

InitMIP-Antarctica experiments with the ice sheet model SICOPOLIS

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The Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) brings together a consortium of international ice sheet and climate models to explore the contribution from the Greenland and Antarctic ice sheets to future sea level rise. For such projections, initialisations are required that provide initial states of the respective ice sheet. InitMIP-Antarctica is an early initiative within ISMIP6 in order to explore this issue for the Antarctic ice sheet across a variety of models and initialisation techniques. We contribute to InitMIP-Antarctica with the ice sheet model SICOPOLIS and a spin-up-type initialisation, that is, a paleoclimatic simulation over 135 ka until the present. A major new component of the model is a physically-based parameterisation of ice shelf basal melting. In this parameterisation, basal melting of ice shelves is computed as a function of both the depth of ice below mean sea level and far-field ocean temperatures. The parameterisation is tuned differently for eight Antarctic sectors in order to achieve reasonable agreement with the modern spatial distribution of ice shelf basal melting. InitMIP-Antarctica also comprises three future climate scenarios, all to be run over 100 a: ctrl (present-day climate), asmb (prescribed schematic surface mass balance anomaly) and abmb (prescribed schematic basal melting anomaly under ice shelves). We present and discuss the performance of the spin-up in terms of agreement between simulated and observed present-day geometry and flow. Further, we investigate the response of the Antarctic ice sheet to the three future climate scenarios.

Keywords: Antarctica, Ice sheet, Ice shelf, Basal melting, Climate change, Modelling

過去21.6万年間の、東南極における気候に依存した表面質量収支のコントラスト

Climate dependent contrast in surface mass balance in East Antarctica over the past 216 ka

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南極大陸やグリーンランドは、数十万年もの間、雪が降り積もってできた氷床で覆われている。氷床を掘削して得られるアイスコアは、過去の地球環境を知る大きな手がかりである。アイスコアの研究において、積雪の堆積率（年間の堆積量（cm/年））を把握することが不可欠であり、従来、堆積率は、アイスコア中の水の酸素や水素の同位体比から推定されてきたが、この推定の不確定性を検証する手段はこれまでなかった。

本国際研究グループは、南極大陸の上で約2,000km離れたドームふじ地域とドームC地域（図1）のそれぞれで掘削された深層アイスコアを対象に、過去21.6万年間の氷に含まれる1,401対の火山噴火に起因するシグナルを比較し、2地点間に生じた積雪の堆積率の比を、同位体比を用いる方法よりも精密に割り出すことに成功した。

火山噴火シグナルから導いた堆積率比は、水の水素同位体比を用いて推定した堆積率比と大まかな傾向としては一致するものの、海洋同位体ステージ5dと呼ばれる約10.6～11.5万年前の時期には、約20%異なることが判明した。この結果は、水素同位体比を用いた従来推定法には、最大で約20%の不確定性があることを意味する。また、最終氷期の始まりの時期である海洋同位体ステージ5dには、南極の広域の積雪堆積パターンや氷床の厚さがダイナミックに変動していたことを示唆している。

さらに、現在の間氷期（約1万年前から現在）の間、火山噴火の信号から導いた堆積率比は±1%の範囲で安定していたことが明らかになった。これは、南極の広域の積雪堆積パターンが、時間的にも空間的にもほとんど変化がなかったことを意味している。そして、南極の内陸部では氷床の厚さが過去約1万5千年にわたり増大を続けていることが明らかになった。

アイスコアを用いた種々の研究において、年間堆積率の推定値は分析の基礎となる重要な情報である。本研究により、アイスコアの年代決定計算など、さまざまな研究の信頼度が向上することが期待できる。また、雪

の堆積率の変動が解明されることにより、氷期・間氷期サイクルのなかでの南極氷床上の降水の分布と氷床変動の関係の解明、ひいては地球全体の気候システムの理解につながると期待できる。

