



SCIENCE PLAN

ANTARCTICA INSYNC



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Introduction

Antarctica InSync – A roadmap towards an internationally coordinated, circumpolar, and year-round Antarctic mission

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Preamble

Antarctica InSync is a global effort to synchronise research across Antarctica and the Southern Ocean, connecting ice, ocean, land, climate, and life to protect this vital region. This roadmap paper introduces the scientific and technological motivation and action plan to build an international programme for a coordinated field season in Antarctica and its surrounding seas. It lays out the international collaboration that is required to realise an ambitious action plan and the opportunities for the science community to address important scientific themes that identify current knowledge gaps. In the spirit of the Antarctic Treaty Consultative Meeting (ATCM), the planned scientific action mandates free data exchange, facilitates international collaboration, and derives expert scientific advice together with the Scientific Committee on Antarctic Research (SCAR). Aligned with challenges of the United Nation Ocean and Cryosphere Decades, we plan a shared global effort to better understand the role of Antarctica and its surrounding ocean for our global futures, building on decades of achievements in polar and ocean science. As a milestone leading up to the next International Polar Year in 2032/33 (IPY5), the ambition is to achieve a new level of cooperation, with opportunities for the next generation of polar scientists around the world by enhancing practices in sharing of ideas, infrastructure and information.

Antje Boetius, Lead of the Antarctica InSync International Steering Board

1. Scientific motivation

Currently, the vast Antarctic and Southern Ocean polar region show signs of immense changes, including unforeseen, rapid climatic changes and shifts in its unique ecosystems. These changes impact the global climate, ocean and biosphere, which are of direct societal relevance. Thus it is a key scientific motivation to overcome substantial knowledge gaps and increase the system's predictability by improved synchronous and pan-Antarctic observation (SCAR Strategic Plan 2023-2028)¹. The exact causes and consequences of the current changes remain to be deciphered. They potentially impact the long-term efforts to limit global surface warming and sea level rise, as well as the conservation of unique Antarctic life. The important role of climatic changes in the southern polar region for the Earth system arises from its unique and vast ocean that circulates the isolated Antarctic continent (**Theme 1**; see below). Here, almost 80% of all global subsurface waters return to the surface², and are altered by interactions with the cold atmosphere and the ice before they are returned to lower latitudes. In this process, over the past decades, the Southern Ocean has taken up about 70% of the excess heat in the global climate system (vs. 91% total ocean update) and about 10-15% of all human-induced carbon-dioxide emission (vs. 25% of the total ocean update)³ – providing key services to our livelihoods.

The future development of Antarctica's contribution to mitigate global surface warming remains unknown, as current Earth System Model simulations are unable to accurately simulate the observed past and current rapid changes in this region⁴. Among these changes is the persistent loss of several million square kilometres of Antarctic sea ice since 2015⁵ (**Theme 2**) that took the research community by surprise. This sea ice decline already reduces the planetary albedo through enhanced solar

absorption. But neither the causes and consequences, nor the future trajectory of this rapid change are well understood⁶. Such uncertainties limit our understanding of the atmospheric and oceanic circulation, air-sea exchange, the ecosystem, the continental ice masses, and possible links to extreme events, such as the recently observed marine and continental heat waves⁷. Beyond these changes in the Antarctic sea ice cover, a major concern is the rapid melting of the ice shelves along the continental margin and loss of ice mass⁸ (**Theme 3**). Several decades of increased basal melt along West Antarctica have already contributed to an enhanced and likely irreversible ice discharge and, consequently, several metres of already committed sea-level rise until the end of the century⁹. Of particular concern are emerging signs of destabilizations of ice shelves of East Antarctica, where current climatic changes could contribute to additional sea-level rise of several tenths of metres in the longer term. At the same time, the magnitude and pace of change in the East Antarctic ice sheet remain highly uncertain, posing a major challenge for projections and significant risk for coastal infrastructures and populations globally¹⁰.

Antarctica and the surrounding seas belong to the least mapped and explored environments of our planet with a high potential for biodiversity discovery. This vast polar region is characterized by a high fraction of rare and highly cryosphere-adapted, endemic species^{11;12}. The changing cryosphere and rapid warming of the region are fundamental risks for the unique local ecosystems (**Theme 4**). For example, Antarctic krill, which forms the basis of the Antarctic food web and is the largest single species biomass on Earth, depends on sea ice as a habitat¹³. The sea ice loss has already led to the fatal loss of several penguin colonies¹⁴. Similarly, many other species are adapted to the narrow temperature range and might suffer from warming and the invasion of non-native organisms. They may disappear before they have even been discovered as many habitats have not yet been explored and are unprotected¹⁵. Therefore, increased protection of the southern polar region is particularly critical and timely as the human pressure has been increasing drastically (**Theme 5**). The higher pressure includes a massive increase in tourism, increased interest from fisheries, enhanced pollution, and progression of diseases. These threats must be countered through increased monitoring and regulation, such as the establishment of major Marine Protected Areas in the Southern Ocean¹⁶.

To better understand and predict climatic changes, and human and environmental pressure in the southern polar region, major improvements in models are needed. A key known issue in models are aerosol-cloud-precipitation processes and their impact on the radiative balance (**Theme 6**). These biases lead to inaccurate surface temperatures and precipitation over the ocean and land that have effects on the simulated mean state and the projected long-term warming and ice mass changes¹⁷. Due to the difficulties in models to accurately simulate past climatic changes and observational records being still short and sparse, it remains uncertain to what extent the currently observed changes are driven by human-induced climate change or reflect longer-term variations⁵ in the regional climate system (**Theme 7**). At the same time, the possibility cannot be excluded that components of the coupled Antarctic ice-ocean-atmosphere-ecosystem are reaching tipping points¹⁰. The impact on a global scale for climate, society and ecosystem could be far reaching, including loss of biodiversity, increasing pressure on Antarctic and Southern Ocean environments, major drawbacks in allowable emissions and carbon pricing, rapid global surface warming on decadal time scales, and increased uncertainties in current sea-level rise commitments for future generations, requiring an urgent and internationally coordinated action. All of these and other functions of the southern polar region are of immense value to society, thus global efforts in stewardship and protection are increasingly critical¹⁸.

The observed changes, emerging risks, and persistent uncertainties along with the substantial opportunities in international collaboration, including new research capacities with remote sensing, stations and ships, technology innovation with autonomous sensors, drones, subsea platforms, robotics and Artificial Intelligence, partnerships with philanthropy and other stakeholders, define the scientific rationale for Antarctica InSync and provide the foundation for the respective research programme.

The seven scientific themes that provide the scientific framework for Antarctica InSync are:

- Theme 1: Southern Ocean physical and biogeochemical cycles in a changing climate
- Theme 2: Rapid sea ice decline and its causes and consequences
- Theme 3: Antarctic ice sheets and ice shelves: processes driving rapid change, from observation to prediction
- Theme 4: Improving knowledge and protection of the unique Antarctic life: from land to ocean and into the deep sea
- Theme 5: Anthropogenic signatures in Antarctica: the race against pollution and other pressures
- Theme 6: Aerosol-cloud-precipitation interactions and radiative feedback
- Theme 7: Variability, extremes, and tipping in a changing Antarctic climate

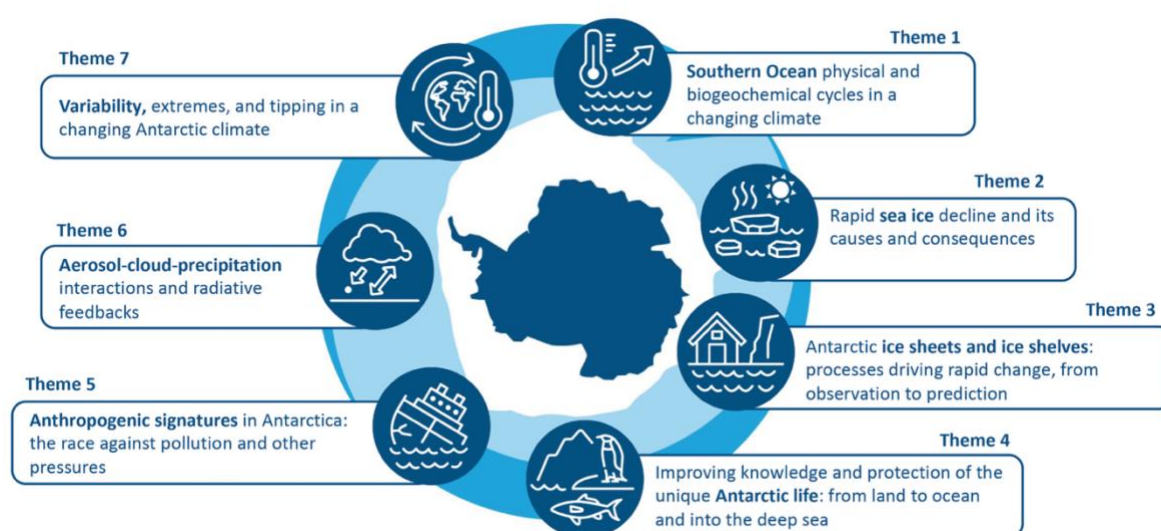


Figure 1: Overview of the Antarctica InSync scientific themes.

2. Development of Antarctica InSync as international programme

Our current understanding of the Southern Ocean and Antarctic climate and ecosystem is still constrained by challenges in observing the harsh and ice-covered polar environment, as well as the remoteness and vast spatial extent of the region. The associated knowledge and data gaps directly limit our ability to realistically model and predict changes in this coupled system. Addressing these challenges requires (i) enhanced international cooperation, shared infrastructure, and open data exchange to enable broader, year-round access across regions, and (ii) improved and sustainable monitoring networks supported by emerging and autonomous technologies. International scientific cooperation is fostered through the Antarctic Treaty System (implemented in 1961), and several coordinated joint efforts to establish strategic observational networks have been endorsed and supported through the Antarctic Treaty Consultative Meeting (ATCM). The Council of Managers of National Antarctic Programs (COMNAP) facilitates support to Antarctic operations amongst the national Antarctic programmes. International cooperation in scientific research programmes and groups is growing under the umbrella of the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR). Important long-term initiatives include the Southern Ocean Observing System (SOOS; since 2011) and the Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED; since 2008). A key observing system programme is the

Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, enabling the year-round pan-Antarctic assessment of the carbon cycle through an array of autonomous biogeochemical floats. The Ecosystem Monitoring Programme of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has provided some of the longest ecological monitoring records and has contributed to the foundation for terrestrial and marine protected areas in Antarctica. The Census of Antarctic Marine Life (CAML; 2005–2010) provided a first comprehensive biodiversity baseline for marine species. The Southern Ocean Regional Panel (SORP) of the Climate and Ocean Variability, Predictability and Change (CLIVAR), together with GEOTRACES, the International Study of the Marine Biogeochemical Cycles of Trace Elements and Their Isotopes, has helped to identify research priorities and synthesise important data on climate and biogeochemistry. Ice and geological drilling programmes have transformed our understanding of Antarctica’s planetary and climate history. New initiatives like SCAR’s RINGS, focusing on the ice sheet margin, have provided pan-Antarctic perspectives on the coastal boundaries of the Antarctic ice sheet. Today, all scientific disciplines have profited from collaboration and data sharing, with major highlight activities during the International Polar Years.

In 2014, the SCAR Horizon Scan¹⁹ outlined the major Antarctic and Southern Ocean research priorities through 80 questions identified by the international community. The report highlights the lack of sustained, wintertime, circumpolar, and year-round coordinated observations needed to address them. The urgency of this gap was further amplified with the rapid climatic changes in the Southern Ocean observed since 2015. In response, the international Southern Ocean community gathered in a workshop in San Diego in 2019²⁰ to initiate a Southern Ocean Action Plan²¹ within the framework of the UN Ocean Decade (2021-2030). A major take-away from the workshop, and the subsequent Action Plan, was the identified need for a year-round Antarctic and Southern Ocean mission to be implemented as a coordinated international effort within the UN Ocean Decade. Such a mission would address the current limitation that observations are sparse, seasonal, and fragmented across national programmes, particularly during winter and in the seasonally ice-covered regions. The international effort would directly build on earlier visions for a sustained Southern Ocean observing network²² and on the lessons learned from prior initiatives, such as the Year of Polar Prediction²³, which provided recommendations for optimized observing networks, supersites, and data–model integration.

Following these recommendations, several national science programmes refined their Antarctic strategic priorities at national levels, for examples in the UK, USA and Australia²⁴, as well as on institutional levels, for example at the Alfred Wegener Institute (AWI)²⁵. At the 44th ATCM conference in Berlin (2022), numerous polar leaders, including representatives from the AWI, the Australian Antarctic Division (AAD), the British Antarctic Survey (BAS), the Scientific Centre of Monaco (CSM), the French Polar Institute Paul-Émile Victor (IPEV), the U.S. National Science Foundation Office of Polar Programs (OPP-NSF), the Norwegian Polar Institute (NPI), and national delegates, met, to initiate a new ambition for an international synchronous research programme for Antarctica, encouraged by previous achievements with the Arctic mission “Multidisciplinary drifting Observatory for the Study of Arctic Climate” (MOSAiC). As a joint outcome of this process, an information paper was submitted to the Antarctic Treaty Consultative Meeting²⁶ in 2023, proposing the “Antarctica International Science & Infrastructure for Synchronous Observation (Antarctica InSync)” programme. In the same year, Antarctica InSync²⁷ was endorsed as a UN Ocean Decade programme contributing to the Ocean Decade objectives #1 (*Identify critical ocean knowledge*), #2 (*Build capacity and generate knowledge*), and #3 (*Increase the use of ocean knowledge*).

Since then, the international partnership has been growing thanks to polar science institutions from 28 countries ([as of April 2026](#)) and submits regular updates to ATCM and COMNAP. Several international organisations, such as SCAR, SOOS, and the European Space Agency (ESA) are partners in the effort

to plan year-round and internationally coordinated observations in the period 2027 to 2029 and a synthesis phase in 2030.

The science themes were initially based on priorities identified in the SCAR Horizon Scan and the Southern Ocean Action Plan. In the years 2023 to 2025, these themes were further developed through community discussions at the SOOS Symposium (Hobart, Australia, 2023), SCAR OSC (Pucon, Chile, 2024), EU Polar Science Week (Copenhagen, Denmark, 2024)²⁸, and a series of dedicated webinars jointly organized with ESA. In addition, the plans were discussed with numerous stakeholders i.e., from philanthropy, NGOs, the EU, national funding agencies, and the International Association of Antarctica Tour Operators (IATOO). The resulting seven themes as outlined above are complemented by three cross-cutting themes identified by the scientific community:

- Earth Observations
- Modelling and AI
- Data management and sharing

The scientific themes are intended to build on existing SCAR expert and action groups as well as SOOS working groups. To strengthen these links, a [SCAR action group on Antarctica InSync](#) has been established in 2026 to enhance coordination between Antarctica InSync and existing SCAR structures, identify opportunities for synergies, and improve the visibility and integration of ongoing activities within the broader programme.

In November 2025, representatives of the international Antarctica InSync community met for a four-day workshop in Frascati (ESRIN ESA, Italy) to start developing the Antarctica InSync Science Plan. Thematic breakout sessions reviewed the existing material and produced initial drafts of the white papers, covering motivation and background, knowledge gaps and research needs, and observing strategies and key variables. These drafts were subsequently expanded, shared, and reviewed within the wider community through SCAR before being finalized in April 2026. Meanwhile more than 20 international working groups have formed and are building their membership, planning and organizing the forthcoming scientific actions, and first commitments for scientific platforms supporting the synchronous work have been aligned.

3. Overarching strategy & vision

Antarctica InSync aims to collect year-round, circumpolar and multidisciplinary observations across Antarctica and the seasonal ice-covered Southern Ocean by integrating in-situ observations, satellite remote sensing, and modelling within one coordinated framework. Through this effort, the programme will assess the state of the rapidly changing regional climate and ecosystem for the period 2027 to 2029. The central objective is to resolve key processes, feedbacks, and thresholds that govern ongoing Antarctic change across the coupled ocean-ice-atmosphere-biosphere-land system, and to translate this improved understanding into more robust monitoring, predictive capability, decision making, and environmental and ecosystem protection, in line with the goals of the UN Ocean Decade. Doing so, Antarctica InSync follows a system-of-systems approach that links national and international efforts into a more coherent, interoperable and sustainable observing network. It is thus a significant milestone in the development of a strategy towards the next International Polar Year 2032/2033 (SCAR/IASC, IASC: International Arctic Science Committee, Figure 2).

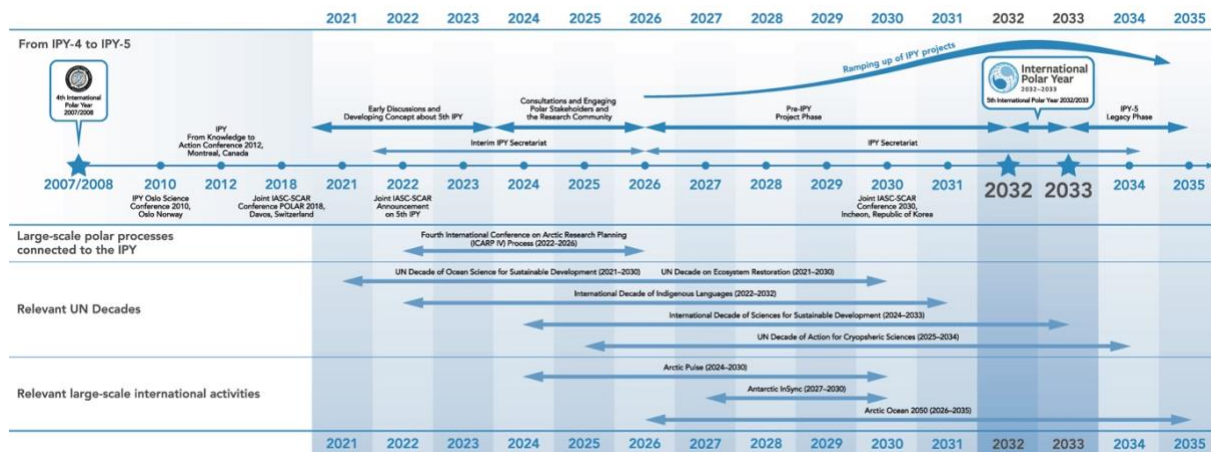


Figure 2: Timeline for the next IPY (https://ipy5.info/media/ltcpl1jm/ipy-timeline_v7.jpg).

A core element of our strategy is a **scale-crossing observational approach** integrating classical and new technologies, from sailing boats to satellites. Once data outputs are defined, in-situ observations can be connected across time and space to resolve fundamental challenges. Especially new autonomous and distributed observing systems can extend ship- and station-based information across seasons and regions. Together, water- and land-based, ice- and airborne observations will capture variability from local to global processes, across scales relevant for satellite footprints and model grid cells. Antarctica InSync is therefore conceived not as an isolated field programme, but as a **coordinated pan-Antarctic observing effort** that builds on and strengthens existing international structures and networks, particularly **SOOS, SCAR and related pan-Antarctic observing activities**. It will also make practical use of emerging coordination tools for shared infrastructure, data sharing, such as SOOSmap, and campaign planning, such as POLARDEX. In this way, Antarctica InSync aims to provide a practical framework for a more coherent, sustainable, and cost-effective Antarctic observing system²⁹ that targets the key current challenges. In July 2024, at the G7 meeting of research ministers, leaders recognized the impact of climate change on polar regions and officially expressed their support to Antarctica InSync.

Antarctica InSync will align the observing capacity of more than 28 national polar programmes in a **shared infrastructure** framework, together with infrastructure provided by national funding agencies, international organizations, such as ESA as well as private foundations and philanthropy. This infrastructure includes research vessels, sailing vessels, ships of opportunity, stations, and aircrafts. Shared access to this infrastructure for the international community will enable a more efficient use of the pooled resources and a strategic deployment and recovery of autonomous instrumentation. Blueprints for such shared infrastructure include programmes such as the European marine research infrastructure alliance (EUROFLEETS+), the Polar Research Infrastructure Network (POLARIN), and the Global Ocean Biogeochemistry Array (GO-BGC) programme under Argo. Currently, the first round of commitments is being assembled, with a particular focus on the notoriously under-observed austral winter in the ice-covered regions.

Earth Observation (EO) provides the circumpolar and long-term observational framework of Antarctica InSync, delivering spatially consistent information across Antarctica and the Southern Ocean beyond the limits of individual campaigns. Within Antarctica InSync, EO is therefore treated as an integral part of the common observational baseline together with in-situ measurements. At the same time, the full scientific value of EO depends on close coordination with field activities through calibration and validation, sustained autonomous observations, and, where possible, coordinated potential supersites that capture variability within satellite footprints. Integration of EO with in-situ observations through AI methods will further enhance the long-term monitoring of important climate

and ecosystem indicators. The detailed priorities, requirements, and mission opportunities for this EO component are described in the dedicated EO White Paper.

Modelling provides the integrative framework that links observations across scales and translates them into process understanding and predictive capability. A particular goal is to enable models to accurately simulate historical changes and reduce uncertainties in future projections. Thus, Antarctica InSync will embed its observational activities within a hierarchy of modelling approaches, from process studies and regional configurations to coupled climate and Earth System models. This hierarchy is essential for connecting local observations to circumpolar assessments, quantifying budgets and exchanges, and assessing how Antarctic change influences the global climate system. A key role of Antarctica InSync is to provide an observational backbone for model development, evaluation, and improvement while fostering closer exchange between modelling and observing communities. Campaign design and priority measurements in terms of Essential Variables need to be aligned from the outset to the identified key modelling challenges³⁰. Important Antarctic processes remain inadequately represented in many models, limiting confidence in regional simulations, re-analyses, forecast and global projections alike. By combining standardized in-situ observations, autonomous measurements, and EO-derived products, Antarctica InSync will deliver benchmark datasets for process understanding, parameterization development, model evaluation, and data assimilation. In this way, Antarctica InSync links directly to the broader Earth system modelling community, digital twin initiatives, and contributes to improving the representation of Antarctic and Southern Ocean processes in regional and global prediction systems, including re-analyses, coupled forecasting frameworks, and Coupled Model Intercomparison Project (CMIP) class models.

Integration across disciplines and observing systems will be enabled through a **common framework** of the already existing and established variable sets, such as Essential Climate Variables (ECVs) identified by GCOS, Essential Ocean Variables (EOVs) identified by GOOS, Ecosystem Essential Ocean Variables (eEOVs) identified by the SOOS community, and Essential Biodiversity and Ecosystem Service Variables (EBVs, EESVs) identified by GEOBON. These variables define the core quantities needed to characterize change across the Antarctic and Southern Ocean system and provide the basis for integration across physical, biogeochemical, and ecological domains. In a next step, these variables will be linked to standard operating procedures (SOPs), harmonized protocols, and shared metadata standards, so that observations collected by different programmes and platforms become directly comparable and reusable. This harmonization is a prerequisite for generating interoperable datasets across Antarctica InSync, and building community standards towards the upcoming **5th International Polar Year** (IPY5, 2032-33)³¹ and beyond, and for linking the initiative to broader international observing and data systems.

The **overarching vision** of Antarctica InSync is therefore not only to deliver a coordinated observing phase, but also to establish the foundation for a more integrated Antarctic and Southern Ocean observing system that combines synchronous observations, interoperable data streams, EO capabilities, and model and AI integration to detect, understand, and predict change in the Antarctic environment. In this way, Antarctica InSync will contribute to advancing the scientific basis and observing framework for Antarctic system science and evidence-based assessments of Antarctic change in a global context. The Antarctic Treaty system is based on the principle of peaceful collaboration and international scientific cooperation. Antarctica InSync will promote equitable and inclusive participation, supporting diversity across gender, career stage, generation, and geography. Research and next-generation scientific capacity will be developed by involving early career scientists, especially through the Association of Polar Early Career Scientists ([APECS](https://www.apecs.is); <https://www.apecs.is>). Particular emphasis will be placed on supporting access for early-career researchers and scientists from geographically diverse regions.

4. Programme structure and governance

Antarctica InSync takes a community-driven approach in which primarily national programmes are aligned and complemented with additional funding, for example through the EU Horizon calls, philanthropy, and existing multilateral programmes. Internationally aligned scientific priorities within the respective themes will play a large role in attracting national, private, and philanthropic support. The science plan will integrate both bottom-up and top-down strategies from all international partners to generate integrative and synthetic observations and information, provide the best-available knowledge for the forthcoming decade, and deliver blueprints for further coordinated and sustainable science, as for example towards the International Polar Year.

The science plan will be enabled by cooperation among national infrastructure programmes involving ships, stations, and aircrafts, as represented in COMNAP, as well as by the coordination and integration of distributed long-term observatories. It will also seek to include autonomous and remote global observing programmes such as Argo, ESA, and NASA. We envision engaging industry, for example through IAATO, ARK and COLTO, as well as private platforms such as sailing vessels, to provide the much-needed presence required to observe, assess and document the dynamic changes occurring in Antarctica. As noted above, we also aim to engage early-career scientists, for example through APECS and ECOP, as well as communities beyond polar research, including engineers, remote-sensing experts, microbiome researchers, and experts on emerging pollutants, to help establish a pan-Antarctic baseline at a time of rapid change.

Antarctica InSync governance (Figure 3) therefore combines international strategic oversight, national coordination, bottom-up scientific leadership, and early career researcher involvement to ensure both a broad participation and an effective and forward-looking implementation. Overall programme leadership is provided by the **International Steering Board**, composed of the heads of the involved polar research institutions from the contributing countries. This board provides the overall strategic direction of Antarctica InSync, supports alignment across national contributions, and links program development to the institutional and logistical capacities required for implementation.

The respective national leads, represented on the International Steering Board, work together with national experts to align the national interests within the National Committees, thereby ensuring a direct connection between national programmes and the needs for international coordination. The **National Committees** form the main coordination structure at national level. Their role is to coordinate national research priorities, capacities, and contributions to Antarctica InSync, and to connect these to the international programme through the respective International Steering Board representative as well as through active participation in the scientific and cross-cutting themes and working groups. The composition of National Committees may vary according to national priorities, capacities, and resources, and does not need to cover all themes equally. However, their structure should aim to ensure broad national coordination and include dedicated early-career representation to strengthen continuity, foster capacity building, and ensure that early-career perspectives are integrated into planning, implementation, and community engagement.

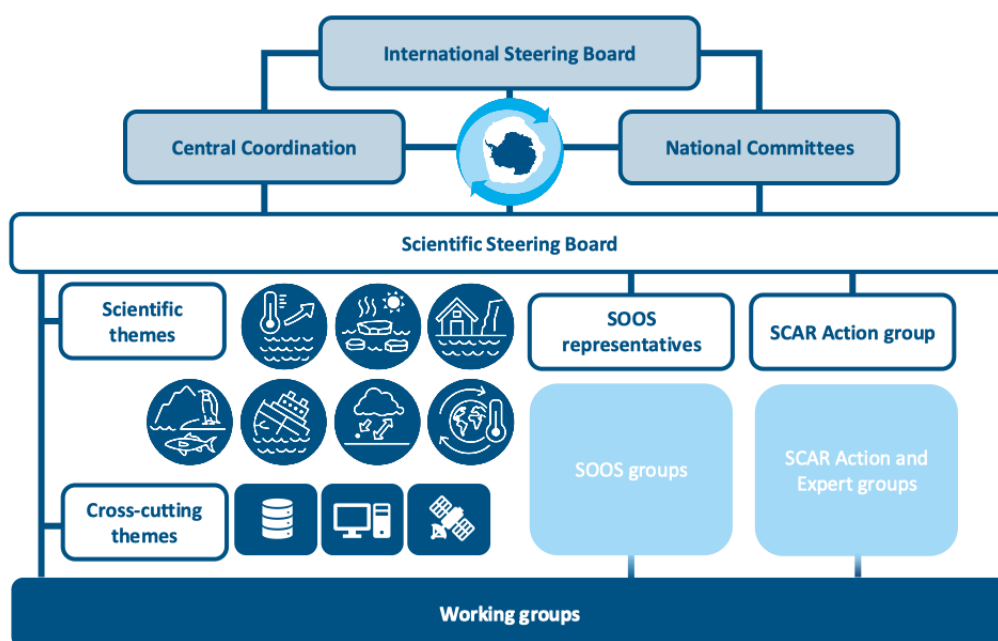


Figure 3: Overview of the Antarctica InSync governance structure.

Scientific coordination at the international level is provided by the **Scientific Steering Board**, which ensures coherence across the scientific and cross-cutting components of Antarctica InSync. It includes several representatives from each scientific theme, one representative from each cross-cutting theme, two SOOS members, and the chairs of the Antarctica InSync SCAR Action Group, thereby ensuring close connection to existing international science groups. The Scientific Steering Board provides scientific coordination and strategic guidance regarding research plans, and integration across themes and cross-cutting areas, thereby supporting the activities of the Working Groups. It highlights major scientific outputs, promotes broad community engagement, and advises the International Steering Board on scientific priorities and emerging needs.

The **Scientific and Cross-cutting themes** are established community-driven research priorities and provide the scientific backbone of Antarctica InSync. The seven scientific themes emerged from earlier assessments of Antarctic and Southern Ocean research needs and define the overarching scientific framework of Antarctica InSync. The cross-cutting themes address shared programme-wide requirements, including, data management and sharing, Earth Observations, and modelling and AI. To strengthen connections across themes while also enabling more detailed discussion of specific subtopics, community-proposed **Working Groups** serve as a mechanism for implementation and exchange. Their development is intended to remain dynamic: Working Groups may build on existing structures, such as SCAR Expert and Action Groups or SOOS groups, or may be newly established. Finally, a **Coordination Office** supports all described governance levels by facilitating communication, coordinating meetings and community activities, supporting webinars and workshops, linking national and international structures, and thus, helping to translate the programme's strategic vision into effective scientific implementation.

