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Future Plan of Antarctic research: towards phase XI of the Japanese Antarctic Research Project (2028-2034), IPY 2032-2033 and beyond

Abstracts

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Continuous aerosol and cloud observations at Syowa station towards JARE phase XI

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The Southern Ocean is one of the cloudiest places on Earth with nearly 80% cloud cover year-round (Mace et al., 2009). Current global numerical models, including Earth System Models and General Ciarculation Models, exhibits a severe positive bias in the downward short-wave radiation over the Southern Ocean (10-20 W m^{-2}; Flato et al., 2013; Mallet et al., 2023), exerting important impacts on simulating sea surface temperature, sea ice, and Soutehrn Hemisphere jet (Ceppi et al., 2014; Flato et al., 2013). This background has motivated the extensive efforts in aerosol and cloud measurements over the Southern Ocean during the last decade (Mallet et al., 2023). Notably, the series of observations has revealed that current climate models largely underestimate number concentrations of cloud-forming particles (CCN) over the Southern Ocean by more than 50% (e.g. Schmale et al., 2019; McCoy et al., 2021), contributing to a severe positive bias of surface solar radiation. Earlier works at Syowa station have revealed a clear seasonal cycle of CCN sources with new particle formation and aerosol growth in the Antarctic free troposphere and boundaly layer during spring – autumn (Hara et al., 2021) and dispersion of sea-ice-origin sea-salt aerosols during winter – spring (Hara et al., 2020, 2025). This trend is well characterized across coastal Antarctica (e.g., Weller et al., 2011), yet the mechanisms causing the large low bias in CCN number concentrations remain unknown. These results encourage further targeted in-situ observations of aerosols, including their precursor gases, to explore missing or inacurately represented processes in current models.

In the presentatioin, we will propose a potential plan for aerosol and cloud observations at Syowa station during the JARE phase XI and IPY 2032-2033, along with our achievements through JARE phase X. Our plan includes wintering field measurements of atmosphere (i.e., aerosols and clouds) and material exchange among atmosphere, cryosphere, and ocean, and model study.

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GODSILA-II (Guided Observations of Dynamic Shear Instability Layers over Antarctica): Year-long Observations at Syowa Station

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The GODSILA collaborative field campaign was carried out between 12/2023 and 02/2024, as part of JARE65. Forty HYFLITS in-situ balloon-borne payloads were successfully launched with guidance from real-time PANSY radar measurements at Syowa Station over the 44-day field campaign. The primary objective was to characterize summertime fine-structure turbulence emerging from atmospheric gravity wave enhancements of unstable shear layers throughout the troposphere and the lower stratosphere up to 20 km AGL (TLS).

Building upon the success of the funding collaboration between NIPR and the US National Science Foundation in conducting GODSILA, we propose to conduct a year-long field observation program, namely GODSILA-II, as part of JARE70. During GODILSA-II we aim to deploy 200 HYFLITS balloon-borne payloads periodically over 365 days between 1st January – 31st December 2029.

GODSILA field campaign provided the first high-resolution in-situ turbulence dataset for diverse instability events occurring in the polar TLS. This enabled detailed intercomparisons with PANSY radar observations of weak summertime turbulence and investigations of the deficiencies in Thorpe inferred turbulence dissipation rates. However, previous observations indicate stronger occurrences of turbulent layers in the wintertime TLS from more frequent orographic and non-orographic gravity wave activity. Thus, the primary science goals of GODSILA-II are to:

- characterize the strong variability in the occurrence and intensity of turbulent layers in the atmospheric column up to 30 km using concurrent in-situ HYFLITS and PANSY radar measurements, and
- investigate the influences of seasonal variations of orographic and non-orographic gravity wave activity on the unstable shear layer enhancements of turbulence and characterize the fine structure of these layers.

This talk briefly focuses on outcomes of the first GODSILA field campaign and outlines the proposed GODSILA-II field program objectives, methodology, budget, and logistics. The HYFLITS balloon-borne instrument remains to be the only cost-effective in-situ turbulence observing platform for TLS measurements. An updated payload design is also outlined, simplifying launches in more extreme Antarctic wintertime surface conditions, and enabling longer-range data telemetry to account for stronger wintertime winds aloft.

So3

Current status and future plans of the LODEWAVE project

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LODEWAVE (LOng-Duration balloon Experiment of gravity WAVE over Antarctica) is a project aiming to observe atmospheric gravity waves in the lower stratosphere over Antarctica using super-pressure balloons (Tomikawa et al., 2023). To date, it has conducted two observation campaigns at Syowa Station in the austral summer. During the first campaign, simultaneous observations with PANSY (Program of the Antarctic Syowa MST/IS radar) successfully captured the wave packet of the same near-inertial frequency gravity waves (Tomikawa et al., 2024). However, in both campaigns, the flight duration was less than three days, falling short of the target duration of ten days or more. Improvements to the super-pressure balloon are currently underway, with the next campaign observation planned for the winter of 2027 by the 68th JARE (Japanese Antarctic Research Expedition) overwintering party. This presentation will introduce the history and future plans of the LODEWAVE project and discuss the direction for Phase XI of the Japanese Antarctic Research Project (FY2028-2033).

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So4

Initial aurora observation results from HySCAI-1 in Kiruna and development of HySCAI-2 for Showa base in Antarctica

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A hyperspectral camera for auroral imaging (HySCAI), which can provide a two-dimensional (2D) aurora image with full spectrum, was developed to study auroral physics [1,2]. HySCAI consists of an all-sky lens, monitor camera, galvanometer scanner, grating spectrograph, and electron-multiplying charge-coupled device (EM-CCD). The galvanometer scanner can scan a slit image of the spectrograph on the all-sky image plane in the direction perpendicular to the slit. The first hyperspectral camera for auroral imaging (HySCAI-1) has been installed at the KEOPS (Kiruna Esrange Optical Platform Site) of the Swedish Space Corporation (SSC) in Kiruna, Sweden, and observations have been underway since 2023.

We focused on the auroral breakup that began around 17:30 UT on January 1, 2025. This breakup was associated with a large substorm with minimum SML index exceeding -2000 nT, and is characterized by intense red color. During this breakup, HySCAI-1 measured the red region (620–720 nm), including the OI (^{1}D) 630.0 nm line, which is the cause of the red aurora, and the vibrational-rotational levels of the N_2 1PG molecule at the following bands: (8,5) 646.7 nm, (7,4) 654.5 nm, (6,3) 662.6 nm, (5,2) 670.1 nm, (4,1) 679.0 nm, (3,0) 687.6 nm, and the Meinel system (3,0) 685–690 nm, (4,1) 705–710 nm. In the red region, prior to the breakup of the red aurora (approximately 6 minutes before), an increase in N_2 1PG was observed. During the breakup of the red aurora, the OI (^{1}D) 630.0 nm line was much brighter than N_2 1PG. This aurora breakup with intense red color lasted approximately 50 minutes. From the spectral shapes of each band of the molecular vibrational-rotational levels of N_2 1PG during the red aurora breakup, the meridional distribution of nitrogen's rotational temperature was obtained.

The figure 1 shows (a) the nitrogen spectrum observed at zenith angles of -56° (south) and 41° (north), (b) the nitrogen spectrum calculated using rotational temperature and vibration temperature as parameters, and (c) the meridional distribution of rotational temperature. The shape of the spectrum changes with rotational temperature, becoming upward-sloping at low rotational temperatures but flattening or downward-sloping as rotational temperature increases. By comparing with model calculations, rotational temperatures can be estimated at each point. As a result, significant differences in rotational temperature were observed, with a minimum of 340 K on the south side and a maximum of 570 K on the north side. Subsequently, this temperature difference decreased over time, and during the latter half of the breakup, the distribution of rotational temperatures became nearly flat.

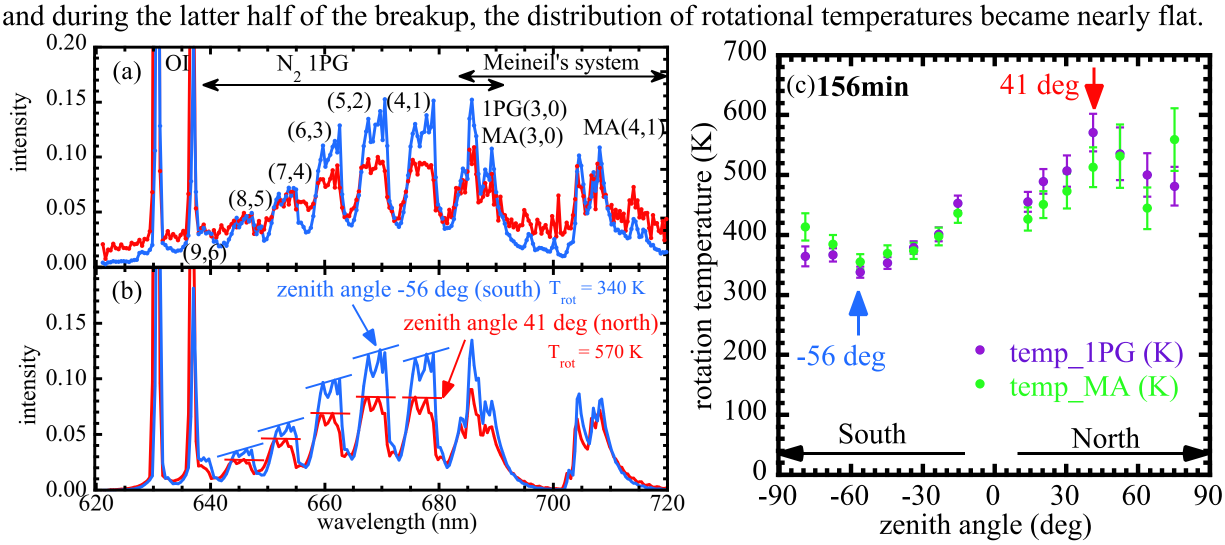

Figure 1. Nitrogen spectrum of (a) observed with HySCAI-1, (b) calculated using rotational temperature and vibration temperature as parameters, at zenith angles of -56° (south) and 41° (north) and (c) meridional distribution of rotational temperature.

Measurements of the polarization of aurora emission are challenging because the degree of polarization is relatively small (a few %). However, the polarization characteristics provide information on precipitating electron properties such as the anisotropy of electron velocity distribution. A 2-dimensional spectrum image of the H□ emission line profile has not been measured. However, the H_β spectrum with high spectral resolution provides information on the velocity distribution of protons. HySCAI-2 has been developed to study 1) polarization characteristics of OI (630.0nm, 636.4nm, 639.2nm) emission and 2) H_β (486.1nm) emission line profile image for proton aurora, as well as a spectrum monitor of all-sky image in the visible range of 400 – 870 nm.

HySCAI-2 is equipped with three gratings for different spectrum ranges and resolutions and a rotating half-wave plate for the detection of small degrees of polarization, as seen in Figure 2. Because the degree of polarization expected is relatively small, the polarization characteristics of aurora emission could be riddled with errors or offset attributed to the atmosphere and optical dome. Therefore, the simultaneous measurements of OI emissions (630.0nm and 636.4nm) that have opposite signs of polarization are selected to minimize the effect of error. The error or offset due to the atmosphere and optical dome is expected to be canceled out by taking the difference of polarization degrees between 630.0nm and 636.4nm emissions. By rotating the half-wave plate, the degree of polarization is extracted from the modulation amplitude at the rotating frequency.

Table 1 shows the spectrum range/resolution and observation target for the three gratings equipped in HySCAI-2. The 150/mm grating is used for the spectrum monitor in the visible range. The spectrum resolution is 3nm, enough to extract a monochromatic image with background subtraction. The 600/mm grating is used to evaluate the rotation temperature of nitrogen molecules from the N2 1PG spectrum shape. This grating is also used to detect the polarization characteristics of OI emissions. The 1800/mm grating is used for the H_β emission line profile. The spectrum resolution (FWHM) is 0.2nm, good enough to detect the expected Hb Doppler shift of 0.5nm.