キーワード：南極、堆積、アイスコア

Keywords: Antarctica, precipitation, ice core

南極ドームふじ氷床コアの O_2/N_2 による年代決定の高精度化（8～16.5万年前）

Improvement in dating of the Dome Fuji ice core using O_2/N_2 (80-165 ka)

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The Dome Fuji ice core preserves valuable information on the climatic changes over the last 720 kyr, which enables to investigate forcings and mechanisms in the Earth's system. Precise ice core chronology is essential to determine sequences and durations of climate events, and to examine the phasing with forcings and other paleoclimatic records. Orbital scale variations in O_2/N_2 ratio of occluded air in the Vostok ice core are similar to those in local summer solstice insolation¹⁾. By using this similarity, Kawamura et al. (2007) synchronized the O_2/N_2 variations in the Dome Fuji and Vostok ice cores with local summer insolation, and established chronology for the ice cores with accuracy generally better than ± 2000 years (DFO-2006). However, it was recently pointed out by using detailed age matching between Dome Fuji, EDC and Chinese speleothem records that the DFO-2006 chronology around 90 kyr BP is too old by ~ 3 kyr³⁾. Possible cause of this error is dislocation of O_2/N_2 peaks because of large noise in the O_2/N_2 record. Recently, O_2/N_2 variations between 300 and 800 kyr has been reconstructed from EPICA Dome C ice core^{4),5)}, however, their records do not always show similar variation with local summer insolation. Thus, their O_2/N_2 record was not used for orbital tuning. These recent studies motivate us to examine the reliability of age markers based on the O_2/N_2 ratio of Dome Fuji ice core. In this study, we reanalyzed O_2/N_2 ratio in the first Dome Fuji ice core for 1200–1974 m, which covers 80–165 kyr BP.

Fractionation of O_2/N_2 ratio occurs from ice surface during storage⁶⁾. Because the first Dome Fuji core has been stored for about 20 years, we expect fractionated O_2/N_2 near the surface of ice. We thus tested different thickness of surface shaving, and found that shaving-off of about 1 cm of surface (and only using the inner part of the ice) is required for precise measurements for the ice samples below 1200 m depth. Because of this careful examination and improvement in methodology, our new O_2/N_2 data set on average do not indicate preferential loss of O_2 . Reproducibility of O_2/N_2 ratio are $\pm 0.425\%$ for 1200–1440 m, $\pm 0.263\%$ for 1440–1640 m and $\pm 0.088\%$ for 1640–1974 m, respectively.

We find large scatter in the new O_2/N_2 data between 1200 and 1440m (typical amplitude: ~ 6 – 10%). This depth range is just below bubble-clathrate transition zone where both air bubbles and clathrate hydrates were observed by microscopes. To investigate the cause of this scatter, we conducted a high-resolution continuous analysis at 2.5-cm resolution for 1399.030–1399.484 m. The O_2/N_2 shows unexpected wave-like variation from -17 to -9% with a wavelength of ~ 18 cm. The amplitude is comparable to the typical scatter in the O_2/N_2 data set from the discrete 11-cm samples. If we take 11 cm average of the high-resolution data, the average ratio only varies by $\pm 1\%$, which is insufficient to explain the scatter in the discrete data. Our current speculation is that the wavelength and/or amplitude of the O_2/N_2 variations in other depths may be larger than those in the investigated section, and that O_2/N_2 of 11 cm samples can also vary by up to 10% .

Our new Dome Fuji O_2/N_2 record confirms strong correlation with local summer insolation. Assuming no phasing between O_2/N_2 and insolation variations, O_2/N_2 data was smoothed by a low-pass filter with the cut-off period of 16.7 – 10.0 kyr, and then tuned with local summer solstice insolation by peak-to-peak matching²⁾. Because the scatter in 1200 – 1440 m does not reflect insolation signal, we rejected data points as outliers if they deviate from fitting curve by more than 3.3%.