An **Antarctica InSync SCAR Action Group** was established to identify SCAR community needs and contributions to Antarctica InSync and to support coordination in the ramp-up towards the 5th International Polar Year. The Action Group will bring together expertise from across SCAR to strengthen pan-Antarctic observations, promote shared infrastructure and FAIR data practices, support synthesis and modelling efforts, and foster inclusive participation across the international community. In doing so, it will help align Antarctica InSync with SCAR's long-term strategies and contribute to a

more integrated understanding of Antarctic change, from local processes to pan-Antarctic perspectives and global teleconnections.

The **timeline for Antarctica InSync** is as follows:

2024–2026: Preparatory Phase. The main task in the preparatory phase is to establish a coordination team, build alliances, set up working groups, engage with stakeholders and logistic teams, and define a framework of collaboration. The here presented Antarctica InSync science plan was developed through the key Southern Ocean and Antarctic international communities, to ensure that identified key challenges, questions and needs for research are appropriately addressed. The plan aims to decipher the drivers, impacts and feedback mechanisms of this key region, together with their global interactions on the oceans, climate, biodiversity, and humanity. Joint data collection and coordinated, synchronous experiments and composite observations will be developed by the international science teams. National programmes and institutions operating polar infrastructure will be asked to coordinate the logistical means to implement the science plan. Some teams are expected to be ready before the international implementation phase, enabling early testing of standards and essential variables for synchronous observation.

2027–2029: Implementation Phase. Beginning of 2027 will see an intense planning of the joint field campaigns and synchronous data assemblies to be carried out from 2027/2028 to 2029, with missions taking place during both austral summer and winter seasons. The commitments to fieldwork are being continuously updated. Joint expedition plans with opportunities to share berths will be developed until the end of 2026 and early 2027.

2030: Completion and Reporting Phase. Analyses of the results of the joint field campaigns and synchronous data assemblies should begin as soon as data become available, using international state-of-the-art data infrastructures and following FAIR principles. Workshops will be held to discuss and compile the knowledge gained from Antarctica InSync, with a focus on synthesis reports as contributions to the finalization of the Ocean Decade in 2030 and the mid-life phase of the Cryosphere Decade. These reports, together with the experience gained through the Antarctica InSync research programme, will provide crucial input for planning the 5th International Polar Year 2032-33.

5. Outlook

The Antarctica InSync programme is open to contributions from the entire international research community and welcomes any participation aiming to collaborate on an international level and following the fundamentals of equality, diversity, and inclusion and FAIR and CARE data principles. The process of proposing Working Groups and White Paper submission by the community will remain open throughout the duration of the programme. A critical next step in the planning will be the implementation phase in the year 2026, with the goal to publish an **Implementation Plan** with the start of the field phase in 2027. This process will follow the same principles of the drafting of the Science Plan in 2026, including community engagement through online webinars, and a following in-person writing workshop.

Antarctica InSync will continue to engage with the **UN Ocean Decade** process, inform the ATCM, engage with the SCAR and SOOS communities, and shape a long-term legacy by contributing to the UN Sustainable Development Goals (SDGs)³². It will put a long-envisioned circumpolar and year-round observing system into practice and thereby provide an important basis for a long-term Southern Ocean and Antarctic monitoring system that is able to support decision making on “urgent action to combat

climate change and its impacts” (SDG13) and on “conservation and sustainable use of the oceans, seas and marine resources for sustainable development” (SDG14). Therefore, the programme will provide critical knowledge for national and international decision makers. A further strategic opportunity lies in its alignment with emerging European and international policy frameworks. The European Ocean Pact, adopted by the European Commission in 2025, highlights ocean research, knowledge, innovation, observation, and international ocean governance as key priorities. Related initiatives, such as the EU Ocean Observation Initiative and European marine knowledge infrastructures including EMODnet, Copernicus Marine, and the European Digital Twin Ocean, provide important opportunities for connection within and beyond the polar community. Antarctica InSync can contribute to this broader agenda by linking field observations, Earth Observation, and modelling within an internationally coordinated framework and by helping to ensure that Antarctic system change is represented in wider ocean observing and knowledge efforts. In this sense, the programme also serves as a crucial stepping-stone towards the **5th International Polar Year** (IPY5, 2032-33) and aims to provide community structures and efforts that can be improved and carried on towards IPY5 and inform the upcoming SCAR Horizon Scan. Within this framework, Antarctica InSync will play an important role in coordinating available capacities and resources in order to ensure their cost-efficient, strategic and sustainable use and to maximize the scientific outcome of research efforts across the Southern Ocean and Antarctica.

The **long-term success of Antarctica InSync** will depend not only on the scientific results generated during the programme itself, but also on the extent to which it establishes durable structures for collaboration, coordination, and sustained observation. Success should therefore be understood in terms of legacy: in the continued use of shared protocols and Essential Polar Variables, in the interoperability, accessibility, and reusability of resulting datasets and protocols, in the sustained engagement of national committees, Working Groups, early careers, and partner organizations, and in the extent to which these structures remain active and useful into the IPY5 phase and beyond. In this way, Antarctica InSync is not only a coordinated scientific effort, but is a lasting contribution to the evolving international stewardship of Antarctic and Southern Ocean research.

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Antarctica InSync Policy Paper

International circum-Antarctic research cooperation to build the scientific foundations for global climate, environmental, and security governance

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Executive Summary

Antarctica InSync (Antarctica International Science & Infrastructure for Synchronous Observation) is an international scientific initiative explicitly designed to deliver synchronised, circumpolar, multi-domain observations of Antarctica and the Southern Ocean. Collaborative fieldwork is planned between 2027 and 2030 to establish a unified observation strategy far exceeding what national programmes can provide. Its purpose is to implement simultaneous measurements and analyses that address key gaps in understanding climate dynamics, cryosphere instability, ocean processes, biodiversity change, and human impacts. By acquiring temporally and spatially aligned observations across all Antarctic basins, Antarctica InSync creates the evidence-base necessary to detect abrupt change, emerging tipping-point risks and to reduce major uncertainties in global climate and sea-level projections as well as in ecological functions such as biodiversity and productivity. The initiative provides authoritative scientific evidence for national and international policymaking, strengthens multilateral climate and environmental governance, and promotes sustainable, more efficient and cooperative scientific operations in the region relevant to progress towards the International Polar Year.

1. Background and objectives

Antarctica InSync unites partners from science, technology, policy, and industry to investigate the interconnected systems of ice, oceans, atmosphere, and biodiversity, as well as the drivers and consequences of their rapid transformation. Unlike existing initiatives that coordinate data only after collection, InSync is explicitly designed to synchronise observations across all Antarctic basins and seasons, enabling a continent-wide, multi-domain assessment of the role of Antarctica in the Earth system. The international initiative implements simultaneous circumpolar measurements using a coordinated fleet of research vessels, aircraft, autonomous platforms, satellite assets and ground stations, supported by innovative technologies such as autonomous sensor networks, integrated observing systems and machine learning to improve data coverage and analytical capacity. By combining and linking existing, mostly disciplinary data infrastructures hosting essential variables, it also establishes the foundations for an “Antarctic Data Cube,” enabling high-quality, interoperable and FAIR-compliant data infrastructure that consolidates heterogeneous datasets into a single, policy-relevant evidence base. It invests in education, training and capacity-building for the next generation of polar experts and provides a structured framework for participation by countries without direct Antarctic infrastructure. The initiative is endorsed by the UN Decade of Ocean Science, COMNAP (Council of Managers of National Antarctic Programs), SOOS (Southern Ocean Observing System) and ESA (European Space Agency), has received support from the G7 Science Ministers in 2024, contributes to the preparation of the 5th International Polar Year (2032–2033) and is working with SCAR (Scientific Committee on Antarctic Research) via an Action Group that will align and coordinate its work with that of existing SCAR groups. Together, these endorsements demonstrate broad international consensus on the need for a coordinated, synchronised approach to observing and understanding a rapidly changing Antarctic system.

2. Why Antarctica InSync is critical now

The Antarctic region is changing rapidly, with significant shifts observed in ice-sheet and sea-ice mass balance, ocean circulation, atmospheric patterns and ecosystem functions. These changes influence global sea-level rise, climate variability including extreme weather events, ocean productivity and marine biodiversity. One consequence of these ocean changes is the rapid, unprecedented sea ice decline during the last 10 years, which in turn, e.g., again affects the CO₂ exchange. These are important factors in socioeconomical development and security, and thus scientific knowledge are key for projections of risks and solutions. Current long-term and national observing efforts form the backbone of Antarctic science and have produced many of the key insights into how the region is changing. Antarctica InSync builds on these strengths by adding the capability to observe multiple regions at the same time, enabling researchers to trace how processes in the ice, ocean, atmosphere and ecosystems are connected across the continent. This synchronised approach provides the additional context needed to understand how local changes relate to wider pan-Antarctic and global dynamics, particularly during periods of rapid change. For example, Antarctica InSync can produce observations and knowledge that can reduce uncertainties in the behaviour of vulnerable marine basins in West and East Antarctica, where different future pathways could lead to markedly different global sea-level outcomes. This addresses the needs identified by the research community, as articulated in comprehensive consultations such as the SCAR Horizon Scan and more recently the Southern Ocean Action Plan.

At the same time, the Southern Ocean plays a critical stabilising role in the global climate system. It has absorbed more than half of the excess heat stored in the Earth system and roughly 40 percent of historical anthropogenic CO₂ emissions. Any reduction in this buffering capacity would have immediate and profound global ramifications. At the same time, the resulting ocean heat and acidification may

affect productivity and diversity. Understanding these evolving dynamics requires observations that capture how changes unfold across regions and domains at the same time. These urgent considerations have motivated the launch of the UN Decade for Cryospheric Sciences in 2025, and a next IPY in 2032-33. Antarctica InSync responds to these international frameworks by coordinating a synchronised, circumpolar observing effort that complements existing national programmes and provides the integrated evidence required to assess emerging risks and improve long-term projections. Working with the partners in the 5th International Polar Year, including SCAR, ensures that the impact of Antarctica InSync will be global and have a clear legacy.

3. Expected impacts of Antarctica InSync

Scientific Advancements

Antarctica InSync is specifically designed to deliver synchronised, pan-Antarctic observations of how ice, ocean and atmosphere processes interact, enabling more robust projections of sea-level rise, biogeochemical cycles and climate extremes. Through harmonised and standardised methodologies, interoperable data infrastructures and strengthened collaboration across disciplines, the initiative will catalyse improvements in climate and Earth system modelling, including future IPCC assessments. Because all data produced under Antarctica InSync will be interoperable and fully FAIR-compliant, ensuring broad accessibility and long-term value for global research. These advancements will be facilitated and amplified by working closely with existing bodies such as SCAR, SOOS, COMNAP and ESA, and will align with IPY-5 efforts.

Evidence-Based Policy Advice

The coordinated scientific evidence produced through Antarctica InSync will inform global and regional strategies for biodiversity protection, climate adaptation and emissions reduction. By working with SCAR and other partners in the policy space it will support negotiations under the Antarctic Treaty System and CCAMLR, as well as international climate and biodiversity governance mechanisms, by providing consistent, policy-ready assessments of risks such as sea-level rise, changes in carbon uptake and ecosystem functions. By generating a shared, synchronised evidence base that complements existing national efforts, Antarctica InSync strengthens multilateral governance, reinforces peaceful science-based cooperation in a geopolitically significant region and supports the development of forward-looking environmental and climate policy across multiple governance levels. It thereby tackles several of the priorities named by ATCM.

Implications for Practice

The initiative will also inform operational practice in Antarctica. By working directly with research operators, tourism actors and fisheries, Antarctica InSync will contribute to more efficient and sustainable logistical planning, help reduce environmental impacts and promote conservation and management strategies grounded in the latest scientific evidence. Along a key priority of ATCM, it will enhance opportunities for collaboration as well as capacity building in science, particularly in relation to climate change and biodiversity discovery. Additionally, the initiative will contribute to the operational framework for the 5th International Polar Year, serving as the scientific basis and model for future large-scale coordinated research efforts across the region.

Global Impact

The consequences of changes occurring in Antarctica and the Southern Ocean are global in nature. Rising sea levels affect coastal stability, freshwater systems and economic resilience worldwide. Shifts in climate dynamics and ocean circulation influence extreme weather patterns and long-term climatic variability. Changes in ecosystem functioning and biodiversity have implications for food security, carbon cycling and marine resource management. By providing synchronised, multi-domain

observations that improve predictive modelling efforts, including those informing the for IPCC (Intergovernmental Panel on Climate Change), IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) CMIP (Coupled Model Intercomparison Project) and Digital Twins of the Ocean, Antarctica InSync strengthens global capacity to anticipate, prepare for and manage climate-related, environmental and societal risks.

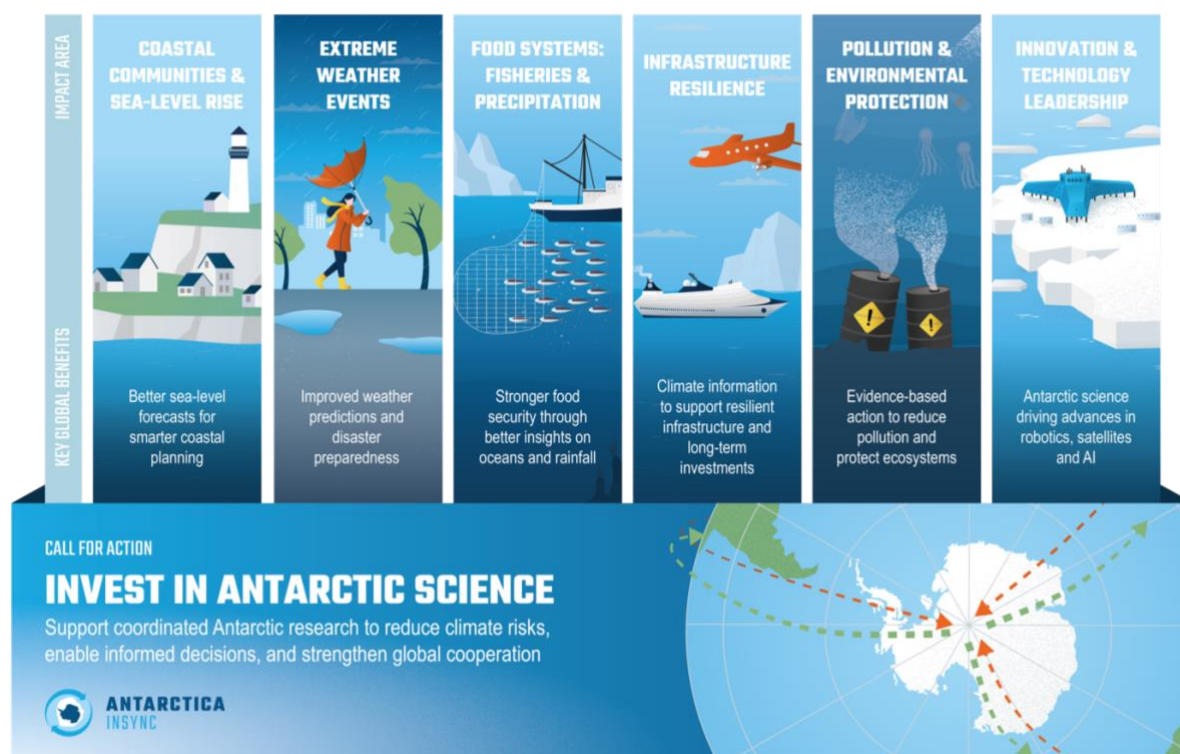


Figure 1: Overview of the global relevance and societal impact of Antarctica InSync, illustrating its contributions to addressing major global challenges and highlighting the urgent need for continued international support and engagement with the programme.

4. Call for action

Given the accelerating pace of climatic and environmental transformation, coordinated international polar research is indispensable. The SCAR Antarctic Climate Change and the Environment (2022) report and the Southern Ocean Action Plan (2022) highlighted the crucial role Antarctica plays in the global climate system. Antarctica InSync provides a structured and collaborative mechanism for synchronised, multi-country observation and analysis, ensuring that scientific insights keep pace with rapid change. Governments, international organisations and scientific institutions are urged to support long-term coordinated Antarctic research, by investing in shared infrastructure, interoperable data systems and integrated observational networks, and to reinforce evidence-based governance within the Antarctic Treaty System. Sustained global engagement is essential to ensure scientific insight, operational preparedness and strategic foresight for a rapidly changing planet. Being an active collaborator in Antarctica InSync strengthens the international community's ability to monitor and anticipate changes that affect global Earth-system stability and to take informed decisions that safeguard prosperity, security, and environmental and societal resilience for future generations.

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Antarctica InSync Scientific Theme 1

Southern Ocean physical and biogeochemical cycles in a changing climate

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Executive Summary and Key Recommendations

Theme 1 addresses the Southern Ocean's (south of 30°S) critical role in regulating Earth's climate through circulation patterns that mediate global exchanges of heat, carbon, freshwater, and nutrients. The region has absorbed over 70% of anthropogenic heat and has contributed to about 40% of the global ocean uptake of human-emitted carbon dioxide (CO₂) while also controlling ice shelf stability and sea level rise. However, fundamental gaps in year-round observations, particularly during austral autumn, winter, and spring, severely limit our understanding of these processes and their responses to rapid climate change. This white paper establishes key knowledge gaps and high-priority recommendations that are tractable within the InSync timeframe through coordinated program execution with strong engagement from national operators and funding agencies. Critical needs include seasonal observations of the marginal ice zone where carbon, heat and nutrient-rich waters upwell, year-round continental shelf measurements where dense water formation and ice-ocean interactions occur, standardized air-sea flux measurements, and strategic monitoring of regional choke points. Success requires international resource sharing, coordinated deployments, and sustained commitment to both process studies and long-term monitoring.

Key Recommendations

1. **Long-Term Time Series Maintenance:** Secure the critical multi-decadal ship/land-based monitoring, mooring, and Argo programs (including biogeochemical and deep) that have been essential for detecting climate and biogeochemical trends in the past decades.
2. **Air-Sea Flux Measurements:** Use underway systems on as many vessels and in situ platforms as possible, ensuring standardised practices, to routinely measure key variables to derive air-sea fluxes of heat, momentum, moisture, CO₂, methane (CH₄), and nitrous oxide (N₂O).
3. **Marginal Ice Zone Process Studies:** Fund interdisciplinary autumn-to-spring ship campaigns in Southern Ocean subpolar regions characterised with large-scale upwelling to capture critical atmosphere-ocean-ice interactions driving the ocean distribution of heat, carbon, (micro)nutrient, and climate-relevant gases, as well as the biological carbon pump.
4. **Year-Round Continental Shelf Observations:** Deploy an internationally coordinated network of ice-capable floats, autonomous platforms, and moorings to observe processes that drive the global ocean circulation and affect global biogeochemical cycles, as well as the southward ocean heat transport threatening ice-sheet stability.
5. **Critical Region Monitoring:** Establish internationally coordinated observation arrays at regional choke points, controlling bottom water export, meridional and vertical transport of heat and other tracers, meltwater pathways and better constrain their influence on biogeochemical cycles.
6. **Ocean-Ice Interface Observations:** Fund observations at the interface between ocean and sea-ice, and ocean and ice shelves, develop open-source ice-capable technology, such as acoustic positioning and navigation, and implement coordinated infrastructure that can operate with those, to observe critical processes year-round.
7. **Enhanced Earth Observation Capabilities:** Ensure the development of new and consistent satellite observation products tailored for Southern Ocean regions to retrieve salinity, temperature, sea level, ocean mass, ice volume, and ocean color for process understanding, integrating these remote observations with in situ where needed.
8. **Process-Based Model Development:** Utilize the expanded observational capabilities to evaluate and improve numerical modeling of key Southern Ocean processes - such as ice-ocean interactions, ocean mixing, water mass formation, and the marine carbon sink - through model enhancement and development of parametrizations, strongly encouraging collaboration with observational groups, also employing novel machine learning tools.
9. **Capabilities:** Ensure the development of new and consistent satellite observation products tailored for Southern Ocean regions to retrieve salinity, temperature, sea level, ocean mass, ice volume, and ocean color for process understanding, integrating these remote observations with in situ where needed.
10. **Process-Based Model Development:** Utilize the expanded observational capabilities to evaluate and improve numerical modeling of key Southern Ocean processes - such as ice-ocean interactions, ocean mixing, water mass formation, and the marine carbon sink - through model enhancement and development of parametrizations, strongly encouraging collaboration with observational groups, also employing novel machine learning tools.
11. **International Resource Sharing:** Formalise shared ship berths, support data sharing and international data portals, coordinated platform deployments, platform sensor hosting, sharing of sampling equipment and other common equipment to maximize coverage and cost-efficiency.

1. Motivation and background

This section establishes the critical role of the Southern Ocean in the global climate system, briefly reviewing current understanding of the physical, chemical, and biological processes that regulate heat distribution, freshwater cycling, carbon sequestration, and biogeochemical cycles. These processes are undergoing rapid change with profound implications for global climate, sea level rise, and ecosystem functioning.

Global Impact and circulation

The Southern Ocean is critical to the Earth's climate system, absorbing over 70% of anthropogenic heat and contributing to about 40% of the global ocean uptake of human-emitted carbon dioxide (CO₂), while also controlling heat delivery to Antarctic ice shelves¹. This, in turn, drives accelerating ice shelf melt with 2-15 meters of potential sea-level rise over coming centuries^{2,3}. Uncertainties in Southern Ocean processes affect projections of the ocean's heat and carbon absorption capacity, sea-ice and precipitation patterns, and global nutrient distribution^{4,5}. The region is particularly vulnerable to ocean acidification, effectively irreversible on millennial timescales⁶.

The Southern Ocean's global importance arises from its circulation, which links all major ocean basins through the Antarctic Circumpolar Current (ACC), while subpolar gyres and the Antarctic Slope Current channel waters toward the Antarctic margin. Closer to the coast, boundary currents steered by troughs influence heat delivery towards ice shelves, the distribution of meltwater, and ocean stratification; the Antarctic Coastal Current connects various shelf seas. These horizontal flows couple with a vertical overturning driven by water mass formation, creating a dynamic three-dimensional circulation, ventilating the ocean interior and redistributing nutrients globally⁷. Wind stress, mesoscale eddies, and sea-ice variability strongly influence this circulation, which now responds to rapid climate changes⁸. These rapid changes modify water mass formation, weakening Dense Shelf Water formation and changing surface transformation, with potential profound consequences for the overturning circulation and global biogeochemistry^{9,10}.

Southern Ocean Heat

Of the 90% of global energy increase that is taken up by the ocean, the Southern Ocean accounts for about 80-90% of industrial-period ocean heat uptake^{1,3}, largely driven by surface water uptake and subsequent export to lower latitudes via mode water formation. Despite this important heat uptake, surface waters south of the ACC show limited warming or even cooling prior to 2016. Instead, significant subsurface warming occurs below the winter mixed layer along the warm Circumpolar Deep Water (CDW) core, observed circumpolarly with a shallowing of this warm upwelling water¹¹. Drivers remain uncertain, potentially related to a combination of stratification changes due to increasing freshwater, shifts in wind forcing, and altered poleward eddy heat transport. This subsurface warming contributes to the negative sea-ice extent anomaly observed since 2016 as it reaches the surface following convective events¹², and has been implicated in enhanced heat flow onto Antarctic continental shelves driving ice shelf basal melt². Intrusions onto the Antarctic continental shelf as modified Circumpolar Deep Water occur across multiple sectors with pronounced zonal asymmetry and local drivers remain poorly understood.

Significant uncertainty remains about sources and mechanisms of subsurface warming. Some processes redistribute heat within the water column, whilst others add or subtract heat via surface fluxes, ice melt, or enhanced poleward transport. Changes in air-sea heat fluxes are poorly understood yet implicated in ongoing changes in water mass formation¹³. High-frequency extreme wind events, polynya formation, and associated mixing and convection remain very poorly observed. These uncertainties directly contribute to long-standing model biases in the Southern Ocean.

Southern Ocean Freshwater

Freshwater plays a central role in regulating Southern Ocean circulation by influencing salinity, density, stratification, and formation of deep and intermediate water masses. Salinity is also undergoing significant change. Off the continental shelf, surface salinity has declined since the 1970s, then reversed toward increasing salinity after 2015^{14,15}. Abyssal regions show long-term freshening^{10,16}, as do continental shelves including key bottom water formation areas although recent salinity increases have also been detected¹⁵.

Several processes contribute to these changes. Global warming intensifies the hydrological cycle, enhancing high-latitude precipitation¹⁷ and leading to surface freshening. Accelerating Antarctic Ice Sheet mass loss releases large meltwater volumes¹⁸. Seasonal sea-ice processes play a critical role: most Antarctic sea-ice forms near the coast and melts offshore, influencing water-mass transformation in both overturning cells¹⁴. Internal redistribution through upwelling, mixing, and lateral circulation modulates regional density patterns and feeds back onto overturning circulation. The relative contributions of precipitation, ice-sheet melt, sea-ice processes, and internal redistribution remain uncertain, limiting ability to predict how Southern Ocean circulation will evolve.

Southern Ocean Carbon

The Southern Ocean's capacity to absorb and store CO₂ results from the intricate interplay between biological, chemical and physical processes throughout the water column –including primary production, ocean mixing, freshwater input, wind-driven circulation, and sea-ice dynamics (link with theme 4)– which together govern the balance between regional CO₂ uptake and outgassing. These processes vary strongly on subseasonal, seasonal and multi-decadal timescales, translating into high temporal variability in the Southern Ocean's marine carbon cycle¹⁹. Spatial heterogeneity and Southern Ocean asymmetry due to dynamic circulation and ecosystems add another dimension of complex variability. Major observational gaps, particularly in winter and sea-ice-covered regions,^{20,21} lead to widely divergent estimates of the carbon sink's magnitude and long-term variability evolution, with models and observational products often showing different trends²².

While the carbon sink appeared to weaken in the 1990s²³, it rebounded rapidly in the 2000s, likely aided by strengthened surface stratification. However, below the winter mixed layer, an increase in carbon content is observed circumpolarly with a shallowing of the core of the upwelled carbon-rich Circumpolar Deep Water²⁴. Since major shifts occurred in the ocean-sea-ice system around 2015-2016¹², it remains uncertain how ongoing changes in both the solubility and the biological carbon pumps will influence the future strength and stability of this CO₂ sink. While the solubility pump drives both background and anthropogenic uptake, emerging evidence suggests that the biological pump, traditionally considered stable, may also be evolving. Given the Southern Ocean's outsized role in global anthropogenic CO₂ uptake, long-term storage, and sensitivity of its marine ecosystems to acidification, understanding the complex mechanisms driving the carbon sink across timescales is essential for predicting both regional and global carbon cycle dynamics under a changing climate.

Climate-Relevant Gases: methane and nitrous oxide

Methane (CH₄) and nitrous oxide (N₂O) are greenhouse gases whose atmospheric radiative capacity is very high compared to CO₂. Despite their importance, uncertainties remain whether the Southern Ocean behaves as a net sink or source of these greenhouse gases. Melting glaciers release CH₄ through meltwater inputs and subglacier discharge, with evidence that an increased release of these gases is occurring as climate change progresses in Antarctica. Other CH₄ sources include seafloor seeps, gas hydrates, active volcanoes, and hydrothermal vents. CH₄ dynamics in the Southern Ocean waters remain largely unknown. Scarcity of observations prevents constraining a CH₄ budget for Antarctica, while a shrinking cryosphere is enhancing CH₄ release into the atmosphere through seafloor and

seawater^{25,26}. Regarding N₂O, the global ocean is an important source, but an Antarctic circumpolar budget is lacking. N₂O is more abundant in intermediate and deep waters, so that change in circulation and deep-water upwelling may increase N₂O outgassing. In addition, changing micro- and macronutrient dynamics will affect plankton community composition, altering the biological production and consumption of CH₄ and N₂O. There are still many uncertainties regarding CH₄ and N₂O dynamics, which urgently needs clarification to better grasp expected change in CH₄ and N₂O fluxes in a rapidly changing Antarctic environment.

Micronutrients and Microbes

Parts of the Southern Ocean sustain one of Earth's most productive and seasonally dynamic marine ecosystems, while in others primary production is heavily limited. Phytoplankton blooms fuel food webs and play a pivotal role in regulating global organic carbon fluxes. Yet, the biological processes sustaining year-round productivity, especially during dark, cold months, remain poorly understood¹⁹. Unlike most ocean regions where nutrients like nitrate and phosphate limit productivity, the Southern Ocean is primarily limited by essential micronutrients, notably iron, manganese, and cofactor vitamins like B₁₂. Even subtle shifts can reshape microbial metabolism and ecosystem structure.

Nutrient gradients across fronts, shelves, and the seasonal ice zone impose strong selective pressures shaping microbial communities, including phytoplankton, bacteria, archaea, viruses and grazers, and their carbon and (micro)nutrient uptake. Physical, cryospheric and biological variability, including ligand availability, mixing regimes and cryospheric metal inputs, modulate micronutrient availability and speciation. Understanding of year-round microbial ecosystem function, (micro)nutrient utilisation and carbon uptake remains incomplete. Most observations concentrate in spring and summer. Far less is known about autumn and winter activity. Better mechanistic understanding of how physical, chemical, and biological processes interact through the annual cycle, and response to recent changes in sea-ice, is needed for improved understanding of current and future changes and their consequences²⁷.