We plan to install the HySCAI-2 in the Showa base in Antarctica at the end of 2026, and start the aurora observation from the aurora season in 2027. The combination of HySCAI-1 and HySCAI-2 eliminates periods when observation is impossible due to the midnight sun and enables us not to miss the aurora observation at a big aurora substom associated with a super solar flare event.

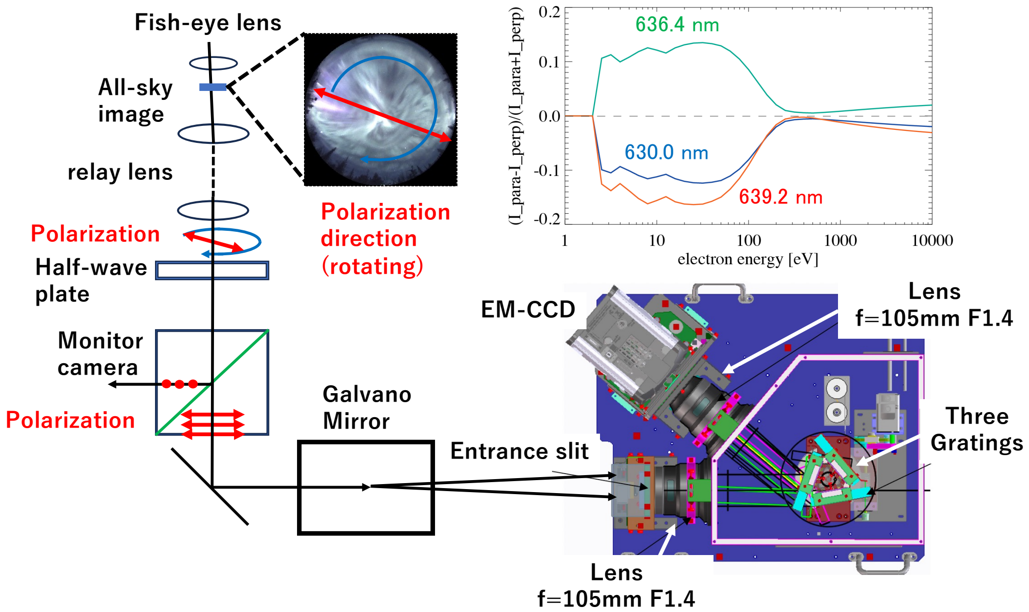

Figure 3. Diagram of HySCAI-2 and expected degree of polarization for OI (630.0nm, 636.4nm, 639.2nm) emission

Table 1. Spectrum range/resolution and observation target

Grating	Spectrum Range	Spectrum Resolution (FWHM)	Observation Target
150/mm	470nm (400-870)	3.13nm @546nm	Spectrum monitor
600/mm	110nm (600-710)	0.72nm @546nm	N_2 1PG and OI polarization
1800/mm	29nm (470-499)	0.19nm @546nm	Proton aurora velocity distribution

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Development of AuroraXcosmic project in Phase XI

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In the Japanese Antarctic Research Project Phase X Six-Year Plan, one of the prioritized research projects “Space environmental changes and atmospheric response explored from the polar cap (AJ1007)”, called auroraXcosmic project, has deployed an array of all-sky cameras across the Antarctic polar cap and auroral zones, including focused observations at Syowa Station. Currently, the all-sky cameras are in operation at 8 manned and 2 unmanned stations, providing crucial data for studying solar wind–magnetosphere-ionosphere interactions. At Syowa Station, several instruments such as a cosmic ray detector (muon detector and neutron monitor), a high-speed imager, a spectral riometer, and a millimeter-wave spectrometer have been operating to investigate how high-energy particles from space affect the polar upper atmosphere. Additionally, by combining data from these wide-area observation sites with numerical simulations and data science techniques, we are trying to create reanalysis datasets for the magnetosphere and ionosphere.

In Phase XI, we plan to expand this project into the following two research directions: (1) contributing to space weather forecasting through data assimilation with global MHD simulations, and (2) investigating cross-scale coupling processes related to auroras. With recent rapid advances in simulation, data assimilation, and artificial intelligence, accurate space weather prediction is becoming more feasible. By assimilating data from our wide-area ground-based observation network, we aim to create reanalysis datasets and improve forecast accuracy. Internationally, the SCOSTEP’s (Scientific Committee on Solar-Terrestrial Physics) new program “COURSE (Cross-scale cOUpling pRo-cesses in the Solar-tErrestrial system)” is planned for 2026–2030, and the SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) satellite mission is scheduled for launch in 2026. SMILE will provide global imaging of auroral ovals and the polar cap using ultraviolet and soft X-ray imagers. By comparing the global-scale auroras with the mesoscale and small-scale auroras captured through the wide-area ground observations, including the focused observations at Syowa Station, we can better understand the coupling processes across different scales in auroral phenomena.

So6

Sea-Ice Variability and Its Role in Coupled Atmosphere–Ocean–Ice Sheet Processes

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Background and Recent Changes

Recent studies have revealed the large-scale ocean circulation field in the Totten region and adjacent seas. These works have identified persistent standing eddy structures (Mizobata et al., 2020; Hirano et al., 2021) and a clockwise coastal circulation known as the Sabrina Gyre (Hirano et al., 2023), arising from the combination of shelf and basin dynamics. More recently, it has been shown that strengthening of the westerlies enhances these clockwise circulations scattered along East Antarctica, thereby intensifying oceanic heat flux toward the continental shelf (Mizobata et al., 2025). Nevertheless, it remains essential to continue research, because sea ice plays a critical role in modulating the exchange of momentum, heat, and materials between the atmosphere and the ocean. In 2023, Antarctic sea-ice extent experienced an abrupt and unprecedented decline, underscoring its vulnerability (Fig. 1). Yet the consequences of sea-ice presence, absence, and qualitative changes for air–sea interactions and heat and materials transports remain poorly understood. This uncertainty provides a central motivation for the proposed program.

Scientific Importance

Sea ice plays a central role in regulating interactions between the atmosphere and the ocean. Variations in its extent, volume, and type not only modulate the transfer of momentum and heat fluxes across the air–sea interface but also exert significant influence on dense shelf water formation, the export of materials from the coast to the open ocean, and the regulation of marine primary productivity. Sea-ice variability is tightly coupled with the atmosphere–ocean system, and thus indirectly affects the stability of ice shelves, dense water formation, and Southern Ocean productivity. Understanding the mechanisms that drive such interconnected processes is therefore crucial for improving projections of ice sheet mass loss, sea-ice decline, and their associated impacts on the global climate system and sea-level rise.

Overall Research Framework

To address these challenges, we propose to develop an integrated research program that elucidates the mechanisms governing variability in the coupled ice sheet–sea ice–ocean system. The project will be based on direct in-situ observations conducted during expeditions of the Japanese icebreaker Shirase, which provides a unique platform for systematic monitoring across the Southern Ocean. These observations will enable us to capture simultaneous changes in ocean stratification, sea-ice properties, and ice–ocean interactions, as well as their impacts on biogeochemical processes, thereby offering a comprehensive view of the coupled system.

International Collaboration and Continuity

The project will build upon Japan–Australia joint observational campaigns planned for 2027–2028, which aim to investigate key physical and biogeochemical processes in the Southern Ocean, including shelf–basin exchange, Antarctic Bottom Water formation, and pathways of oceanic heat transport toward vulnerable ice shelves, in alignment with the framework of the Fifth International Polar Year (IPY-5). This collaboration is anticipated to extend beyond 2029, providing a strong foundation for sustained, multi-national observations and coordinated data analysis. Integration of these international efforts with the Japanese Antarctic Research Expedition will significantly enhance both the scientific outcomes and the global relevance of the research.

Proposal for the 11th Japanese Antarctic Research Expedition (JARE XI)

We propose this project as a priority observation program of the 11th Japanese Antarctic Research Expedition (JARE XI), beginning in 2028. By combining Japan's observational capabilities with international collaboration and advanced numerical modeling, the project aims to elucidate the processes linking sea-ice variability, ice-shelf stability, and ocean circulation. The outcomes will make a significant contribution to reducing uncertainties in projections of Antarctic ice-sheet mass balance, global sea-level rise, and future changes in the Southern Ocean ecosystem.

Strategic Focus

This study seeks to comprehensively capture the processes that connect the atmosphere–ocean–ice sheet system, with a particular focus on variability in sea-ice distribution. Specifically, we identify three key themes: (1) air–sea heat and material exchange over the continental shelf and basin, together with vertical transport within the ocean, (2) modulation of the processes contributing to horizontal oceanic heat transport, and (3) horizontal material transport carried by the sea ice itself (Fig. 1). Through these approaches, we aim to advance understanding of how sea-ice variability shapes the links between ice-shelf stability and ocean circulation, and how these affect on biogeochemical cycles and the future changes.

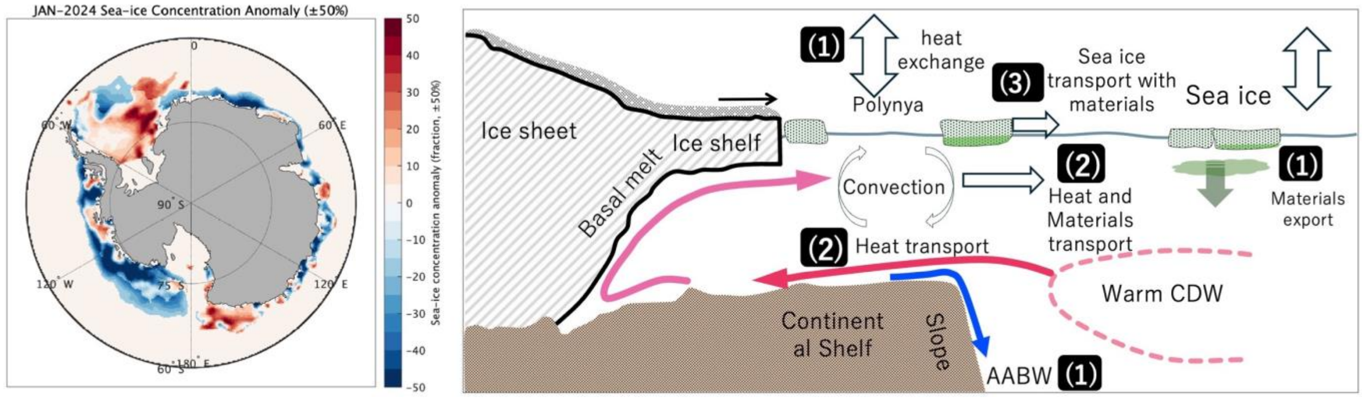

Figure 1. Left: Sea-ice concentration anomaly in January 2024 relative to the 1981–2010 climatology, highlighting the record-low extent and strong regional contrasts. Right: Conceptual diagram of the three research targets proposed in this study: (1) air–sea heat and material exchange and vertical transport in the shelf–basin system, (2) modulation of poleward oceanic heat transport processes by sea-ice variability, and (3) horizontal material transport carried by sea ice itself. Together, these perspectives aim to clarify the processes linking sea-ice variability, ice-shelf stability, and Southern Ocean circulation.

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Routine Marine Observation and Ocean Monitoring (former Marine Ecosystem Monitoring)

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Changes in the global thermohaline ocean circulation due to warming and freshening of the Antarctic Bottom Water (AABW) could have substantial impacts on Earth's climate. However, current field observations in the Southern Ocean, particularly the bottom layer, have not been conducted comprehensively from an international perspective. Consequently, the lack of data has hindered a comprehensive understanding and validation of the driving mechanisms of ocean circulation. Therefore, elucidating the formation processes of AABW is important for predicting the future ocean circulation, which significantly impacts on global climate change.