Compared with the DFO-2006 chronology, the new age scale (DF-2016) is younger around 90 and 130 kyr BP, while it is older around 150 kyr BP. There were sharp steps in annual layer thickness (calculated from depth – age relationship) at 94.2 and 150.3 kyr BP from DFO-2006³⁾, but these unnatural steps disappeared in that from DF-2016. The DF-2016 and speleothem (U-Th) age scales agree within 1000 yrs. These results indicate that the revised chronology greatly improved from the DFO-2006 chronology.

To summarize, even though large O_2/N_2 fractionation occurs near the surface of the ice core over two decades of storage, the original O_2/N_2 ratio is preserved in the inner part of ice if it is stored at -50°C , and it can be precisely measured by sufficiently removing the ice surface. Accurate chronology can be constructed by orbital tuning of the high quality O_2/N_2 ratio from the Dome Fuji ice core with local summer insolation.

1) Bender, M. L., EPSL, 2002. 2) Kawamura et al., Nature, 2007. 3) Fujita et al., CP, 2015. 4) Landais et al., CP, 2012. 5) Bazin et al., CP, 2016. 6) Ikeda-Fukazawa et al., EPSL, 2005.

キーワード：アイスコア、ドームふじ、年代決定、 O_2/N_2

Keywords: ice core, Dome Fuji, chronology, O_2/N_2

東南極大陸縁辺の海底地形調査

Seafloor topography surveys around the East Antarctic continental margin

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Seafloor topography is fundamental information for marine research. However, the detailed topography in the Southern Ocean has not generally been understood yet. Especially, seafloor topography around the Antarctica margin covered by sea ices has been unknown. The Antarctic continental margin is the boundary area between ice sheet and ocean and the bathymetry around this region is essential element to understand the interaction between ice sheet and ocean as well as the tectonic evolutions. Single beam echo soundings have been conducted by old icebreaker Shirase, and multi beam echo-sounder has been installed on new icebreaker Shirase and the swath bathymetry data have been obtained since the 51st Japanese Antarctic Research Expedition (2009-2010). Moreover, sub-bottom profiler has also been equipped on the new icebreaker. Unknown seafloor topography and sub-bottom profiles under sea ices around the Antarctic margin such as continental shelf and sloop are becoming clear, and those data are used as basic data for the Antarctic bottom water channels as well as paleoenvironment studies. Those data combined with magnetic and gravity anomalies have also contributed to the study related to the continental breakup. But there is a limit to observations by the icebreaker. The surveys under sea ices using ROV and/or AUV should be considered. We introduce the present status of multi beam echo-sounder and sub-bottom profiler obtained around the East Antarctic continental margin by icebreaker Shirase and future development of research using ROV and/or AUV are discussed.

キーワード：海底地形、東南極、大陸縁辺

Keywords: seafloor topography, East Antarctica, continental margin

氷期の南極温暖イベントに対応した南大洋における海氷拡大 Sea ice expansion in Antarctic warming events 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. However, millennial-scale sea ice coverage and its impacts are not well understood. Here we show high-resolution records of sea ice-rafted debris (SIRD) and diatom assemblage to reveal a rapid change of sea ice distribution in the glacial Southern Ocean. The depositions of rock-fragment SIRD 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. The extent of sea ice in the Southern Ocean is occurred during the Antarctic isotope maximum (AIM) events, which is partly linked with the Heinrich Events in the Northern Hemisphere.

