MIS34-01 Room:414 Time:May 2 14:15-14:30

Sources of freshwater to the Antarctic continental shelf -distributions and multi-decadal changes-

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The Antarctic continental shelf is the gateway to the global ocean from the Antarctic Ice Sheet, the largest freshwater reservoir on Earth surface. Discharge of the freshwater occurs as the processes such as basal melting of ice shelves and calving of icebergs. On the other hand, sea ice formation and melting on the shelf redistribute the freshwater, affecting the overturning circulations of oceans. These two processes of freshwater transport are closely related to the surrounding oceanic and atmospheric conditions, and therefore estimating their contributions and clarifying their relationships with underlying environments are necessary to quantify the overall impacts to the ocean and its temporal change.

From observed salinity and stable oxygen isotope ratio of sea water with a few assumptions applied, meteoric and sea ice fractions in sea water are estimated on the shelf and their geographical distributions are studied. Meteoric ice fraction is largest in the surface layer of West Antarctica, but the water column inventory is largest in the Ross Sea and surprisingly uniform around Antarctica. The column inventory of meteoric ice retains the broadly consistent signature of ice shelf basal melting, which is proposed by the recent studies, but its oceanic stock is rather homogenized due to the effects such as oceanic advection and basin-scale circulation. Sea ice fraction contributes large production in the areas of strong katabatic wind and shows negligible production/net melting in the West and central East Antarctica. The vigorous vertical mixing due to high production also distributes the meteoric fraction to a wider depth range.

Observed salinity trend suggests a possibility of temporal change in these freshwater transports. The salinity trend at the bottom of the shelf for the recent four decades reveals the salinification in the West Antarctica and freshening in the Ross Sea. Repeated observations on the shelf region off the Adélie Land Coast indicate freshening for the recent two decades. These signatures might be consistent with the accelerating discharge of the west Antarctic ice sheet. The signatures are consistent with the structure of the recent salinity change of Antarctic Bottom Water, suggesting the on-going impact of the Antarctic shelf on the global scale.

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The fourth Antarctic Bottom Water: Cape Darnley Bottom Water

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Antarctic Bottom Water (AABW) is the cold, dense water that occupies the abyssal layer of the global ocean, accounting for 30-40 % of its mass (Johnson, 2008). The production of AABW is a key process in the global overturning circulation, representing a significant sink for heat and CO_2. It is currently recognized that AABW is formed in the Weddell Sea, the Ross Sea and off the Adelie Coast (Orsi et al., 1999). A fourth variety of AABW has been identified in the eastern sector of the Weddell-Enderby Basin (Meredith et al., 2000). However, its production has never been observed, nor its exact dense shelf water (DSW) source located. Recently, satellite-derived estimates of sea ice production suggest that the Cape Darnley Polynya (65-69E), located northwest of the Amery Ice Shelf, has the second highest ice production after the Ross Sea Polynya (Tamura et al., 2008). As such, this polynya is promoted as a strong candidate for DSW source of the AABW identified in the Weddell-Enderby Basin.

As part of the Japanese International Polar Year program, we conducted mooring observations in 2008-2009 offshore from the Cape Darnley Polynya, and revealed that the enhanced sea-ice production in this polynya is the missing source of the AABW (Ohshima et al., 2013). Moored instruments observed overflows of newly formed AABW, about 300 m thick and bottom-intensified, cascading down the canyons north of Cape Darnley. We propose to name this AABW Cape Darnley Bottom Water (CDBW). This result is novel because this AABW is produced purely from sea-ice production without the assistance of an ice shelf and/or large storage volume on the continental shelf, in contrast to the traditional paradigm. We therefore speculate that there could be further AABW-formation discoveries in similar polynyas, particularly those in East Antarctica.

We estimate that 0.3-0.7 Sv of DSW is transformed into CDBW, accounting for 6-13 % of the circumpolar total. The CDBW migrate westward, and increase its volume by gradual mixing with Circumpolar Deep Water, to ultimately constitute part of the AABW in the Weddell Sea (Atlantic sector) referred to as Weddell Sea Deep Water (WSDW). Production of WSDW originating from CDBW is estimated to be 0.65-1.5 Sv, which is about 13-30 % of the Atlantic AABW production. The WSDW is a major component of the AABW driving the lower limb of the meridional overturning circulation (MOC) of the Atlantic Sector. It has been reported that WSDW has been warming since the 1980s, with its volume possibly contracting (Purkey and Johnson, 2012), and that this could result in a weakening of the MOC. Additionally, sediment-core records taken around the CDP indirectly suggest that there has been millennium-scale variability in the local AABW production. It is vital that CDBW be incorporated into the global assessment of the MOC, a key element of the climate system. This will improve numerical simulations predicting its response to long-term climate change.