The Japanese Antarctic Research Expedition (JARE) has been conducted sustained ocean observation over the past 60 years. In addition to observations by icebreakers Fuji and Shirase, time-series observations using multiple vessels under the Studies of the Antarctic Ocean and Global Environment (STAGE) program were carried out in collaboration with Australia in the early 2000s (JARE 43 and 44). This initiative has been continued and updated through the "Routine Marine Observation" in collaboration with Tokyo University of Marine Science and Technology (TUMSAT) on the platform TV *Umitaka-maru* since 2012. In particular, we have enhanced an observation network of AABW by providing monitoring data of water temperature and salinity at depths >3,000 m to relevant international and domestic organizations and with the observation stations near sea ice edge and internationally fixed-point observation sites. In addition, these cruises have played a role as a part of the Marine Ecosystem Monitoring and Prioritized Research Project. Within the next few years, however, TUMSAT has planned to construct a new TV *Umitaka-maru* which has no capability of operation in polar region. As an alternative way, we desire to continue the Routine Marine Observation by installing a new CTD and water sampling system into icebreaker *Shirase*. We also hope to conduct Ocean Monitoring, former Marine Ecosystem Monitoring, adding several enhanced instruments and oceanographic parameters linking with the Routine Marine Observation.

While the Routine Marine Observation have primarily focused on AABW, recent significant declines in sea ice, increase in iceberg calving and ice-shelf melting, and the occurrence of marine heatwaves have profoundly altered the ocean surface, a part of the changes exceeded the rate of physiological threshold. Consequently, the potential impact on marine ecosystem and biogeochemical cycles are concerned. Therefore, we propose to continue AABW observations near the ice edge as well as to comprehensively understand oceanographic changes at the ocean surface, including water temperature, salinity, plankton community structure through imaging techniques, photosynthetic activity, pCO_2, and so on, with an organic link between routine and monitoring observations. Additionally, we will try to monitor sea ice/ice-shelf meltwaters using dissolved inorganic carbon (DIC), alkalinity, and $\delta^{18}O$ and fluorescent dissolved organic matter (FDOM) to detect the changes in marine ecosystems and biogeochemical cycles. Note that the near bottom observations with a CTD by Shirase have to be obligation to make the best efforts until Shirase is equipped with a dynamic positioning system. However, observations carried out from Fremantle to the ice edge will provide valuable data for comparative analysis with past observations.

The period from 2026 to 2032 is "the Pre-International Polar Year (IPY) project phase" of the fifth IPY (IPY5, 2032-2033). During the phase, circumpolar synchronous observations under the framework of "Antarctica InSync" are scheduled for 2027-2030, and Japan has committed to conducting joint observations of East Antarctica in collaboration with Australia.

Our proposed observations extend beyond the primary purpose, "routine and monitoring", and can be the fundamental observation for the Prioritized Research Project. We will analyze the water sample from Routine Marine Observation in accordance with GO-SHIP methods to ensure the utmost accuracy which can be acceptable for international collaborative projects and analyses. These efforts will highlight and substantiate Japan’s contributions to IPY5. Furthermore, the datasets from our observations will be provided as valuable predictive tools for future global environments and ecosystem changes, contributing to the formulation of appropriate adaptation measures for humanity.

So8

Warming in the Dome Fuji region of East Antarctica and its impact on atmospheric circulation changes

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The recognition of warming trend in the Antarctic Peninsula and West Antarctica since the mid-20th century has prompted significant growth in research. By contrast, research on climate change in East Antarctica has been far less extensive, and the region has considered less sensitive to ongoing climate change. However, a recent study has cast doubt on this view. The new temperature records from three inland stations (Mizuho, Relay Station, and Dome Fuji) showed statistically significant warming over the past 30 tears (1993-2022), exceeding the global average by more than twice (Kurita et al., 2025). This warming trend has been attributed to the warming of the southern Indian Ocean, which is due to increased heat uptake from the warmed atmosphere. Therefore, we can say that anthropogenic factors are altering the climate of the Dome Fuji and the surrounding region (Dome Fuji region), making it more vulnerable to atmospheric and oceanic changes. As the impacts of climate change become more apparent, it is crucial to improve climate change monitoring in the Dome Fuji region.

Climate models predict that extreme events will become more frequent and impactful as global warming progresses. This trend has already started to be observed in the Dome Fuji region. Over the past 30 years, the frequency of daily mean temperatures has shifted towards warmer conditions. This results in an increase (decrease) in the frequency of extremely hot (cold) days at Dome Fuji and Relay Station. In particular, the frequency of extremely hot days increased significantly during the warm season from October to January. During this season, the extremely hot days did not appear as short-lived heat spikes, but rather heatwaves (HWs) that lasted for several days. Generally, heatwaves are triggered by the heat transport by the blocking high pressure ridge that develops into the Antarctic interior. And then, the ridge becomes cut off from the mean flow and develops into a cut-off high pressure field. The extremely hot days continued during the while the area covered by the cut-off high. From the late 1990s through the 2000s, the blocking ridge that developed from the Pacific sector to East Antarctic's interior (Fig.1a) was the primary driver of HWs. However, since the 2010s, the blocking ridges from the Indian Ocean sector (Fig.1b) have become much more frequent. This has resulted in an increase in the frequency of HWs in the Dome Fuji region. Interestingly, most of the blocking ridges from the Indian Ocean are accompanied with the atmospheric river (AR) landfalls on the coast of the East Antarctica. Thus, the major back trajectory pathways of air masses that caused HWs extend from off the coast of South Africa to Dome Fuji region (Fig.1b).

This reminds us that heat and moisture, as well as aerosols and various anthropogenic chemicals, can now easily be transported into the Antarctic interior. Dome Fuji region is a unique place where the atmospheric transport pathway to the Antarctic interior has changed significantly. Now is a good time to explore the unknown process of moisture and chemical transport to the interior of Antarctica. Understanding of this process helps us to understand the variability of the water isotopes and the chemical components archived in ice cores. interior. Therefore, in this presentation, I will propose research projects aimed at enhancing climate monitoring and elucidating the processes of moisture and chemical transport to the Dome Fuji region.

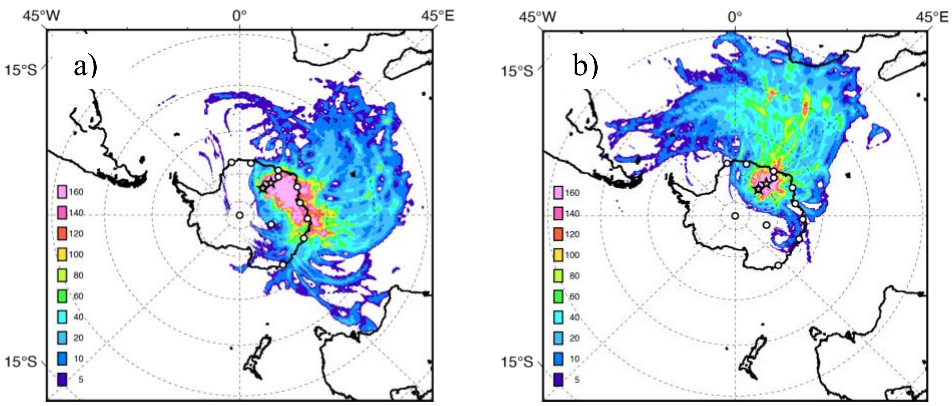

Figure 1. A composite map of 5-days back trajectories of air masses transported by the blocking ridges from a) the Pacific Ocean sector and b) Indian Ocean sector over the past 32 years (1994-2024). The colors represent the number of trajectory counts at 30-min intervals on a 0.75° x 0.75° grid.

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Uncertainties in the Antarctic ice sheet mass loss: Quantifying how much and how fast in a warming climate

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The Antarctic Ice Sheet is undergoing rapid mass loss, primarily along its coastal margins, where thinning and retreat of ice shelves have accelerated in recent decades. Ocean-driven basal melting and iceberg calving have triggered grounding-line retreat and flow acceleration of ice streams. In contrast, atmospheric warming resulted in an increase in moisture transport in some parts of Antarctica and caused snow accumulation to compensate for the ice mass loss. Despite recent extensive research, fundamental questions remain unsolved: how much ice will be lost, and how fast will these changes accelerate under ongoing global warming?

To address this uncertainty, we have conducted multidisciplinary studies, particularly in Lützow-Holm Bay, East Antarctica. Remote sensing dataset analysis revealed recent dynamic changes of outlet glaciers (Kondo and Sugiyama, 2023), and rapid and cyclic discharge from an ice-marginal lake (Hata et al., 2023). Intensive field campaigns provided insights into basal melting (Minowa et al., 2021), meltwater-induced flow acceleration, and ice shelf hydrofracture. These efforts are complemented by airborne surveys equipped with ice-penetrating radar, altimeter, and gravimetry, extending spatial coverage to Enderby Land in collaboration with international partners.

In the next decade, we aim to identify and quantify the dominant drivers of Antarctic ice sheet change by integrating field observations, remote sensing, airborne geophysics, and numerical simulations. Our goal is to reduce uncertainties in projections of mass loss, both in magnitude and in rate, to improve future sea-level rise projections.

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So10

Toward an Integrated Understanding of Antarctic Ice Sheet Variability and Next-Generation Inland Observations

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The accelerated mass loss of the Antarctic Ice Sheet (AIS) has raised global concerns about the potential for abrupt sea-level rise in the near future. To improve the reliability of future projections, it is essential to obtain robust geological evidence, particularly from past warm periods, in order to better understand the AIS's response to global climate change and the mechanisms driving its large-scale retreat. In previous studies, including our own expeditions, it has been hypothesized that the East Antarctic Ice Sheet (EAIS), particularly in the Dronning Maud Land region, may demonstrate a distinctive response to climate forcing. Building on these findings, it is critically important to develop a comprehensive understanding of AIS variability over longer timescales and across broader spatial ranges through an integrated approach combining glaciology, geology, geophysics, and biological diversity. Concurrently, the rapid expansion of mass loss zones across Antarctica underscores the growing need for internationally coordinated observations.

This proposal aims to reconstruct the past dynamics of the East Antarctic Ice Sheet (EAIS), with a particular focus on the period since the Last Interglacial (~130 thousand years ago) and the recent past, covering the last few hundred years prior to the start of modern observations. It will also assess the current state and ongoing changes in regions that have been difficult to access. The target areas are Dronning Maud Land, Enderby Land, and the Totten Glacier margin. Coordinated observations will be conducted in inland, coastal, and deep-sea environments. A key challenge of the project is establishing a next-generation inland observation framework, involving the maintenance of expertise, the renewal of personnel and equipment, and the adoption of advanced technologies. These efforts are intended to prepare for large-scale operations in future Japanese Antarctic Research Expeditions. Specifically, we plan to resume inland traverses in the Yamato and Belgica mountain ranges, which have remained unexplored for decades. These expeditions will utilize satellite remote sensing, crevasse radar, geodetic and geophysical surveys, and ice-sheet structural mapping in order to characterize ice dynamics. The resulting observations will lay the groundwork for future blue ice coring, subglacial geological investigations, and biogeographical studies. To enable additional spot surveys by helicopter following the expeditions, a new inland observation base will be established in the Yamato Mountains.

