean interaction in the Antarctica is of importance for the stability of Antarctic Ice Sheet. Sea level rise and its rate due to deglaciation northern hemispheric ice sheets (Ritz et al., 2001, Goelzer et al., 2016), increased basal melting of ice shelves due to warming in seawater temperature around Antarctica has proposed as important mechanism to retreat Antarctic Ice Sheet, and glacial meltwater release from Antarctic ice sheet as a possible amplifying mechanism by enhanced stratification in the Southern Ocean and warmed subsurface ocean (Golledge et al., 2014). The rate of basal melting beneath ice shelf is determined by seawater temperature below ice shelves, but this seawater temperature is often different from that in the subsurface Southern Ocean because of sea ice production in the Antarctic Coast and associated cold and dense shelf water formation (Obase et al., submitted). Previous ice sheet modeling studies, however, lack representation in this physical process because they use subsurface seawater temperature in the Southern Ocean directly to parameterize the rate of basal melting of ice shelves. In this study, we make a parameterization of basal melting which is able to apply ice sheet models, based on model experiments using a regional ocean model and an atmosphere-ocean coupled GCM. We perform 2-d ice sheet model experiments to investigate fundamental behavior of ice sheet-ice shelf system to forcings of ocean-induced basal melting and sea level rise and to quantify the relative importance of external conditions on the threshold of Antarctic ice sheet retreats.

Keywords: Antarctic Ice Sheet, Southern Ocean, Antarctic ice-ocean interaction, Ice shelf

Mooring measurement of sea ice and ocean in the Cape Darnley Polynya, Antarctica

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Recent remote-sensing, hydrographic and mooring studies have shown that the Cape Darnley Polynya located northwest of the Amery Ice Shelf is an active formation region of Antarctic Bottom Water (Ohshima, Fukamachi and Williams et al., 2013). To reveal production of sea ice and high salinity shelf water, total of five moorings were deployed between 2010 to 2015 by the Japanese Antarctic Research Expedition over the continental shelf within the Cape Darnley Polynya. The experiment yielded sea-ice thickness data for the first time in the Antarctic coastal polynyas as well as velocity and water property data. The water property data revealed high salinity shelf water associated with sea-ice production in the polynya.

Keywords: polynya, sea ice, mooring

The role of turbulent mixing in the modified Shelf Water overflows that produce Cape Darnley Bottom Water

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The mixing process associated with modified Shelf Water (mSW) overflows that eventually mix to form Cape Darnley Bottom Water (CDBW) was investigated by hydrographic and microstructure observations off the Cape Darnley Polynya (CDP), East Antarctica, in January 2009. Closely spaced microstructure observations revealed that mSW properties varied considerably within a distance of ~4 km across the shelf edge. Near the bottom, the rate of turbulent kinetic energy dissipation was enhanced to values greater than 10^{-7} W kg^{-1}, and the vertical scale of the bottom boundary layer (BBL) was on the order of 10 m. The observed BBL around the shelf edge was characterized by strong vertical mixing with turbulent eddy diffusivities of ~$O(10^{-3}$–$10^{-2})$ m^2 s^{-1}. A geostrophically balanced density current, which resulted from the presence of mSW over the continental shelf, is considered the primary energy source for the turbulent mixing in the BBL. This turbulent mixing transforms the overflowing mSW through mixing with ambient water masses, specifically with the overlying modified Circumpolar Deep Water. The BBL is also thought to partly contribute to the gradual descent of mSW down the continental slope through bottom Ekman transport. We conclude that turbulent mixing, primarily caused by a density current, plays an important role in CDBW formation, by modifying the mSW overflowing from the CDP.

Keywords: turbulent mixing, modified Shelf Water, Cape Darnley Bottom Water

Relative importance of bottom water originating from the Vincennes Bay Polynya on AABW in the Australia-Antarctic Basin

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Antarctic Bottom Water (AABW) is the densest water in the ocean and globally significant. Historically there have been three well-known source regions in the Weddell and Ross Seas, and off Adélie Land. One-year moorings in 2013-14 at 3200m and 3400m depths on the eastern slope of ridge at the north of Vincennes Bay reveal the property of the AABW originating from the Vincennes Bay Polynya (hereinafter VBBW). The VBBW had a thickness of 300m at least and reached at the bottom of 3400m depth. Observational result obtained from 2011 to 2016 have shown that the water property of AABW off Vincennes Bay was mainly influenced by Australian-Antarctic Basin AABW (AA-AABW), which is the mixed water of Ross Sea Bottom Water (RSBW) and Adélie Land Bottom Water (ADLBW), and the VBBW were distributed over them. Long-term water mass changes during 1994-2015 have been examined and significant freshening trends of AA-AABW were detected along 110E. This change of water property was considered to increase relative impact of the VBBW on the AABW in the Australian-Antarctic Basin.