キーワード：南大洋、海氷、南極温暖イベント、ハインリッヒイベント

Keywords: Southern Ocean, sea-ice, Antarctic warming events, Heinrich Event

コンラッドライズにおける最終氷期以降の放散虫群集変化と海洋環境との関係

Radiolarian changes since the last glacial period in the Conrad Rise and their relation to the oceanic environments

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It is well known that the oceanic circulation in the Southern Ocean plays an important role in the global climate changes. For reconstruction of the past ocean circulation in the Southern Ocean, siliceous microfossils such as diatoms and radiolarians preserved abundantly in deep-sea sediments are widely used as paleoceanographic proxies. Fossil assemblages of diatoms (phytoplankton) indicate usually surface water environments, while radiolarians (zooplankton) can be used as indicator for not only surface but also intermediate and deep water conditions because of their discrete habitat depths for each species. In this study, quantitative analysis of radiolarians was conducted for core COR-1bPC (54°S) from Conrad Rise in the Indian Ocean sector of the Southern Ocean.

キーワード：古海洋学、生物生産性、中層水

Keywords: paleoceanography, biogenic productivity, intermediate water

最終間氷期の突然かつ急激な南極氷床崩壊イベントの検証とメカニズムの 解明に向けて

Toward understanding the cause and mechanism of catastrophic collapse of Antarctic ice sheets during the last interglacial

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現在進行中の地球温暖化は我々の生活に様々な影響をもたらすが、中でも“海面上昇”は最も深刻な脅威の一つと考えられている。最新の観測から予想を超える急速なペースでの極域氷床の融解が進行中であることが明らかになり、温暖化の進行によって海面が大きく上昇する懸念が高まっている。こうした将来の海水準変動を予測する上で過去の温暖期の海水準変動がどうであったかを調べるのは有益である。これまでの古環境の研究において、現在よりも僅かに温暖な最終間氷期（13-11.5万年前）の末期には、6mもの突然かつ急激な海面上昇があったと報告されている。これが事実であれば、現在のような間氷期の気候状態で、氷床の大規模な崩壊とそれに伴う海水準上昇を誘発する臨界点が極域の氷床に存在することになる。この最終間氷期における劇的な海面上昇に対するグリーンランド氷床融解の寄与は最大の見積もりでも2m程度とされるので、当時の海水準上昇の主因は南極氷床の大規模な融解によるものと考えられる。近年の温暖化によって現在の気候状態（全球平均の表層海水温度）はすでに最終間氷期のレベルに達しており、南極氷床の大規模な崩壊が将来に起こり得る可能性を検証することは喫緊の課題と言える。この問題に取り組むためには、最終間氷期に実際に急激な南極氷床の大規模崩壊があったかを精査することが重要である。しかし、最終間氷期の南極氷床縁辺海域における気候・海洋情報は、ほとんど蓄積されておらず、最終間氷期に南極氷床が大規模崩壊した直接的な証拠はいまだに得られていない。本講演では不可逆的な氷床融解への臨界点である「ティッピング・ポイント」の理解において過去の温暖期に起こった突然かつ急激な南極氷床崩壊イベントの検証とそのメカニズムを解明することの重要性について解説する予定である。

キーワード：南極氷床、最終間氷期、海水準上昇

Keywords: Antarctic ice sheet, last interglacial, sea level rise

Amundsen Sea simulation with optimized ocean, sea ice, and thermodynamic ice shelf model parameters

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The ice shelves and glaciers of the West Antarctic Ice Sheet (WAIS) are melting and thinning rapidly in the Amundsen Sea (AS) and Bellingshausen Sea (BS), with consequences for global sea level rise and ocean circulation. First, approximately 10% of the observed sea level rise has been attributed to the thinning of WAIS between 2005 and 2010. Second, the melting of ice shelves in the AS and BS will freshen the shelf water locally as well as downstream in the Ross Sea (RS), which may lead to a change in the characteristics of Antarctic Bottom Water formed in the RS and thus influence the global thermohaline circulation.

Agreement between model results and observations are crucial for understanding and projecting these impacts on the current and future climate. Thus, we aim to conduct model optimization for a regional Amundsen and Bellingshausen Seas configuration of the MITgcm. Currently, we have adjusted a small number of model parameters to better fit the available observations during the 2007-2010 period using trial-and-error adjustment and a Green's function approach. As a result of adjustments, our model shows significantly better match with observations than previous modeling studies, especially for Winter Water (WW). Since density of sea water depends largely on salinity at low temperature, this is important for assessing the impact of WW on Pine Island Glacier melt rate. We also conduct several sensitivity studies, showing the impact of surface heat loss on the thickness and properties of WW.