In coastal areas, coring of lakes and shallow marine environments, as well as geomorphological investigations, will be conducted through international collaboration. This builds on efforts initiated in the X-phase of the Japanese Antarctic Research Expedition. The study area will also be expanded to include permanently ice-covered lakes, thereby improving reconstructions of past and present ice-sheet variability across multiple sites. In offshore regions, long coring and deep-sea samplers, including the development and use of new types of corers such as vibrocorers, will be employed to collect sediment samples from the East Antarctic margin, enhancing our understanding of recent changes to the ice sheet. In anticipation of the 12th expedition phase, we also intend to explore the possibility of conducting collaborative marine seismic surveys targeting deep sedimentary structures. These multi-scale observations will be integrated with geodynamic, ice-sheet, climate, and ocean models in order to refine estimates of ice-sheet volume change and timing since the Last Interglacial. The aim is also to identify the role of warm water intrusions as potential drivers of large-scale AIS retreat. The project will contribute to global initiatives, such as the successor to the SWAIS-2C deep drilling programme, to promote a unified understanding of West and East Antarctic ice-sheet dynamics and improve the accuracy of sea-level rise projections. Ultimately, this research aims to elucidate the mechanisms by which the AIS responds to global climate change and to strengthen Japan's leadership in international Antarctic science through a transdisciplinary approach.

Investigating metamorphic fluid history during continental crust evolution

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Fluid phases are responsible for mass and heat transfer, deformation of rocks, and changing of the melting temperatures (e.g., Johannes & Holtz, 1996; Ague, 2003; Thompson, 2010). This results in a critical role of crustal fluids in the Earth's dynamic processes, potentially being a trigger of earthquakes and volcanic eruptions. The physicochemical characteristics of fluids change depending on the *P-T* conditions and their chemical compositions. Especially, low water activity fluids have been recognized as important fluid species present in the lower crust (e.g., Touret & Huizenga, 2011). NaCl-CO_2-H_2O system is often assumed as fluid composition in the crust (Liebscher & Heinrich, 2007). Since NaCl-bearing fluids tend to dissolve minerals, they play an important role in mass transfer rather than CO_2-bearing ones (Newton & Manning, 2010). Recently, geophysical observation technologies using satellites and other tools have made remarkable progress. However, interpretation of this data requires not only theoretical but also petrological approaches. In particular, chemical compositions of the deep crustal fluids are still difficult to constrain using geophysical data such as seismic waves and gravity anomalies alone. Therefore, petrological study is necessary to understand behavior of fluids in the deep crust.

The Sør Rondane Mountains (SRM), East Antarctica are located in eastern Dronning Maud Land, where the Late Proterozoic to Cambrian gneisses and granitoids are widely exposed (Shiraishi et al., 1997). They are thought to be a part of the collision zone between East and West Gondwana during the East African-Antarctic Orogeny (Jacobs et al., 2003), or a part of the hanging wall of a top-to-the-southwest mega-nappe complex involving collision between Northern and Southern Gondwana (Grantham et al., 2013) during the Kuunga Orogeny following the East African Orogeny (Meert, 2003). Various *P-T* paths and geochronological data, which are inconsistent with the tectonic model of Osanai et al. (2013), reported from the entire SRM suggest that the tectonic model for the SRM formation needs to be re-evaluated (e.g., Higashino et al., 2023; Kawakami et al., 2017; Ruppel et al., 2021). Although the tectonic models are still in debate, the SRM have an advantage for fundamental study of fluid-rock interaction in the lower crust.

Higashino et al (2013) revealed largest field distribution of brine over 200 km in the SRM which is somewhat linear along large-scale shear zones. Multiple timings of brine and saline fluid infiltrations are detected from peak to retrograde *P-T* conditions. Origin of retrograde saline fluid is interpreted to be post-kinematic granitoid intrusions (Kawakami et al., 2025). Geochemical behavior of zirconium (Zr) was examined by Higashino et al. (2015) in Brattnipene, central SRM. They reported that Zr behaves as an immobile element during brine infiltration. This is inconsistent with experimental studies which concluded that zircon, which is the principal host mineral of whole-rock Zr, can be altered by Cl-rich brines during high-*T* metamorphic conditions (Dunkley, 2010). The inconsistency is possibly due to *P-T* conditions and the fluid compositions including trace element components. These findings represent the importance of petrological investigation using natural samples in understanding mass transfer during fluid-rock interaction. In contrast to Zr, various elements were transferred by the brine infiltration (Higashino et al., 2019). Since there are no enough studies investigating fluid-rock interaction in the deep crust, knowledge of mass transfer depends on each individual sample. In order to understand which elements can be mobile in the deep crust, further analysis is needed to create a dataset because experimental study is not appropriate due to a lot of components. Therefore, the aim of this project is to construct a dataset of mass transfer combined with *P-T-t-fluid* paths. This fundamental dataset will help deal with upcoming environmental issues. The newly identified field distribution of brine possibly reveals unknown shear zones and detachement stductures.

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Understanding the Seafloor Structure of Lützow-Holmbukta Bay, East Antarctica

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Understanding the seafloor structure is indispensable for elucidating the geospheric evolution of Antarctica and clarifying its role in the present Earth system. In Lützow-Holmbukta Bay (LHB), however, a complete picture of the seafloor remains elusive despite repeated surveys since the 9th Japanese Antarctic Research Expedition (JARE) in 1968. Efforts have included early wintering measurements, single-beam mapping, and, more recently, multibeam echosounding introduced during the 51st JARE in 2009. Yet our knowledge of seafloor morphology and stratigraphy is still limited: the overall configuration of the submarine canyon system is unresolved, the western sector has not been surveyed for decades, and sub-bottom profiling suffers from poor penetration, preventing detailed imaging of sedimentary and structural layers.

A comprehensive understanding of seafloor morphology and geology in this region is crucial for multiple disciplines, including oceanography, paleoenvironmental reconstructions, numerical modeling, and investigations of wave and fast-ice dynamics. Acoustic surveys require an understanding of the sound velocity structure of the water column, which must be constrained by CTD or related observations. Moreover, the inflow of modified circumpolar deep water and the presence of glacial meltwater suggest an asymmetric oceanographic structure, making coordinated observations essential.

In this presentation, we propose a renewed effort to map and characterize the seafloor of LHB. In addition to high-resolution multibeam bathymetry, targeted geological sampling by dredging or by new underwater observation technologies such as ROVs, as well as multi-channel seismic surveys, will be required. We particularly emphasize the need for an intensive survey campaign of approximately two to three weeks within a single austral summer season, in order to maximize ship time efficiency and ensure comprehensive coverage. A major advantage of seafloor investigations is their complementarity to onshore studies: while many critical geological boundaries on land are hidden beneath overlying glaciers and thus inaccessible, such boundaries may be directly exposed and observable on the seafloor. Such data are indispensable for understanding the initial stages of continental breakup and the origin and evolution of the continental shelf, and their integration with geophysical, petrological, mineralogical, and geochemical studies is particularly important. While this presentation focuses on LHB, continued mapping of the adjacent abyssal basins is also essential, given the spatial connectivity between shelf and deep-sea basin and the temporal evolution of continental breakup and basin formation. In addition, not only in LHB but also in adjacent glacier–ocean–seafloor systems, pursuing such integrated land–marine geological investigations would be of significant international importance. Moreover, the seafloor morphology together with shipborne gravity and magnetic measurements will provide key reference data for airborne geophysical observations, supporting future reconstructions of sub–ice-shelf structures and enhancing our understanding of unexplored regions.

Reviewing the sea-ice conditions and ship operations over the past decade indicates that such surveys are feasible even in previously unmapped areas. The data obtained will not only advance solid Earth and paleoenvironmental research but also provide essential constraints for numerical predictions, improve navigation safety, and directly contribute to the progress of Japanese Antarctic research. These efforts will at last provide a reliable chart of Antarctic home waters.

So13

SLR at Both Poles: Closing North–South Geometry Gaps in Global Geodesy

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In recent decades, the development of geodesy has been led largely by the progress of space geodetic techniques (Plag and Pearlman, 2009). Among these techniques, Satellite Laser Ranging (SLR) has played a key role by providing highly precise and independent measurements of satellite orbits and geocentric positions. Such measurements are fundamental for improving our knowledge of the Earth system. One of the major international goals in geodesy today is to establish and maintain a terrestrial reference frame with millimeter-level accuracy on a global scale, which is essential for monitoring long-term changes in the Earth's environment, such as sea level rise, ice mass loss, and tectonic motion.

Achieving this demanding goal, however, is not straightforward. In order to reach this level of precision, it is necessary not only to improve the accuracy of each individual technique but also to expand and balance the global distribution of observation stations. A well-distributed network ensures that measurements are not biased toward particular regions and that the reference frame remains stable and reliable worldwide. For SLR, in particular, there remain significant observational gaps. Large areas of the Earth, such as the Arctic, the Antarctic, and the equatorial regions, are still poorly covered by existing stations (Fig. 1). Filling these gaps will be critical for strengthening the global observation network and for realizing the full potential of SLR in the future. For instance, Otsubo et al. (2016) studied how the SLR network could be expanded to improve global geodetic parameters. They testes the effect of adding new SLR stations in different parts of the world. Results showed that by placing new stations in under-observed areas, the accuracy of Earth rotation, geocenter motion, and reference frames can be improved.

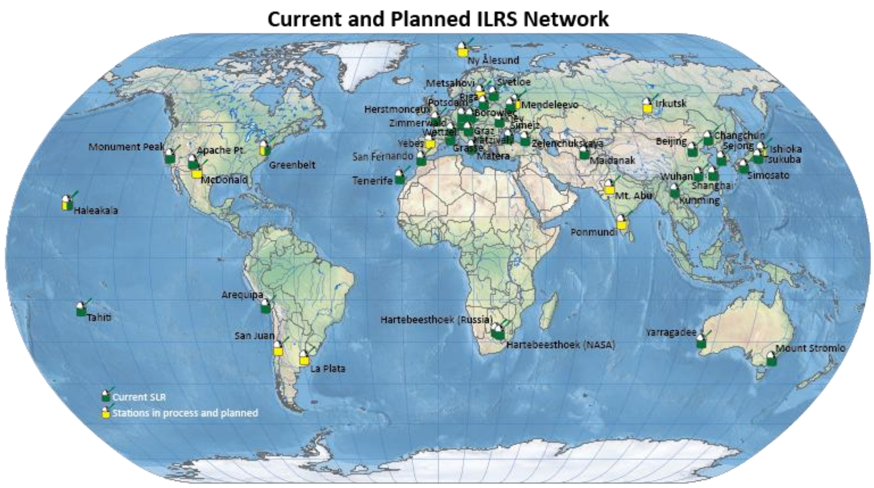

Fig. 1. SLR stations in the world, provided by ILRS.

NASA has been developing SGSLR, the next-generation SLR system, to replace its aging legacy SLR network. SGSLR will offer improved precision and stability for the global geodetic parameters. It realizes largely automated operation with minimal human input. Integration and testing of the first SGSLR unit is ongoing at Goddard Space Flight Center. The first operational station will be installed in Ny-Ålesund, Svalbard (79N 12E).

In Japan, Hitotsubashi University initiated the compact and low-cost "Omni-SLR" system, with National Astronomical Observatory of Japan and the University of Tokyo. The project aims to make SLR more accessible worldwide. The system is very light, under 100 kg, and consumes less than 100 W, while using mainly commercial off-the-shelf components. First ranging results were achieved at National Institute of Polar Research in December 2023, and further tests are continuing at Ishioka Geodetic Observing Station of Geospatial Information Authority of Japan, since 2024 (Fig. 2). The system is designed not only for standard SLR but also for applications such as time transfer and spacebourne/airbourne communications. A first Antarctic deployment is planned for 2026–2027, by installing it in Syowa Station (69S 40E). At present, there are no SLR stations located south of 36S, and the high-latitude region of the Southern Hemisphere remains the largest gap in the global network.