2. Knowledge gaps and research needs

Despite the Southern Ocean's critical importance outlined above, fundamental gaps in our observational and modelling capabilities and process understanding severely limit our ability to predict future changes and their global consequences. This section identifies the most pressing knowledge gaps that must be addressed through coordinated research efforts during Antarctic InSync. The ability of Antarctica InSync to observe multiple regions over a short period of time should allow the community to address interactions between various Southern Ocean circulation features as well as non-local responses to forcing perturbations and the time scales over which they occur. Disentangling changes to water mass properties, water mass transformation rates, and the overturning circulation in a transient state is a challenging but critical task.

Air-Sea Heat Fluxes

One of the most significant and challenging gaps in the global observing network is the lack of measurements of air-sea heat fluxes over the Southern Ocean. Currently, high-quality direct in situ observations of air-sea heat fluxes are limited to a single mooring on the northern edge of the Southern Ocean²⁸, and to a handful of research vessels and autonomous surface vehicles, primarily in summer, which are not representative of many important winter physical regimes. There is an urgent need for innovative systems to conduct both direct and bulk-derived in situ measurements of turbulent and radiative heat fluxes. These require to be taken in the autumn-winter-spring period when observations are extremely scarce and in the southern-most domains of the Southern Ocean where current observation capability is limited in sea-ice impacted regions. Both in situ and satellite data must be used to refine physical parameterisations of these fluxes and improve the representation of air-sea heat fluxes

in numerical models. In addition to improved data coverage, synchronous observations of the air-sea flux with sea state, such as wave age and height, are required to improve bulk parameterisations for the unique wind-wave interactions of the Southern Ocean. Surface fluxes are crucial for correctly representing feedbacks in climate models and are currently not sufficiently constrained by observations in the Southern Ocean.

Antarctic Circumpolar Current

The ACC, driven by winds and density gradients and shaped by topography, acts as a dynamical barrier that forces water masses into spiralling pathways, modulating meridional heat and freshwater exchange between polar and lower-latitude regions. Topography-jet interactions in frontal regions are hotspots for submesoscale to mesoscale ocean variability, which are important for setting meridional pathways of heat, carbon, nutrient, as well as vertical pathways between the surface and deep ocean^{29,30}. These processes are often insufficiently sampled by observational platforms and inaccurately simulated by numerical models. Future changes in the Southern Ocean will affect this major three-dimensional dynamical current system and its global impact, but in ways that remain highly uncertain because of persisting lack of process understanding of how dynamical and thermodynamical change will unfold^{31, 32}. Numerical models unable to resolve mesoscale eddies have been shown to inaccurately simulate the response of the ACC and of the meridional overturning circulation to climate change, highlighting the need for improved resolution and/or parameterization of eddy processes. In addition, while fronts of the ACC have been recognized to act as important biogeographical boundaries that have led to distinct Antarctic ecosystems, high levels of endemism, and extreme physiological traits³³, the ecosystem impacts of ongoing change in the ACC system remains very poorly understood.

Upper Ocean Circulation and Water Mass Renewal

Our understanding of the circulation of the upper ocean in the ice-covered Southern Ocean is severely limited due to a lack of year-round observations, particularly during the autumn, winter and spring months, when key transformation processes occur. The seasonal cycle of water mass properties over continental shelves and within the marginal ice zone is not well understood, which hinders our ability to understand and model how sea-ice formation and melting drive changes in stratification and transform deep waters into lighter or denser water masses. In particular, there are critical gaps in our understanding of the mechanisms by which deep waters upwell and transform into surface waters through interactions with the mixed layer base, sea-ice and the atmosphere, and how deep waters exchange with the continental shelf water masses across the Antarctic Slope Front. These processes are central to the Southern Ocean overturning circulation, and thus key to: delivering heat towards Antarctica; controlling the intensity of the Southern Ocean anthropogenic heat sink; setting the rate of natural CO₂ outgassing; absorbing anthropogenic carbon; supplying micronutrients to surface ecosystems; and contributing to the global redistribution of macronutrients, supporting low latitude primary production. Many other important knowledge gaps are associated with the entrainment and mixing due to intense near-surface buoyancy fluxes, whilst the role of finescale, mesoscale and submesoscale processes in mediating vertical and horizontal exchanges and mixing also remains poorly quantified, particularly due to the lack of direct observations near and under sea-ice. As models steadily advance to explicitly resolve these processes, observational support for validation is increasingly required.

Antarctic Bottom Water Formation and Export

Antarctic Bottom Water (AABW) remains poorly observed due to the difficulty of accessing formation sites and remote export pathways. Attributing drivers to trends in exported AABW properties, notably warming, freshening, and lightening¹⁰, is therefore extremely difficult. Lack of process understanding inhibits accurate modelling of AABW properties downslope overflow, particularly in climate models where this is an acknowledged high-priority weakness. The fundamental reason for these gaps is a lack

of autumn and wintertime observations of ocean stratification and dense shelf water formation on the Antarctic continental shelf, as well as subsequent off-shelf export and entrainment. Full-depth observations of seasonal shelf water mass properties are needed to characterize the properties of the AABW precursor water mass, AABW formation processes, and variability¹⁶. Process understanding requires improved observations of sea-ice formation rates, air-sea heat fluxes, and atmospheric properties driving ocean heat loss. Following dense shelf water formation, the process of overflow from the continental shelf to the abyss (particularly gravity-driven cascading and turbulent entrainment) remains largely unknown, and contributes to the difficulty of representing AABW formation in numerical ocean models. Some limited observations of this process exist, but the role of topography in setting these conditions, interannual variability and spatial evolution of properties/mixing rates, and biogeochemical consequences thereof, are largely unknown. Although there are some observations of the subsequent export of AABW from the Weddell and Ross Seas via mooring arrays, these are limited in their spatial and temporal extent. Meanwhile, the export from the Amery/Cape Darnley and other East Antarctic formation sites remains largely unconstrained.

Continental Shelf Processes

The Antarctic continental shelves remain among the most poorly observed regions on Earth despite their critical role in mediating heat and freshwater exchanges between the open ocean and ice shelves. The continental shelf serves as the primary site for dense shelf water formation discussed in the previous paragraph, and for Circumpolar Deep Water intrusions onto the continental shelf that impact ice shelf stability and Antarctic Ice Shelf mass loss. Moreover, these regions are among the most productive on Earth, sustaining the unique ecosystems, contributing to carbon uptake, and remaining particularly vulnerable to acidification. Yet the processes that support this productivity, e.g. iron supply, and the ecosystem responses to acidification remain poorly constrained. Year-round observations of continental shelf water properties are almost entirely absent, particularly during winter when crucial water-mass transformation processes occur. This observational void severely limits our understanding of why changes are occurring, such as the link between warm intrusions and dense shelf water freshening, or between counter-intuitive increasing salinity in the Ross Sea and massive freshwater inputs from accelerating glacial discharge in adjacent sectors. In addition, recent observations stress the importance of zonal contrasts in background water-mass structure, wind forcing, and the strength of coastal currents shaping substantial regional variability across Antarctica that demand coordinated observations in various dynamical sectors. In the Atlantic sector of the Southern Ocean, a potential shift from a cold-shelf to warm-shelf regime was proposed, where the interplay between freshwater advection from the east and dense water formation on the Southern Weddell continental shelf determines heat supply to the Filchner Ronne ice shelf^{34,35}. Mechanisms governing cross-shelf exchange, including eddies, topographic interactions, tidal forcing, and slope current variability, together with poorly constrained vertical mixing processes that regulate heat and freshwater fluxes between water masses, remain poorly characterized. Critical gaps also exist in understanding lateral transport and mixing of water masses along the continental shelf, which may link upstream changes in one sector to downstream impacts in another region¹⁶.

Freshwater Budget Components

Salinity is influenced by several processes including precipitation, evaporation, sea ice formation and melting, advection of snow on sea ice, land ice melt, and internal ocean redistribution by ocean circulation. Precipitation observations are sparse, limited to a few stations and ship-based campaigns. The community primarily relies on models and reanalysis products, which struggle to accurately represent precipitation, particularly in coastal regions. Land ice is often not properly represented in models lacking interactive ice sheets and thus melt estimates depend on satellite observations and models. This leaves significant uncertainties in the temporal and spatial variability of freshwater inputs.

There remains large discrepancies between in situ and satellite-based ice shelf melt estimates², resulting in large scenario uncertainty for model projections³⁶. Improved satellite estimates combined with coordinated calibration-validation experiments are essential. Sea-ice induced freshwater flux is limited by our knowledge of snow depth, ice and snow density, and thickness, which hinders efforts to quantify changes in sea-ice mass and freshwater fluxes. Internal salt redistribution through circulation and mixing can alter local salinity, influencing large-scale overturning, but observation of this redistribution is limited by poor observational coverage of circulation and mixing¹⁶. Expanded in situ observations of all of these variables, e.g. from autonomous platforms, are urgently required to better quantify the Southern Ocean freshwater cycle. Although chemical tracers such as oxygen isotopes and noble gases are valuable tools for quantifying the contributions of different freshwater sources, time series length and laboratory intercomparison must be improved to understand long-term changes.

Southern Ocean Carbon Sink

Processes governing the Southern Ocean carbon sink remain poorly constrained. Spatial and seasonal data gaps, particularly during autumn, winter, and spring as well as in sea-ice-covered regions, limit our ability to characterize air-sea CO₂ exchange, carbon export and storage. Recent estimates suggest the release of ancient natural carbon may be much larger than previously thought³⁷. Even in summer, understanding of the drivers of the net CO₂ fluxes is limited because of the complex biological and physical processes that govern it, which requires sustained high-resolution measurements and process studies to disentangle process contributions and reduce discrepancies in flux estimates^{19,22}. CO₂ air-sea exchanges are tightly coupled to ocean interior dynamics (e.g. carbon export, vertical mixing, and carbon transport), which can create hotspots of exchanges in specific regions, but the relative contribution of these compared to the wider-scale open ocean fluxes remains poorly quantified. Sea-ice dynamics and freshwater input to the ocean modulate vertical ocean connectivity and associated carbon pathways. Ongoing shifts in sea-ice regimes¹² and salinity¹⁵ are increasing uncertainty in the long-term capacity of the Southern Ocean to mitigate climate change through CO₂ uptake and storage. Addressing these uncertainties requires sustained, year-round observations integrating ship-based measurements, process studies, and autonomous platforms, including maintaining the international array of autonomous floats capable of observing biogeochemical variables relevant to CO₂ fluxes (BGC-Argo). These observations are central for the production of observational products, which require sophisticated machine learning methods, and for the evaluation of ocean biogeochemical models, which are still affected by major biases including incorrect seasonality and decadal variability of air-sea CO₂ fluxes as well as surface to interior carbon sequestration.

Climate-Relevant Gases methane (CH₄) and nitrous oxide (N₂O)

There is an overall lack of CH₄ and N₂O observations, with most concentrated observations found in some parts of Antarctica (e.g. Antarctic Peninsula) while large regions like the Amundsen-Bellinghousen Sea remain unobserved despite their potential critical role due to their very high glacier melting rates that are potentially releasing large amounts of CH₄. Similarly, there is information of CH₄ seeps in the Ross Sea whereas there is no information for the rest of Antarctica. Due to multiple sources and sinks, the spatiotemporal variability of CH₄ and N₂O concentration is larger than for other gases (CO₂), requiring observations at broad temporal and spatial coverage. There is currently very limited data on CH₄ concentrations in potential sources like meltwater, groundwater, lakes, glacial streams, soils, marine seeps and gas hydrates. Similar to intermediate and deep waters for N₂O. Without constraining these sources, producing a CH₄ and N₂O budget is impossible. CH₄ seeps have only been mapped around the Ross Sea. Bathymetric and acoustic data may help map seeps elsewhere, while concurrent atmospheric observations are needed to assess air-sea fluxes. Incubation experiments are needed to measure production and consumption rates along with genetic data showing which processes dominate. There is no data on potential CH₄ reservoirs beneath the Antarctic ice sheet.

Micronutrients and Microbial Interactions

To advance our understanding of the critical role that micronutrients and microbial interactions play in biogeochemical cycles, carbon fluxes and transformations in the Southern Ocean, a coordinated, interdisciplinary approach is essential. A particularly urgent need is to elucidate how microbial communities sustain activity throughout the extreme seasonal cycle. Physiological and ecological strategies enabling survival under cold, dark winter conditions remain largely unknown as are the metabolic needs and costs. Roles of grazers, viruses, and detrital processes in modulating carbon fluxes and nutrient recycling are poorly constrained¹⁹. On the physicochemical side, a better understanding is needed of how physical and chemical processes regulate seasonal supply, transformation, and bioavailability of micronutrients²⁷. This includes the influence of circulation, mixing, upwelling of deeper metal-rich waters (island, seamount or submarine canyon fertilization effects), dust deposition, and cryospheric inputs, on the timing, localization and magnitude of micronutrient delivery and subsequent biological responses and carbon uptake. Additionally, the roles of redox transformations, organic ligands, and particle interactions require further investigation. The relative contributions of atmospheric deposition, sediment resuspension, and glacial inputs to regional and seasonal variability in micronutrient supply—and their downstream effects on biogeochemical cycles and carbon cycling – need additional attention. The impact of anthropogenic contaminant metals, such as mercury or lead, on microbial processes and biogeochemical cycles in the Southern Ocean is addressed in Theme 5.

3. Observing strategies and essential variables

Addressing the knowledge gaps identified in Section 2 requires a coordinated, multi-national observing strategy that leverages diverse platforms and standardized methodologies. Indeed, many of the key processes identified above vary substantially across Antarctic sectors and often occur in regions that remain chronically under-observed, such as the marginal ice zone, shelf break, and coastal current systems, particularly in autumn and winter. This section outlines an observational strategy that is designed to capture both circumpolar coherence and regional differences, with an emphasis on platforms capable of accessing these challenging environments. To enlarge the scientific value of newly collected data, we recommend integrating numerical modeling and machine learning in observational programs or at least an intense exchange with respective experts. Numerical models can be used, in combination with machine learning, to inform observational sampling strategies and to constrain uncertainties related scarce sampling. Machine learning methods can be used to fill observational data gaps and to fuse different observation types, as well as to improve model parameterizations of key sub-grid processes.

Observational Strategies

Antarctic InSync represents an opportunity for multi-national coordinated observing campaigns. Optimal strategies will address multiple gaps and provide platforms for multidisciplinary work whilst leveraging coordination and data sharing to produce synchronous and circumpolar datasets. Key target areas include regions of significant water mass transformation, such as glacial melt outflows, major polynyas, AABW export pathways, subpolar gyre inflow and outflow regions, deep water upwelling and intermediate and mode water formation regions.

A clear requirement has emerged for seasonal resolution of ocean, sea-ice, and atmospheric processes responsible for upwelling of carbon, heat, and nutrient-rich circumpolar deep waters, particularly in the vastly under-observed autumn, winter, and spring seasons. This would help reconcile discrepancies between observational and model estimates of CO₂ fluxes, validating available satellite observations, identify hotspots of heat exchange between the atmosphere and ocean interior, provide insights into processes delivering heat to the surface implicated in recent sea-ice loss, and provide a platform for

understanding micronutrient delivery and ecological preconditioning prior to spring blooms. Combined with ongoing multi-year autonomous instrumentation, coordinated semi-synchronous, quasi-circumpolar ship-based observations on the northern marginal ice zone and key frontal regions of the ACC outside summer would provide cornerstone datasets during the InSync observing period, to close model-observational gaps in climate-relevant ocean-atmosphere exchanges and key biogeochemical cycles. InSync's biogeochemical observing strategy must be adaptive since the processes governing cycling in productive (marginal sea ice zone, continental shelf and waters) and non-productive (open waters) areas occur at different space-time scales. The InSync observing period should also be targeted for bringing the circumpolar Argo profiling float array, including biogeochemical and deep as well as core Argo, to full design strength.

A second major gap is the seasonal cycle of the ice-covered ocean, particularly continental shelves. Two priorities were identified. First, recent studies have indicated that extending a float-based observing system over the continental shelf is a robust way to monitor hydrographic properties throughout the year and in extreme environments. Floats have already captured multiple seasonal cycles of the shelf surface mixed layer^{38,39}, under-ice shelf circulation and ocean-ice exchange⁴⁰, and eddy transport at an ice-shelf face⁴¹. Extensive deployments of such floats (including BGC-floats) from routine summer voyages would revolutionize shelf coverage. Advantages of the floats include well-understood data infrastructure, inexpensive instruments, and low logistical footprint. The second is to develop targeted year-round shelf observations through mooring arrays including the upper water column. Deployment strategies would target important choke points and water mass transformation regions such as deep-water pathways, coastal currents near ice shelves, dense shelf water formation sites, and bottom water export pathways. Other promising approaches involve extending sound source mooring arrays to permit under-ice navigation of Autonomous Underwater Vehicles and gliders, and to geolocate under-ice Argo-style floats in targeted regions.

Synchronous deployments, supplemented by in situ biogeochemical and biological sampling, would add significant value by filling regional gaps linking water flow from one region to another as well as the drivers of biological carbon pump in these seasonally extremely productive regions. Case study regions could include year-round shelf observations between the Amundsen-Bellingshausen Seas and the Ross Sea, linking ice shelf melt-focused programmes with regions where freshwater delivery changes are implicated in sea-ice and bottom water variability. Another two example locations are the southwest Weddell Sea in front of the Ronne Ice Shelf, the largest unobserved ocean region and a primary formation site of dense shelf water, and Cape Adare, which connects West Antarctica to East Antarctica, but could include others.

Seafloor-sea-air fluxes are extremely variable in space and time. Due to complex processes at all scales, we lack capability to identify drivers. Gaps in surface flux measurements across a multitude of dynamical ocean regimes, and particularly during winter, represent some of the largest global ocean data deserts. One impactful strategy to solve this gap would rely on a coordinated, multi-platform observing system, building on existing international coordination efforts such as GO-SHIP and SOCONET. By leveraging and complementing existing underway systems of all InSync vessels with consistent calibration and data-sharing procedures, we would expand circumpolar coverage while capturing variability of near-coastal and near-sea-ice environments. Another emerging technology that can play an important role in filling the data desert is the free-drifting expendable spar buoy. Spar buoys deployed across targeted regimes of air-sea flux variability can provide the much-needed full annual cycle of direct covariance and bulk flux measurements. Bringing together ships, moorings and autonomous platforms – including USVs, gliders, and surface buoys – InSync would provide sustained observation of fluxes and co-located upper ocean processes, including vertical velocities, turbulence and mixed layer dynamics, in key dynamical regions to capture fine-scale variability.

To better understand the critical role of micronutrients and microbial interactions in the Southern Ocean, connecting the GEOTRACES and BioGeoSCAPES communities would enable standardized measurements of micronutrients, contaminant metals, and microbial processes. Coordinated, seasonally resolved field campaigns, complemented by autonomous platforms, could address critical gaps if a minimum core set of measurements were acquired in a coordinated manner: (1) micronutrient and contaminant metal concentrations, (2) the rate of at least one key process and (3) omics datasets (e.g. metagenomics, transcriptomics and metabolomics). This integrated approach would enable us to establish mechanistic linkages between chemical, biological and metabolic processes, including drivers of air-sea fluxes.

Thematic Variables

To address key knowledge gaps, we promote the implementation of the above observation strategy, focusing on a core set of multidisciplinary variables that are consistently measured on all feasible platforms. This will eventually result in the establishment of a year-round, pan-Antarctic key dataset. Essential to all topics are basic oceanographic parameters: salinity, temperature, and pressure, defining physical structure of water masses, plus where feasible, horizontal and vertical velocity measurements to monitor currents and transport. Complementary information on sea-ice (thickness, type, density, surface freeze-up and melt time) is fundamental for understanding ocean variability and change, as well as sea-ice changes driven by atmospheric and oceanic processes. Air-sea fluxes of heat, freshwater, and momentum are also fundamental, notably including the turbulent (air temperature, humidity, wind, sea surface temperature) as well as radiative (long and shortwave) components of heat. Observations of significant wave height and wave period are further needed to refine the bulk air-sea flux formula for the unique sea state of the Southern Ocean. Such key quantities should ideally also be available from model output and their definition thus be discussed among observational and modeling communities.

Marine chemical observations of highest priority to address InSync Theme 1 include dissolved oxygen, oxygen isotopes, marine carbonate system (CO_2 partial pressure/dissolved inorganic carbon/total alkalinity/pH; at least two parameters measured simultaneously), macro- (nitrate, phosphate, silicate) and micronutrients (at least iron and manganese), and climate-relevant gases (carbon dioxide, methane, nitrous oxide in seawater as well as a potential hydrological, geological and atmospheric sources). These variables allow investigations into biogeochemical processes and are necessary for sensor calibration. Seafloor-sea-air fluxes require hydrological, geological, atmospheric and seawater observations plus meteorological variables driving flux strength.

To assess the role of the biological component in seafloor-sea-air fluxes as well as transformation, transport and biogeochemical cycling, abundance or biomass observations (e.g. chlorophyll, particulate and dissolved organic carbon, colored dissolved organic matter) are required along with process rates (e.g. rates of nutrient uptake, primary production, grazing, viral lysis) and omics data (e.g. genomic, transcriptomic, metabolomic) to identify the actors in these processes. Sampling and measurement protocols should be standardized to ensure consistent and intercomparable datasets.

Platforms

The fundamental basis for marine data collection for Theme 1 during Antarctica InSync depends on synchronised expeditions with research vessels with varying ice-breaking capabilities. These research vessels are essential for collecting highest quality data, calibration for autonomous platforms and Earth Observation data, field access, instrument deployment and performing field experiments. As access to research vessels is limited, an international sharing of these resources (ship time, berth, shared instrumentation, co-deployment and recovery of instruments) is critical for the success of Antarctica InSync. Important new opportunities for field access in coastal regions in summertime arise from a fleet of sailing vessels that enable targeted sample collection and light weight instrument deployments on

the continental shelf. On a large-scale underway data collection and instrument deployment should be supported by sailing vessels and ships of opportunity during summer. Underway data collection is complemented by autonomous vehicles for surface fluxes and profiling glider missions for underwater high-resolution ocean processes.

Year-round vertical profiles of physical and biogeochemical seawater properties should be collected by Argo and sensors on instrumented marine mammals to provide a circumpolar picture of the upper Southern Ocean. A particular focus should be given to under-ice observations with Argo floats, ice-tethered buoys, and moorings deployed at the start of the program to monitor the system throughout the Antarctica InSync period. Acoustic positioning (Argo) and navigation (gliders) through sound sources should improve under-ice observational data collection. Continued technological developments of BGC-Argo floats — including zooplankton imaging systems, micro-sonars targeting micronekton, and direct pCO₂ and pH sensors — will substantially improve the quantification of the oceanic carbon sink and provide a better understanding of ecosystem functioning. We recommend monitoring the large-scale inflow of CDW and outflow of AABW with dedicated mooring arrays at strategic chokepoints in the subpolar gyres. On the continental shelf, year-round oceanographic observations should be obtained through bottom landing Argo floats as well as strategically deployed moorings to monitor along- and across-shelf heat and freshwater transport and dense water formation sites such as polynyas.

4. Summary

While the Southern Ocean plays an outsized role in Earth's climate, fundamental gaps in year-round observations, particularly during autumn, winter, and spring, severely constrain our understanding of the complex interplay between physical circulation, air-sea interactions, ocean-cryosphere interactions, biogeochemical cycles, and ecosystem dynamics. The difficulty by climate models to correctly project variability and trends in the Southern Ocean, which is even more highlighted by the dramatic and unexpected 2014 sea-ice high, 2015-2016 regime shift, and subsequent sea-ice decline underscore the urgent need for sustained, coordinated observations.

Antarctic InSync represents a unique opportunity to address these gaps and biases through multinational coordination, and is perfectly time to prepare for a successful fifth International Polar Year. By strategically deploying year-round autonomous platforms, coordinating seasonal ship-based campaigns, standardizing measurements, and sharing resources internationally, we can achieve the first comprehensive, pan-Antarctic dataset spanning physical, chemical, and biological domains. Such effort is most welcomed by the modelling community offering unique opportunities for close collaboration⁴². Priority regions include the marginal ice zone where heat and carbon-rich deep waters upwell, continental shelves where dense water formation occurs, and observing processes and regions controlling water mass exchanges.

The observing strategy emphasizes multi-platform, multidisciplinary approaches leveraging existing infrastructure, while developing new capabilities for ice-covered regions. Coordinated deployments of Argo floats (with BGC capability), moorings, gliders, uncrewed surface vehicles, and standardized ship-based measurements will provide unprecedented coverage. Integration with satellite Earth Observations, advanced modeling and novel machine learning methods will maximize scientific return.

Success requires formalized international collaboration including shared ship time and infrastructure, coordinated platform deployments, standardized protocols, and open data sharing aligned with established international infrastructures. The scientific return will be transformational: constraining the Southern Ocean's role in global heat and carbon budgets, understanding ecosystem responses to rapid change, and providing the observational foundation needed to reduce uncertainty in climate models.

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Antarctica InSync Scientific Theme 2

Rapid sea ice decline and its causes and consequences

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Executive Summary

Since 2015, Antarctic sea ice has entered a period of persistent record-low extent after decades of strong regional variability and large swings. The speed and persistence of this decline point to a system that may be changing state, with implications for the Southern Ocean, Antarctic ecosystems, and the global climate system. What is driving this shift remains insufficiently understood. Atmospheric variability plays a role, but ocean processes, including subsurface heat release and changes in stratification, are increasingly recognized as key pieces of the puzzle, alongside feedbacks involving snow, ice shelves, clouds, and freshwater input.

This white paper focuses on four areas where progress is needed. First, improved understanding is needed of sea ice mass balance and dynamics: how sea ice grows, melts, moves, and deforms. Second, exchanges of heat, mass, and momentum between ocean, atmosphere, sea ice, and ice shelves need to be quantified across seasons and regions. Third, the consequences for ecosystems and biogeochemistry are likely substantial. Sea ice supports productive microbial communities and carbon and nutrient cycling, so its decline will affect polar food webs and Southern Ocean carbon storage. Finally, climate feedbacks, from albedo changes to cloud and ocean interactions, remain poorly constrained but could amplify ongoing change.

A recurring limitation is the lack of coordinated, year-round observations across Antarctica. Existing data are sparse and uneven in space and time. Antarctica InSync is designed to address this by bringing together satellite observations, autonomous platforms, field campaigns, coastal observatories, harmonized data products, and modelling across pack ice, the marginal ice zone, landfast ice, and polynyas. The white paper recommends standardized observations of essential sea ice, snow, ocean, atmospheric, ecosystem, and biogeochemical variables, integrated into interoperable data products and models. Addressing these gaps is essential to improve predictability and anticipate future Antarctic sea ice change.

1. Motivation and background

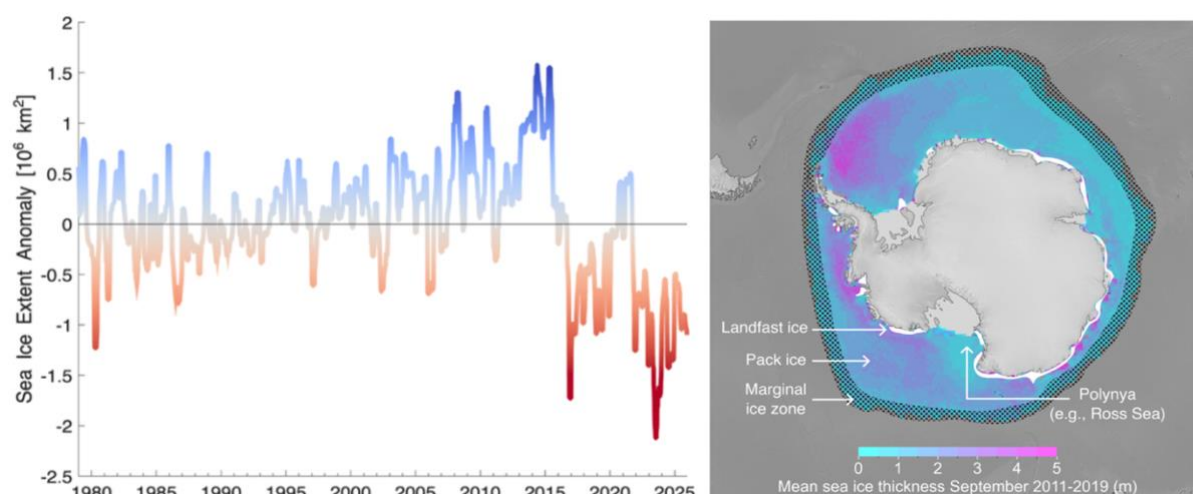


Figure 1: Left: Antarctic sea ice extent anomalies for 1979 – 2025 (smoothed (90-day median) daily anomalies in reference to the 1979–2025 seasonal cycle; satellite data: meereisportal.de). Right: Mean sea ice thickness for September derived from CryoSat-2 over 2011-2019 ([ESA Climate Change Initiative, Sea Ice Mass Balance Assessment: Southern Ocean](#)). The dotted area indicates schematically the marginal ice zone, while the white areas show landfast ice, with polynyas regularly forming alongside.

