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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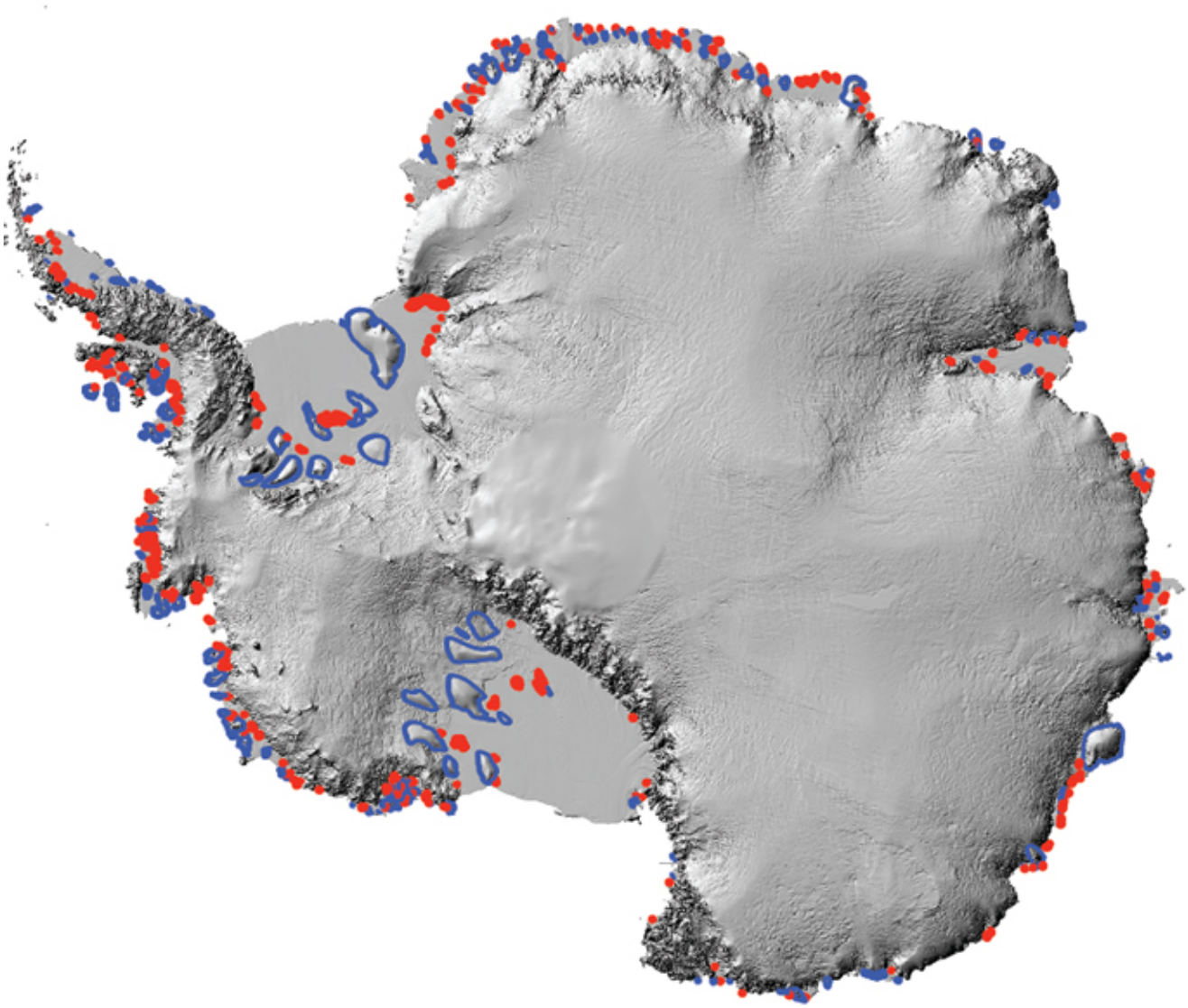
Locally grounded features in ice shelves, called ice rises and rumples, play a key role buttressing discharge from the Antarctic Ice Sheet and regulating its contribution to sea level. Ice rises typically rise several hundreds of meters above the surrounding ice shelf; shelf flow is diverted around them. 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