The installation and operation of SLR in the polar regions will be the first attempt in the world, and several challenges must be addressed. Because the instruments are exposed to very low temperatures, some countermeasures against cold conditions are necessary. During the summer season, there is continuous daylight, which means that nighttime axis calibration cannot be carried out in the usual way. In addition, transportation to the site is highly restricted, and the number of personnel available on site is very limited. These issues must be overcome for successful polar SLR operation.

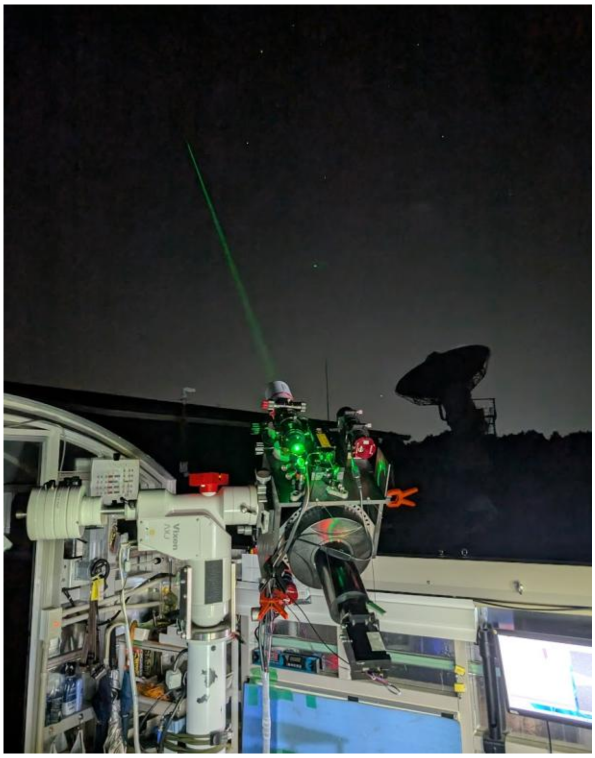

Fig. 2. The Omni-SLR system at Ishioka Geodetic Observing Station of GSI.

The number and pattern of satellite passes differ greatly depending on the latitude of an observing station. For SLR satellites, at stations such as Syowa and Ny-Ålesund, there are almost no opportunities to track low-orbit satellites with small inclination angles, such as Ajisai or Starlette. On the other hand, satellites in near-polar orbits, such as Stella, GRACE Follow-On, and CryoSat-2, pass frequently and provide many opportunities. As a result, the observing schedule changes significantly. In the case of polar-orbiting satellites, the present SLR network cannot observe them during polar crossings. For altimeter missions over ice or ocean, adding SLR observations in these regions would improve orbit determination accuracy and naturally increase the reliability of the altimeter data.

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So14

Development and Field Testing of Penetrator-Type Observation Systems in the Antarctic Region

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A "penetrator" is an impact-type observation device designed to enable in-situ measurements in areas inaccessible due to distance or topography by being deployed from the air. It is particularly suitable for seismic and positioning observations that require anchoring through penetration of approximately one meter. Although penetrators were previously developed for constructing artificial seismic arrays in Antarctica (JARE43), they could not reach practical implementation. In this study, we incorporated novel deployment systems, state-of-the-art observation instruments, and satellite communication systems, and carried out development and testing during JARE 64–66 as an Exploratory Research Project.

(1) Deployment systems

Traditionally, penetrators were deployed only from manned helicopters. In addition, we introduced newly developed penetrator-deployment drone and Unmanned Aerial Vehicle (UAV) in addition to the conventional method.

Manned helicopter deployment as shown in Fig.1a involved manually releasing the penetrator from an open door, a primitive but simple approach requiring no special equipment. However, disturbances imparted during hand release led to attitude instability, and a deployment altitude of at least 300 m was found necessary to achieve stable attitude after release.

We developed a drone capable of deploying penetrators (Fig. 1b), which, although limited by short flight time, proved effective for inaccessible but proximate locations, such as placing observation points from glacier margins toward central areas. Since magnetic compasses were unreliable in polar regions, we implemented a dual-GPS navigation system for directional stability. This allowed stable flight and drop tests, and approximately ten successful penetration tests were conducted at S16.

UAV deployment represented the most challenging attempt (Fig. 1c), enabling fully unmanned, long-range placement. While autopilot systems functioned successfully during JARE 65 test flights, insufficient ground run speed on snow prevented takeoff. Improvements to autopilot logic are still required, but recent advances in vertical take-off UAVs may provide practical solution

Figure 1. (a) The penetrator dropped from an AS350 helicopter and penetration installation observed from the air, (b) Drone with penetrator at S16 (left) ,and (c) UAV just before takeoff test at the S17 site

(2) Penetration Characteristics

During JARE 64–66, penetration tests were conducted at various locations. Fig. 2(a) summarizes the relation between drop altitude and penetration depth. Results indicated weak correlation with drop height (velocity), suggesting surface conditions exerted greater influence than impact speed.

Hardness of the ground condition varied significantly within meter scales at S16, making pre-assessment difficult. On glaciers, bare ice surfaces were found nearly impossible to penetrate (Fig. 2(b)). Conversely, very soft snow during JARE 66 allowed penetration depths exceeding 1 m. However, communication failures occurred at depths greater than ~1.5 m.

Thus, predicting ideal surface hardness for penetration is nearly impossible, highlighting the necessity of ensuring at least reliable communication under all conditions. To address this, a "separation-type" penetrator was experimentally introduced during JARE 66, leaving only the communication antenna at or near the surface regardless of penetration depth or attitude. During field trials at Shirase Glacier, communication was lost in one of three penetrators, but this separation-type (aft-body) design is expected to greatly enhance operational success rates.

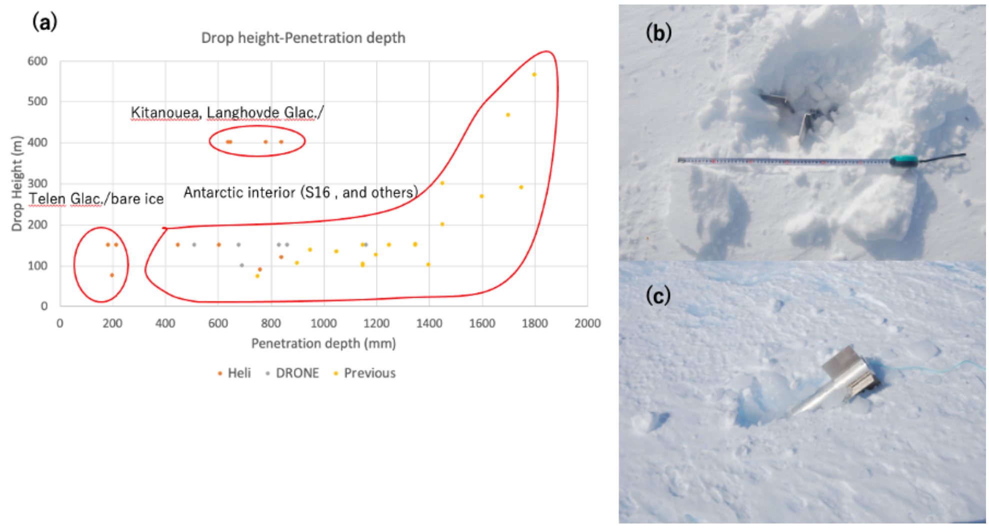

Figure 2. (a)Relationship between drop altitude and penetration depth of penetrators tested to date (including results from JARE-43), (b) Penetration conditions of penetrators at Site S16, and (c) Telen Glacier (bare ice surface).

(3) Observation Instruments

The developed penetrator payload included seismic, infrasound, and GPS positioning sensors. The seismic system was based on the high-sensitivity, shock-resistant seismometer originally developed for the space mission (natural frequency: 3 Hz, sensitivity: 150 V/m/s@3Hz**)**, mounted on a gimbal mechanism (Fig. 3(a))0. The infrasound sensor was developed at Kochi University of Technology for potential Mars exploration, while GPS utilized commercially available modules.

The data acquisition system employed a Raspberry Pi CPU, with Iridium short-burst satellite communication. Since continuous seismic waveform data exceeded bandwidth limits, an event-triggered recording scheme with command-based data selection was implemented. For long-term operation, ultra-low-power CPUs were selected, but development was not completed within the project timeframe. GPS-only payloads were also tested, with three units deployed by helicopter at Shirase Glacier. Data from two units were received successfully, with the most downstream unit continuing transmission for over seven months (as of 4 Septempber 2025).

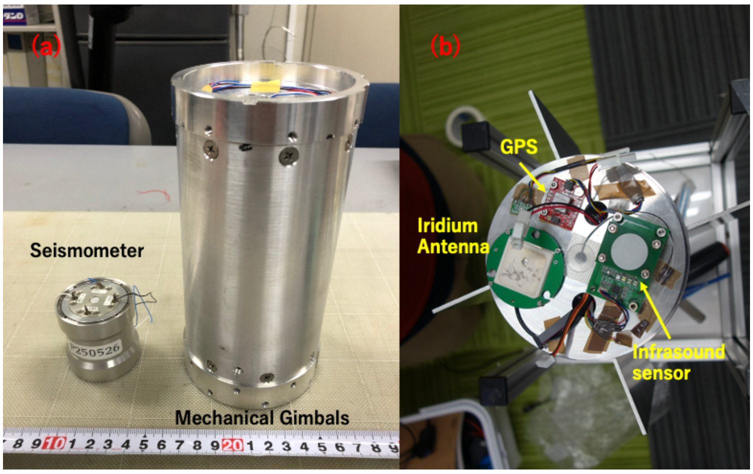

Figure 3. Sensors mounted on the penetrator: (b) Seismometer with gimbal mechanism used for post-penetration angle adjustment, (B) Infrasound sensor and GPS mounted at the tail part

(4) Conclusion and future perspective

Through three years of development, Antarctic penetrators have advanced to a level much closer to practical application compared with earlier attempts. Future challenges include improving robustness so that observations can be conducted under any surface condition, and implementing intelligent systems for seismic measurements. In parallel, we are also reviewing the required observation accuracy and exploring possibilities for reducing development costs. Potential future applications include the automatic seismic array measurements originally envisioned during JARE-43, as well as the deployment of smaller GPS-equipped penetrators with high-precision positioning capabilities for multi-site installations on glaciers. These advancements are expected to elevate penetrators to a level where they can provide powerful tools for elucidating subsurface structures and for in-situ monitoring of glacier dynamics.

So15

Towards efficient and reliable icebreaker navigation in the Antarctic expedition

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1. Introduction

The Japanese Antarctic Research Expedition (JARE) began in 1957, when the Syowa Station was established on East Ongul Island in Lützow-Holm Bay. For nearly 70 years since its initiation, Syowa Station has been inhabited, providing a unique extended observational dataset. The key to its success was the icebreakers: Soya from 1957 to 1963, Fuji from 1967 to 1973, Shirase from 1973 to 2008, and the new Shirase from 2009 to now. Transportation of supplies and people depends on the successful berthing of Shirase at the Syowa station. Lützow Holm Bay is covered by sea ice throughout the year, where a multi-year land-fast ice can grow and prevent the ice breaker from berthing. Neither Soya nor Fuji was designed to break thick multi-year ice, but Shirase and the new Shirase were both designed to navigate through the thick sea ice in the bay. Nevertheless, Shirase failed to berth consecutively in JARE53 (2011-2012) and JARE54 (2012-2013) partly because of the development of the thick multi-year ice near the station, and also because of the dense drift ice zone in the North of the bay. In this presentation, we first review the past navigation history and the observations related to ship performance and environmental conditions. Then, the field campaign results of the first 3 years of phase X of the Japanese Antarctic Research Project (2022-2028) will be reviewed. The plans in the remaining 3 years will be introduced in conjunction with the new JSPS Kaken-S project (2025-2030). Finally, future plans on the phase XI Project (2028-2034) will be discussed.