After a long, slow increase over previous decades, Antarctic sea ice has since 2015 rapidly decreased, with the five lowest summer sea ice extent minima of the satellite era in the last nine years and the three lowest winter sea ice maxima in the last three years (Figure 1). These well-documented changes in sea ice characteristics could reflect a regime shift in the Southern Ocean and Antarctic climate system¹. Sustained Antarctic sea ice loss would have significant impacts on the climate system, including implications for the radiation balance, the atmosphere and ocean with globally important processes such as water mass transformation, heat and carbon budgets, the stability of glaciers and ice shelves, and the key functions of Antarctic marine ecosystems². Despite this importance, large gaps remain in understanding the drivers of recent changes, including the pre-2015 increase in overall sea ice extent followed by the abrupt post-2015 decline (Figure 1). We identified four overarching topics that are essential for making progress in understanding the rapid sea ice decline, its causes and consequences, outlined in the next paragraphs.

Sea Ice Mass Balance and Dynamics

The recent rapid sea ice decline has an obvious direct impact on the sea ice mass balance, but also on how sea ice drifts and deforms. The responsible processes and feedbacks are, however, poorly understood, in part due to a lack of long-term, robust observations of sea ice (mass, drift, internal properties), and of the overlying snow (coverage, depth, and properties)³. Climate models project continued Antarctic sea ice decrease as the planet warms⁴ and indicate that internal variability alone is unlikely to explain recent losses⁵. To confidently attribute the effects of anthropogenic carbon emissions to Antarctic sea ice loss, and predict its future, we need to understand the physical mechanisms across the range of temporal (link to Theme 7) and spatial scales (link to Earth Observation (EO) group Whitepaper) that are driving recent extreme variability. In this context, coordinated research efforts are urgently needed.

Coupled Ocean–Sea Ice–Atmosphere–Ice Sheet Interactions

Sea ice variability is primarily driven by changes in the atmosphere (link to Theme 6) and ocean (link to Theme 1). Over most of the satellite record starting in the 1970s, Antarctic sea-ice variability has

generally been consistent with atmospheric forcing, such as changes in the strength and position of the circumpolar westerly winds¹, which modify wind and temperature patterns, and thereby influence sea-ice dynamics, freezing rates, and growth⁶. While the atmosphere and related surface energy budget, including an enhanced cloud-radiative feedback (link to Theme 6), is implicated in recent losses¹, it is becoming increasingly evident that atmosphere forcing alone cannot explain the recent extreme sea ice loss. The ocean must be a major driving factor, with hypotheses including release of accumulated subsurface heat via increased upwelling of relatively warm deep waters⁷, and the surface accumulation of solar radiation from consecutive low sea ice summers⁸. However, complex, possibly competing effects are also at play: increased meltwater release from ice shelves (link to Theme 3) and icebergs can substantially stratify the ocean and increase sea ice growth, which in turn affects regional ocean circulation, with possible feedbacks on ice shelf melting⁹.

Ecosystem and Biogeochemical Responses

Sea ice in the Southern Ocean is a critical regulator of the Earth's climate system and ocean biogeochemistry^{4,10} (link to Themes 4 and 6). Beyond its radiative role, sea ice modulates air-sea exchange of carbon and other trace gases, influences aerosol formation, and shapes the coupling between the ocean and atmosphere¹¹. Its brine network hosts dense, highly active microbial communities that sustain intense primary production and drive key transformations in the carbon and nutrient cycles, including nitrogen, silicon, phosphorus, sulphur, and iron^{12,13}. Ice algae can reach some of the highest chlorophyll-a concentrations observed in aquatic environments and together with pelagic phytoplankton form the foundation of polar food webs, supporting key species such as Antarctic krill (link to Theme 4,¹⁴). Ice-associated production also contributes to the biological carbon pump (link to Theme 1) through the formation of sinking aggregates¹⁵, while microbial nitrogen transformation regulates nitrogen availability for downstream ecosystems¹³. During melt, sea ice releases concentrated bioavailable iron, stimulating phytoplankton blooms in the otherwise iron-limited Southern Ocean¹⁶. In addition, sea ice microorganisms produce dimethylated sulphur compounds¹⁷ and other trace gases that act as precursors of cloud-condensation nuclei, linking sea-ice biogeochemistry directly to atmospheric chemistry and climate feedbacks. Despite this central role, the contribution of sea ice to these interconnected processes remains poorly constrained. The recent and unprecedented retreat of Antarctic sea ice raises urgent questions about future carbon sequestration, nutrient regeneration, atmospheric chemical processing, and climate regulation in the Southern Ocean, as well as about how changes in sea-ice seasonality affect the phenology of primary production and associated food webs.

Climate Feedbacks

The rapid decline of Antarctic sea ice is suspected to have profound implications for the global climate system. Changes in the sea ice cover influence the global distribution of atmospheric heat and moisture, as well as atmospheric variability and several teleconnections. Changes in air-ice-ocean interactions related to Antarctic sea ice retreat involve several air-sea-ice processes and feedbacks, according to recent studies¹⁸. Indeed, the Antarctic sea ice region is subject to numerous feedback processes, which can either amplify or dampen sea ice loss¹⁹. Key feedbacks for sea ice coverage include radiative feedbacks, in particular the ice-albedo feedback, snow feedbacks, several ice-ocean feedbacks, atmospheric and cloud feedbacks (either positive or negative), and feedbacks from continental ice forms such as ice shelves and icebergs (mostly negative). Of these, not all are known in the same degree of detail. Possibly critical aspects include the storage of heat in and its entrainment from the ocean subsurface, the response of clouds to sea ice loss, with implications for air-sea fluxes of moisture and biogenic aerosols, essential to the formation of Southern Ocean clouds²⁰, and the effect of increased continental ice melting on sea ice growth and melt via changes in ocean stratification. The future response of Antarctic sea ice will depend on the combined effects of all these processes and feedbacks. However, which will dominate is difficult to say without a detailed process understanding. Given

substantial observation gaps in the polar Southern Ocean, a coordinated circumpolar effort will largely help advance understanding of these processes.

The Urgency of Circumpolar, Year-round Observations

Antarctica InSync addresses the critical need for coordinated year-round, circumpolar observations of key sea ice properties to capture sea ice's relevant spatial and seasonal variability. The relatively short temporal scales over which significant changes in the sea ice system occur, circumpolar observations are crucial for addressing the causes and consequences of rapid sea ice decline. Current data coverage is sparse and fragmented, with most measurements concentrated in spring and limited to locations that are accessible through national polar programs. The Antarctica InSync multinational effort enables the coordinated and standardized acquisition of unprecedented high-resolution observations of key sea ice variables: ice thickness and snow depth, drift and deformation, and ice biological and biogeochemical properties, measured across diverse Antarctic environments and over a full seasonal cycle. A central outcome will be the aggregation of all available Antarctic sea ice data, including historical records, autonomous measurements, satellite products, and new results from the Antarctica InSync campaign. To ensure accessibility and interoperability of the aggregated datasets, Antarctica InSync will support the development of standardized tools that automatically extract, harmonize, and annotate relevant data and metadata. These efforts will contribute to the Southern Ocean Observing System (SOOS) data portal, SOOSmap, providing an advanced querying interface for researchers, forecasters, and modelers.

By establishing a unified, comprehensive data infrastructure, Antarctica InSync will lay the foundation for transformative progress in understanding and predicting Antarctic sea ice dynamics.

Antarctica InSync can provide major progress for the understanding of the four overarching topics discussed above, which lead us to the following four research questions (RQ):

- **Sea Ice Mass Balance and Dynamics:** What coupled (thermodynamic and dynamic) processes and feedbacks are responsible for rapid sea ice decline, and how do they vary around Antarctica and over time? **(RQ1)**
- **Coupled Ocean–Sea Ice–Atmosphere–Ice Sheet Exchanges:** How do exchanges of mass, heat, and momentum between sea ice and other components of the Earth System (ocean, atmosphere, ice sheet) drive rapid sea ice decline? **(RQ2)**
- **Ecosystem and Biogeochemical Responses:** What are the consequences of rapid sea ice decline on the ecosystem dynamics and biogeochemical processes in the Southern Ocean? **(RQ3)**
- **Climate Implications and Feedbacks:** How does the rapid sea ice decline impact the global climate system and amplify climate change? **(RQ4)**

2. Knowledge gaps and research needs

Theme 2 | Key processes

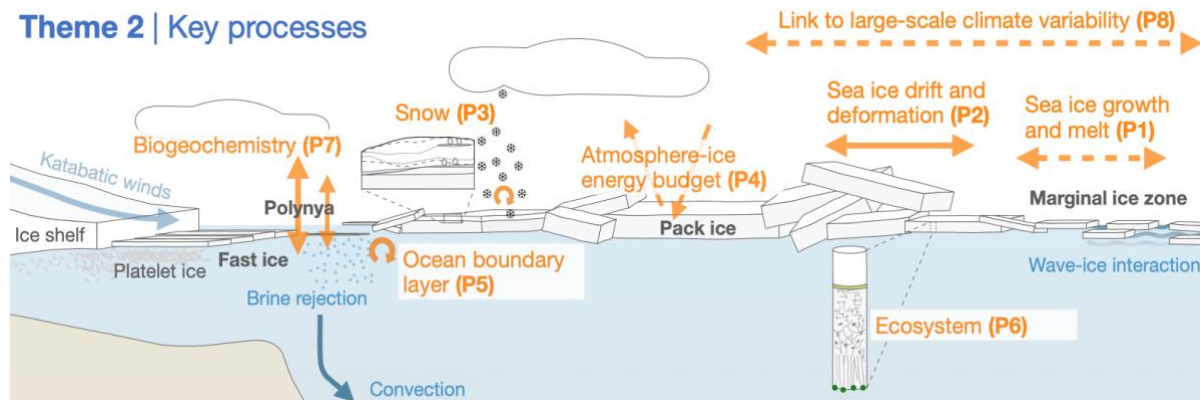


Figure 2: Schematic of the outlined key processes (P1-8) relevant for Theme 2.

Addressing the four overarching research questions requires a process-based understanding of key thermodynamic, dynamic, and biogeochemical (BGC) processes, with emphasis on current knowledge gaps and research needs. Also, the complexity in ice and snow structure poses **Antarctic-specific challenges for Earth Observation** (see EO group White paper), as unresolved internal boundaries and the limited availability of in-situ observations reduce confidence in satellite-based assessments. The observable key variables (highlighted in bold below and summarized in Table 1) are needed to increase our knowledge of the identified key processes (P1-8) and are essential for guiding future observing strategies, outlined in section 3: Observing strategies and essential variables.

Sea ice growth and melt (P1)

The annual cycle of Antarctic sea ice growth and melt is one of the largest seasonal signals on Earth, but it has never been observed directly in its entirety and over all seasons. In autumn and winter, sea ice forms and grows in response to **ocean heat loss**, leading to large-scale **sea ice concentration/area** changes. Frazil ice crystals develop in open water around the ice pack, in **leads** and polynyas, and below sea ice with associated brine rejection into the ocean. These crystals eventually consolidate into floes through the so-called “pancake ice cycle” in a turbulent Southern Ocean. The ice thickens via vertical **heat fluxes**, rafting, and **ridging**. In spring-summer, increasing solar radiation increases the availability of ocean and atmospheric heat, triggering surface, lateral, and basal sea ice melt. The **snow and ice temperature** profile gets more isothermal and remaining **salt** is released into the ocean affecting the **density** of the ice. The **sea ice age** increases for ice that survives the summer becoming second-year and, in rare cases, multiyear ice after the next summer. The thermodynamic evolution of sea ice is strongly affected by snow, due to the low snow thermal conductivity and highly **reflective properties (albedo)**. Snow contributes to **sea ice thickness** by forming **snow-ice**, when basal snow layers flood and refreeze, a process common in Southern Ocean regions with high **snow depth**. Knowledge gaps remain in understanding sea ice growth from pancake ice to larger **floes of different size**, and in particular the relative contributions of different growth modes such as frazil, congelation, snow-ice, and **superimposed ice**, preserved in **sea ice crystal microstructure**, multiphase composition, and **stable isotopes**. Additionally, the magnitude and drivers of surface, basal, and lateral melt remain poorly constrained, limiting predictive skill in sea ice models (link to modelling) under changing climate conditions.

Sea ice drift and deformation (P2)

Sea ice breaks up, drifts, and deforms under the combined influence of **wind and ocean stress**, **internal ice stress**, and Earth’s rotation. **Sea ice drift** and level of fragmentation define distinct sub-ice zones:

landfast ice remains largely immobile; pack ice drifts horizontally; and the marginal ice zone experiences additional vertical motion under the influence of waves. Antarctic pack ice drift pattern is dominated by an intense westward coastal current, the Weddell, Ross, and Prydz Bay gyres, and an overall eastward drift over the deeper ocean associated with the Antarctic Circumpolar Current. **Sea ice deformation, i.e. ice strain rates**, modifies **ice thickness** through processes such as **ridging**, rafting, and **lead formation**, which in turn shape the **top and bottom ice topography**. While **ocean waves** are responsible for sea ice fragmentation, which impacts the **floe size distribution**. Despite the large-scale sea ice drift and **ice age** along the drift trajectory being generally well described, major gaps remain in understanding Antarctic sea ice dynamics. Sea ice drift vectors, ice strain rates, internal ice stress (and pressure), and floe size distribution are important yet poorly documented, in particular at fine spatial and temporal scales. Moreover, the contribution of sea ice deformation on shaping sea ice thickness distribution across temporal and spatial scales remains poorly understood. Also, the dynamical interactions between **tides**, icebergs, and sea ice could contribute to **sea ice drift** and landfast ice break up in some coastal regions, yet these remain largely unstudied.

Snow (P3)

Snow on Antarctic sea ice plays a central role in regulating sea ice thermodynamics, surface energy exchange, and mass balance. It acts as an insulating layer, modulating heat fluxes, contributing directly to ice growth through **meteoric ice formation** (snow-ice and superimposed ice), and delaying melt onset. However, **snow water equivalent (SWE)**, **snow accumulation rates**, and **snow depth** in Antarctica are highly variable across both horizontal and vertical scales, shaped by intense winds, uneven **surface topography/roughness**, and complex in-ice processes. Katabatic winds redistribute snow on sea ice in the near-coastal zone into dense snow drifts and sastrugi fields, or remove snow entirely via sublimation or wind transport. Yet, the magnitude of such snow loss remains unquantified. Internally, the snowpack evolves dynamically as **temperature gradients**, compaction, melt-refreeze cycles, and **brine** infiltration reshape its structure and composition. This produces strong vertical heterogeneity in **snow density**, which, together with **microstructural anisotropy**, governs **thermal conductivity**, and, in turn, alters snow insulation, melt timing, and the resulting **liquid water content** in the snowpack, as well as electromagnetic properties critical for satellite remote sensing retrievals. The **isotopic composition** of snow layers further carries signals of precipitation history and meltwater cycling, offering valuable insights into past surface-atmosphere interactions. This evolving physical and chemical complexity leads to critical knowledge gaps, including a limited understanding of the seasonal evolution of internal snow stratigraphy, as quantified by the **specific surface area (SSA)**, **density**, and other **microstructural parameters** that define the small-scale spatial variability, and feedbacks between snow properties and ice-ocean-atmosphere exchanges.

Atmosphere-ice energy budget (P4)

Sea ice is an effective energy barrier between the atmosphere and the ocean. Determining the Antarctic sea ice surface energy balance is hampered by the lack of in-situ time series and the consequent relatively crude parameterizations of relevant processes. The components of the surface energy budget include **radiation (longwave and shortwave)**, the turbulent heat fluxes (including **air temperature**, **relative humidity**, **wind speed and direction**, and surface roughness), heat supplied by **precipitation** (especially rain), heat conduction through snow and ice, and the supply of sensible heat by the ocean (**ocean heat flux**). Longwave radiation depends on cloud cover and **surface temperature**, but ground-based measurements are needed to validate existing cloud parameterizations and close the energy budget. Even though the influence of **albedo** on radiative transfer processes is well studied, current models often use simplified albedo/radiative transfer schemes that fail to capture the observed spatial and temporal variability of the **optical properties of snow and ice (SSA, density)**, especially over rough surfaces, which can lead to significant biases in model results. Turbulent heat exchange between

the ice/snow surface and the overlying atmosphere is more complex and strongly depends on high-quality input data, which are seldom available for Antarctic sea ice, as well as on **sea ice surface roughness**. Therefore, there is a need to develop more robust, data-based parameterizations of **sensible and latent turbulent heat fluxes** over Antarctic sea ice, which likely differ across sea ice regimes and regions defined by surface roughness and relevant meteorological states. The last component of the surface energy budget that inhibits model uncertainties is **snow depth distribution** and the **thermal conductivity of snow**. While the thermal conductivity of sea ice is largely determined by its **brine fraction**, and **sea ice density** plays a minor role, the thermal conductivity of snow depends on both snow density and **microstructural anisotropy**.

Ocean boundary layer (P5)

The ocean boundary layer is the uppermost portion of the ocean that directly interacts with the sea ice and the atmosphere. In this layer, temperature, salinity, momentum, and density evolve because of ice-ocean freshwater and salt exchanges, and because of shear induced by the ice drift-ocean velocity difference, and because of **radiative fluxes** in the near-surface. Net salt rejection from growing sea ice and freshwater release from melting sea ice strongly affect **sea surface salinity** and **density**, thereby fostering or dampening vertical mixing and convection. Convection arises from changes in **temperature** and **salinity** at both the upper (ice-ocean) and lower (deep-ocean) interfaces. Convection entrains water masses from the ocean interior, feeding back on sea ice growth and melt by bringing subsurface heat near the surface. In coastal polynyas, where rapid ice formation leads to the largest net **salt fluxes**, this convection ventilates the deep ocean, contributing to Antarctic Bottom Water formation, with far-reaching consequences for Southern Ocean heat and carbon storage. Under landfast sea ice, near the mouth of cold ice shelves, the ocean boundary layer can be supercooled and filled with free-floating frazil crystals and platelet ice. The marginal ice zone (MIZ) further modulates upper-ocean structure through wave-induced mixing and ice-ocean interactions. Additionally, **under-ice turbulence**, driven by ice drift, internal waves, and ocean shear, controls **vertical heat, salt, and momentum fluxes** but remains poorly constrained. Better understanding the physics of the ocean boundary layer, and its interactions with sea ice drift and thermodynamics, requires year-round observations of **under-ice temperature, salinity, velocity and turbulence**, alongside **physical sea ice properties**.

Ecosystems (P6)

The sea ice zone hosts complex and diverse microbial communities comprising **bacteria, archaea**, and **eukaryotes** such as **algae** and **fauna**. These communities inhabit brine inclusions, sea ice interfaces with the ocean and atmosphere, and the under-ice water column. Their metabolic activity regulates **nutrient regeneration rates, organic matter transformation**, and the **production rates of climate-relevant gases**. **Light** availability within biologically active sea ice layers constrains **photosynthetic activity**, yet remains poorly quantified due to limited observations. Other key controls on sea ice biological production and community structure include nutrient availability, **brine temperature** and **salinity**, all of which are poorly quantified across Antarctic sea ice. Ice-associated organisms play a pivotal role in the **biological carbon pump** by transforming **inorganic carbon** into **organic carbon** that can be exported to depth through **sinking aggregates fluxes** and **zooplankton grazing rates**. This export may be enhanced by the formation of **cryominerals** and the production of **extracellular polymeric substances** (EPS), contributing to carbon export efficiency and influencing oceanic carbon storage. Despite their importance, the diversity, activity, and productivity of sea-ice microbial communities remain undercharacterized, particularly during seasonal transitions and under thinning or melting sea ice conditions. The relative contribution of **ice algae primary production, phytoplankton primary production**, and their respective **export fluxes** to the biological carbon pump in the Southern Ocean sea ice zone remains uncertain. Targeted research is therefore needed to quantify microbial

growth rates, carbon transformation pathways, and nutrient cycling rates across ice-ocean interfaces. Key knowledge gaps also include microbial physiological responses to rapid environmental change and the contribution of sea-ice-zone primary production to global carbon budgets. In addition, sea ice influences productivity in surrounding waters through biological seeding and nutrient release fluxes.

Biogeochemistry (P7)

Sea ice and its snow cover act as a physical and chemical buffer between the ocean and the atmosphere, regulating the exchange of **greenhouse gas fluxes**, including CO₂ and methane, as well as **reactive trace gas fluxes** and **aerosol precursor emissions**, such as dimethyl sulfide (DMS). These exchanges influence **cloud cover**, **radiative forcing**, and regional-to-global climate feedback through changes in **cloud condensation nuclei concentrations**. Sea ice also mediates the biogeochemical cycling of **carbon**, **nitrogen**, **phosphorus**, **silicon**, **iron**, and **sulfur** via processes such as **nitrification rates**, **microbial metabolic activity**, **iron release fluxes**, and **DMS production rates**. During spring melt, sea ice releases bioavailable iron, fueling phytoplankton bloom magnitude and extent across the Southern Ocean sea ice zone. The **snow cover** functions as a chemical reactor medium for atmospheric processing, while **organic carbon concentrations** within the ice and snow contribute to biological and chemical transformations rates. The rapid decline of Antarctic sea ice is altering the **magnitude**, **timing** and **spatial distribution** of **biogeochemical fluxes** at sea ice interfaces, yet their spatial variability remains poorly constrained, as does the potential release of **anthropogenic contaminants concentrations** accumulated during winter (link to Theme 5). Key knowledge gaps include the role of seasonal transitions, and the influence of **snow depth**, **snow salinity**, **sea ice thickness**, **ice temperature**, **ice salinity**, **light transmittance**, and **sea ice age** on **microbial process rates** and air-ice-ocean **gas fluxes**. Improved observations of these variables are critical for quantifying coupled ocean-ice-atmosphere feedbacks and for constraining Earth system model parametrizations, thereby improving projections of future climate dynamics.

Link to large-scale climate variability (P8)

Antarctic sea ice variability is closely linked to large-scale climate variability driven by **sea surface temperature and albedo**, **atmospheric boundary layer**, **precipitation** patterns and **ocean currents**. The variability is often described by climate patterns (link to Theme 7) such as Southern Annular Mode (SAM), the El Niño-Southern Oscillation (ENSO) and the Amundsen Sea Low, to name a few. Changes in **sea ice drift**, **concentration**, **extent and volume** modify **ice surface heat**, **moisture**, **momentum and radiative fluxes**, altering jet-stream dynamics, storm tracks, and tropical teleconnections. Emerging evidence indicates that Antarctic sea ice change is no longer merely a response to these modes but increasingly a driver of hemispheric circulation and global energy exchange. The seasonality of sea ice is a major moderator, sometimes amplifier of ocean changes to the atmosphere and vice versa through shaping surface conditions and fluxes. Air-sea-ice feedbacks can affect the climate system at larger scales, linking Antarctic anomalies to ENSO evolution, Southern Hemisphere weather extremes, and mid-latitude precipitation shifts. Major knowledge gaps remain in quantifying the mechanisms, amplitudes, and timescales of these linkages (e.g., using historical, instrumental, and/or paleoclimate records). The relative roles of the different feedbacks are poorly constrained, and most models fail to capture abrupt changes. Research needs include coordinated coupled model reanalyses and projections, improved Earth observation and data assimilation of **sea ice state and properties**, and model studies on how sea ice loss and variability alter teleconnections. As Antarctic sea ice shows signs of reduced resilience — failing to fully recover after record-low years — there is growing concern that feedbacks may reinforce sea ice loss, shift climate modes, and push the system toward abrupt transitions with far-reaching consequences, beyond the Southern Ocean.

3. Observing strategies and key variables

3.1 Key Variables

The following table (Table 1) synthesizes the key variables needed to observe and understand the processes identified in Section 2 (P1–8), each of which is directly linked to the four overarching research questions (RQ1–4). These variables were derived from the process-based analyses and reflect the core observational targets required to capture the drivers, responses, and consequences of rapid Antarctic sea ice change. They provide the foundation for designing an integrated observing system that combines satellite, in situ, and modeling approaches across the Southern Ocean and *across all scales*, as outlined in section 3.2: Key Regimes and Observing Strategies. While all identified key variables are necessary for understanding the sea ice system processes in the Southern Ocean, the GCOS Essential Climate Variables (Table 1, bold) should be the minimum requirement for Antarctica InSync observations.

Research Question	Key process	Key variables
What coupled (thermodynamic and dynamic) processes and feedbacks are responsible for rapid sea ice decline, and how do they vary around Antarctica and over time? (RQ1)	Sea ice growth and melt (P1)	Sea ice concentration/area, sea ice thickness , sea ice age, snow depth on sea ice, sea ice temperature , sea ice salinity, sea ice density, sea ice oxygen isotopes, sea ice crystallographic texture, meteoric ice fraction (superimposed and snow ice), snow temperature, latent heat flux, sensible heat flux, sea ice surface albedo , ridge fraction, floe size distribution.
	Sea ice drift and deformation (P2)	Sea ice drift vector, sea ice strain rates, internal ice stress, ocean surface stress (through wind), subsurface ocean velocity (vertical mixing), wave height , tides, sea ice top and bottom topography, lead fraction, ridge fraction, floe size, sea ice thickness, sea ice age .
How do exchanges of mass, heat, and momentum, between sea ice and other components of the Earth System (ocean, atmosphere, ice sheet) drive the rapid sea ice decline? (RQ2)	Snow (P3)	Snow accumulation, accumulated precipitation, SWE (snow water equivalent), snow depth on sea ice , snow density, snow temperature, snow salinity, snow isotopic composition, snow thermal conductivity, snow liquid water content, snow specific surface area (SSA), snow microstructure, meteoric ice fraction (superimposed and snow ice), sea ice surface roughness/topography.
	Atmosphere–ice energy budget (P4)	Longwave irradiance at the surface (upward/downward), shortwave irradiance at the surface (upward/downward), sea ice surface temperature, sea ice surface albedo, accumulated precipitation, air temperature (near surface), relative humidity (near surface), air specific humidity (near surface), wind speed and direction (near surface), sensible heat flux, latent heat flux , optical snow and ice properties (SSA, density), snow microstructure, sea ice surface topography/roughness, snow depth on sea ice , snow/ice thermal conductivity, sea ice brine fraction, sea ice density.
	Ocean boundary layer (P5)	Ocean surface stress, surface currents (Ekman Currents and Surface Geostrophic Currents), sea surface and upper ocean temperature, sea surface and upper ocean salinity, latent heat flux, sensible heat flux, salt fluxes, vertical mixing/subsurface ocean velocity (upper ocean), radiative heat flux (longwave irradiance at

		the surface (upward/downward), shortwave irradiance at the surface (upward/downward)).
What are the consequences of rapid sea ice decline on the ecosystem dynamics and biogeochemical processes in the Southern Ocean? (RQ3)	Ecosystem-related processes (P6)	Biological communities (composition, abundance, biomass, phenology); Primary production (ice algal vs phytoplankton, photosynthetic efficiency, microbial growth rates); Carbon cycling and export (POC, DOC, carbon export fluxes, sinking aggregate fluxes, EPS concentrations, cryomineral formation rates).
	Biogeochemical processes (P7)	Air-ice-ocean exchange (CO₂ fluxes , CH₄ fluxes , reactive trace gases fluxes (e.g., DMS) , aerosol precursor emissions , cloud condensation nuclei concentrations); Elemental and Nutrient Cycling (DIC , nitrogen species concentrations , nutrient concentrations (NH₄⁺, NO₂⁻, NO₃⁻) , phosphorous concentrations , silicate concentrations , iron concentrations and speciation , sulfur compounds); Process rates (nitrification rates , microbial metabolic rates , iron release fluxes , DMS production rates); Physical-chemical controls (snow depth , snow salinity , sea ice thickness , sea ice temperature , sea ice salinity , light transmittance , sea ice age).
How does the rapid sea ice decline impact the global climate system and amplify climate change? (RQ4)	Link to large-scale climate variability (P8)	Sea ice concentration, sea ice thickness, sea ice drift vectors, sea ice surface albedo, longwave irradiance at the surface (upward/downward), shortwave irradiance at the surface (upward/downward), sensible heat flux, latent heat flux, sea surface salinity, upper ocean salinity, sea surface temperature, upper ocean temperature, ocean surface stress, relative humidity (near surface), air specific humidity (near surface), air pressure (near surface), upper and mid-atmosphere level pressure, wind speed and wind direction (vector) (near surface), air temperature (near surface), atmospheric temperature in the boundary layer, accumulated precipitation.

Table 1: Key variables needed to observe and understand the knowledge gaps identified in Section 2 (P1–8). In **bold** are Essential Climate Variables (ECVs) quantities as defined by the Global Climate Observing System (GCOS), and biogeochemistry- and ecosystem-related variables of fundamental importance.

3.2 Key Regimes and Observing Strategies

Overarching Observing Strategies

Observing strategies vary by region and logistical possibilities/infrastructures²¹. In this section, we introduce four key sea ice regimes: Pack ice, Marginal ice, Landfast ice, and Polynyas, and lay out a proposed observing strategy for each of them. For all regimes described, measurements would ideally be conducted circumpolar and throughout all seasons, requiring regular and repeated visits, strong international cooperation, and coordination to facilitate infrastructure sharing. **Earth Observation** (EO) by satellites are the only means to observe all four sea ice regimes in their entirety and over longer time scales. Thus, EO is key for our observing strategy and details are described in the Antarctica InSync EO group White paper. Additionally, sea ice expeditions by icebreaker provide the means to simultaneously observe all key variables on a local scale and are thus observational supersites for this theme and Themes 1, 4 and 6.