Keywords: Antarctic Bottom Water, freshening, Australian-Antarctic Basin

Rapid and persistent freshening of Antarctic Bottom Water in the Australian-Antarctic Basin

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Summer hydrographic data obtained along 110°E meridional transect are used to document multi-decadal change in abyssal hydrographic condition south of 60°S. Data are obtained every year after 2011and it is clarified that freshening observed at beginning of 2000s (e.g., Aoki et al., 2005) is still persistent in the recent years. The observed freshening is clearly intensified to the bottom, and thus, likely induced by increased fresh water discharge near the formation regions of Antarctic Bottom Water. Also, observed freshening implies rise in sea level. Haline component of sea level rise (against 1995) in the recent years (~13.5 mm) is quadrupled after 2005 and is comparable to that of thermal component (~11.0 mm). Thus it is concerned that haline component can be the main contributor to sea level rise in the Southern Ocean in near future.

Keywords: Antarctic Bottom Water, freshening, sea level rise

Southern Ocean eddies observed by Argo floats

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There is no landmass that blocks zonally flowing Antarctic Circumpolar Current (ACC) in the Southern Ocean. This means all meridional transport in the upper layer is driven by non-geostrophic dynamics; the Ekman transport by the westerly jet and by mesoscale eddies. Synoptic observation of these Southern Ocean eddies were limited to the surface where satellite altemetry data are available, but recent increase in number of Argo floats, thanks to the vibrant effort of the community, deployed in the Southern Ocean now enables us to describe the eddies in the mid-depth (1000 m). The eddies are highly localised to several locations where the ACC negotiates the bottom topography. In these "eddy hot spots", such important physics were observed as efficient downward transport of eastward momentum imposed by the wind at the surface and upgradient eddy transport.

Keywords: Southern Ocean, Eddy

Interannual Variation of Surface Wind Field over the Southern Ocean and DPOI

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The Southern Ocean (SO) is a single oceanic domain encircling the globe, and covered by the strong eastward flowing Antarctic Circumpolar Current (ACC). Especially, westerly winds principally drive the ACC, and the easterlies are critical for the westward flow along the Antarctic continental margin. Previous studies pointed out that there are some dominant atmospheric variabilities over the SO such as the Southern Annular Mode (SAM), the Antarctic Oscillation (AAO) and the Pacific South America (PSA), and they are related to the strength of westerly winds and affect large change of ecological environment in the Antarctic/Southern Ocean during recent decades (Boyd and Roberts, 1993). Naganobu et al.(1999, 2008) found significant correlations between the krill recruitment and DPOI (Drake Passage Oscillation Index) which is a climate index defined by the sea-level pressure differences between Rio Gallegos at the southern edge of the South America and Esperanza at the northern edge of the Antarctic Peninsula. DPOI can be taken as an index of the climate-ocean-environmental ecosystem variability in the Antarctic Peninsula.

In this study, we examine dominant variations in the atmospheric field over the SO by comparing with dominant modes revealed by previous studies. To clarify spatial features for interannual variation in the surface wind field over the SO, we investigate relationships among DPOI, AAOI and dominant modes in surface wind field.

In order to investigate the spatial structures of zonal wind variations, we perform empirical orthogonal function (EOF) analysis. The spatial feature of the 1st EOF mode for the zonal wind, having contribution ratio of 27.6%, is similar to that of the AAOI pattern derived from the 1st mode of the 700-hPa height in the NCEP reanalysis. The score of this mode has a high correlation with the AAOI (0.74). Thus, the leading EOF mode of the zonal wind is related to the Atmospheric SAM pattern. The spatial distribution of the 2nd EOF mode, having contribution ratio of 15.4% reveals a dominant pattern in the Atlantic and Indian sectors with maxima, poleward of that for the 1st EOF mode. The score of this mode has high correlation with DPOI (0.62).These suggest that the DPOI-related variations are characterized by spatial features in the 2nd EOF mode of the zonal wind, and their mechanisms will be examined in further studies.

Keywords: Westerly Wind, DPOI, AAOI, Interannual Variation, Air-Sea interaction