Keywords: Antarctic Bottom Water, coastal polynya, sea-ice production, dense shelf water, mooring, Cape Darnley

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Southern Ocean: the key factor of climate change

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Ocean keeps a lot of heat, oxygen, CO2, and nutrients, and transports these to the world ocean by the global ocean circulation. Polar oceans having sea ice is ”Canary of Climate”, and are very sensitive to the climate change, e.g., the global warming. Antarctic Bottom Water (AABW) formed in the Southern Ocean is the main actor for these two mechanisms, however, it is still difficult to clarify the whole image of AABW only by the in-situ observation. Our purpose is the estimation of AABW formation, sinking process, and its spread in the bottom layer by the numerical modeling, by using the following three different methods; monitoring of sea ice production by the satellite remote sensing, high-resolution mapping of water temperature and salinity by in-situ observation, and numerical modeling by high-resolution model. This study is challenging to the final and most difficult blank area for the global climate system, and could contribute to the prediction of future climate change.

By our recent results, we got the following two progresses; (1) hemispheric-scale and long-term monitoring of sea ice production which directly links to the AABW formation becomes possible by the accumulation of satellite data and the development and improvement of the algorithms (Tamura et al., 2008) and (2) the result from the numerical modeling could compare to the in-situ results directly by the improvement of the numerical model (Matsumura and Hasumi, 2011). Under these our past works, it is possible to detect the actual dynamics of AABW by the following three independent methods; (a) monitoring of sea ice production by the satellite remote sensing, (b) high-resolution mapping of water temperature and salinity based on the in-situ observation data, and (c) high-resolution ocean modeling.

This study try to clarify the process of AABW formation quantitatively by using our dataset, algorithm, and numerical model. Specifically, our purpose is to estimate the AABW formation, its sinking process, and its expansion in the bottom layer. By using the latest in-situ and satellite data and numerical modeling, we try to clarify the following three questions; Where and how much does the dense water (the origin of the AABW) generate?, How much does the dense water mix with the surrounding water during the process of sinking around the shelf break?, and Where and how much does the AABW exist in the bottom of the world ocean and how does AABW spread?

In our talk, we will introduce updated results for our three ongoing projects; (I) mapping of sea ice production by the satellite remote sensing, (II) improvement of in-situ ocean observation data set, (III) ice shelf-sea ice-ocean coupled modeling, and (IV) micro-scale modeling.

Keywords: Southern Ocean, Antarctic Bottom Water, Sea Ice Production, In-situ Ocean Observation Data Set, Ice shelf - Sea ice - Ocean Interaction, Micro-scale Modeling

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High resolution Modeling on the Antarctic Bottom Water Formation

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At the Antarctic continental margin, a great amount of dense water is created due to intense cooling and active sea ice formation. A part of this dense water descends down to the depth on the continental slope and provides a source of Antarctic Bottom Water (AABW), the densest water mass of the world ocean. This deep water formation drives and controls the global thermohaline circulation. Thus, quantitative understanding of where and how much such dense water descends to which depth with what water mass property is necessary for discussing the structure and intensity of the global thermohaline circulation and hence the earth's climate.

The AABW formation involves various processes with wider range of spatial and temporal scales, such as turbulent mixing induced by vertical velocity shear of descending dense water, influences of small scale submarine ridges and canyons of O(1) km, the surface buoyancy flux highly controlled by openings and closings of coastal polynyas. It is very difficult to perform a numerical simulation which resolves all of these processes because such simulation requires a huge amount of computational resource. Therefore, modeling studies on the AABW formation have been restricted to very idealized experimental settings. In particular, small scale processes such as turbulent mixing and vertical convection cannot represented by widely used general ocean circulation models with hydrostatic approximation, and a non-hydrostatic model is required. The numerical cost of non-hydrostatic models has been much greater than the hydrostatic models due to the cost of three-dimensional Poisson solver required to diagnose pressure field. To overcome this problem, we developed a non-hydrostatic ocean model with a very numerically-efficient and scalable Poisson solver using the multigirid method. The totla cost of our non-hydrostatic model stays less than twice of that of hydrostatic one even with huge amount of grid cells on massively parallel super computers. With using this newly developed model code and present days computational resources, multi-scale and multi-process modeling on the AABW formation, whose results are competent to be quantitatively compered with direct observations, is becoming a reality.