Pack ice

The pack ice – the mobile, drifting sea ice that covers the polar oceans – accounts for the majority of Antarctic sea ice area and volume. It is predominantly first-year ice that grows each autumn–winter and melts in spring–summer. Its thinner, seasonal character makes Antarctic pack ice highly responsive to atmosphere and ocean forcing²². Antarctica InSync aims to deliver the first year-round, system-scale view of Antarctic pack ice, closing long-standing gaps in understanding thermodynamic and dynamic processes (**P1 & P2**). A central component will be the deployment of **autonomous observational networks**, such as on-ice tethered platforms (e.g., Snow Buoys, Ice Mass Balance buoys, Weather and Radiation Stations), ice-tethered profilers (ITPs) or upward-looking sonars (ULS) to continuously monitor atmosphere–ice–ocean interactions (**P4**), in conjunction with *in situ* sampling (e.g., ice coring, snow pits). These measurements will capture key variables relating to thermodynamic and dynamic processes and snow redistribution (**P3**), as well as ecological and biogeochemical processes (**P6 & P7**). To address thermodynamic and dynamic processes on larger spatial and temporal scales, Antarctica InSync will integrate **satellite observations** to map sea ice concentration and thickness, drift and deformation, snow depth, and mass changes, and will identify zones of active sea ice formation (**P1, P2 & P3**)²³. These regions will be targeted with **ship-based** and **airborne surveys** that also serve as validation for satellite-based observations. These surveys will measure snow and ice thicknesses, characterize frazil and pancake ice, and will be supported by **under-ice acoustic instruments** to quantify suspended frazil ice. Concurrent oceanographic measurements will document mixed-layer evolution and ice–ocean heat and salt fluxes (**P5**) (link to Theme 1), as well as light, nutrient, trace element availability, and lower trophic level biomass (**P6 & P7**). On the **modeling** front, Antarctica InSync aims to improve pack-ice representation in coupled systems by incorporating pancake-ice formation model parameterizations and refined mechanical rheologies informed by new observations of floe breakup and ridge density (**P8**), building on insights from coupled modeling studies of Antarctic sea-ice feedbacks¹⁹. Together, these coordinated efforts will address the full spectrum of processes (**P1–P8**) across spatial and temporal scales, from in-situ observations to airborne measurements and satellite-based monitoring.

Marginal ice zone and ocean processes

The marginal ice zone (MIZ) is the outer fringe of the sea ice cover, a highly dynamic region where ocean, sea ice, and atmosphere strongly interact (**P1, P2, P4, P5**), playing a crucial role in both climate regulation (link to Theme 7) and marine ecosystems (link to Theme 4)²⁴. The region exhibits high temporal and spatial variability in response to atmospheric and ocean drivers (**P4 & P5**), including intense exchanges of heat, moisture, and energy across the entire sea ice zone due to generally thin ice and significant areas of open water (**P4 & P5**). Oceanic drivers include waves, mesoscale eddies, and fronts (link to Theme 1). As sea ice melts, freshwater is released into the ocean, creating a stratified surface layer (**P1 & P5**). This stratification may trigger intense phytoplankton blooms along the receding ice edge by releasing nutrients accumulated during winter scavenging, thus fertilizing the blooms (**P6 & P7**). Resulting bursts of biological productivity in the MIZ support krill and other zooplankton, the base of the Antarctic food web, contributing to the biological carbon pump and providing food for higher trophic organisms (**P6**) (link to Theme 4 and 1). Intense exchanges of the ocean and sea ice/snow with the atmosphere nourish a cascade of atmospheric processes from aerosol–cloud interactions (link to Theme 6) in the MIZ (**P3, P7, P8**). Despite its importance, the MIZ remains difficult to observe and model due to its complex and rapidly changing nature. In situ measurements are logistically challenging, satellite remote sensing struggles with heterogeneous ice–water conditions, and traditional continuum-based sea ice models poorly represent critical processes such as wave-induced breakup and floe-size-dependent melting (**P2 & P5**). Although emerging approaches account for floe-size distributions or individual floe dynamics, they remain computationally demanding and

data-limited²⁵. Furthermore, the recent decline in sea ice extent and warming upper-ocean conditions further highlight unresolved feedbacks among atmosphere, ocean, and ice, underscoring the MIZ's pivotal yet poorly understood role in the polar climate system (**P1, P5, P8**). To address these challenges, an integrated program of observations and modeling will be implemented. This includes the deployment of **autonomous platforms** such as **biogeochemical Argo floats** (measuring temperature, salinity, oxygen, nitrate, chlorophyll, backscattering, pH, under-ice light availability), **gliders** that will survey frontal zones near the ice edge, **surface wave and wave-ice buoys** and **drones** that will monitor wave states and floe-size impacts, and coordinated satellite observations using **high-resolution passive microwave and radar** data that will be validated by targeted field campaigns. On the modeling side, high-resolution, **wave-ice-eddy-resolving models** will be applied for selected Antarctic sectors and will be tested against Antarctica InSync observations, with results feeding into global climate model parameterizations of floe-size dynamics and seasonal cycles. Together, these efforts will link sea ice physics, ocean and atmosphere dynamics, and carbon cycle processes (**P1-P8**) to enhance understanding of the MIZ's role in a rapidly changing Southern Ocean.

Landfast ice

Landfast sea ice (or “fast ice”) is immobile sea ice anchored to coasts, continental ice forms, or grounded over shoals²⁶. Unlike the standard Arctic case, where landfast ice is mainly held in place by deformed ice, mostly grounded pressure ridges on shallow continental shelves, Antarctic landfast ice is typically stabilized by attachment to coasts, ice shelves, and grounded icebergs. Being immobile, it changes only through thermodynamic processes. Landfast sea ice is readily accessible from coastal stations, making it ideal for long-term observations. Despite this accessibility, significant knowledge gaps remain in key landfast-ice dynamical and thermodynamical processes. These include wind-driven snow redistribution, frazil and platelet ice formation and consolidation processes, under-ice hydrography (currents, tides), landfast ice locking and breakup mechanisms, and the **remote sensing** of landfast ice properties, especially thickness and snow distribution. Antarctica InSync will deliver synchronised, year-round **monitoring** of landfast ice properties across multiple sites, progressing on long-standing gaps in our understanding of its coupled atmosphere–ice–ocean–ecosystem processes. A central component will be the Antarctic Fast Ice Network (AFIN;²⁷), which coordinates coastal observatories of landfast ice. Antarctica InSync will expand the network by adding new stations to improve spatial coverage and by advancing standardized, and where possible, **autonomous measurements** of physical, biogeochemical, and ecological sea-ice processes. These coordinated in situ observations will target the thickness of consolidated and sub-ice platelet layer ice components (**P1**), the mechanisms of landfast ice locking and break-up (**P2**), **snow** redistribution and properties (**P3**), air–ice and ice–ocean interface energy budgets (**P4, P5**), and biogeochemical and ecological variables (**P6, P7**). Remote sensing activities will focus on documenting landfast ice thickness (**P1**) and snow depth (**P3**), and on improving retrieval methods by combining **field-based surveys** (e.g., **drilling, ground-penetrating radar**) with **EO** techniques. Together, these coordinated efforts will strengthen the observational basis for understanding landfast ice processes and interaction with icebergs and ice shelves (link to Theme 3), and enhance the integration of field and satellite data within the Antarctic observing system.

Polynyas

Polynyas are open-water areas within the Antarctic sea ice cover that form through persistent winds (latent-heat) or ocean upwelling (sensible-heat)²⁸. Polynyas have a wide influence. Their role in sea ice production by rapid ice growth (**P1**) and dynamic drift and deformation (**P2**) depend on changing winds, ocean heat, coastal geometry and landfast sea ice presence, yet the thresholds that control their opening and closure remain poorly quantified. Spatial and vertical snow distribution (**P3**) alters local albedo and surface fluxes, while the atmospheric boundary layer (**P4**) above polynyas is characterized by intense

turbulence and heat exchange that remain sparsely measured. Beneath the surface, ocean boundary layer (P5) mixing and upwelling govern dense-water formation and control the Antarctic Bottom Water formation (link to Theme 1) but are under-observed, particularly in winter, and misrepresented in models, which often fail to reproduce their timing, extent, and variability, due to coarse resolution and missing coupled physics. The open-water environment enhances ecological productivity (P6) and affects biogeochemical cycles (P7) through air-sea gas exchange and salt release, though their variability is not well constrained. Finally, links to large-scale climate variability (P8) indicate that polynyas both respond to and influence modes such as SAM (Southern Annular Mode), ASL (Amundsen Sea Low), and ENSO (El Niño-Southern Oscillation)²⁹, embedding them in the global climate feedback network (link to Theme 7). Antarctica InSync can combine **EO-based detection** (daily polynya area, ice thickness, and flux retrievals), **autonomous observations** (gliders, floats, flux buoys), and **high-resolution coupled models** to resolve multiscale interactions, from local fluxes to hemispheric climate linkages, across seasons and regions.

4. Summary

Since 2015, Antarctic sea ice has shifted from a period of slow expansion to repeated record-low sea ice extremes. While the recent decline is broadly consistent with long-standing climate projections, the speed and abruptness of the transition were unexpected and remain poorly attributed, highlighting a system that is increasingly recognized as multi-scale and multi-component, coupling the atmosphere, ocean, cryosphere, biogeochemistry, and ecosystems. Understanding Antarctic sea ice, therefore, requires improved process-level understanding, with sustained, year-round circumpolar observations as a critical first step. These efforts would leverage recent advances in observing systems and models for Antarctic sea ice, and cover pack ice, landfast ice, marginal ice zone, and polynyas. Ultimately, this will support the development of robust, interoperable sea-ice geophysical data products that integrate in situ, autonomous, satellite, and modelling platforms. Antarctica InSync provides the framework that enables this next step by synchronizing international efforts, harmonizing standards, filling critical gaps, and creating a durable data legacy. As a pathfinder toward the next International Polar Year, it establishes the integrated infrastructure and observing-to-prediction pipelines needed to anticipate rapid Antarctic sea-ice change and its global impacts.

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Antarctica InSync Scientific Theme 3

Antarctic ice sheets and ice shelves: processes driving rapid change, from observation to prediction

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Executive Summary

Rapid and accelerating changes across the Antarctic Ice Sheet are driven by coupled ice–ocean–atmosphere–solid Earth processes. This impacts sea-level change, ocean circulation and climate feedbacks, all of which remain insufficiently understood. Despite major advances in observations and modelling, critical uncertainties persist regarding ice-shelf stability, ice–ocean heat exchange, basal melt, surface melt and mass accumulation variability, and the influence of bedrock motion and subglacial hydrology on ice dynamics. This white paper identifies four major Knowledge Gaps (KG) that must be addressed to improve predictions of the future evolution of the Antarctic Ice Sheet (AIS). Here, we outline the methodological advances, Key Variables (KV) and coordinated observing strategies – including the development of observational super-sites – needed to close these gaps. Antarctica InSync offers a unique opportunity to implement and test these approaches ahead of International Polar Year-5 (IPY-5), providing the foundation for sustained long-term observations of key Antarctic regions. The proposed recommendations strengthen links between process understanding, sustained observations and model development to improve knowledge of AIS interactions with the ocean, atmosphere and solid Earth, along with its projected contribution to global sea-level change in a warming climate.

1. Motivation and background

Human-induced global warming is accelerating mass loss from the Antarctic Ice Sheet (AIS) at unprecedented rates, driven by both oceanic and atmospheric forcing that promotes ice-shelf thinning, grounding-line retreat and ice-stream acceleration¹. These changes have major consequences for freshwater input to the Southern Ocean and global sea-level rise. Increased freshwater fluxes from basal melting and subglacial discharge influence ocean circulation, sea-ice formation and marine productivity in complex and still poorly constrained ways^{2–8}. Current Antarctic sea-level contributions already track the high-end International Panel on Climate Change (IPCC) scenario, with far-reaching implications for coastal systems, ocean circulation patterns and global climate feedbacks. At the same time, record snowfall has recently temporarily offset dynamic mass loss from West Antarctica⁹ with corresponding impacts in East Antarctica, illustrating the interplay between long-term trends and short-term variability and highlighting the importance of sustained long-term observations¹⁰.

The AIS is a dynamic, interconnected system that continuously exchanges mass and energy with the ocean, atmosphere and solid Earth¹¹. Predicting its future evolution requires improved understanding of the processes governing these interactions, supported by new synchronous pan-Antarctic observations and integrated, interdisciplinary data synthesis. Advances in satellite remote sensing, autonomous observing systems and geophysical surveys now provide unprecedented insight into ice-sheet and ice-shelf behaviour, revealing previously undetected modes of variability such as seasonal ice-velocity change on the Antarctic Peninsula¹², and variability in subglacial hydrology¹³. Meanwhile, progress in numerical modelling has significantly improved our understanding of the current system, enabling increasingly accurate projections of the AIS contribution to sea-level rise on centennial scales¹⁴. Nevertheless, further development is urgently required to capture small-scale processes and feedbacks, which can trigger large-scale change through features such as basal melt channels, crevasse-field evolution and subglacial freshwater discharge^{15,16,17}. Such advances are also needed to strengthen coupling between ice, ocean, atmosphere, and solid Earth systems and to improve our understanding of changes occurring on shorter, decadal timescales. While satellite observations, Automatic Weather

Stations (AWS) amongst other methods provide valuable year-round monitoring, wintertime in situ observations remain relatively sparse and must be further expanded.

Despite these advances, significant knowledge gaps persist, especially at the interfaces between ice, ocean, atmosphere and the solid Earth, and in the processes that control abrupt or irreversible change. These include limited understanding of:

- the structural and dynamic evolution of the ice-sheet–ice-shelf system (e.g., speed change, fractures, hydrofracture pathways, grounding-line migration);
- the mechanisms governing ice–ocean interactions and basal melt;
- the spatio-temporal variability of surface mass balance and its sensitivity to extreme atmospheric events;
- the role of basement rock, sedimentary basins, unconsolidated sediments, geothermal heat flow, ground-water and subglacial hydrology in modulating ice dynamics and stability.

Addressing these challenges requires coordinated and integrated international efforts, combining ground-based observations, airborne and ship-based surveys, satellite remote sensing, numerical modelling and shared research infrastructure. Antarctica InSync provides this framework under *Theme 3 - Antarctic Ice Sheets and Ice Shelves: Processes driving rapid change, from observation to prediction*. This initiative will work alongside existing Scientific Committee on Antarctic Research (SCAR) and partner programmes to; close critical observation and modelling gaps, to strengthen our knowledge of the physical mechanisms driving change in Antarctica, and to reduce uncertainty in its future sea-level contribution and evolution in a changing climate.

2. Knowledge gaps and research needs

The scientific challenges outlined in this white paper build directly on long-standing priorities identified by the Antarctic research community. The SCAR Horizon Scan and its associated roadmap¹⁸ highlighted the need to understand the stability of the AIS, the processes controlling ice-ocean-atmosphere interactions, and the influence of solid Earth conditions on ice dynamics; recognising these as questions of global importance for climate, ocean circulation and sea-level rise. The subsequent SCAR synthesis of Horizon Scan outcomes further emphasised that progress requires coordinated, interdisciplinary approaches across physical, biological and geological domains, along with improved predictive capabilities and sustained observations.

A decade later, rapid changes in Antarctica—many occurring faster or more abruptly than anticipated in 2014—underscore the urgency of renewed attention for these unresolved questions. Recent climate extremes illustrate how sensitive the Antarctic system is to short-term perturbations. Increasingly frequent atmospheric rivers are delivering intense pulses of heat and moisture that can trigger both extreme snowfall events and widespread surface melt¹⁹. At the same time, the record decline in Antarctic sea-ice extent since 2016 has exposed ice shelves to enhanced oceanic and atmospheric forcing in ways that were not foreseen a decade ago²⁰. New observational and modelling advances have revealed complex interactions and feedbacks (e.g. ²¹²²), but these emerging behaviours also expose critical gaps that limit our ability to detect early warning signals of ice-sheet and -shelf instability and to produce robust projections of future change.

Motivated by these community-identified priorities and by the evolving evidence of rapid Antarctic change, we identify four major Knowledge Gaps (KG1-KG4) that must be addressed to advance scientific understanding and predictive skill:

- KG1** - the structural integrity and dynamic behaviour of the ice-sheet and ice-shelf system;
- KG2** - the mechanisms governing ice–ocean interaction and basal melt;
- KG3** - the role of surface melt and mass accumulation, and the influence of atmospheric processes and extreme events on ice-sheet–ice-shelf behaviour;
- KG4** - the role of basal properties, grounding zones, and subglacial hydrology in modulating ice velocity, grounding-line retreat and ice stream stability.

These Knowledge Gaps (Figure 1) translate the high-level scientific priorities of the SCAR Horizon Scan into a focused and actionable framework for *Theme 3 - Antarctic Ice Sheets and Ice Shelves: Processes driving rapid change, from observation to prediction* within the Antarctica InSync initiative. They form the scientific foundation for the working groups and coordinated research strategies proposed in this white paper.

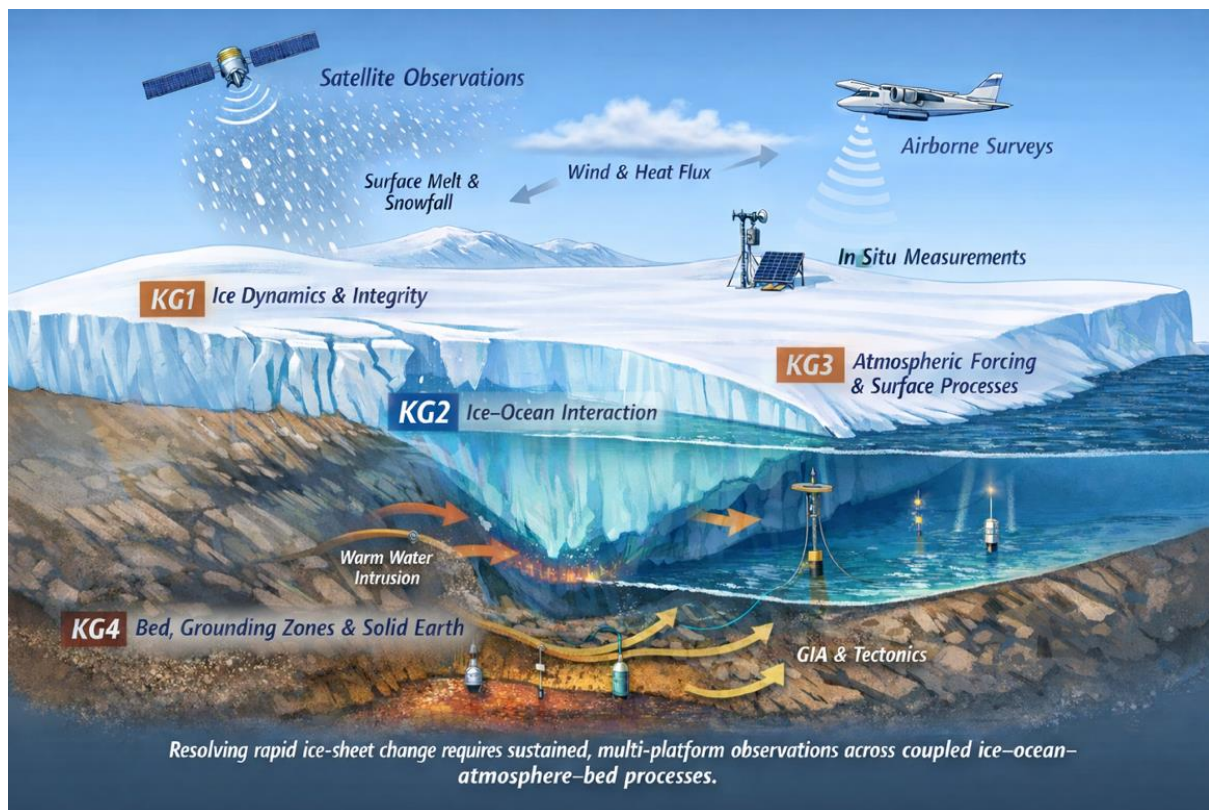


Figure 1 Schematic of the identified KGs and examples of the related observation technology.

2.1 KG1: The structural integrity and dynamic behaviour of the ice-sheet and ice-shelf system

The structural integrity and dynamic behaviour of Antarctica’s Ice Sheets and Ice Shelves remain among the most critical and least understood components of the cryosphere. Ice shelves regulate the discharge of inland ice through mechanical buttressing, while the grounded ice sheet continuously responds to change in surface mass balance, basal conditions and oceanic forcing at its margins. Yet the physical processes that weaken ice shelves, propagate fractures, alter buttressing and drive grounding-line migration, are still poorly constrained by observations and are inadequately represented in current models. This limits our ability to detect early signs of destabilisation, quantify the thresholds for rapid ice shelf collapse and to predict abrupt change in ice flow.

Major gaps persist in understanding the initiation, growth, and coalescence of fractures within ice shelves that lead to calving and in quantifying how damage evolves under varying mechanical and thermal conditions. Hydrofracture processes, particularly those linked to surface meltwater, firn aquifers and supraglacial lake formation, have been widely observed²³ but remain insufficiently

understood, meaning that the conditions leading to rapid ice-shelf collapse are not well-defined. These uncertainties extend to how ice-shelf thinning and changes in mechanical rigidity modify buttressing forces and stress transmission, influencing the potential for upstream glacier acceleration.

Knowledge of short-term and seasonal ice-dynamic variability is also limited, especially regarding how ice speed responds to changes in basal friction, ocean forcing, surface hydrology, or extreme atmospheric events. Determining grounding-line position and migration at high temporal resolution remains challenging, restricting assessments of stability regimes and the potential for marine ice-sheet instability. In addition, the coupling between surface, englacial and subglacial hydrology is poorly understood. Processes such as firn aquifer evolution, surface meltwater production, meltwater routing, supraglacial lake formation and drainage and the behaviour of subglacial drainage systems, including lake drainage and channel formation, may strongly affect both local stress fields and basal drag, but their net influence on ice flow and ice shelf stability is not well quantified.

Finally, the ice-sheet–ice-shelf system lacks the integrated, multi-scale observations needed to resolve these coupled processes. Coordinated measurements that capture surface conditions, internal structure, basal properties and frontal dynamics simultaneously are still rare. Continuous observation of deformation and damage is especially limited, particularly its evolution at high-temporal-resolution. Without such observations it remains difficult to constrain model physics or evaluate the processes most critical for accurately projecting ice-sheet change.

Together, these gaps limit our capacity to assess the resilience of Antarctic Ice Shelves, to quantify the likelihood and timing of rapid ice-loss events, and to represent key dynamical and structural processes in predictive ice-sheet models. This includes damage evolution, ice speed change, hydrofracture, grounding-line migration and calving processes. Closing this knowledge gap is essential for understanding near-term ice-sheet evolution, evaluating potential tipping-point behaviour and improving projections of Antarctica’s future contribution to sea-level change.

2.2 KG2: The mechanisms governing ice–ocean interaction and basal melt

Ice–ocean interactions exert a dominant control on Antarctic mass loss yet the mechanisms governing basal melt, ocean heat delivery and cavity circulation remain among the most significant sources of uncertainty in predicting the future of the ice-sheet–ice-shelf system. Despite major advances in ocean observations and modelling, we still lack a quantitative spatio-temporal understanding of how heat is transported across the continental shelves, how it enters and exits the sub–ice-shelf cavities and how this heat interacts with the ice base to drive ice shelf basal melting. This limits our ability to assess the sensitivity of ice shelves to oceanic change, to detect the onset of destabilising feedbacks and to constrain basal-melt parameterisations in ice-sheet models²⁴.

Large uncertainties remain in characterising spatially and temporally varying basal melt rates. While satellite observations provide the only continent-wide view of ice shelf basal melt patterns and their variability, discrepancies between Earth observation, continuous surface-based measurements of ice-thickness changes and oceanographic reconstructions highlight gaps in calibration and physical understanding. These discrepancies reflect incomplete knowledge of the small-scale processes that control heat flux at the ice–ocean boundary, such as turbulence, mixing, plume dynamics, the effect of basal ice topography/roughness and stratification. Many of these processes occur at scales that make them challenging to observe in-situ and poor representation in existing models hampers reliable projection of basal melt under future climate conditions. This limitation is reflected in recent studies showing that altimetry-based estimates may underestimate melt rates where channelised basal melting occurs, potentially biasing large-scale assessments of ice-shelf thinning and melt patterns¹⁷.

Knowledge of sub–ice-shelf cavity geometry, including grounding-zone morphology, bathymetric features such as troughs and sills, pinning points and water-column structure, is still fragmented, particularly beneath thick or logistically remote ice shelves. This lack of information makes it difficult

to characterise where and how warmer water intrudes into cavities, how circulation patterns develop and how sensitive specific regions are to changing ocean forcing. Even basic parameters such as ocean thermal driving (the temperature above the in-situ freezing point), vertical tidal motion, cavity roughness and spatial variability in water-mass properties, remain poorly known at the continental scale.

The coupling between the Antarctic Ice Shelf and Sheet system and the Southern Ocean is also poorly constrained and will be advanced through collaboration across the Antarctica InSync Themes. We lack a full understanding of what determines on-shelf ocean circulation through ocean heat inflow (T1), how it is connected to anthropogenic and natural atmospheric forcing (T5), and how freshwater input from basal melt, subglacial discharge and iceberg melt modifies local and regional circulation, sea-ice formation (T2), overturning and water-mass transformation. These processes, in turn, influence the delivery of heat to ice-shelf cavities, generating feedbacks that may either stabilise or destabilise vulnerable sectors of Antarctica. The role of sea ice, polynyas, ocean waves and iceberg–shelf-front interactions in modulating melting and calving remains similarly poorly constrained, as does the influence of meltwater-induced upwelling on micronutrient supply and Southern Ocean productivity. These processes also affect coastal ecosystems and blue carbon dynamics (T4; ²⁵²⁶).

Compounding these challenges, long-term ocean observations beneath ice shelves remain extremely limited. Autonomous platforms, moorings and under-ice vehicles have begun to transform our understanding of cavity processes, but the observational record is still sparse in time and space, often limited to short-duration campaigns or single sites. Expanding sustained sub-ice shelf ocean observations across diverse oceanographic regimes is required to capture variability on sub-seasonal to multi-year timescales. At the same time, coupled ice–ocean models remain rare, are inconsistent in their treatment of key processes and are insufficiently constrained by empirical data, limiting our ability to represent basal melting and its response to future climate forcing.

Together, these uncertainties reflect the complexity of the ice–ocean system and the lack of integrated observations and models capable of resolving its multiscale dynamics. Without improved understanding of the pathways and efficiency of ocean heat transport, the controls on basal melting, the feedbacks linking freshwater fluxes to regional and global circulation, projections of Antarctic evolution, the ice sheet contribution to sea-level change and its wider influence on the global climate system will remain deeply uncertain. Addressing this Knowledge Gap is therefore fundamental to improving predictive capability and identifying early indicators of ice-shelf destabilisation and therefore critical sectors of Antarctica.

2.3 KG3: The role of surface melt and mass accumulation and the influence of atmospheric processes and extreme events on ice sheet–ice shelf behaviour

Antarctica’s surface mass balance (SMB) is shaped by a complex interplay of snowfall, sublimation, melt, refreezing, drifting snow²⁷. Under certain conditions, these processes can occur as extreme atmospheric events. Variability in SMB remains one of the largest sources of uncertainty in determining the current and future mass balance of AIS and its contribution to sea-level change. Although recent advances in regional climate modelling, remote sensing and surface-based observations have improved our understanding, large gaps persist in quantifying the magnitude, spatial pattern and drivers of SMB variability – particularly in regions where accumulation is low, atmospheric dynamics are complex, or observational coverage is sparse. Symptomatically, SMB is one of the few but highly relevant parameters which is not part of the list of Key Variables.

A first major uncertainty lies in the limited spatial and temporal coverage of ground-based measurements and the lack of our ability to observe SMB remotely from space. Stake arrays, firn cores, snow pits and accumulation radar surveys remain geographically restricted, especially across East Antarctica and coastal zones where SMB gradients are steep. Weather stations with radiation sensors

to robustly calculate melt rate are scarce and far apart. This hampers efforts to calibrate and validate satellite-derived products and climate-model outputs^{28, 29, 30}, leading to divergent reconstructions of past variability and inconsistent assessments of present-day trends. The influence of drifting and blowing snow on accumulation and sublimation remains especially difficult to constrain, despite its critical role in redistributing mass across the continent.

The representation of atmospheric processes in models remains another central limitation. Moisture transport, water, ice, and mixed-phase cloud microphysics, katabatic winds and the formation of atmospheric rivers, which are increasingly recognised for their ability to induce both extreme snowfall and widespread melt, are still imperfectly captured in regional and global climate models. These deficiencies contribute to significant spread in modelled precipitation, melt and surface energy balance, and limit our ability to simulate extreme events such as heatwaves, intense storms, or foehn intrusions that can trigger rapid surface mass-loss or melt-pond formation³¹. The recent occurrence of unprecedented atmospheric rivers and extreme temperature events over East Antarctica highlights how sensitive SMB and even ice sheet mass balance is to rare but high-impact events whose frequency and magnitude remain poorly understood.