Our work is a first step toward improved representation of ice-shelf ocean interactions in the ECCO (Estimating the Circulation and Climate of the Ocean) global ocean retrospective analysis. In this presentation, we briefly explain our overall project and present some preliminary results pertaining to sensitivity simulations using high resolution (2 km) configuration and adjoint sensitivity simulations.

キーワード : Amundsen/Bellingshausen Sea, Ice shelf-ocean interaction, Circumpolar Deep Water
Keywords: Amundsen/Bellingshausen Sea, Ice shelf-ocean interaction, Circumpolar Deep Water

白瀬氷河における氷舌—海洋相互作用の現場観測

Observations of ice tongue-ocean interaction at Shirase Glacier

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Shirase Glacier Tongue (SGT) is a thick floating slab of ice that forms where the glacier flows down onto the ocean surface at the southern closed-section of Lutzow-Holm Bay (LHB) off Enderby Land, East Antarctica. Compared with other major ice shelves/tongues around Antarctica, SGT is smaller in area but its basal melt rate was estimated to be relatively high at a rate of ~7 m per year (Rignot et al., 2013) based on presence of warm deep water. Although comprehensive hydrographic observations in LHB is indispensable for understanding the SGT-ocean interaction, they are extremely limited, with exception of those conducted by wintering party of the 31st Japanese Antarctic Research Expedition (JARE) in 1990/92. Detailed analysis of the JARE-31 winter hydrographic observations suggests a 3-dimensional circulation, associated with the SGT-ocean interaction, that comprises: (1) warm modified CDW (Circumpolar Deep Water) flows southward at the deep layer of submarine canyon that leads into the region beneath SGT, (2) mCDW meets to melt the base of SGT, and (3) mixture of mCDW and basal melt water exports northward at subsurface layer.

To explore in detail the SGT-ocean interaction, summer comprehensive hydrographic observations in LHB are now in progress during JARE-58 in 2016/17 under the project called ROBOTICA. In this talk, preliminary results from the JARE-58 hydrographic observations are also presented.

キーワード：白瀬氷河氷舌、底面融解、周極深層水

Keywords: Shirase Glacier Tongue, basal melt, Circumpolar Deep Water

Breakup of land-fast sea ice in Lutzow-Holm Bay, East Antarctica and its teleconnection to tropical Pacific

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A large land-fast sea ice breakup occurred in 2016 in Lutzow-Holm Bay, East Antarctica. The breakup caused calving from the Shirase Glacier Tongue (SGT), which is otherwise held back by the ice. Although similar breakups and calving have been observed in the past, the timing and magnitudes are not well-constrained. We analyzed the ice's breakup latitude during 1997-2016 to investigate the variables controlling breakup and examine correlation with local calving for a longer period. The breakup latitude had a persistently high correlation with sea-surface temperature (SST) in the tropical Pacific, which exceeds correlations with local atmospheric variables. The multi-decadal variability of the tropical SST can explain the multi-decadal variation of the calving front of SGT from the 1950s through the breakup of fast ice. The SST-regressed breakup latitude can potentially explain 5 out of 6 SGT calving events from the mid-20th century, including its frontal retreat in the 1980s. Our proposed teleconnection between tropical SST and Antarctic sea ice could lead to better predictions of breakup and might impact the glacier flux for a wider region.