In our talk, we will introduce the outline of the newly developed numerical model and discuss the results of high-resolution AABW formation simulation with focusing on the effects of small scale topographic features and the turbulent entrainment processes induced by Kelvin-Helmholtz instability.

Keywords: Antarctic Bottom Water, non-hydrostatic model

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Modeling basal melting of Antarctic ice shelves

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We have incorporated an ice shelf component into a sea ice-ocean coupled model. Basal melting of all Antarctic ice shelves are investigated with the circumpolar ice shelf-sea ice-ocean coupled model and we have estimated the total basal melting of 770-944 Gt/yr under present-day climate conditions. We present a comparison of the basal melting with previous observational and modeling estimates for each ice shelf in detail. It is found that heat sources for basal melting are largely different among the ice shelves. From a series of numerical experiments, sensitivities of the basal melting to surface air warming and to enhanced westerly winds over the Antarctic Circumpolar Current are investigated. In this model the total basal melting strongly depends on the surface air warming but is hardly affected by the change of westerly winds. The magnitude of the basal melting response to the warming varies widely from one ice shelf to another. The largest response is found at ice shelves in the Bellingshausen Sea, followed by those in the Eastern Weddell Sea and the Indian sector. These increases of basal melting are caused by increases of Circumpolar Deep Water and/or Antarctic Surface Water into ice shelf cavities. By contrast, basal melting of ice shelves in the Ross and Weddell Seas is insensitive to the surface air warming, because even in the warming experiments there is high sea ice production at the front of the ice shelves that keeps the water temperature to the surface freezing point. Weakening of the thermohaline circulation driven by Antarctic dense water formation under warming climate conditions is enhanced by basal melting of ice shelves.

Keywords: Antarctic ice shelves, Ice shelf-sea ice-ocean coupled model, Climate change

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A possible scenario of a drastic change in Antarctic coastal polynyas associated with ice sheet loss

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Coastal polynyas, which are newly-forming sea-ice areas surrounded by pack ice, are formed by divergent ice motion driven by winds and/or ocean currents. Antarctic coastal polynyas are very high sea-ice production areas, because the heat insulation effect of sea ice is reduced significantly in the case of thin ice and accordingly huge heat loss to the atmosphere occurs. The resultant large amount of brine rejection leads to dense water formation. The dense water is a major source of Antarctic Bottom Water (AABW), which is a key player in the global climate system as a significant sink for heat and possibly carbon dioxide. Coastal polynyas are also sites of biological "hot spots", because of much-enhanced primary productivity.

Very recent studies have suggested that landfast sea ice, which is stationary sea ice attached to coastal features such as grounded icebergs and glacier tongues play an important role in the formation of some coastal polynyas by blocking ice advection to cause divergence. Key examples are the Cape Darnley Polynya and Mertz Polynya, both of which are major source areas of AABW.

In this study, we present the first combined circumpolar mapping of Antarctic coastal polynyas and fast ice, based on satellite observation to examine and quantify the linkage between coastal polynyas and fast ice. The map reveals that most coastal polynyas are formed on the western side of fast ice, suggesting that fast ice is an essential element for the formation of most coastal polynyas. Furthermore, we demonstrate that a drastic change in fast ice extent, which is particularly vulnerable to climate change, causes dramatic changes in associated polynyas and possibly AABW formation that can potentially contribute to further climate change.