Uncertainty also persists in how firn evolves under present and future climate forcing including the increasing occurrence of liquid precipitation in coastal areas³². Firn densification, refreezing capacity, crust formation and the development of deeply buried firn aquifers and near-surface hydrological pathways, strongly modulate the partitioning between meltwater storage, runoff and refreezing. However, observations of firn structure are limited, and models struggle to capture its spatial variability or response to repeated melt events. This limits our ability to determine whether firn will buffer or amplify surface mass loss under warming conditions, particularly on ice shelves where enhanced firn saturation can precondition systems for hydrofracture and collapse.

Finally, insufficient integration exists between the modelling of SMB and ice-dynamics. Differences in spatial resolution, parameterisations and temporal scales impede consistent treatment of accumulation, melt and surface forcing in ice sheet projections. Large uncertainties in SMB therefore propagate directly into estimates of total AIS mass balance and future sea-level contributions.

Together, these gaps reveal that a more complete understanding of SMB requires coordinated, multi-scale in situ, airborne and spaceborne observations, improved representation of atmospheric and firn processes in models and closer coupling between atmospheric, cryospheric and oceanic systems. Closing this Knowledge Gap is essential for constraining present-day mass balance, for predicting SMB response to a warmer and more variable climate and for identifying the atmospheric processes most likely to drive future episodes of rapid mass loss.

2.4 KG4 – The role of basal properties, grounding zones, and subglacial hydrology in modulating velocity, grounding-line retreat and ice stream stability

The stability and evolution of AIS are fundamentally shaped by the properties and behaviour of the subglacial environment and the solid Earth. Subglacial topography, subglacial properties (sediment, hard bed, etc.), geothermal heat flow and the structure and organisation of subglacial hydrological systems all influence ice motion and grounding-line stability, yet many of these boundary conditions remain poorly known. Because ice flow is highly sensitive to basal traction and grounding zones critically control the response of marine-based sectors, limited knowledge of these processes directly constrains our ability to assess present-day vulnerability and to project future change.

Large regions of Antarctica still lack detailed mapping of bed topography and geological structure at the resolution required for next-generation models³³. In addition, bathymetry and morphology of Antarctic continental shelves also remain incompletely mapped, despite their key role in reconstructing past ice-sheet evolution and controlling ocean pathways toward grounding zones. Uncertainties in bathymetry underneath ice shelves, the distribution of pinning points and the geometry of grounding

zones impede our capacity to diagnose where the ice sheet is most susceptible to ocean intrusion or ungrounding. Sparse observations of grounding-line position and its temporal migration further limit our understanding of the conditions that drive retreat, stabilisation, or episodic readvance. These gaps are especially consequential in regions where small topographic features or sedimentary basins exert disproportionate control over grounding-line behaviour.

Knowledge of subglacial hydrology remains limited despite its central role in modulating basal sliding and ice-flow variability. The structure and connectivity of drainage systems, the behaviour of active and stable subglacial lakes, and the pathways and fluxes of subglacial water remain poorly constrained. Variability in water pressure, basal roughness and sediment properties strongly influence effective pressure and sliding, yet these parameters are only sparsely observed and difficult to infer at scale. Furthermore, the influence of subglacial discharge on grounding-zone melt rates, through the delivery of buoyant freshwater that enhances mixing and ocean heat flux, remains insufficiently understood, creating important links between this Knowledge Gap and KG2 on ice–ocean interaction.

Geothermal heat flow and the thermal properties of the lithosphere add an additional layer of uncertainty. Spatial variability in heat flux modulates basal melting, ice viscosity and subglacial water production, but direct measurements are extremely scarce, and geological proxies are limited in precision³⁴. Similarly, the solid Earth response to changing ice loads – both elastic and viscoelastic – affects bed elevation, grounding-line migration and local stability conditions. Long-term GNSS observations remain essential to constrain solid-Earth deformation and glacial isostatic adjustment. Uncertainties in mantle viscosity, crustal structure and past ice-loading history therefore feed directly into uncertainties in GIA and present-day mass balance estimates³⁵.

Antarctic subglacial permafrost thermophysical properties (thermal state, sediment characteristics, ice-content, solute concentrations, hydrology, rheology) and relation to ice sheet basal thermal conditions are still poorly understood. Permafrost is a key variable at the Solid Earth – ice sheet interface, as a modulator of basal slip and basal water fluxes. Fast deglaciation, especially in the Antarctic Peninsula is increasingly exposing new land in ice-marginal settings. In continental Antarctica, ice-free areas are vantage localities for studying glacier-permafrost interactions. Research on these areas, using geophysical, sedimentological and remote sensing techniques along the ice-margin, will allow for obtaining new data on recently exposed permafrost, providing insight into the characteristics of subglacial permafrost, but also to improve the understanding of the impacts of deglaciation on permafrost in the newly formed ice-free areas.

Finally, the integration of solid Earth, geophysical and subglacial hydrological data into ice-sheet models remains limited. Heterogeneous datasets collected across different times, platforms and methodologies are difficult to reconcile and their assimilation into modelling frameworks is still at an early stage. Without improved methods to incorporate basal boundary conditions and geological heterogeneity into predictive models, controls on ice-sheet sensitivity will remain poorly represented. Together, these gaps mean that the basal and solid Earth conditions governing ice-sheet stability are among the largest sources of uncertainty in AIS projections. Reducing these uncertainties requires coordinated geophysical surveys, improved mapping of grounding zones and sub-ice-shelf bathymetry, expanded observations of subglacial hydrology, and more robust coupling between geodynamic, hydrological and ice-flow models. Addressing KG4 is essential for understanding the physical controls on grounding-line behaviour, for identifying regions most vulnerable to retreat and for improving predictions of AIS contribution to sea-level rise under future climate forcing.

2.5 Methods Needs

Addressing the identified Knowledge Gaps requires a step change in the observational, modelling, and data-integration capabilities available to the Antarctic research community. The processes governing ice sheet, ice shelf, ocean, sea ice, atmospheric and solid Earth interactions operate across a wide range

of spatial and temporal scales and are often tightly coupled. As a result, progress depends on the development of coordinated, multi-scale observing systems, improved model frameworks capable of representing small-scale processes and their feedbacks and robust data infrastructures that enable integration, synthesis and open access. Together, these methodological needs form the foundation upon which Theme 3 can deliver the synchronous measurements, cross-domain linkages and predictive understanding envisioned by Antarctica InSync. Achieving this will require close coordination with other Antarctica InSync themes to ensure integrated observations, modelling and data sharing across the programme.

A major requirement is the expansion and coordination of observational capabilities. Long-term, year-round measurements remain sparse in many of the regions that are most critical for detecting ice-sheet change, including melt-prone grounding zones, ice-shelf cavities, coastal domes, fast-flowing ice streams and the polar plateau. Sustained observing systems – combining satellites, autonomous platforms, airborne surveys seismic and acoustic monitoring and long-term surface-based measurements – are essential to capture the variability of ice, ocean, atmosphere and solid Earth processes on time scales from hours to decades. Autonomous systems such as gliders, floats, Automatic Underwater Vehicles (AUVs), Unmanned Aerial Vehicles (UAVs) and on- and under-ice vehicles require improved endurance, sensor suites and navigation capabilities to operate reliably in the harsh Antarctic environment. Airborne geophysical campaigns must be strengthened to provide high-resolution mapping of bed topography, sub-ice-shelf bathymetry, firn structure, englacial layering and grounding-line geometry, linking marine, terrestrial, and atmospheric observations. Hidden processes in, and immediately above, grounding-zone locations must be benchmarked using ground-based geophysical observations. Across all platforms, enhanced satellite capabilities are needed to observe complex and dynamic regions, fractured ice shelves, calving fronts and heterogeneous snow surfaces. These observational advances must be coupled with harmonised calibration and validation efforts, including systematic comparison of satellite and ground-truth observations, alongside shared measurement protocols and interoperable metadata and data-sharing standards to ensure consistency and comparability across national programs. There is a need for international cooperation between national programmes and scientific teams, to ensure the full suite of KVs is acquired across Antarctica and these pressing science questions are addressed.

Parallel advances in modelling, integration and prediction frameworks are equally essential. Current models often struggle to represent small-scale processes – cloud microphysics, ocean turbulence, plume dynamics, fracture mechanics, firn evolution, subglacial hydrology – that control ice-sheet stability and ice-ocean-atmosphere feedbacks. A new generation of coupled Earth System Models capable of resolving interactions across the ice, ocean, atmosphere and solid Earth, are needed to translate process understanding into improved projections. Hierarchical modelling strategies that link process models to regional and continental-scale simulations will be essential for capturing the influence of boundary conditions, grounding-zone dynamics and evolving environmental forcing. Model-observation integration must be strengthened, with targeted “super-sites” identified as regions of dedicated coordinated focus where key processes are exemplified. This may include stations or regions hosting a suite of complementary instrumentation used to make the high-value observations required for calibration, validation and in situ process understanding. Improved frameworks for ensemble prediction and uncertainty quantification are also needed to assess the range of plausible ice sheet futures and to diagnose sensitivity to environmental change. Emerging digital twin concepts, AI-assisted parameterisations and physics-informed data assimilation approaches offer promising avenues for achieving near-real-time predictive capability.

Finally, progress across observation and modelling efforts depends on a robust and interoperable data infrastructure. Achieving FAIR data principles – findability, accessibility, interoperability, and reusability – is essential for ensuring that observations, model outputs, and derived products can be

shared, synthesised, and reused across the international community. This requires harmonised metadata standards, shared repositories, and well-documented workflows for survey planning, data integration and knowledge synthesis. A coordinated data pipeline linking surface-based measurements, airborne and satellite observations, process studies and model outputs will enable the development of curated, community-wide datasets that support super-site activities, cross-theme collaboration and long-term observations. Such datasets will also provide important constraints for reconstructing past ice-sheet evolution and benchmarking models against geological and paleoclimate evidence.

Together, these methodological advances – expanded observing systems, improved modelling and prediction frameworks, and integrated data infrastructures – are critical for reducing the uncertainties outlined in KG1–KG4. They will allow the Theme 3 community to build a coherent, multi-scale understanding of Antarctic processes, improve predictive skill, provide the tools needed to identify early warning signals of instability and forecast the future contribution of AIS to global sea-level change and response to climate change.

3. Observing strategies and key variables

Building on the methodological needs outlined above, an effective observing strategy for Theme 3 requires identifying the measurements that are most critical for reducing the uncertainties highlighted in KG1–KG4. A Key Variable (KV) represents the core physical quantity that must be monitored consistently across Antarctica to detect change, understand key processes, support model development and enable predictive capability (Figure 2). They span the ice-sheet and ice-shelf system, along with the ocean, atmosphere and solid Earth, reflecting the intrinsically coupled nature of Antarctic change. Establishing a clear set of KVs provides the foundation for designing coordinated, pan-Antarctic observing systems, planning super-site activities, harmonising measurement protocols and ensuring that observational efforts directly address the scientific priorities identified in this white paper. Table 1 summarises the KVs for Theme 3 and highlights the aspects of the ice-sheet–ice-shelf–ocean system they are intended to constrain.

Defining the KVs clarifies what must be measured to address the KGs identified in Section 2, but an effective observing system must also determine where and how these measurements can be acquired in a coordinated and efficient manner. Delivering these variables in a way that captures the coupled behaviour of the Antarctic ice, ocean, atmosphere, and solid Earth requires a strategic approach to observation design. In particular, coordinated efforts focused on a limited number of well-chosen regions (potential ‘super-sites’) offer a means of obtaining synchronous, multi-domain measurements while avoiding the fragmentation of effort across too many Antarctic targets. While super-sites enable detailed process studies, coordinated pan-Antarctic observations of key variables remain essential to achieve the synchronous continent-wide measurements envisioned by InSync. These super-sites are not predefined fixed locations; rather, they represent candidate regions whose selection should be guided jointly by the Knowledge Gaps they can address and by realistic and efficient logistical implementation. Table 2 outlines a set of such super-sites, illustrating the scientific rationale for each, their relevance to specific Knowledge Gaps and the processes and Key Variables they would allow Theme 3 to observe in a coherent and integrated way. At the same time, super-site-focused activities must be complemented by coordinated in situ and remote-sensing strategies – including scientific traverses and transects – that link these sites and ensure adequate spatial coverage of Key Variables across the Antarctic continent.

Knowledge Gap	Key Variables	Scientific Purpose / Process Link
KG1 Ice Sheet & Ice Shelf System	• Mass balance of drainage basins and ice shelves • Ice-sheet and ice-shelf thickness and thickness change • Surface elevation and elevation change • Ice velocity, velocity change and strain rate • Grounding-line location and migration • Calving-front position and iceberg flux • Fracture and crevasse evolution	Constrains ice dynamics, mass balance, buttressing, thinning processes, calving behaviour, and indicators of structural weakening and instability.
KG2 Ice–Ocean Interaction	• Ice-shelf basal melt rate and refreezing • Tidal corrections for ice-shelf motion • Grounding-line processes forced by tides and dynamic change • Ocean temperature, salinity, and density • Ocean currents, turbulence, and heat fluxes under ice shelves and at the ice front • Ocean tracers (e.g., $\delta^{18}\text{O}$, nutrients) • Sea-ice concentration and thickness • Supply of micronutrients (Fe, Mn) from meltwater or melt-driven upwelling	Quantifies ocean heat delivery, cavity circulation, ocean turbulence and vertical heat fluxes, basal melt, freshwater fluxes, ice shelf/sea-ice/ocean feedbacks, and melt-driven biogeochemical pathways. Contributes to understanding of ice shelf and ice sheet stability, and knowledge of dynamic processes.
KG3 Surface Mass Balance & Atmospheric Processes	• Large scale circulation, clouds and precipitation • Surface melt, refreezing, runoff, surface roughness • Density, air- and liquid water content and near-surface structure of firm • Stable water isotopes in snow and firm • Accumulation, ablation and surface melt rate controlling SMB • Katabatic winds, drifting and blowing snow and sublimation • Radiative and turbulent heat fluxes, subsurface heat flux • Atmospheric boundary-layer profiles (energy and mass fluxes) • Surface hydrological network (supraglacial lake volume, streams, slush, firm aquifers, discharge pathways) • Paleoclimate SMB records (cross-theme link with Theme 7)	Captures precipitation variability, extreme events, surface melt processes and their impacts, firm evolution, and energy balance controls on SMB and ice-sheet and ice-shelf vulnerability.
KG4 Solid Earth, Bed, Grounding Zones & Subglacial Hydrology	• Bed topography beneath ice sheet and ice shelves • Sub-ice-shelf bathymetry and cavity geometry • Geothermal heat flow distribution • Grounding line location and pinning point area • Basal shear stress, roughness, and effective pressure • Subglacial sediment deformation, basal sliding, subglacial hydrology, pathways, lakes, and discharge fluxes • Geodetic measurements of viscoelastic response to Glacial Isostatic Adjustment (GIA)	Defines basal boundary conditions, controls on grounding-zone stability, subglacial water routing and dynamics, and solid Earth feedbacks on ice dynamics, ocean circulation and cavity hydrography.

Table 1: The Key Variables (KV) for Theme 3 are grouped according to the major components of the ice sheet–ice shelf–ocean system and their associated Knowledge Gaps (KG). For each domain, the table identifies the key measurements required to characterise system state, variability and change, and to support coupled modelling and data-integration efforts.

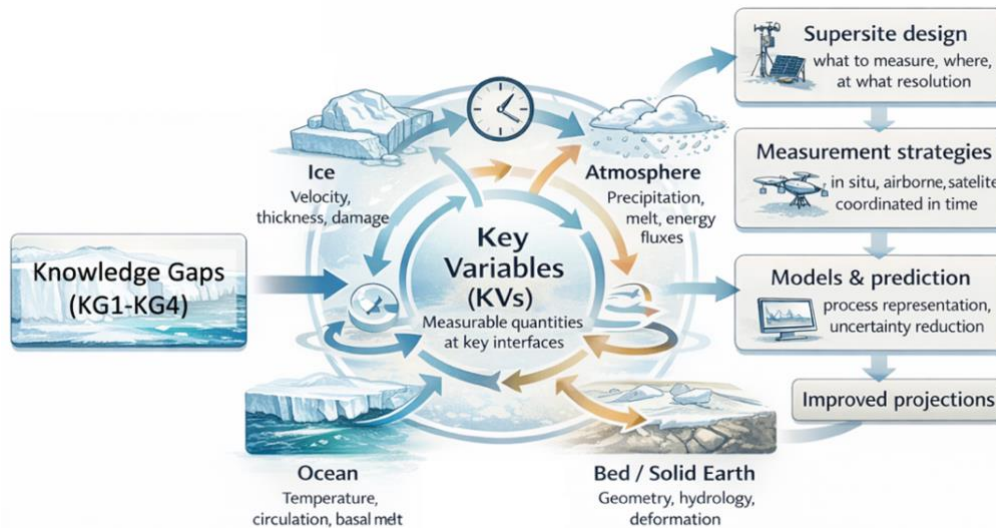


Figure 2: Sub-systems with their Key Variables and related observation and modelling approaches.

Supersite, Ant. Sector	Subregion	KGs Addressed	Key Processes / Parameters of Interest	Scientific Rationale	Relevant Key Variables
Antarctic Peninsula	East and West	KG1, KG3, KG2	Surface melt, supra glacial lake formation and drainage, hydrological network evolution, firm evolution, atmospheric rivers, ice-shelf thinning and weakening, seasonal ice-speed variability	Fastest-warming Antarctic region; strong atmospheric forcing; in-creasing surface melt; dynamic ice-shelf response	Large scale circulation, surface melt and hydrological network, SMB components, firm density, fracture evolution, ice velocity, ice shelf and ice sheet thickness change, energy fluxes
Antarctic Peninsula	West	KG1, KG3	Seasonal ice-speed change, atmospheric forcing, runoff, surface hydrology, perennial firm aquifers	Strongly forced by atmospheric processes; ideal for testing SMB–dynamics coupling	Ice velocity change, SMB fluxes, melt and runoff, surface hydrology, atmospheric profiles, ice shelf thickness and thickness change
Antarctic Peninsula	Eastern AP, Weddell Sea	KG2, KG3	Sea-ice feedbacks on melt, polynya dynamics, ocean transport	Region of strong sea-ice variability and atmosphere–ocean exchange; possible link to sea-ice decline	Sea-ice thickness, ocean currents, ocean tracers, basal melt
Queen Elizabeth Land	Filchner–Ronne Ice Shelf	KG2, KG1	Cold-to-warm cavity transition, basal melt sensitivity, frontal processes	Undergoing shifts in cavity circulation; key benchmark system for warm-water intrusion	Basal melt rate, ocean temperature & salinity, tidal motion, ice-shelf thickness and thickness change
Dronning Maud Land	Coastal ice sheet	KG1, KG2, KG3,	Surface melt (katabatic-driven), basal melt, drifting snow,	Accessible region with documented surface melt, weakening ice	Surface melt, basal melt, surface hydrology, grounding-line

(DML)		KG4	fractures, sub-glacial and surface hydrology, grounding-line evolution, coastal ice cores	shelves, active sub-glacial systems; strong cross-domain coupling	position, firm structure, SMB, sub-glacial discharge
DML	Ice shelves (Riiser-Larsen to Fimbul)	KG2, KG1	Basal melt, cavity structure, benchmark warm vs. cold processes	Known for contrasting melt regimes; suitable for process modelling and calibration	Basal melt, ocean properties, tidal corrections, ice velocity, ice shelf thickness and its change
DML	Mountains & Plateau	KG3, KG4	SMB variability, ice-core records, firm processes, subglacial structure, drifting snow, blue ice	Ideal for integrated ice-core, radar, and atmosphere–surface measurements; strong SMB gradients	Accumulation, isotopes, firm density, energy balance, englacial stratigraphy
Wilkes, Aurora Subglacial Basin, Lambert-Amery sectors		KG1, KG2, KG4	Potential marine ice-sheet instability, grounding-line sensitivity, bed geometry	Large ice volume at risk; vulnerable to ocean intrusion; limited existing observations	Bed topography, grounding-line position, basal conditions, ocean properties near margin, ice shelf and ice sheet thickness change and ice speed change
Ross Sea	Ross Ice Shelf	KG2, KG4, KG1	Cold cavity benchmark, melt variability, ocean–ice feedbacks, grounding-zone dynamics	Largest ice shelf; critical for contrasting warm vs. cold cavity processes and calibrating models	Ocean heat flux, basal melt, cavity geometry, currents, sea-ice conditions, changes in ice shelf and ice sheet thickness, and changes in ice velocity
Amundsen Sea Sector	Thwaites, Pine Island, Getz	KG1, KG2, KG4	Grounding-line retreat, vertical ocean heat fluxes, basal melt, subglacial discharge, cavity circulation, glacier acceleration	Site of most rapid Antarctic mass loss; MISI already underway; decisive for global sea-level rise	Basal melt rate, ocean heat flux, cavity geometry, grounding-line migration, velocity change, ice shelf and ice sheet thickness change, fracture evolution
East Antarctic Plateau	All sectors >2000m a.s.l.	KG3	Firm evolution & processes, SMB variability, ice-core records, drifting snow, firm temperature, atmospheric boundary layer	Low accumulation region of large extent with very little observations of recent changes and baseline characteristics; indications for temperature and accumulation and increase in last decades	SMB components, firm density & structure, SSA, firm temperature

Table 2: Candidate regions for super-sites and spatial interlinkages – final selection must be driven jointly by Knowledge Gaps (K1-K4) and logistical feasibility.

4. Key recommendations

Addressing the Knowledge Gaps identified in this white paper requires close coordination across the full Antarctica InSync programme. Many key processes – such as calving impacts on ocean heat redistribution, sea-ice-controlled freshwater fluxes, basal melt drivers, nutrient export, atmospheric forcing on melt and precipitation, and the ecological consequences of ice-shelf change – span multiple domains and therefore demand collaboration among several Antarctica InSync Themes. These linkages highlight the need for integrated observing strategies across land, ice, ocean, atmosphere and biosphere, along with community agreement on super-site locations, shared Key Variables for polar regions and sustained interaction with existing international groups and programmes, such as SCAR INSTANT, RINGS, FRISP, SOOS, AntClimNow, Groundwater, and AntArchitecture or IUGG commissions like JCIOL. Together, these efforts should enable coordinated pan-Antarctic observations that support synchronous measurements of key variables across the continent, a central objective of the InSync initiative. Progress will also depend on inclusive participation, training opportunities, and open data access, particularly for early-career scientists and researchers from underrepresented nations.

The coordinated scientific framework developed through Antarctica InSync positions the community to make decisive progress on the major Knowledge Gaps identified in this white paper. With rapid changes occurring across the Antarctic ice, ocean, atmosphere, and solid Earth systems, the coming years offer a critical window to establish the observations, modelling tools, and collaborative structures needed to improve predictive capability beyond IPCC AR7. This timeline aligns strategically with the preparations and the initialisation of multi-year observations for the Fifth International Polar Year (IPY-5). Antarctica InSync provides an unparalleled opportunity to develop and test the methodologies, super-site concepts, and integrated observing approaches that can be scaled up and reinforced during IPY-5, ultimately forming the basis for sustained, long-term observations in key Antarctic regions. Such observations start with InSync and are expected to seamlessly transition into the long-term observation strategies of IPY-5, assuming the continued support of national and international funding agencies.

Our final recommendations articulate the core actions through which Theme 3 can deliver this progress. Each recommendation is directly linked to the four identified Knowledge Gaps (KG1–KG4) and is designed to ensure that process understanding, sustained monitoring, and long-term model development advance in a coherent and mutually reinforcing way.

1. Define and implement coordinated Antarctica InSync “super-sites” for synchronous measurements across ice–ocean–atmosphere–solid Earth interfaces to advance process understanding.

KG1: Design super-sites to resolve the processes controlling ice-shelf weakening and calving, including fracture initiation, damage evolution, hydrofracture, and stress redistribution. These sites should combine high-frequency ice-dynamic observations (velocity, strain, elevation change), structural monitoring (crevasses, rifts), and surface hydrology measurements to identify the precursors of rapid ice loss.

KG2: Implement ocean–ice super-sites that directly sample sub–ice-shelf cavities, grounding zones, and ice fronts to constrain ocean heat transport, turbulence and basal melt processes. Super-sites should be selected based on their relevance to predicted future change and regime shifts in ice-shelf systems, including transitions from cold to warm cavities and increased ocean access to grounding zones. These sites should be used to reconcile satellite-derived melt estimates with surface-based observations and to benchmark basal-melt parameterisations used in coupled models.

KG3: Establish super-sites and complementary autonomous observing stations at carefully selected locations to resolve the processes governing surface mass and energy exchange. These should include satellite-linked stations for snowfall, sublimation, erosion, spectral albedo, melt rates, and drifting-snow

fluxes, complemented by dedicated firn stations to quantify subsurface meltwater percolation, refreezing, and densification. Where feasible, co-located ground-based radar and lidar systems should provide vertical profiling of clouds, precipitation, and boundary-layer structure to link atmospheric forcing with surface and firn processes.

KG4: Develop ice sheet super-sites that span regions of change, grounding zones, and adjacent ocean cavities to resolve modes of ice sheet dynamic variability and the coupling between bed topography, subglacial hydrology, geothermal heat flow, and grounding-line stability. These sites should explicitly link terrestrial geophysics with marine observations across the grounding line and capture the known modes of ice dynamic variability including seasonal, annual and decadal change.

2. Establish sustained and coordinated monitoring of ice-sheet and ice-shelf climate variables using satellite, airborne, ship, and surface-based observations, at high spatial and temporal resolutions.

KG1: Ensure long-term, high-frequency monitoring of ice thickness, ice velocity, grounding-line position, calving fronts, and structural integrity indicators to detect both gradual change and early warning signals of instability. Sustained observations should be designed not only to document trends, but also to support process understanding, by capturing the temporal evolution of stress, damage, and buttressing under changing environmental forcing. Near-real-time delivery of key products is essential for tracking rapid events.

KG2: Sustain multi-year observations of ocean temperature, salinity, circulation, sea ice and basal melt across contrasting cavity regimes, including both warm- and cold-water systems. Continuous records are required to capture variability on seasonal to decadal timescales and to assess the consequences of recent Antarctic sea-ice decline on ice-shelf melt.

KG3: Maintain continent-wide monitoring of accumulation, surface melt, refreezing, runoff, firn evolution and precipitation phase, combining satellite products with targeted in situ calibration. Sustained observations are required to quantify trends, variability, and the growing influence of extreme weather events on SMB and ice sheet mass balance.

KG4: Support repeated and continuous observations of basal boundary conditions, including grounding-line migration, subglacial water activity and solid-Earth deformation. Monitoring should capture not only static geometry, but also temporal evolution driven by changing ice load and hydrological conditions.

3. Strengthen the link between process understanding, monitoring and long-term model development.

KG1: Ensure that knowledge gained from super-sites and monitoring leads to new scientific insights about physical processes driving present day change, and feeds directly into the development of ice-sheet models to improve the accuracy of future projections. Improved representations of fracture, damage, calving, and buttressing and their impact on ice dynamics are of particular importance. Process understanding should be progressively incorporated into community models and assessed through coordinated model intercomparison activities.

KG2: Super-site observations should be used systematically to constrain and evaluate coupled ice–ocean models, with explicit feedback loops between cavity measurements, basal melt estimates, and model development. Hierarchical modelling approaches are required to span the range of scales between the small-scale turbulent processes that control basal melting and the large-scale regional and global models used for ice-sheet projections. This hierarchy should include turbulence-resolving DNS/LES simulations, idealised process-scale models, cavity-scale models and their integration into continental-scale frameworks.

KG3: Strengthen the representation of surface mass balance and atmospheric forcing in ice-sheet projections through improved, high-resolution non-hydrostatic regional climate models with interactively coupled, multi-layer snow and firn schemes. These models should explicitly represent grain-size and density evolution, vertical and lateral meltwater percolation beyond simple bucket approaches, and realistic surface–atmosphere energy exchanges. Insights gained at regional scales should inform improved parameterisations in global Earth System Models, enhancing their performance over the Antarctic Ice Sheet.

KG4: Advance coupled modelling frameworks that link ice flow with subglacial hydrology and solid-Earth processes, including glacial isostatic adjustment. Models and observations should be used both to improve projections and to identify where uncertainties in basal conditions most strongly limit predictive capability.

Across all three recommendations, success should be measured through systematic benchmarking, uncertainty quantification and model–observation intercomparison, ensuring that coordinated observations and process understanding translate into demonstrable reductions in uncertainty in projections of Antarctic change.

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Antarctica InSync Scientific Theme 4

Improving knowledge and protection of the unique Antarctic life: from land to ocean and into the deep sea

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Executive Summary

Antarctica and its surrounding ocean host unique, endemic and cold adapted ecosystems. The Southern Ocean is furthermore, highly productive and provides globally important ecosystem services, from carbon sequestration to substantial genetic resources. The Antarctic region is a natural reserve for iconic marine mammals, penguins and flying seabirds, as well as krill and wider zooplankton communities that underpin pelagic food webs and biogeochemical cycling. Recent environmental changes such as rapid warming, ice loss, permafrost thawing, ocean acidification and arrival of pathogens and pollutants pose risks and uncertainties to Antarctic life as we know it. Furthermore, Antarctica and the Southern Ocean still host the least studied regions, and the largest gaps in biodiversity knowledge. This theme thus aims to strengthen the scientific basis for understanding and protecting Antarctic life across environmental boundaries, from terrestrial and intertidal habitats and ice shelves, surface waters down to the seafloor, and from microbes to top predators. It will integrate novel approaches for rapid biodiversity discovery and functional analyses of the networks of life in the Antarctic region. By integrating observations of terrestrial, sea-ice, pelagic and benthic biota and habitats, standardising protocols, and building cross-national collaborations, Antarctica InSync will enable a more holistic circum-Antarctic view of ecosystem dynamics and resilience in a rapidly changing environment. However, delivering representative circumpolar observations will depend on coordinated governance and operations across national programmes, including logistics, permitting pathways, standardised QA/QC procedures and harmonised data stewardship.