2. Historical perspective

Since the beginning of JARE, the design of the icbreaker was the central issue in the success of the expedition. Fuji, which replaced Soya, was designed to break 0.8 to 1.2 m sea ice continuously. Despite her designed ice-breaking capacity (equivalent to Polar Class 5), Fuji failed to berth at Syowa station 12 times out of the 18 expeditions. Both Shirase and the new Shirase are designed to break 1.5 m-thick ice continuosuly and are classified as equivalent to PC3 and PC2, respectively. The new Shirase is more capable than the original Shirase. Despite that, the new Shirase failed to berth for two consecutive years from 2011 to 2013. Studies in the past have revealed that the number of ramming operations changed over the decades (Fig. 1), and the quasi-periodic cycle was explained as due to a decadal change in the properties of sea ice (Ushio and Toyota). As the sea ice thickens due to accumulation of snow, the ice weakens and catastrophically breaks up due to incoming swells from the Southern Ocean, followed by a decade-long lack of multi-year ice. The measurement of the mechanical properties of sea ice was attempted for the first time in 1986 (JARE27), and the down-looking video camera was used for the first time to measure the sea ice thickness in 1988 (JARE29). A continuous measurement of the sea ice by an EM (Electromagnetic induction) sensor and the visual observation (ASPeCt) were conducted for the first time in 2000 (JARE42). The measurements are still ongoing, providing an invaluable asset for both engineering (icebreaker performance evaluation) and science (mechanism of decadal change of sea ice in the Lützow Holm Bay) research.

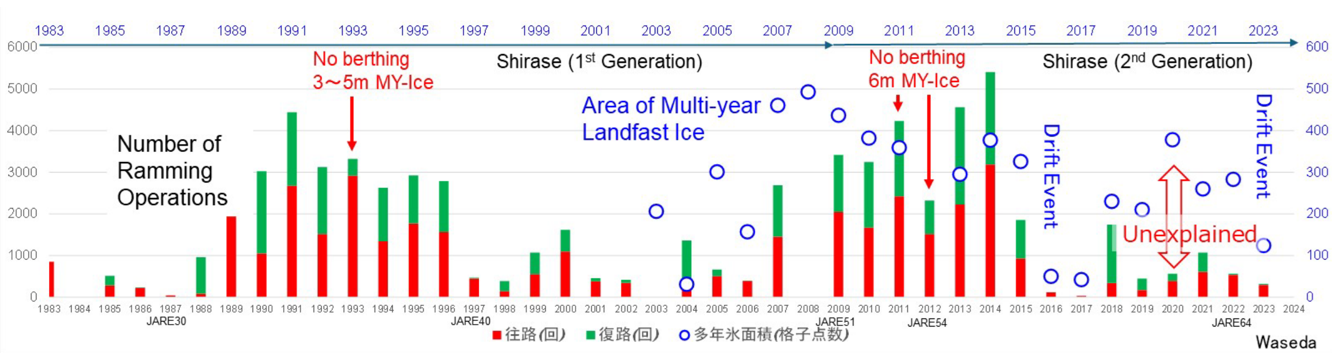

Figure 1. The number of ramming operations of Shirase and the new Shirase.

3. Observations made during the phase X JARE

The 6-year field campaign "Understanding the mechanism of the marginal, packed, and fast ice variations and its application for optimized routing of Shirase" was initiated in 2022 as a part of the phase X JARE (AP1001). The research aims to conduct observations instrumental in developing a navigation support system of Shirase: they are classified into (i) Climatic, (ii) Strategical, and (iii) Tactical routings. The main objective of the climatic routing is to understand the mechanism of the quasi-decadal phase shifts between the period of multi-year land-fast ice formation (MYI-decade) and the first-year land-fast ice dominant period (FYI-decade) in the Lützow Holm Bay. The phase transition from the MYI-decade to FYI-decade is triggered by a large-scale sea ice breakup by the incoming swell. The phase X period coincides with the FYI-decade. Repeated breakups caused by incoming swells were observed by wave buoys deployed on the land-fast ice (15~21) for three consecutive years (2023, 2024, and 2025). For a strategic routing, the ship monitoring data obtained during the JARE65 was exploited to estimate an alternative route, where the ship speed as a function of sea ice thickness was determined empirically. A large detour route via the west side of the bay, avoiding the dense pack ice zone in the east, reduced both the navigation time and the fuel consumption by more than 40 %. Finally, for the tactical navigation system, near-real-time visualizations of the ship monitoring data, satellite data, EM-measured ice thickness, etc., were developed.

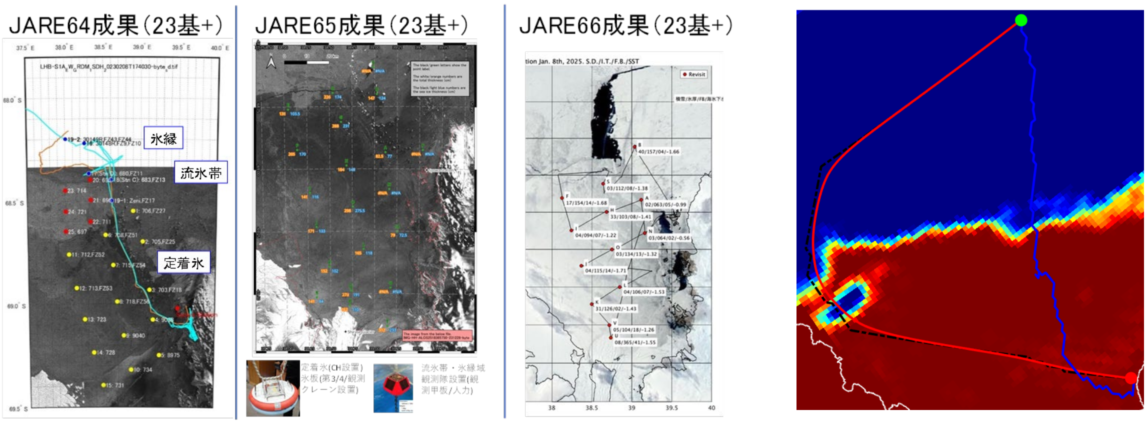

Figure 2. Wave buoys were deployed on the land-fast ice to monitor ice breakup events by waves (left, JARE64, 65 & 66); the Optimum route that circumvents the packed ice zone saves time and fuel consumption by 40 % (right, JARE65).

4. Future plans: phase XI JARE

In the 2023 winter, the Antarctic sea ice extent recorded a historical minimum, and it does not seem to be recovering. Global climate change may have started to affect the sea ice in the Lützow Holm Bay. In phase XI, monitoring sea ice breakup using distributed wave buoys is crucial for detecting the signature of climate change. Whether the multi-year ice develops or not gives us a clue whether the Antarctic Ocean tipping point was crossed or not. Monitoring the mechanical properties of sea ice is critical in designing the future icebreaker for JARE. Although the significant detour may appear as a plausible choice when the land-fast sea ice is relatively thin, the presence of icebergs and bottom topography was not considered in the simulation. The accuracy of satellite sea ice thickness data should be evaluated as well. Therefore, the accumulation of a combined knowledge of a broader area in the Lützow Holm Bay is necessary. Based on such reliable information, new ship navigation routes in the Lützow Holm Bay should be explored during phase XI. New in-situ sea ice measurement methods should be developed for tactical navigation, such as ship-borne Lidar/Radar and sensors on a fixed-wing drone. Concurrent ocean observation is critical as well, as the oceanic condition may affect the material strength of sea ice. Lastly, modeling of the wave-ice-ocean coupled system is essential for both scientific and engineering needs. Establishing the "digital twin" model of the bay will lead to a sustainable use of the Syowa station.

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Governance and Future Pathways in Antarctic Tourism: A Multi-National Perspective

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Abstract

Antarctic tourism has rapidly expanded over recent decades, raising significant concerns about its environmental footprint and long-term sustainability. Governance of this activity is distinctive, as no single nation holds sovereignty; instead, management occurs collectively under the Antarctic Treaty System (ATS) and the Protocol on Environmental Protection. The effectiveness of existing governance instruments—particularly Environmental Impact Assessments (EIAs), national permitting processes, and self-regulation through the International Association of Antarctica Tour Operators (IAATO)—remains contested.

This study aims to critically examine how different nations interpret and implement governance measures for Antarctic tourism, identify gaps and inconsistencies in current approaches, and explore future pathways that can strengthen governance to ensure environmental protection while allowing responsible tourism growth. The research adopts a mixed-methods design: (i) comparative analysis of national EIA reports, permitting systems, and policy submissions to Antarctic Treaty Consultative Meetings (ATCMs); (ii) semi-structured interviews with policymakers, operators, and experts; and (iii) an online survey targeting stakeholders in the Antarctic tourism sector. Together, these methods provide a comprehensive assessment of governance practices and their effectiveness.

Preliminary findings indicate that governance practices vary considerably among nations, with some adopting stringent environmental safeguards while others rely on minimal compliance, leading to uneven implementation. Industry self-regulation through IAATO provides value but remains limited in addressing cumulative impacts and climate-related vulnerabilities. The study anticipates that harmonization of EIA standards, improved monitoring and data-sharing mechanisms, and scenario-based adaptive governance models represent promising pathways for the future. By identifying strengths and weaknesses in the current system, this research contributes to both academic debates on environmental governance and practical policymaking within the ATS, aiming to ensure that Antarctic tourism evolves sustainably in the face of environmental and geopolitical challenges.

Keywords: Antarctic tourism, governance, Environmental Impact Assessment, Antarctic Treaty System, adaptive governance

Enhancing Antarctic Research through Data Infrastructure: The Role of ADS

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[1] *National Institute of Polar Research*

1. Introduction

In recent years, the impacts of global climate change have become increasingly evident in Antarctica, with accelerated warming observed even in its inland regions. Ocean warming has led to the melting of ice shelves, and the resulting glacial discharge has heightened the risk of sea-level rise. Furthermore, the decline in sea ice has had severe consequences for ecosystems, including penguin populations. Antarctica is no longer a remote polar region, but rather a critical area that epitomizes global environmental change. To understand the current state of the Antarctic climate system and its broader implications, interdisciplinary research is essential, drawing on in-situ observations, satellite remote sensing, and numerical modeling. At the same time, the concept of "open science" is becoming increasingly established. This approach aims to make research outputs-such as publications and datasets generated through public funding-widely and easily accessible to industry and the public, thereby opening new pathways for knowledge creation, promoting more effective scientific research, and fostering innovation. On the other hund, funding bodies such as JSPS have emphasized the appropriate management and utilization of research data, based on the "*Basic Concept on the Management and Utilization of Research Data Generated by Publicly Funded Research"*. JSPS has also formulated the "*Basic Policy on Handling Research Data"*, encouraging the promotion of proper data management in research activities.

2. Data Management at the National Institute of Polar Research

The National Institute of Polar Research (NIPR) has conducted Antarctic observation programs and, since 1968, has published the JARE Data Report as an outcome of these activities. In the Arctic, the NIPR Arctic Data Reports have been issued since 1998. Subsequently, through projects such as GRENE, ArCS, and ArCS II, the accumulation and sharing of Arctic data have advanced, leading to the development and operation of the Arctic Data archive System (ADS) with the aim of promoting inter-field collaboration and integration. Initially, due to restrictions associated with specific funding sources, ADS was limited to handling Arctic data. However, since 2018, it has also incorporated Antarctic datasets. Furthermore, since 2017, ADS has served as the primary repository for the Polar Data Journal (PDJ) published by NIPR. For datasets associated with PDJ articles, ADS assigns Digital Object Identifiers (DOIs), thereby enhancing accessibility and citation.