The map presented in this study reveals that many of the coastal polynyas are formed along the East Antarctic coast where fast ice dominates. In the West Antarctic sector, it was suggested that intrusion of relatively warm Circumpolar Deep Water (CDW) onto the continental shelf causes the basal melting of ice shelves, possibly leading to acceleration of iceberg calving. Future climate change might precipitate a similar situation also in the East Antarctic sector where the location of CDW is relatively close to the continent. This possibly causes drastic changes of fast ice extent directly by melting, or indirectly by acceleration of iceberg calving. The drastic change in fast ice extent is expected to cause a dramatic change in the polynya area and sea-ice production. Further, a huge tabular iceberg can directly affect the polynya area by covering over as shown in the Ross Sea Polynyas area in 2000 and 2002; giant icebergs B-15 and C-19, calved from the Ross Ice Shelf, causing a significant reduction of the polynya area and sea-ice production. The results of this study suggest that fast ice and precise polynya processes should be addressed by next-generation models to reproduce the formation and variability of sea-ice production, dense water, and AABW properly. The mapping presented in this study would give the boundary/validation data of fast ice and sea-ice production for such models.

Keywords: Coastal polynya, Landfast sea ice, Antarctic Bottom Water, Iceberg, Ice sheet

MIS34-07 Room:414 Time:May 2 15:45-16:00

Wind-buoyancy dichotomy of the Southern Ocean carbon storage

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We use a hierarchy of ocean climate-carbon models to investigate the future scenarios of the Southern Ocean carbon storage. Intensified and poleward-shifted westerly wind is hypothesized to enhance the upwelling of deep water and thermocline ventilation, which may be counteracted by the warming and freshening of the surface waters. We analyze the solubility and biological carbon pumps in the Southern Ocean as simulated by the Climate Model Inter-comparison Project phase 5 (CMIP-5) models. Model-model differences in the regional carbon storage are significant, O(100PgC), reflecting the organized changes in the two carbon pumps. To investigate the underlying mechanisms, we perform a suite of numerical sensitivity experiments using an ocean biogeochemistry model, where we purposefully impose (1) a global warming of sea surface temperature, (2) an intensification of freshwater forcing and (3) an increase in the Southern Ocean wind. Comparing the simulated patterns of carbon and oxygen changes, we find that the future increase in the biological carbon storage is likely due to the warming and freshening of the surface water dominating over the increasing wind.

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Incorporation of trace elements by diatom frustules: Significance of sediment-trap observation in the Southern Ocean

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Diatoms contribute to more than half of the primary production of the oceans and it is well established that the formation and dissolution of diatom opal governs the distribution of dissolved silica in ocean columns (Nelson et al., 1995). Owing to the physical and chemical difficulty in isolating diatom opal from clays (Shemesh et al., 1988; Beck et al., 2002), however, it is difficult to clarify the trace composition of opal and thus to understand how diatoms contribute to the ocean circulation of trace elements. To date, no direct determination of rare earth elements (REEs) in diatoms has been made, and the role of diatoms has not been considered in the circulation of REEs (Sholkovitz et al., 1994; Oka et al., 2009; Siddall et al., 2008; Arsouze et al., 2009; Tachikawa et al., 2003).

The recent study, based on the dissolution kinetics of diatom silica frustules and the incorporation theory of silicic acid complexes, unveiled the composition of diatom frustules and identified the role of diatoms in the oceans (Akagi et al., 2011: Akagi, 2013). Diatoms incorporate metal-silicate complexes, silicate minerals as well as dissolved silica, to form their silica frustules. They recycle rare earth elements in the water column and disintegrate silicate minerals to change rare earth elements in refractory silicates to readily dissolvable forms. Diatom frustules are no longer regarded as pure hydrated silica, but impure matter able to transport some elements to the deep water. In the Bering Sea diatoms are found to incorporate island-arc matter with a high εNd value (Akagi et al., in press). Diatoms are important in distributing this high εNd signature to the ocean. This new insight may affect the interpretation of the Nd isotope variation recorded in ferromanganese crusts and foraminifera, which synchronizes with the glacial-interglacial periodical variations.

The new insight on diatom frustules has been established based mainly on sediment trap samples from the Bering Sea, a rather special sea, and ocean chemists tend to treat the insight a rather exceptional case. To generalize the insight, the same line of study should be extended to the sediment trap samples from more normal oceans such as the Southern Ocean.

To date, the possibility of silicic acid complex formation with metal ions has not been explored in the research on marine chemistry. Some elements classified as high field strength elements, HFSEs, are considered to be in the form of OH complex in seawater (Byrne, 2002). Most of elements classified to high field strength elements (HFSEs) have a valency of 3+ or 4+, and considering their thermodynamic properties, it was found that they are likely to have fairly high complex formation constants with silicic acid (Wang et al., 2009; Wang and Xu, 2001). Although silica has been long studied, this study is the first to discover the possibility that it is an important carrier of many elements in marine chemistry. To establish this view, again, studies using trap samples from the Southern Ocean would be highly requested.