This will contribute directly to the objectives of SCAR, [SOOS](#), the Conservation of Antarctic Marine Living Resources ([CCAMLR](#)) and the [IWC](#), as well as international initiatives such as the UN Ocean Decade, the 30 by 30 target, and the 5th International Polar Year, by improving the representation of biological ecosystems in circumpolar assessments and models and providing essential data to support future conservation and management frameworks.

1. Background and motivation

Within Antarctica InSync, Theme 4 provides the biological foundation for synchronised circumpolar observations by linking biodiversity across terrestrial, coastal, pelagic and deep-sea systems with concurrent physical, cryospheric and biogeochemical measurements. This integration enables biodiversity patterns and processes to be compared across regions and time within the broader InSync observational framework.

Antarctic biota differs markedly from other regions due to its evolution in isolation over the past 100 Mio years¹. Antarctic ecosystems are highly endemic, and differ in their connectivity depending on whether they are terrestrial or marine. On land, ecosystems are fragmented and restricted to ice-free

areas that function as ecological islands, where permafrost and active-layer dynamics strongly influence hydrology, geomorphology and habitat development. In contrast, marine ecosystems are highly connected, productive and seasonal, structured by sea-ice dynamics, ocean currents and complex pelagic-benthic coupling. Together, these features create ecosystems that are both globally significant and particularly sensitive to environmental change.

Over the past two centuries, excessive hunting, whaling and fishing led to the Antarctic Treaty System, regulating the sustainable use of Antarctic biological resources. Today, external drivers such as climate change, ocean acidification, invasive species, and other anthropogenic pressures are increasingly impacting the rich and highly endemic flora and fauna of Antarctica and the Southern Ocean, as well as the diversity of associated microbial communities that underpin organismal performance, ecosystem stability and the quality of the services that they provide. External pressures may alter ecological interactions and threaten the stability of unique ecosystems essential to global biogeochemical cycles and biodiversity. Increasingly, these pressures act simultaneously rather than in isolation, and their non-linear interaction may generate biological responses that are not detectable in single-driver studies. Understanding these processes requires robust, evidence-based scientific findings that can be effectively communicated to decision-makers, including the CCAMLR, the Antarctic Treaty System ([ATS](#)) and international frameworks such as the Intergovernmental Panel on Climate Change ([IPCC](#)), the Intergovernmental Platform on Biodiversity and Ecosystem Services ([IPBES](#))/Convention on Biological Diversity ([CBD](#)), alongside the new High Seas Treaty ([BBNJ](#)). Highlighting extreme dynamics in key biological functions, recent scientific evidence calls for much more holistic assessments of Antarctica's ecosystems. Examples of such dynamic changes include the fast greening of Antarctica's peninsula²; the temporal and spatial shifts in algal blooms³; the emergence and rapid dispersal of Avian influenza⁴; but also the substantial whale recovery and its feedback with a growing krill fishery⁵. Recent findings also demonstrate the many interlinkages between Antarctica's most remote habitats, *e.g.*, how hydrothermal vents fertilise the ocean with iron⁶.

Theme 4 of Antarctica InSync reflects the drive to understand, assess and conserve Antarctica's unique ecosystems and their roles within the Earth system. One challenge is determining how biodiversity is structured across spatial and temporal scales and biological levels, from the sub-Antarctic to the high Antarctic, from ice sheets to the deep sea, and from microbes to top predators. Identifying patterns of population and community structure is essential for assessing ecosystem resilience and vulnerability to climate-driven change and other pressures, and the capacity of Antarctic life to sustain critical ecosystem services.

Antarctic biologists have delivered step changes in ecosystem knowledge through large-scale collaborations, including the Census of Antarctic Marine Life (CAML, 2005), the Antarctic Conservation Biogeographic Regions ⁷, the SCAR Biogeographic Atlas of the Southern Ocean ⁸, the Retrospective Analysis of Antarctic Tracking Data (RAATD SCAR, ⁹), SOCCOM's integration of biogeochemical [ARGO](#) floats, and the Marine Ecosystem Assessment for the Southern Ocean (MEASO ¹⁰) among many others, all providing data and perspectives that underpin current understanding of Antarctic biodiversity and ecosystem functioning. Alongside the SCAR Horizon Scan (2014) and the Southern Ocean Action Plan (2022), these efforts have revealed major knowledge gaps and priorities, highlighting the need for coordinated research across habitats, biota and disciplines. Building on this foundation, Theme 4 seeks to improve knowledge and protection of Antarctic biota through observation, shared and standardised methodologies, and the co-development of essential biodiversity and ecosystem variables, ensuring that the diversity and dynamics of Antarctic life have a circumpolar representation to assess change and inform conservation and environmental policy.

Theme 4 links explicitly to all other themes of Antarctica InSync: Theme 1 through biogeochemical and element cycles and in particular the biological carbon pump; Theme 2 through the influence of sea-ice dynamics on marine ecosystems from ice algae, phytoplankton and bacterioplankton to higher

predators; Theme 3 through the influence of ice-sheets on terrestrial and marine habitats; Theme 5 through the impacts of anthropogenic stressors on species, habitats and ecosystem services; Theme 6 through emissions of reactive atmospheric compounds and cloud condensation nuclei from ice algal and phytoplankton communities; and Theme 7 through combined evolutionary and ecological responses to climate change impacts and reduced uncertainties in climate reconstructions. Theme 4 will contribute to cross-cutting tasks such as data integration, modelling and technological innovation in biological observations and sampling.

2. Knowledge gaps and research needs

Antarctica InSync provides a unique opportunity to design and execute a coordinated international, multidisciplinary assessment of Antarctic ecosystems through synchronous environmental observations, biological sampling, and integrated data processing and analyses across the vast and heterogeneous regions of Antarctica and the Southern Ocean. By connecting national efforts and disciplines under a co-designed framework, this initiative can expand the spatial and temporal coverage of biological observations and monitoring, improve standardisation of sampling and data analyses, and strengthen our ability to detect ecological and evolutionary responses to complex environmental and anthropogenic drivers.

Key questions include:

- How do past, ongoing and future changes affect Antarctic ecosystems?
- How resilient are functional groups, habitats, and species to climate change and increasing human pressures?
- What are the feedbacks caused by environmental shifts in terms of nutrient fluxes, carbon sequestration and energy flow?
- What are the potential consequences of ecosystem shifts for the provision of ecosystem functions and ecosystem services?

Theme 4 builds upon a foundational framework designed to advance our understanding of Antarctic biodiversity and ecosystem functioning. This includes (Fig. 1):

(1) Circumpolar biodiversity assessments: revealed that Biodiversity is still underestimated, with many species being complexes of several discrete genetic groups, each likely to be an undescribed species. Building on CAML legacy, and including genetic and omics tools, the continuing assessment will: identify and validate distributions of species/taxa/organisms and the habitats in which they occur; jointly assess population sizes, connectivity, philodiversity and genetic diversity; infer conservation status, and provide recommendations (Fig. 1, Block 1). The CAML database and the [GEBCO Seabed 2030](#) assessment provide important resources for identifying priorities for spatial analyses.

(2) Ecosystem functioning: linking biological dynamics with environmental and habitat conditions to decipher trophic and functional relationships and traits; metabolic interactions; energy fluxes; primary productivity and predator-prey dynamics; and examining how these processes and interactions may respond to environmental changes using both *in situ* and laboratory-based approaches (Fig. 1, Block 2). New technologies allow for unprecedented integration in observation, combining remote tracking and sensing with autonomous floats, gliders, moored platforms, and ship-based transects to measure environmental variables.

(3) Nature's contributions to people: assessing how biodiversity and ecosystems of Antarctica and the Southern Ocean support ecosystem services and contribute to societal value through conservation and sustainable use (e.g., provision of biomass, fisheries management, genetic materials, nutrient cycling, blue carbon; providing societal and cultural values such as scientific knowledge, option value, recreation and tourism) (Fig. 1, Block 3). This work calls for transdisciplinary analyses with the policy and industry stakeholders. To achieve progress in all these tasks, it is essential to link biological, physical, chemical, and geological properties of specific habitats, providing a truly interdisciplinary foundation for integrated ecosystem understanding.

This cascade will provide vital information to conservation organizations like CCAMLR and the ATS, supporting informed decision-making and conservation efforts. In order to address these challenges, circumpolar biodiversity data are essential for conservation efforts, particularly in the design and monitoring of representative systems of Marine Protected Areas (MPAs) and Antarctic Specially Protected Areas (ASPAs). They also support global conservation frameworks like IPBES and IUCN.

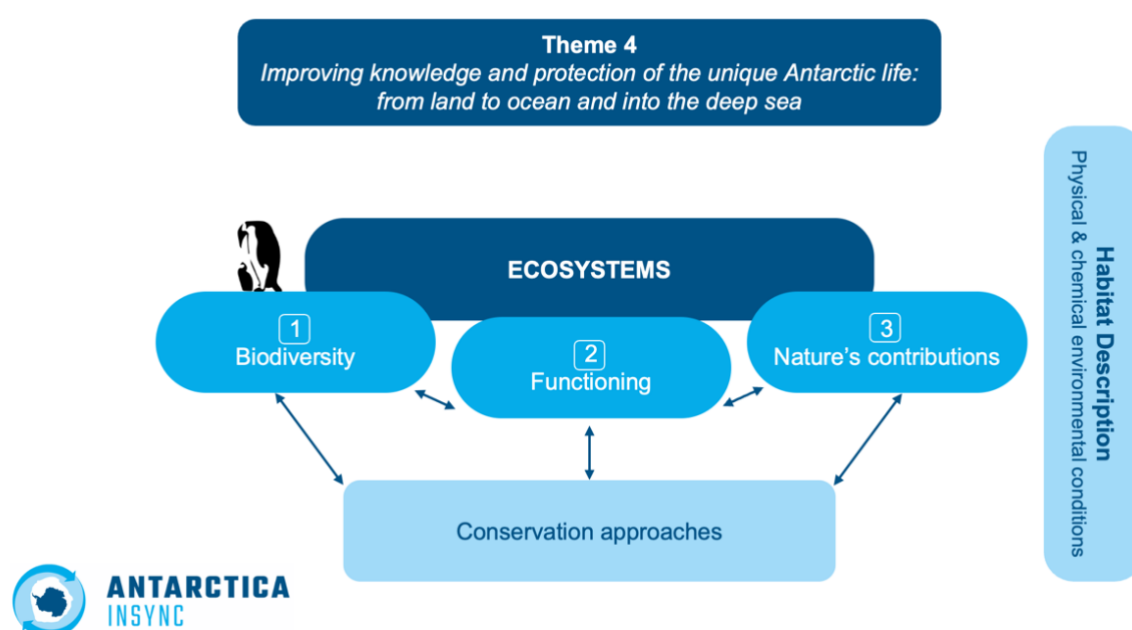


Figure 1: Theme 4 and its three pillars to be assessed, the cross-cutting importance of linkages with physical and chemical environmental conditions showing the potential of conservation approaches to draw on all aspects of the work.

2.1 Circumpolar Biodiversity Assessments

Recent advances in technology and methodology, such as machine learning, omics tools, and remotely operated vehicles, combined with expert taxonomy assessment, enable a faster and finer-scale identification of biodiversity patterns, networks and community structures. Despite these advances, spatial coverage and biodiversity knowledge remain uneven across the Southern Ocean and Antarctica, with clear biases toward accessible coastal regions. InSync will apply these tools at the circumpolar scale.

Scalable eDNA sampling across habitats will provide key baseline data. Multi-omics approaches reveal historical demographic and evolutionary processes linked to glaciological and climate history (Theme 7), providing crucial context for interpreting present and future Antarctic biodiversity. Targeted sampling in undersampled regions will improve species distribution and community models as well as better constrain ice-sheet (Theme 3) and oceanographic (Theme 1) models that rely on biological data. Integrating biological, physical, chemical and genomic datasets will reveal biodiversity hotspots,

connectivity and areas of resilience or vulnerability to climate change and human activities (Theme 5). Beyond scalable sampling and observation technologies, we need taxonomically consistent inventories; species distribution modelling to forecast climate-driven range shifts; and ML-based methods to integrate heterogeneous datasets and improve ecosystem models.

Terrestrial ecosystems: The emerging paradigm for Antarctic terrestrial biodiversity in ice-free habitats carries legacies of population persistence in glacial refugia, and expansion into new habitats following glacier and ice sheet retreat¹¹, and, contrastingly, episodic high meltwater wash-away of terrestrial vegetation. Habitat suitability frequently plays a significant role in determining community structure and function in many areas. These communities are connected by dispersal, shaped by organism traits and physical drivers. Understanding their relative importance is critical for predicting how climate change will impact biodiversity (Themes 3, 7), and guiding management¹². Antarctica's terrestrial ecosystems function more like an archipelago than a continent¹³, due to their separation by vast expanses of inhospitable ice. Moreover, substantial environmental variation characterises distant ice-free areas across the entire Antarctic⁷. In many Antarctic ice-free regions, permafrost and active-layer dynamics strongly influence soil moisture, geomorphological processes and habitat stability, yet observations of permafrost temperature, active-layer thickness and moisture remain sparse and unevenly distributed. Ecological theory¹⁴ suggests that the interactions between abiotic filtering, dispersal, adaptation, biotic interactions, and ecological stochasticity drive biodiversity responses to change. Coordinated, standardised pan-Antarctic biodiversity observations are needed to map species distributions and ranges, evaluate niche versus neutral processes, especially aeolian dispersal, and improve projections and conservation actions. Greater connectivity from increased glacial melt may redistribute species and facilitate spread of non-native species¹³. For microbes, moss and lichen spores, plant seeds and microinvertebrates, continent-wide airshed modelling is needed to simulate the transport of biological particles, based on size and density. Although organisms on and in glacial surfaces are a crucial contributor and connected to the scarce terrestrial ecosystems of Antarctica, this cryoflora remains largely understudied¹⁵ and is threatened to be lost by melt events. Also, coordinated biodiversity assessments using different complementary techniques, including omics approaches, remote sensing and modelling, can reveal the taxonomic composition and range size of these communities, and predict their response to climate and environmental changes¹⁶. Joint ice sheet traverses (Theme 3) will allow for substantial progress with such questions.

Marine ecosystems: Accepted range-based models of Southern Ocean biogeography suggest widespread, well-connected assemblages, inferring general resilience. However, many nominal 'species' comprise multiple lineages with restricted ranges, low effective population sizes, and poor connectivity *e.g.*,^{17,18}, implying greater vulnerability to environmental change than assumed. Yet, local adaptation and acclimation potential remain understudied for some species, as does the likelihood of poleward range contractions versus expansions. A major challenge is to understand how cumulative, interacting drivers shape biodiversity across biological levels, from host-associated microbiomes to populations, communities and ecosystems, and across temporal scales spanning contemporary change and historical baselines preserved in biological archives. Calcifying organisms, in particular, can preserve skeletal records of environmental conditions and biological responses, helping link past biodiversity dynamics with present patterns and future trajectories.

Given the reliance on species names for effective conservation management, the unrecognised diversity of the Southern Ocean remains underappreciated and potentially inadequately protected. A clear knowledge gap is the extent of biodiversity underestimation, and the spatial patterns that emerge when cryptic or unrecognised species are mapped. An example is our limited spatial understanding of benthic marine forests and the distributions of the species that comprise these unique circumpolar ecosystems. A key question is whether diversity data, including genomic data, can be used to project biogeographic and evolutionary patterns under future change and identify priority regions for conservation^{19,20}. In this

context, increasing evidence of “silent” range expansions and invasions in polar regions, particularly among sessile benthic taxa, highlights the need to link circumpolar biodiversity assessment with early detection frameworks for non-native and range-expanding species.

A major hurdle in understanding Southern Ocean biodiversity is the limited incorporation of fine-scale habitat variation and environmental drivers into high-resolution circumpolar assessments, partly due to. Uneven sampling across ice regimes and depth zones, despite clear differences, such as in benthic communities²¹. More comprehensive assessments are needed to link biodiversity patterns with ecological and physical dynamics by combining. These should integrate taxonomic, molecular and archival evidence to reconstruct past biodiversity, identify cryptic diversity, and improve predictions of future biodiversity change under ongoing environmental stress. Omics tools now enable both fine-scale (*e.g.*,²²) and broad-scale assessments (*e.g.*,²³), yet reference genomes remain scarce. There is also a lack of long-term international coordination and repeated sampling transects across the Southern Ocean, limiting consistent biodiversity mapping and conservation planning.

In the pelagic realm, a major research gap is the response of productivity, community composition and carbon export to seasonal controls such as light, temperature, sea-ice extent, trace metals and macronutrients (Theme 1). Whilst the biodiversity and distribution of some phytoplankton and zooplankton groups have been fairly well studied, data coverage is still limited to certain regions and mostly the spring and summer months. While range shifts in some species are well documented, shifts in understudied zooplankton, including copepods, salps, pteropods and gelatinous taxa²⁴ could reshape energy transfer to predators, disrupt nutrient cycling and alter pathways of organic matter export to the seafloor affecting the benthic biodiversity. Recent findings suggest there is a broad functional biodiversity within Southern Ocean microbial communities that we are still unaware of. Additionally, pathogens and disease dynamics are another largely overlooked component of Southern Ocean ecosystem functioning.

Across taxonomic groups, their functional genetic diversity, and environmental realms, we still lack a fundamental understanding of microbial processes in the Southern Ocean, their seasonal cycles, how biogeochemistry and trace-metal co-limitation shape community composition and distribution, and in turn environmental functions. Microbial life in sea-ice, its origin and role in reseeding the water column during retreat are yet to be parameterised in light of receding sea ice extent (Theme 2). The benthic ecosystem integrates organic matter transferred from the pelagic realm, linking primary production and pelagic community dynamics to sediment biodiversity and functional variability across regions and habitats. Although benthic biodiversity underpins ecosystem functions (*e.g.*, carbon sequestration), circumpolar and seasonal data remain sparse, yet are crucial to understand how pelagic-benthic coupling shapes the benthic ecosystem biodiversity. A coordinated circumpolar approach, crossing a range of physical and chemical environments would seek to answer these questions.

Antarctica’s predators are a vital, yet poorly understood, link in the vertical transfer and recycling of organic matter and micro/macronutrients, coupling biological and chemical processes across both trophic levels and spatial scales. While some regional population estimates exist, many are outdated, and circumpolar efforts are largely absent. Addressing this gap requires integrating traditional surveys with modern bio-logging, acoustic methods, and remote sensing approaches that together can provide up-to-date large-scale assessments. Compounding the urgency of rapidly changing sea-ice dynamics, the ongoing recovery of whale species from historical whaling introduces additional, poorly understood top-down pressures on prey fields and community dynamics, underscoring the need for a comprehensive reassessment of their populations and distributions.

2.2 Ecosystem Functioning

Knowledge of ecosystem functioning in the Southern Ocean and Antarctica is scattered geographically and restricted in time, quantity and interdisciplinarity of the archived data sets. A crucial challenge in

predicting and identifying trends and changes is posed by the requirement for the aggregation and synthesis of available data sets into a shared data and information system. Such a system will be essential for modelling and understanding ecosystem functioning and ecosystem management. In this context, a biodiversity-centred, holobiont-based perspective is increasingly needed, recognising that species distributions, resilience and adaptive potential are shaped not only by host traits but also by the diversity and composition of associated microbiomes. We must also consider the connectivity of ecosystems at a larger scale, particularly between terrestrial and marine systems, which presently represents another key knowledge gap. To fill this, *in situ* measurements of ecosystem processes such as primary and secondary production, respiration, nutrient mineralisation rates and cycling, and gas fluxes and host-pathogen interactions need to be combined with meta-omics approaches over habitats, seasonal cycles and spatial scales.

Terrestrial ecosystems: All terrestrial Antarctic taxa face severe knowledge gaps with regard to tolerance breadth for environmental conditions, functional traits, their variability, and their ecological significance in these extreme environments¹². In addition, the role of biotic interactions in structuring Antarctic terrestrial ecosystems and maintaining their functions remains largely unknown. Climate change (Theme 7), human pressures (Theme 5) and increased glacial melt (Theme 3) affect terrestrial and lacustrine primary production, nutrient and carbon cycling, and other ecosystem functions (*e.g.*, gas fluxes). Permafrost and active-layer dynamics are also critical controls on these processes in ice-free areas, regulating soil temperature, moisture levels, geomorphological stability and carbon cycling. However, observations remain sparse, limiting our ability to model future changes and their downstream impacts. A key knowledge gap concerns how ecosystem functions and energy fluxes respond to spatial and temporal variability in abiotic and biotic conditions. *In situ* data are therefore essential for ground-truthing and calibrating remote-sensing products that estimate ecosystem functions and properties (*e.g.*, vegetation cover and health, primary production, newly ice-free areas, potential for vegetation colonisation).

Marine ecosystems: While summertime upper-ocean processes are relatively well described, under-ice, year-round and cross-habitat observations remain scarce in pelagic and benthic zones. Consequently, seasonal dynamics of processes such as the biological carbon pump (Themes 1, 2), nutrient transformations and remineralisation, and life histories, remain uncertain, limiting predictions of ecosystem responses to sea ice loss (Theme 2) and glacial and ice shelf melt (Theme 3). Coordinated, all-season sampling is needed to better understand how micro/macronutrients, sea ice and other factors regulate carbon cycling and benthic-pelagic coupling²⁵ and ecosystem dynamics.

Phytoplankton and zooplankton communities underpin Southern Ocean food-webs, yet productivity and adaptations outside the austral summer, and the role of micro/macronutrients remain poorly understood, both in open water and under the ice, across gradients set by ocean currents (Theme 1), snow cover and sea ice dynamics (Theme 2, 3). Improving predictions of biogeochemical change will require integrating AI-assisted approaches with ecosystem modelling and interdisciplinary observations to better understand ecosystem dynamics and climate impacts (Theme 7).

In the pelagic realm, spatial and temporal change is increasingly evident. Antarctic krill biomass is retreating polewards while salps are extending into higher latitudes^{26,27}; other zooplankton and nekton are also likely to shift but remain understudied²⁸. For top predators, alterations to sea ice dynamics and changes in prey fields raise foraging costs, depress juvenile survival and adult fitness, potentially driving range shifts. These species remain valuable eco-indicators of under-ice ecosystem conditions, yet knowledge of their functional responses (*i.e.*, energetic payoff vs. prey abundance) remains limited. Trophic cascades link pelagic systems to the benthos, where variations in food supply, sedimentation rates and particulate organic matter affect ecosystem functioning alongside evolutionary processes such as dispersal, drift and geographic isolation. Benthic communities mediate key processes including

carbon storage and sequestration, remineralisation and nutrient cycling. Identifying ecological hotspots alongside energy fluxes between trophic levels will therefore support guide management of ecologically critical areas in the Southern Ocean²⁹. In particular, ice-covered regions, including the mid- and deep-water column, seamounts and ridges, remain understudied and require new technological approaches in mapping and camera surveying for their discovery.

2.3 Ecosystem Services

Antarctic ecosystem delivers critical and global services, including long-term carbon sequestration³⁰, nutrient recycling, genetic resources, and climate system feedback (Themes 1, 6, 7). However, the scale and variability of these services, particularly for less visible communities (*e.g.*, benthos), remain poorly quantified. Antarctic biota show high endemism and unique adaptations making them vulnerable to climate change, habitat loss, invasive species and pathogens, and threatening both biodiversity and ecosystem functions that sustain services. Moreover, human interactions with the Antarctic and Southern Ocean ecosystems and the ecosystem services they demand, have a direct impact on the very ecosystem functions and services provided (Theme 5).

Identifying and assessing Antarctic ecosystem services are important for protecting essential ecological processes (biophysical structure and processes) both within and outside of the Antarctic region. Despite not having a permanent human population, *i.e.*, local “beneficiaries” of these services, we can still outline provisioning ecosystem services directly linked to in-situ activities (*e.g.*, marine living resources, genetic resources), regulating services that are indirect and concern ex-situ global societies (*e.g.*, atmospheric circulation, nutrient cycling) and cultural services that consider the bequest values, cultural heritage, scientific and educational opportunities that Antarctica reveals³¹.

A circumpolar, multidisciplinary approach coupling biological, biogeochemical and physical observations will be crucial to quantify and model Antarctic marine (including sea ice, pelagic, and benthic) and terrestrial ecosystem services under future climate scenarios (Theme 7). This knowledge will not only support global assessments, such as IPBES and IPCC, but also inform the adaptive management strategies of conservation bodies including CCAMLR and the ATS.

Terrestrial ecosystems: Antarctic terrestrial ecosystems provide important ecosystem services and habitats that support unique biodiversity³¹; many species are endemic, especially in the microbiota, and remain undiscovered. There are limited species descriptions for all major groups and underexplored regions reveal considerable potential for further discoveries³², raising the need to biobank genetic information before it is lost. In addition, these habitats have an enormous wilderness value, and many Antarctic terrestrial habitats are unique on Earth. Moreover, Antarctic terrestrial ecosystems are connected to the marine realm through meltwater input, marine birds and mammal migration and it is largely unknown how this connectivity might affect ecosystem services (*e.g.*, nutrient cycling³³) and, vice versa, how they may affect marine life (*e.g.*, as reservoirs for pathogens). Antarctic ice-free sites have a strong attraction for the growing Antarctic tourism industry, which visits an increasing number of terrestrial sites in the Antarctic Peninsula and elsewhere, for their wildlife (*i.e.*, nesting birds), historic remains and scenic beauty.

Marine ecosystems: Antarctic marine ecosystems provide valuable provisioning services (*e.g.*, fisheries), regulating services (*e.g.*, climate), and cultural services (*e.g.*, tourism, science). Despite their functional role, many ecosystem services contributions remain largely unaccounted for or poorly integrated in current conservation frameworks. For instance, MPA initiatives have primarily focused on “commercially” relevant species and marine resources, while overlooking ecosystem engineers, such as seafloor communities as regulators of carbon storage and biogeochemical cycling (Theme 1). Estimates of carbon storage and potential sequestration on the Antarctic shelf have considerable societal value³⁰ while coastal areas, marginal ice zones, polynyas and retreating fjords in particular are hotspots of carbon drawdown and/or storage³⁴ that are likely still underestimated³⁵. Understanding these benthic and pelagic processes, and integrating them into conservation and management strategies, is essential

to capture the true ecological, climate and aesthetic/cultural value of Antarctic ecosystems. Emerging marine spatial planning and ecosystem-service assessment frameworks, applied elsewhere globally, provide tools to integrate these values and evaluate trade-offs among fisheries, tourism, climate regulations and scientific activities in marine management³⁶.

3. Observing strategies and essential variables

Developing an effective, integrated marine observation system requires a foundational design that uses existing platforms whilst remaining receptive to technological innovation. Specific observing strategies that close knowledge gaps and work towards connected knowledge bases will be developed by international working groups of experts rooted in the broader paradigm of Open Science. Working group efforts build upon previous developments of Essential Variables for Antarctica and the Southern Ocean^{37,38}, aiming for the integration of new technologies such as rapid biodiversity discovery, autonomous sensing, bio-logging, and remote observation into the framework of tasks. International workshops will help to align standards across data collection platforms, thereby creating a dynamic tool box for current and future international programs, especially IPY-5. Within this framework, adherence to FAIR principles (Findable, Accessible, Interoperable, and Reusable) significantly enhances data consistency, interoperability, and long-term usability. Furthermore, to achieve genuine reproducibility, strict traceability, and transparency, the application of FAIR principles must transcend initial metadata and raw datasets. True Open Science mandates that these principles be systematically extended to all non-data assets, encompassing analytical workflows, methodologies, algorithms, and computational tools. Ultimately, this holistic and transparent approach facilitates the ongoing evaluation of data coverage and utility, thereby ensuring that the resulting scientific outputs meaningfully, equitably, and reliably inform policy formulation and conservation decisions.

3.1 Biodiversity assessment

Data on the distribution, abundance, biomass, population sizes, and genetic diversity are essential biodiversity variables (EBVs) for assessing circum-Antarctic patterns of species richness, genetic richness, niche range, endemism and community structure across different taxonomic groups and systems. For the Antarctic region, [SCAR](#), [SOOS](#) and [GEOBON](#) experts are interacting to provide a scheme of EBVs for biodiversity assessments. These variables can be obtained through complementary approaches and observing strategies, including direct sampling (such as plankton nets, targeted trawls, cores and grabs), standardised settlement devices and colonisation systems in combination with non-invasive methods, such as visual surveys using camera mosaics, ROVs, AUVs, under water video profilers (UVPs) and remote sensing. Complementary morphology-based identifications (with vouchered specimens) alongside AI/ML methods and molecular species delineation further enhance detection across diverse habitats. Integrating these biotic variables with measurements of environmental properties, including local chemical and physical characteristics, biotic interactions, the historical context, as well as past and present-day connectivity will identify the drivers of taxa distributions and co-occurrences. Such approaches also enable explanation of spatial and temporal variations in population densities, community composition, and range sizes, and provide a robust foundation for circumpolar biodiversity assessment and ecosystem management. Working groups plan to organise circumpolar eDNA sampling of ice, ocean waters, and land to sea transects, as well as microbial, pelagic and benthic multi-size class surveys and sampling schemes in undersampled regions. New variables will be integrated such as land and ocean soundscapes, with links to top predator circumpolar surveys.