アルゴフロートにより観測された南極環海流の定常蛇行

Standing meanders of the Antarctic Circumpolar Current as observed by Argo floats

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1. 海洋研究開発機構

1. JAMSTEC

南大洋の渦は、たとえば渦運動エネルギーや渦運動量鉛直輸送などで定量化されてきたが、近年「流線の長さ」に着目する研究が現れた。南大洋には世界最大流量を誇る南極環海流がある。この海流の流量は西風の数年規模の変動に対してほとんど変動しない事が知られてきた。これが定常蛇行の近辺で風の変動に対する調整がおこっているせいではないか、という仮説がある。その調整にともなう現象として流線が長くなる事象が渦分解数値モデルで見られた。

アルゴフロートを用いて類似した現象が観測されうるか調べた。南極環海流に沿って7つの定常蛇行が観測された。この定常蛇行近辺の上層1000mの渦輸送を計算すると、渦に伴って流線の曲率半径が増加すなわち流線が長くなっている事が示唆された。この効果は海底地形東側（環海流の下流側）で特に大きい。下流側は多くの場合極向きの渦輸送を持ち、子午面循環や運動量収支でも重要な役割を果たすが、流線の長さの決定にも重要な事が分かった。

キーワード：南極環海流、年々変動、渦輸送、曲率

Keywords: Antarctic Circumpolar Current, Interdecadal variability, Eddy transport, Curvature

南極氷床と気候の変動及び相互作用に関する研究展望

Research prospects on variations and interactions of Antarctic ice sheet and climate

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南極気候変動研究の一環として、以下を提案する。

アイスコアの分析や氷床の直接観測により、南極氷床と全球気候の現在や過去の状態を明らかにし、それらの変動メカニズムと相互作用を解明する。特に、過去数十万年の気温や降雪量、海氷、炭素循環に関する分析や、氷床質量収支や海洋との相互作用にかかる観測を軸とする。

【研究内容】

1) ドームふじ等で採取されたアイスコアを解析し、南極及び全球の環境変動を復元する。氷床・気候モデルの入力となる二酸化炭素や、気温や海水温復元のための水同位体や希ガス、放射強制力や物質循環に関わるエアロゾル、海氷由来物質、気候不安定性復元のためのメタン濃度、標高変化に関連する空気含有量、年代精度向上のための成分などを分析する。特に、南極氷床が縮小した「スーパー温暖期」に着目し、数値モデルや海底コアデータを用いた比較研究を行う（古海洋・モデル研究と連携）。古環境シグナル形成プロセスの研究も実施する。

2) 氷河と氷床の現地観測とリモートセンシングにより氷床流動と質量変化を測定する。氷床沿岸部や氷河流域全体での質量収支・氷損失を定量化し、氷河加速や棚氷底面融解、接地線移動などの状態とメカニズムを理解する（海洋観測・固体地球観測と連携）。観測成果を用いて氷床モデルの精緻化に寄与し、氷床量と海水準の将来予測精度向上に貢献する（気候等のモデル研究と連携）。

キーワード：南極氷床、気候変動、アイスコア、氷床融解

Keywords: Antarctic ice sheet, Climate change, Ice cores, Ice sheet melting

大気海洋結合モデルや氷床モデルを組み合わせた過去から将来の南極南大洋の統合的モデリングの現状

Current climate-ice sheet studies related to Antarctica and Southern ocean using Earth system models

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Climate-Antarctica ice sheet and Southern ocean interaction not only affects the local climate but also affect the global climate and ocean. We present some of our current modelling studies and plan using coupled atmosphere and ocean model and ice sheet model. In one of our studies, Eocene experiments were carried out to test the model's ability to reproduce proxy data and to investigate the climate system under high CO₂ concentration. Furthermore, in order to investigate to what extent topographical changes are responsible for the difference between the Eocene and present day climates, we created Eocene-like geometries from the present day topography. We present the individual effects of the Drake Passage, Tasman Gateway, Antarctica Ice Sheet on the climate.

キーワード：古気候、気候モデリング、南極氷床

Keywords: paleoclimate, Climate modeling, Antarctica ice sheet