Keywords: diatom frustules, trace elements, sediment trap, Southern Ocean

MIS34-09 Room:414 Time:May 2 16:30-16:45

Millennial-scale sea ice expansion in the glacial Southern Ocean

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The Southern Ocean has played an important role in the evolution of the global climate system. Area of sea ice shows a large seasonal variation in the Southern Ocean. Sea ice coverage on sea surface strongly affects the climate of the Southern Hemisphere through its impacts on the energy and gas budget, on the atmospheric circulation, on the hydrological cycle, and on the biological productivity. In this study, we have conducted fundamental analyses of ice-rafted debris (IRD) and diatom assemblage to reveal a rapid change of sea ice distribution in the glacial Southern Ocean. A piston core COR-1bPC was collected from the Conrad Rise, Indian sector of the Southern Ocean. Core site is located in the Polar Frontal Zone. Sediments are composed of diatom ooze. Age model of COR-1bPC was established by 14C dating and oxygen isotope stratigraphy of planktic foraminifera. Records of IRD concentration suggest millennial-scale pulses of IRD delivery during the last glacial period. The depositions of rock-fragment IRD excluding volcanic glass and pumice were associated with increasing of sea-ice diatoms, suggesting that the millennial-scale events of cooling and sea-ice expansion were occurred in the glacial South Indian Ocean. Similar episodic IRD depositions were identified in the South Atlantic during the last glacial period (Kanfoush et al., 2000). However, Nielsen et al. (2007) proposed that the tephra-rich grains in the South Atlantic IRD events (SA-IRD events) were mainly derived from South Sandwich Island volcanic arc, and concluded that sea-ice was the dominant ice rafting transport of such IRD grains. Preliminary provenance study of IRD grains suggest that the source of IRD in the South Indian Ocean was also volcanic arc in the South Atlantic, based on chemical compositions of rock-fragment IRD grains. Thus prominent IRD layers in the glacial South Indian Ocean correlate the SA-IRD event, suggesting episodes of sea ice expansion and cooling in the Atlantic and Indian sectors of the Southern Ocean.

Keywords: Southern Ocean, sea ice, millennial-scale, dust

MIS34-10 Room:414 Time:May 2 16:45-17:00

The ANDRILL Coulman High Project: Japanese contribution to the next phase of the Antarctic Geological Drilling

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The Coulman High Project (CHP) proposes to recover two, high-quality, continuous drill-cores by drilling into Paleogene to lowest Miocene strata beneath the Ross Ice Shelf on the Coulman High in the Ross Embayment, Antarctica. The overarching objective is to establish a history of Cenozoic climate, tectonic and glacial changes in an ice-proximal setting to determine the sensitivity of Antarctica's ice sheets to a range of climatic and tectonic forcings. The sedimentary archives to be recovered in these two ~800-m drill holes will offer a window into the range of environments, ecosystems and tectonic events in the Ross Sea region as it stepped from the warm, high-CO_2 Greenhouse world of the Eocene into the lower-CO_2 and highly variable Icehouse climate of the Oligocene and early Miocene. Antarctica was the keystone in this global climate transition and hosted the growth of ice sheets that started major cryosphere influence on global systems. The sensitivity of the climate system to elevated levels of greenhouse gases, the strength of polar amplification, and the behavior of the AIS in a world warmer than today remain fundamental questions to be addressed by CHP's integrated data-climate modeling studies. These seek to reduce the large uncertainties in predictions of future ice-sheet dynamics and sea level, in part by testing models with ancient scenarios under conditions warmer than today. To improve predictions of long-term future climate and sea level, it is imperative to obtain geological records of past polar climates and ice sheets from time intervals when atmospheric CO2 was two to four times higher than present levels. Modern observations and instrumental records provide details regarding current and short-term change, but high-fidelity climate records that span previous periods characterized by higher-than-present CO2 are only available from the Earth's geological records.

The Japanese ANDRILL consortium has decided to join the CHP. In this talk, we will introduce the scientific backgrounds, logistics, and schedule of this drilling project.