3. ADS Initiatives and Future Prospects

Currently, ADS functions as a principal data repository of NIPR and serves as a foundational data platform for both Arctic and Antarctic research in Japan. In recent years, in collaboration with the Sea Ice Information Center, ADS has supported research on Arctic sea ice forecast modeling. Looking ahead, these efforts aim to provide integrated sea ice information for both Arctic and Antarctic regions. ADS should continue to be recognized as an indispensable data infrastructure for Antarctic research, with its role as a platform supporting interdisciplinary studies and international collaboration further strengthened in the years to come.

Sp2

Crustal structure of Dronning Maud Land, East Antarctica: Insights into multi-phase collisional events during Gondwana assembly

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In the eastern part of Dronning Maud Land, East Antarctica, the Japanese Antarctic Research Expedition (JARE) has conducted geological investigations in regions such as the Sør Rondane Mountains, the Yamato–Belgica Mountains, and the Lützow-Holm Complex. These areas are characterized by widespread distributions of igneous and metamorphic rocks formed during the assembly of the Gondwana supercontinent.

Two major models have been proposed regarding the configuration of orogenic belts during Gondwana assembly. Jacobs and Thomas (2004) suggested a single orogenic belt—the East African–Antarctic Orogen (EAAO)—active between ca. 650–500 Ma. In contrast, Meert (2003) proposed the existence of two distinct orogens: the East African Orogen (EAO, ca. 750–620 Ma) and the Kuunga Orogen (ca. 570–530 Ma). The eastern part of the Dronning Maud Land lies at the core of these proposed orogenic systems, making it an ideal location for testing these models and for understanding the temporal evolution of crustal processes such as magmatism, metamorphism, deformation, and fluid activity associated with supercontinent assembly.

Recent studies have identified geological boundaries in the Sør Rondane Mountains (Adachi et al., 2023) and the Lützow-Holm Complex (Nakano et al., 2025), where geological units that experienced metamorphism at ca. 600 Ma and ca. 550 Ma are juxtaposed with those affected only by the latter event. These findings suggest multiple continental collision events. However, the number of confirmed outcrops remains limited, necessitating further accumulation of similar observational data and detailed analysis.

This project proposes a regional geological survey in eastern Dronning Maud Land to identify outcrops where geological units with distinct metamorphic histories are in contact. The aim is to elucidate the origin, behavior, and temporal evolution of these geological units within the orogenic belt. The survey will involve early-career researchers to ensure the transfer of field expertise gained from previous investigations in the Sør Rondane Mountains and the Lützow-Holm Complex. Additionally, the project seeks to resume geological exploration in the Yamato–Belgica Mountains, where no surveys have been conducted for over two decades. This includes reassessing existing routes, improving logistical access, and exploring the feasibility of direct helicopter approaches from the icebreaker Shirase, thereby laying the groundwork for future inland surveys.

Analytical approaches will include: (1) Petrochronological analysis to reconstruct metamorphic and deformational histories, enabling lithological classification and interpretation of their three-dimensional behavior; (2) Integrated geochemical and geochronological studies of igneous and metamorphosed igneous rocks, including whole-rock chemistry and zircon U–Pb and Hf isotopes, to constrain source materials and the temporal change of tectonic settings. By combining these datasets, the project aims to achieve a comprehensive understanding of the nature of orogenic processes associated with the assembly of the Gondwana supercontinent, with a particular focus on exploring the possibility of multi-phase continental collisions and the associated distinctive geological phenomena.

This project aims to analyze the three-dimensional distribution of the basement geology, while also acquiring physical property data such as rock density, magnetic susceptibility, and radiogenic heat production. These data will enhance the accuracy of interpretations of geophysical observations, including gravity, geomagnetism, and seismic waves, thereby improving the reliability of inverse modeling. Furthermore, these data are essential for understanding ice sheet dynamics and melting processes influenced by bedrock properties, as well as glacial isostatic adjustment (GIA) associated with ice sheet fluctuations, thereby serving as a foundation for more precise assessments of Antarctic ice sheet stability. In this way, geological data provide cross-disciplinary value across multiple research fields and are expected to serve as fundamental data for advancing integrative scientific studies, including those addressing the urgent global issue of climate change.

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The importance of the Enderby Land region in Antarctica: a geological perspective

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The JARE's basement geology programs have covered the area of longitude between 10°E and 55°E of the Antarctic continent, and published total 39 sheets of geological map series. This part of the Antarctic continent comprises of deep crustal high-grade metamorphic and plutonic rocks that recorded the geologic history over 3 billion years, and is, therefore, ideal field for investigating long Earth history and deep crustal processes. Following the temporal geologic summary by Shiraishi et al. (2008), significant scientific advance has been made for the basement geology especially of eastern part of Dronnning Maud Land and Enderby Land regions by JARE geology group. (e.g., Hokada et al., 2024; and references therein).

In Enderby Land, two distinct Proterozoic-Cambrian metamorphic terranes, the Rayner and the Western Rayner Complexes (e.g., Shiraishi et al., 2008) bound the southern margin of the Archaean Napier Complex. The Rayner Complex is characterized by >2500–1000 Ma protolith and 980–910 Ma granulite-facies metamorphic ages (e.g., Kelly et al., 2002). The Western Rayner Complex is granulite-facies and partly UHT metamorphism and 2400–700 Ma protolith and 540–520 Ma metamorphic ages were reported (Shiraishi et al., 1997). Boundary between the Rayner and the Western Rayner Complex has been not clearly defined until when Horie et al. (2016) obtained 934–894 Ma SHIRMP zircon U-Pb ages from Mt. Lira, Condon Hills and Mt. Yuzhnaya regions with minor 590–570 Ma zircons from Mt. Yuzhnaya.

The Archaean Napier Complex in East Antarctica is a 400 x 200 km large ancient craton that is characterized by a long crustal history with ages ranging from 3850 to 2480 Ma, and UHT~granulite-facies regional metamorphism at about 2550–2480 Ma (see summary in Harley et al., 2019; Hokada and Harley, 2025; and references therein). Earlier geological surveys of Enderby Land were conducted by British-Australian-New Zealand Antarctic Research Expedition (BANZARE) in 1930, Soviet Antarctic Expedition (SAE) in 1960s, and Australian National Antarctic Research Expedition (ANARE) in 1950s–1980 (e.g., Kamenev, 1972; Sheraton et al., 1987). They defined the Archean Napier Complex and the Proterozoic Rayner Complex, and established the 1:500,000 scale regional geological map and the explanatory text including comprehensive petrography, geochemistry, metamorphism, structural geology and radiometric ages (Sheraton et al., 1987). The area was subsequently explored intermittently by the Japanese Antarctic Research Expedition (JARE) especially in the western part of the Enderby Land (see Ishizuka, 2008; and references therein). Detailed geological maps of two major localities, Mt. Riiser-Larsen (Ishikawa et al., 2000) and Tonagh Island (Osanai et al., 2001), are published.

Since then, the Japanese Antarctic program made short visits and sampling at several small nunataks in the Napier, Rayner and Western Rayner Complexes. This presentation summarizes the current understanding of the geologic flame work of this part of Antarctica, and also the future geological perspective for next phase of JARE program (phase-XI; JARE 70-).

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Sp4

Next-generation satellite-exploration hybrid geological survey in Antarctica leading earthquake science, resource geology, and tectonics

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Metamorphic soles in East Antarctica, glacier-polished and continuously exposed for tens to hundreds of kilometers, provide a uniquely accessible window into the Earth's interior. Unlike other mountain belts such as the Alps or Himalaya, where vegetation and weathering obscure exposures, the Antarctic outcrops allow direct observation of crustal sections over unprecedented spatial scales. In regions such as the central Dronning Maud Land and Enderby Land in East Antarctica, metamorphic rocks record pressure–temperature conditions of ~500–1100 °C and 0.1–1 GPa (0–30 km depth; e.g., Hokada et al., 2024; Satish-Kumar et al., 2008). These conditions coincide with those of magma generation (Engvik et al., 2005; Jamtveit, 2010; Uno et al., 2017), deep slow earthquake nucleation (Mindaleva et al., 2023, 2020), and mineral resource formation (Talalay and Zhang, 2022), making East Antarctica one of the very few places on Earth where such processes can be studied from μm to hundreds of km scales.

Recent advances in hyperspectral infrared (IR) remote sensing are revolutionizing this opportunity. New-generation satellites (e.g., PRISMA, EnMAP, EMIT, HISUI), launched since 2017, provide >200 spectral channels with resolutions of ~5–10 nm, replacing the previous coarse multi-band systems of Landsat or ASTER. This enables accurate identification of hydrous minerals (e.g., white mica, amphibole) and carbonates (e.g., calcite, dolomite) with unprecedented spatial resolution and coverage (~2m for the entire ~10 km scale; e.g., Wan et al., 2021). Identification of these key minerals is crucial for tracing fluid–rock reactions that control earthquake mechanics, CO_2 storage, and ore deposit formation. Hyperspectral remote sensing is significantly effective for critical mineral exploration (e.g., Asadzadeh et al., 2024). As such, application of hyperspectral IR imaging across the tens of kilometers of glacier-polished exposure in Antarctica would provide a chance to map fluid-rock reaction, seismogenic fault, and critical mineral exploration for unprecedented spatial resolution and coverage.

Previous Japanese Antarctic Research Expeditions have already revealed tectonic events such as Gondwana assembly and Archean continental collisions through detailed petrography and geochronology for over the Sør Rondane Mountains(e.g., Osanai et al., 2013; Shiraishi et al., 1997) and for coastal areas of Enderby Land (Hokada, 2001). Indeed, the Japanese Antarctic Research Expedition has found pseudotachylite (Motoyoshi, 1996; Toyoshima et al., 1999) and critical minerals such as vanadium-rich mineral deposits (Osanai et al., 1990). Recently, a whole ~600 m pseudotachylite has been revealed in the field survey (Toyoshima et al., 2020 NIPR symposium), which would provide a unique observational window of the whole seismogenic fault in the deep crust. These ground-truth geological maps, petrochronological datasets, combined with the unparalleled exposures, now provide the essential foundation to integrate field geology with satellite IR spectroscopy.

Together, the combination of extensive exposures, robust petrochronological frameworks, and rapidly advancing remote sensing technology makes East Antarctica the only natural laboratory where the dynamics of deep earthquakes, large-scale fluid–rock interaction, and mineral resource formation can be directly investigated at crustal scales. In the 21st century, East Antarctica stands as a frontier capable of leading global Earth interior science.

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Future Perspectives of Japanese Antarctic Meteorite Exploration: Towards JARE Phase XI and IPY 2032–2033

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Introduction

The discovery of meteorites in the Yamato Mountains in 1969 by JARE-10 revolutionized planetary science, revealing Antarctica as the richest source of extraterrestrial materials on Earth. Since then, more than 49,000 Antarctic meteorites have been recovered, comprising over 60% of the world's collections. These include rare lunar and Martian meteorites, which have provided paradigm-shifting insights into planetary evolution, early solar system chronology, and volatile processes. Moreover, micrometeorites, which may sample isotopic reservoirs not observed in meteorite collections, have also been abundantly collected from Antarctica. With the recent successes of asteroid sample-return missions such as Hayabusa2 and OSIRIS-REx, the scientific importance of Antarctic meteorites has become even greater. They provide the broad comparative framework necessary to place limited-returned samples into context, revealing both the diversity and representativeness of solar system materials. Importantly, the long-term achievements of Japanese Antarctic meteorite exploration have also been internationally recognized: the Antarctic meteorite collection curated at the National Institute of Polar Research (NIPR) was recently designated as part of the IUGS "Geoheritage" collections, highlighting its enduring scientific and cultural value.

Planning for JARE Phase XI

Looking ahead, the Japanese Antarctic Research Project is now entering discussions on Phase XI (2028–2034). As part of these early considerations, one proposal is to expand systematic, large-scale exploration of the Yamato Mountains blue ice fields—the largest meteorite concentration area in Antarctica. Since more than 25 years have passed since the last major Japanese expedition to this region, it is reasonable to expect that new meteorites have been brought to the surface by ongoing ice flow and ablation. Renewed exploration therefore offers the prospect of accessing previously unavailable samples with significant scientific value. Such a program could combine reconnaissance and detailed searches, supported by robust logistics and route preparation to address the well-known challenges of crevasse zones, steep slopes, and sastrugi barriers. It is further suggested that continuity be secured by involving both experienced and early-career researchers, with all participants directly engaged not only in field collection but also in laboratory studies of the recovered samples. This integrated vision underlines that the exploration is research-driven, with immediate scientific use of the collected materials.

International Collaboration and Technological Innovation

An important idea under consideration is to strengthen international collaboration. Belgium, which has recently succeeded in Belgica Mountains expeditions, is planning an independent field campaign near the Yamato region around 2027, using Princess Elisabeth Antarctica (PEA) Station as a base. Although this campaign will be operated as a Belgian initiative, several Japanese researchers are already participating as Co-Investigators, ensuring that scientific exchange is embedded from the outset. Building on this foundation, Phase XI could envisage a framework for joint Japan–Belgium exploration that combines field and scientific expertise. Two complementary access routes are being discussed: (1) the established inland traverse from Syowa Station, refined through decades of Japanese expeditions, and (2) an airborne route from PEA Station, which has now been operationally established. Although initially more expensive, this airborne access allows rapid camp deployment within just one to two days, thereby offering logistical efficiency and potential cost savings in the long term. The coexistence of these two approaches, still at the conceptual stage, could provide greater flexibility for future cooperative exploration in the context of IPY 2032–2033.

Another key aspect of the proposal is the adoption of new technologies. The potential deployment of UAVs (drones), high-resolution remote sensing, ground-penetrating radar, and automated detection systems could transform field operations by enabling more precise mapping of meteorite concentrations, enhancing safety and efficiency, and revealing glaciological controls on meteorite accumulation. While the current capabilities of UAVs for meteorite detection remain limited, future improvements could make them a powerful tool in Antarctic exploration. These innovations, if realized, would greatly expand the scientific return, facilitating discoveries of rare and scientifically invaluable specimens.

Conclusion

Through these discussions and proposals—integrating international cooperation, technological innovation, and the strong research-oriented culture of JARE—Phase XI is envisioned as a major contribution to planetary science in the lead-up to IPY 2032–2033 and beyond. While still at an early conceptual stage, such a framework highlights how Antarctic meteorites will continue to provide unique and irreplaceable insights that complement space missions and advance our understanding of the solar system.

Sp6

Mass balance monitoring of the Antarctic ice sheet: Observational results during Phase X and perspectives for Phase XI

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The Antarctic ice sheet contains about 90% of the Earth's land-based freshwater, and its mass variations not only respond to climate change but are also closely connected with global sea level fluctuations. To understand these variations, it is essential to continuously monitor the surface mass balance, which is the result of accumulation and ablation processes. Under the Japanese Antarctic Research Project Phase X Six-Year Plan, the "Mass Balance Monitoring of the Antarctic Ice Sheet" project aims to monitor surface mass balance from the ice sheet margins to the inland region through stake measurements. Furthermore, to accurately evaluate the effects of climate change in the ice sheet interior, continuous and high-density meteorological observations—achieved through the establishment and expansion of an automatic weather station (AWS) network—are indispensable.

Since the early 1990s, surface mass balance observations have been carried out using stakes installed at approximately 2 km intervals along a ~1,000 km inland traverse route, extending from the ice sheet margin to Dome Fuji. In addition, seven AWSs along this route have continuously recorded meteorological and glaciological parameters, such as air temperature, wind direction and speed, radiation, and snow depth. At this symposium, we will present the observational results obtained during Phase X and outline the monitoring strategy for the upcoming Phase XI.

Toward Laser Heterodyne Spectroscopy of the 1.1-Micron Band of Metastable Helium in the Earth's Atmosphere: Development of a Mobile High Spectral Resolution Spectrometer

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The region of the Earth's atmosphere at altitudes of 300–500 km, known as the upper thermosphere, represents an "observational gap region," where ground-based measurements are extremely limited due to the scarcity of suitable optical targets. The upper thremosphere is becoming increasingly important from a space weather perspective, as it has significant impacts on the operation of low-Earth-orbit satellites (Hapgood et al., 2022). Metastable helium layer is confined to the upper thermosphere and the lower exosphere, and it distributes from 300 km to 1000 km with a density-peak altitude of about 500 km. Thus, metastable helium is an attractive candidate for remote sensing target of atmospheric dynamics in this region. Metastable helium airglow emissions have been observed primarily at low and mid-latitudes. However, very few studies have been conducted at high latitudes, where metastable helium is expected to show strong variability in response to geomagnetic activity. Observations of metastable helium airglow at 388.9 nm were carried out in Longyearbyen, Svalbard (Henriksen et al., 1985), and intermittent brightness enhancements were reported, thought to result from the direct entry of He^+ ions and/or alpha particles from the solar wind. The typical brightness, however, was very low (< 20 Rayleigh), and the long integration time (~15 min) required made it difficult to capture rapid variations associated with particle precipitation. In addition, it is well known that helium density in the upper thermosphere reaches its maximum in the winter hemisphere. This north–south asymmetry in global helium distribution, known as the winter helium bulge, is believed to be closely linked to the highest layer of meridional atmospheric circulation. However, it remains poorly understood due to the lack of long-term monitoring in both hemispheres.

The goal of this study is to perform the world's first observations of metastable helium airglow using laser heterodyne spectroscopy in the 1.1-μm band, achieving unprecedented temporal and spectral resolution. In this project, we will develop a compact, mobile spectrometer by combining an optical system capable of efficiently coupling the weak helium resonance-scattered light into an optical fiber with dedicated receiver electronics. A semiconductor laser with a linewidth of 1 MHz and a tunable wavelength range of several nanometers will be employed as the reference light. By applying laser heterodyne spectroscopy, we will achieve a spectral resolution 1,000 times higher than conventional techniques in *Nishiyama et al*. 2024, enabling us to derive helium temperatures in the upper thermosphere from the measured spectral broadening. This will pave the way toward a quantitative understanding of the fundamental physics of helium and its dominant sources during atmospheric disturbances, as well as the overall dynamics of the upper thermosphere. Furthermore, we will evaluate the spectral resolution, signal-to-noise ratio, and stability of the observations, laying the groundwork for future high-precision measurements of Doppler shifts—ultimately enabling simultaneous measurements of temperature and wind velocity in the upper thermosphere.

We are currently developing a prototype of the laser heterodyne system and aim to conduct test observations in Japan and the Arctic within the next two years. After evaluating and refining the prototype, we plan to install the system at Syowa Station during the latter part of Phase XI of the Japanese Antarctic Research Project (2028–2034).

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SuperDARN future plan for Phase XI JARE project

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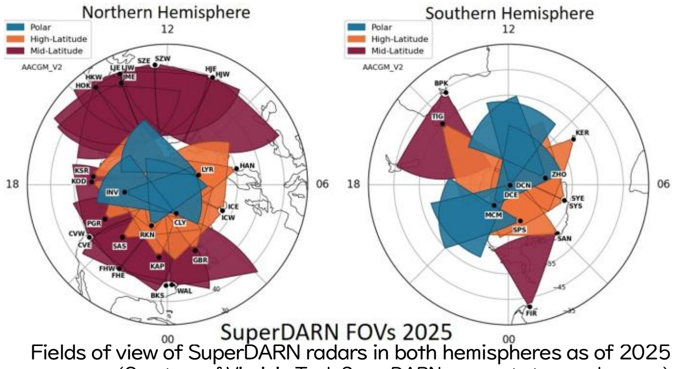
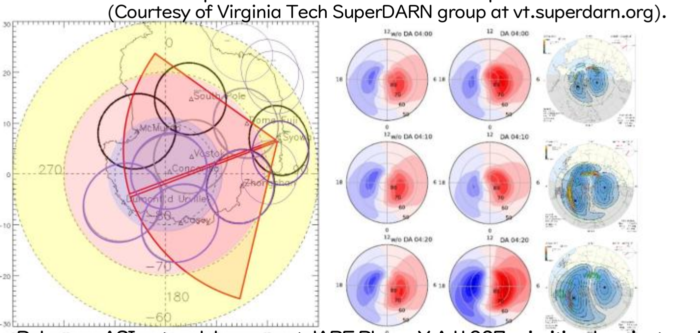
SuperDARN, i.e., Super Dual Auroral Radar Network is an international over-the-horizon high-frequency coherent radar network established in 1995. Each radar has a horizontally large field-of-view in upper atmosphere (mainly ionosphere) reaching more than 3000 km in horizontal radial direction and about or more than 50 degrees in azimuthal direction. About 40 radars are currently distributed from middle to polar latitudes in both hemispheres and running and operated by more than 15 research institutes in about 10 countries. One of the original main scientific objectives was to obtain real global (mainly high - auroral to polar cap - latitude) plasma flow or convection maps and electric field potential maps (so called "space weather map") not in a statistical manner, which had never been done before by any ground-based or airborne/space observation, to contribute primarily to Space Weather research. The number of researchers, research institutes and radars has still been growing and the fields-of-view now cover considerable portion of middle to high latitude upper atmosphere. As a result, research areas and collaborative studies with other observational, theoretical and simulation groups have also expanded. It can now address many aspects of scientific questions not only on polar ionospheric and magnetospheric physics, its coupling, solar terrestrial physics (aeronomy), and space weather/space climate including geomagnetic and auroral storms and substorms, but also on subauroral ionosphere, inner magnetosphere, global upper atmosphere including neutral atmosphere and its coupling with ionised atmosphere (mesosphere-thermosphere-ionosphere coupling) as well as high-mid latitude interaction, influence of geospace on lower atmosphere and possible global climate change, plasma physics, and practical applied physics including space weather nowcast/forecast relating to communication, geodetic/positioning and satellite failure/errors, major power grid outage and warning/alert system to astronautical activities, and so on.



Fields of view of SuperDARN radars in both hemispheres as of 2025 (Courtesy of Virginia Tech SuperDARN group at vt.superdarn.org).



Polar cap ASI network by current JARE Phase X AJ1007 prioritised project and SENSU FOVs, and a simulation result with data assimilation using SuperDARN.

Syowa SENSU SuperDARN radars

NIPR has joined the SuperDARN project since its beginning in 1995 and run 2 SENSU SuperDARN radars, Syowa South and Syowa East radars (SENSU stands for "Syowa South & East HF Radars of NIPR for SuperDARN") in Japanese Antarctic Syowa station (69.00 S, 39.58 E) in polar auroral zone. Both radars have substantially contributed to the SuperDARN project and scientific researches, such as studies on various types of auroral phenomena, geomagnetic pulsations, substorms, reconnection, precise neutral wind observation around mesopause region using meteor echoes, studies on polar mesospheric summer echoes (PMSEs), magnetosphere-ionosphere-neutral atmosphere vertical coupling, studies on influence of low solar activity or grand minimum on geospace space weather with a various observational and theoretical collaborative research. Due to the importance of the obtained basic physical parameters widely used and referred, and also of the long-term observation, this project moved to JARE monitoring observation since current phase X JARE project with close collaboration with AJ1007 prioritized project for space weather/space climate research. We here summarise our important achievements so far and will discuss on issues remaining unresolved and ways forward and the future perspective of the scientific direction of our SENSU SuperDARN research towards phase XI JARE period and beyond as one of the comprehensive observations at Syowa station and as one of the most important basic and cutting-edge geospace scientific tools.

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