3.2 Ecosystem functioning

Ecosystem functioning in Antarctic terrestrial and marine habitats can be quantified using a

combination of molecular, physiological, and ecological measurements alongside observations, including omics approaches. These molecular insights are complemented by measurements of ecosystem processes across scales from meters to 100 kms, for primary production, respiration, grazing, nutrient uptake and (re-)mineralisation rates to study processes at larger spatial scales. Further upscaling of process understanding can be achieved by complementing *in situ* measurements with remote-sensing approaches and data assimilations by modeling. In terrestrial settings, lichens and mosses are some of the main contributors to Antarctic plant diversity and regulate the ecosystem processes associated with toxin accumulation and soil elemental cycling, so should be examined in this context, as well as their anti-stress responses to environmental drivers/extremes.

In the Southern Ocean, information on trace metal concentrations and bioavailability is essential to understand productivity patterns across the food web. Species interactions and food-web structure can be analysed using a wide range of approaches across all trophic levels. Genomic and transcriptomic analyses on microbial and key metazoan species will inform us on connectivity, local adaptation and resilience to change. Profilers, floats equipped with biogeochemical sensors and remote sensing for ocean color will provide key environmental variables (Themes 1,2).

In benthic ecosystems, ecosystem functioning essential variables also include bioturbation and bioirrigation rates, sediment oxygen consumption and redox potential, and the input, degradation and burial of organic matter. Alongside downward fluxes of carbon and other elements, these processes underpin carbon storage and flow, nutrient cycling and energy transfer between the pelagic and benthic systems as well as between pelagic and cryospheric habitats.

When using top predators as ecoindicators, a series of variables that describe prey-predator interactions can be extracted from bio-logging and bio-telemetry approaches, such as prey encounter event, energy expended, foraging/hunting times and energy gained. Coupling these animal-borne sensor measurements to data collected by autonomous buoys, moored systems, or UAVs would offer a complete view of ecosystem processes, especially those occurring under sea ice. In parallel, more “classical” on land measurements of breeding success and morphometrics complement the picture. In addition, a wide variety of variables such as dietary regimes, oxidative stress balance, parasitic load, immune status and so on, can be obtained by collecting blood, faeces and teguments from these predators.

Together, these variables provide a framework to quantify ecosystem functioning, connecting across trophic levels, enabling a mechanistic understanding of the ecological and biogeochemical processes sustaining Antarctic and Southern Ocean biodiversity. In the EBV system, these are captured by the classes of Ecosystem Functioning and Ecosystem Structure, and are complemented by ecosystem Essential Ocean Variables (eEOVs), such as biomass, growth rates, predator-prey interactions.

3.3 Ecosystem services

Global climate change is shaping the ecological processes in the polar regions and having profound effects on the ecosystems and the services they provide to society. The specific variables related to the identification and analysis of Antarctic ecosystem services could be related to the supply and demand for those ecosystem services, as well as to the interactions between humans and nature, and further downscaled into variables related to the abiotic factors, biophysical settings of the environment, and socio-economic indicators. These variables would then showcase the changes in human-environment interactions³⁹. To analyse the ecosystem services, a definition of the ecosystem types and delineation of the service providing units (SPUs) and appropriate mapping units should be performed.

Terrestrial ecosystems: quantifying Antarctic ecosystem services is largely based on expert assessments aimed at, for example, identifying those habitats supporting a particularly unique diversity, a high incidence of endemism, or having exceptional wilderness, aesthetic or scientific values. To the best of our knowledge the application of the ecosystem services concept in Antarctica has limited popularity

among the environmental studies and assessments of Antarctic ecosystems that are performed on local scales. A holistic and well-systematised analysis requires the integration of different methods and approaches, both qualitative and quantitative, such as expert-based assessment, and biophysical modelling, and the application of a coherent typology.

Marine ecosystems: Antarctica and the Southern Ocean provide numerous ecosystem services, including tourism or commercial fisheries, as well as many other invisible to markets and decision makers, such as carbon sequestration. A conservative estimate values these at \$180 billion annually⁴⁰. Biodiversity change directly affects the provision of these services. There is a need to identify, quantify and evaluate services derived from the marine system, along with threats to these services. From primary producers to the great whales, Antarctic marine systems are tightly coupled to the extent and duration of sea ice cover (Theme 2)⁴¹. Freshwater inputs and water availability further modulate physico-chemical and biological processes, including pollutant transport (Theme 5). Considering shifts in species composition, harvest, and other anthropogenic pressures within a changing climate is therefore essential to assess, and safeguard, the ecosystem's capacity to sustain these benefits. The EBV system foresees integrating these variables into the class "Ecosystem Services", with the focus on bridging data to policy-relevant information for decision-makers. Collaborative approaches with CCAMLR will define specific essential variables to this class, and working groups will be formed with a focus on conservation-relevant indicators.

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Antarctica InSync Scientific Theme 5

Anthropogenic signatures in Antarctica: the race against pollution and other pressures

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Executive Summary and Key Recommendations

Theme 5 examines the impacts of human activities in Antarctica, including scientific operations, tourism, shipping, local and global pollution, and krill fisheries, as well as their interactions with climate change, to inform environmental policy within and beyond the Antarctic Treaty System. Local pressures generate chemical and plastic pollution, black carbon, underwater noise, wildlife disturbance, invasive species, and antimicrobial resistance, affecting ecosystem resilience. The theme seeks to quantify and monitor anthropogenic pressures through standardized, internationally coordinated protocols spanning chemical, biological, ecological, and cultural dimensions during InSync. Key topics include pollutants and plastics, underwater soundscapes, tourism impacts, fishery ecosystem effects and management, environmental DNA and antimicrobial resistance, marine pollution impacts and climate feedback, and the cultural legacies of historic expeditions. Approaches combine harmonized sampling, long-term monitoring, remote sensing, in situ observations, and modelling to identify hotspots and cumulative impacts. By integrating open-access data across disciplines, Theme 5 advances predictive risk assessment, science-based mitigation, and conservation strategies to detect anthropogenic signatures and strengthen the protection of Antarctic ecosystems.

1. Background and motivation

Antarctica is experiencing growing pressure from both local and remote human activities that are increasing in scale and diversity, including fisheries, scientific operations, tourism and culture, and other non-governmental activities¹. Chemical impacts are mainly due to long-range transport of pollutants to Antarctica from distant sources, recently modified and eventually intensified by global environmental changes, including climate change (Themes 1 and 2) and ocean acidification. In addition, local activities generate pressures, despite their paucity in the Antarctic Region, and include additional plastic and chemical pollution e.g., persistent organic pollutants (POPs), heavy metals, emerging contaminants, macro-, micro- and nano-plastics, solid waste, black carbon, and underwater noise, as well as ecological disturbances such as wildlife disruption and the introduction of invasive species, pathogens, and antimicrobial resistance (AMR).

Understanding and mitigating of negative anthropogenic influences is critical for protecting Antarctica's unique ecosystems and its role in regulating planetary health. Identifying emerging risks, vulnerabilities, ecological hot-spot regions, and areas with disproportionately high human impact is essential for enabling timely and effective protective and management measures. Such actions align with the Protocol on Environmental Protection to the Antarctic Treaty, which provides the regulatory framework guiding human activities within the Treaty area.

Scientific studies highlight the long-term consequences of anthropogenic pressures for ice dynamics, biodiversity, and global climate feedback². The combined effects of climate change and human activities may produce cumulative impacts that remain poorly understood and difficult to predict due to limited long-term monitoring. In such uncertain multi-stressor situations, decision-making should be guided by the precautionary principle, implementing proactive measures to prevent harm even under scientific uncertainty³.

Theme 5 highlights the urgent need for sustainable, reliable and reproducible practices in impact assessment and environmental observation, alongside strengthened international cooperation to prevent harm from multiple anthropogenic signatures (Fig. 1). The outcomes of Theme 5 have important implications for guiding policy and practice, including the development of continuous, circum-polar observation systems; the implementation of mitigation measures by tourism operators, fisheries, and National Antarctic Programs; the design of conservation strategies for Antarctic ecosystems, and its cultural heritage based on the best available science; and contributions to ongoing policy processes aimed at reducing human impacts.

Theme 5 aims to quantify and understand the pressures from anthropogenic signatures in Antarctica, Research under this theme encompasses:

- (A) Chemical and plastic pollution in Antarctica,
- (B) Underwater noise pollution in Antarctic waters,
- (C) Monitoring tourism visitation impacts,
- (D) Assessment and management of wildlife disturbances by fisheries,
- (E) Biosecurity and invasive species surveillance and prevention,
- (F) Effects of marine pollution on Southern Ocean phytoplankton and climate feedback,
- (G) Encounters at the end of the world – Tracing Antarctic expedition legacies: Cultural signatures and evolving narratives.

Harmonized and reproducible protocols for impact assessment and observation will be developed across these topics, supporting science-based mitigation and conservation strategies. The research provides evidence to inform policy and precautionary measures aimed at reducing anthropogenic signatures in line with the Antarctic Treaty System.

Effective management of human pressures in Antarctica depends on strong coordination between scientific institutions, regulatory authorities, and policymakers. Harmonized policies enable consistent application of monitoring protocols, data sharing, and mitigation measures, reducing fragmentation and enhancing environmental protection under the Antarctic Treaty system and other international agreements. Effective science-to-policy communication of usable advances in knowledge is essential for evidence-based decision-making, and will be supported by this theme⁴.

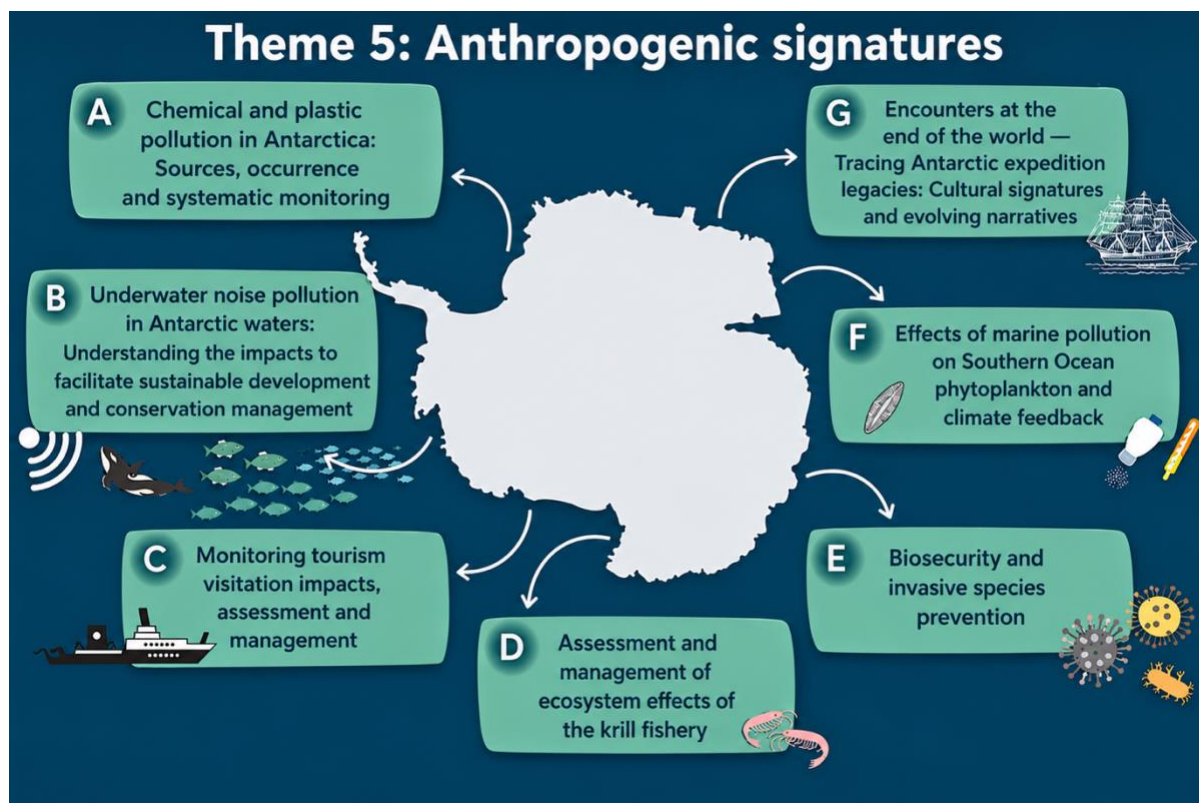


Figure 1: Overview of the InSync Theme 5 “Anthropogenic Signatures” research framework, which illustrates the overarching proposal and seven interconnected research topics addressing human impacts in Antarctica, including scientific operations, tourism, fisheries, culture, shipping, biosecurity, and pollution. The integrated approach highlights interdisciplinary collaboration, harmonized research programs, and data-driven strategies to understand and moderate anthropogenic signatures.

The Theme 5 program connects science directly with policy-relevant and legal instruments both within and outside the Antarctic Treaty system. Effective knowledge exchange with policymakers will be integral to the planning of the program from the earliest stages. Opportunities exist to explore new methods to promote information exchange at the science-policy interface, including the identification/development of tools to enable the research findings of Theme 5 (and InSync more generally) to directly inform applied environmental management⁵. Lessons from Arctic research show that such integrated approaches substantially improve protection of polar environments under rapid change. The establishment of an Antarctic Monitoring and Assessment Programme (AnMAP) in 2024 follows this approach and aims to facilitate sufficient and reliable chemical data from the Antarctic region, in support of global chemical policy. By linking scientific evidence to policy action, Theme 5 supports anticipatory, adaptive governance in Antarctica, enhancing early warning capacities, guiding timely interventions, and safeguarding ecosystems against cumulative human and environmental impacts.

2. Knowledge gaps and research needs

Research under Theme 5 relies on internationally agreed variables to quantify anthropogenic pressures in Antarctica. A cross-disciplinary approach, combined with close collaboration with other InSync themes, is essential to ensure that observations, sampling, and measurements are consistent, standardized, and reproducible. Integrating diverse data sources including environmental, biological, cultural and socio-economic information enables a comprehensive understanding of human impacts.

Open access and interoperable data systems are critical to facilitate robust analysis, informed decision-making, and evidence-based policy development. Currently, the Ocean Biodiversity Information System (OBIS) and the Global Biodiversity Information Facility (GBIF) host substantial amounts of Antarctic biotic and abiotic data. For instance, OBIS contains more than 1,200,000 occurrence records from Antarctica, representing 6,308 marine species (data retrieved on 22.02.2026; not quality-controlled).

Theme 5 is structured around targeted topics addressing key knowledge gaps, operationalized through coordinated working groups. These groups support the systematic assessment, monitoring, and management of human activities across Antarctica, encompassing both local pressures and their interactions with broader environmental changes. By harmonizing methodologies and promoting collaboration, Theme 5 aims to generate actionable insights that guide science-based mitigation strategies and the sustainable stewardship of Antarctic ecosystems.

Topic A: Chemical and plastic pollution in Antarctica: Sources, occurrence and systematic monitoring

General introduction

Chemical and plastic pollution in Antarctica results from a combination of long-range environmental transport (LRET) and local human activities. Pollutant sources are also including research stations (e.g., buildings, wharfs, landing strips, large equipment, large equipment, fuel storage infrastructure and refuelling points), fisheries, and tourism. POPs; (e.g., per- and polyfluorinated alkyl substances (PFASs), brominated flame retardants (BFRs), and organochlorine pesticides (OCPs)), as well as metals have been detected in both abiotic and biotic compartments, highlighting both the vulnerability of Antarctic ecosystems to local pressures, as well as their role as sinks for some highly mobile global contaminants⁶. Both POPs and metals may originate from natural and anthropogenic sources. These persistent and globally-transported contaminants tend to accumulate and biomagnify in food webs and exert toxic effects on organisms. LRET associated pathways to Antarctica and the Southern Ocean may be atmospheric, hydrospheric, or animal vector-mediated.

Contaminants of emerging Antarctic concern (CEAnC), including pharmaceuticals and personal care products (PPCPs), surfactants, phenolic endocrine disruptors, PFAS replacements, and other bioactive compounds, are increasingly recognized as relevant Antarctic pollutants⁷. Their persistence, toxicity, bioactivity, and interactions with polar food webs pose growing risks to ecosystem health and resilience. In addition, plastic pollution (including macro-, micro- and nanoplastics and associated chemicals such as additives) is not solely restricted to chemical exposure risk⁸. Plastic pollution must be considered as a type of combined physical, chemical, and biological pollution that harms ecosystems in multiple ways⁹. As a biological pollutant, plastics provide durable substrates for rafting and biofouling communities, potentially transporting propagules across biogeographic boundaries and increasing the probability of non-native introductions into Antarctic coastal and benthic habitats.

Cryosphere processes, such as loss of permafrost, ice melting and freeze-thaw cycles, has the potential to remobilize sequestered contaminants and accelerate fragmentation of plastic debris, generating secondary emissions that influence contaminant bioavailability as already confirmed from Arctic studies⁹. Data on contaminants in Antarctica however, remain limited, and the lack of harmonized, systematic sampling and analytical protocols hampers comparability, baseline development, and trend detection. Establishing comprehensive, standardized, high-resolution datasets for both legacy and emerging chemical and plastic pollution is urgently needed. These data are essential for effective environmental surveillance, risk assessment, and the development of science-based policies and management strategies to protect Antarctic ecosystems¹⁰.

The currently reported measurements of POPs, metals, and microplastics in Antarctic snow, ice, and biota show concentrations that cannot be explained by local sources only. This data confirms atmospheric and oceanic transport from distant industrial regions as an important pollution source in Antarctica¹¹. These findings collectively prove that even remote regions like Antarctica are not isolated from global pollution, emphasizing the need for international emission controls.

Research gaps

Despite increasing awareness of environmental threats in Antarctica, chemical and plastic pollution remain poorly characterized and lack systematic monitoring. Harmonized sampling and analytical protocols across environmental matrices are lacking, and there is no consensus on priority contaminants for monitoring. Comprehensive spatial monitoring networks are absent, and data collection is often biased towards specific seasons and regions. The existing long-term time series are insufficient to detect trends, and information on some pollutants such as nanoplastics is extremely limited due to challenges in measurement with current methods. The role of macro- and microplastics as dispersal vectors is still poorly understood, as we lack detailed data on the species that colonize them, how biofouling varies across polymer types, and how these changes affect plastic buoyancy and transport. Biofouling can increase plastic density and decrease buoyancy, exposing seafloor communities and potentially spreading non-native species. Moreover, plastic-associated chemicals can be liberated over time and increase exposure of and potential impacts on local ecosystems. Major knowledge gaps persist regarding the cumulative impacts of contaminants, their behavior and transformation over time, bioaccumulation in key species, and toxicological effects on endemic organisms.

The fate of atmospheric mercury delivered to the Southern Ocean, from deposition to oceanic speciation and food-web transfer, remains poorly quantified and lacks sufficient observational and process-based constraints, hindering reliable evaluation of contaminant exposure in Antarctic ecosystems and the regional effectiveness of global mercury mitigation measures of the Minamata Convention.

Furthermore, the links between pollution loads and ecological consequences remain poorly understood, limiting the ability to assess the full environmental and biological risks posed by chemical and plastic pollution in Antarctic ecosystems. Potential synergistic effects between contaminants and climate stressors (e.g. acidification, temperature change) remain poorly quantified¹². Chemical pollution research is fragmented by national programs and lacks binding legal frameworks within the Antarctic Treaty System.

Climate change accelerates microbial pollution risks in Antarctica by increasing ice melt and human activity, which introduce pathogens into previously isolated ecosystems. Warmer temperatures and changing precipitation patterns create conditions that favor microbial survival and dispersal. These shifts raise concerns about disease transmission to native species and potential disruption of fragile Antarctic food webs. Cumulative impacts may weaken organism's immune response and make them more prone to pathogens; in turn, these pathological conditions may increase the effects of chemical impacts on their health.

Objectives

The objectives of Topic A are to establish a coordinated international network for chemical and plastic pollution monitoring and to harmonize efforts across pollutant-related initiatives such as AnMAP, SCAR-IMPACT, SCAR-Plastic (SPEG), APECS plastic group and national programs. Specific objectives of the theme include the following:

- Establish a coordinated international network for organic micropollutant, plastic, and inorganic contaminant monitoring in Antarctica, aligning and harmonizing efforts across AnMAP, SCAR-IMPACT, SPEG, APECS, and relevant national programs.
- Determine standardized target abiotic and biotic matrices for long-term monitoring.
- Develop and implement standardized transects and long-term monitoring sites to enable comparable, high-quality observations across regions and time.

- Build a shared, openly accessible Antarctic chemical pollution database
- Develop Antarctic specimen banks to support long-term assessments and retrospective analyses.
- Deploy autonomous and innovative monitoring technologies on research and tourism vessels, Antarctic stations, and floating buoys, ideally to enable continuous sampling and monitoring of pollutants.
- Supporting lab-based experiments alongside *in-situ* monitoring to generate ecotoxicological data, and produce reliable impact assessments.
- Investigate the impacts of climate-driven changes, such as warming, declining ice cover, and oceanographic shifts on pollutant transport, mobility, bioavailability, and toxicity.
- Investigate the role of plastics as biological dispersal vectors, including characterization of rafting and biofouling communities, polymer-specific colonization patterns, buoyancy changes, and associated risks of non-native species introductions in Antarctic coastal and benthic ecosystems.
- Identify ecological hotspot regions and assess risks to key species and ecosystems from chemical pollution under changing environmental conditions.
- Determine and quantify the processes linking atmospheric mercury transport and deposition to oceanic transformation, air–sea exchange, and trophic transfer in the Southern Ocean to establish its role in the global mercury cycle and associated exposure risks.
- Provide robust, evidence-based scientific input to inform environmental management and policy decisions within the Antarctic Treaty System.

Key essential variables

Key essential variables for measurement under Topic A include legacy and emerging organic chemicals of concern, inorganic contaminants, and plastic pollution levels across multiple environmental matrices, as well as identification of sources, transport pathways and exchange fluxes as a prerequisite for the development of mitigation measures. Determination of exposure pathways and assessment of accumulation of pollutants in key species at various trophic levels is essential for the evaluation of species bioconcentration, bioaccumulation with time, and biomagnification along food chains. For plastics, essential variables should also include debris characteristics (polymer type, size, weathering state, and source), biofouling load and community composition, release of plastic-associated chemicals and indicators of predictors of likely fate, linking pollution monitoring with biological dispersal risk. These data are interpreted alongside crucial environmental and climate-related drivers, including temperature trends, wind and atmospheric circulation patterns, ocean currents, melting dynamics, humidity, precipitation, pH, and aerosol properties. Geographic variables include distance from research stations, Antarctic protected areas, and tourism and national program cruise routes, while human-activity variables include fuel combustion, wastewater discharges, and station emissions and scientific activities as well as fluxes from legacy contaminated sites.

Proposed strategies

Strategies for Topic A focus on designing and mobilizing coordinated, long-term chemical monitoring across research stations, dedicated year-round observatories, regular monitoring from icebreakers, international coordinated scientific expeditions. Observations should cover all environmental matrices and contrasting environments including protected areas. Standardized sampling and analytical methods will support efficient collection of abiotic and biotic matrices. Key priorities include modelling climate-driven shifts in LRET, tracking pollutant remobilization from melting ice, and assessing biovector and plastics pathways and input (e.g., weathering and fragmentation of plastics and related leaching of plastic-associated chemicals). Monitoring must also distinguish remote sources of pollution from local human emissions. Integrated datasets, shared platforms, and international expert collaboration will enable trend detection, predictive risk assessment, and the development of effective mitigation and management policies under the Antarctic Treaty System. The Antarctic Treaty Consultative Meeting

(ATCM 47) recently adopted Resolution 5 (2025) in Milan, establishing a collaborative international framework to combat plastic pollution through direct government action informed by rigorous scientific research.

Topic B: Underwater noise pollution in Antarctic waters: Understanding the impacts to facilitate sustainable development and conservation management

General description

Anthropogenic sound emissions are increasingly impacting the world's oceans¹³. Underwater sound is of vital importance for many marine species, ranging from invertebrates to the great whales. To date, the Southern Ocean is generally still considered to represent one of the planet's last pristine marine soundscapes¹⁴. However, Antarctic ecosystems are increasingly impacted by tourism, local and regional overharvesting, pollution and introduction of alien species. Global climate change is exerting further pressure through rising ocean temperatures and receding sea ice. Together, these pressures are also increasingly affecting Antarctic marine soundscapes by altering habitats, changing animal (acoustic) behavior, distribution patterns and community composition. Given the environmental change that is resulting from the increased anthropogenic presence, the quantification of anthropogenic noise and assessment of its potential impact on Antarctic marine soundscapes is timely.

Research gaps

To be able to quantify the risks and impacts of human-made underwater noise and effectively manage and mitigate human activities in the future to conserve Antarctic soundscapes, the natural baseline needs to be fully understood. This entails appraisal of overall ambient noise levels as well as spectro-temporal characterization and quantification of Antarctic marine soundscapes. The unique momentum that the Antarctica InSync program creates for investigations on a circum-Antarctic scale will boost and support international collaboration with partners to compare and map circumpolar Antarctic marine soundscapes. Furthermore, by comparing current soundscape data to historic recordings, trends in underwater noise can be assessed for selected sites. Within Antarctica InSync Theme 5, we aim to carry out internationally coordinated, standardized, large-scale comparisons of multi-year data to assess the status and potential effects of noise pollution on polar soundscapes and marine life in the Anthropocene.

Key essential variables

Ocean sound is considered a cross-disciplinary Essential Ocean Variable by the Global Ocean Observing System (GOOS). Current international efforts aim to establish the implementation of ocean sound within global ocean monitoring networks¹⁵ and work towards internationally applied standards on underwater noise monitoring¹⁶.

Objectives

- Circum-Antarctic assessment of the *status quo* of polar soundscapes' compositions in different Southern Ocean basins, providing baseline knowledge on pristine soundscapes
- Improve our understanding of (and how) Antarctic soundscapes intercompare over space and time
- Comprehensive evaluation of the impacts of anthropogenic noise on pristine Antarctic soundscapes

Proposed strategies

The circum-Antarctic evaluation of marine soundscapes that we propose here will be based on existing, and where possible including historic, multi-year and multi-site datasets, from which subsets of data will be collated, selected according to predefined requirements such as spatial or temporal coverage. Soundscape analyses will be built on previous pioneering work applying ecoacoustic metrics and MSFD (Marine Strategy Framework Directive)¹⁶ noise band measures on polar marine data¹⁷. Well-documented, standardized analyses will not only provide baseline knowledge on soundscape

characteristics of pristine marine environments but will also allow for pan-Antarctic monitoring of anthropogenic noise budgets and trends in an increasingly anthropocentric Southern Ocean.

Topic C: Monitoring tourism visitation impacts, assessment and management

General description

Antarctic tourism has grown significantly, with more than one hundred and twenty thousand visitors arriving each year to experience its unparalleled landscapes and wildlife. Antarctic tourism has experienced sustained long-term growth¹⁸. Tourism in Antarctica is associated with a range of environmental pressures, including risks of habitat degradation and wildlife disturbance, noise, pollution (e.g. waste, emissions, hull fouling and plastic debris hosting biofouling communities), and the introduction of non-native species and diseases^{19,20}. Lessons learned during Covid-associated closures of the industry also suggest unexpected impacts related to wildlife site selection²¹.

Besides the instruments adopted by the Antarctic Treaty Consultative Parties, most tour operators and tourists visit Antarctica in accordance with guidelines developed and promoted by the International Association of Antarctica Tour Operators (IAATO), which aim to minimize tourism's ecological impacts and emphasize the importance of visitor education and stringent impact mitigation measures. At present, all commercial cruise and deep-field operators active in Antarctica are members of IAATO, with a small proportion of primarily smaller yachts operating outside of this self-regulatory scheme. Most of the current Antarctic tourism modalities include visits to approximately 600 Antarctic terrestrial and marine sites (i.e. expedition cruises, air-cruising, yacht tourism and deep-field expeditions) to conduct an increasing number of activities -e.g. scuba diving, snorkeling, kayaking, skiing, ziplining, and diving in a submersible. Tourism governance in Antarctica is currently characterized by a fragmented and heterogeneous set of regulatory instruments, guidelines, and practices, with limited harmonization in how tourism activities and their environmental implications are assessed and managed across sites and regions. Over the past decades, a substantial share of practical visitor management has effectively been delegated to the tourism industry, in particular through the self-regulatory framework developed and implemented by IAATO, which has played a significant role in establishing and operationalizing site-based rules, operational standards, and compliance mechanisms. At the same time, formal regulatory instruments under the Antarctic Treaty System remain unevenly developed and applied, and no comprehensive, system-wide framework for assessing, comparing, and monitoring tourism activities currently exists. Although the Environmental Protocol to the Antarctic Treaty requires that activities be monitored to detect and assess environmental impacts, monitoring of tourism activities has so far been implemented in a piecemeal manner, without a coordinated system, shared indicators, or harmonized conditions across sites and operators.

Research gaps

The diversification and expansion of tourism operations in Antarctica, together with the critical overlap between the tourist season and key ecological processes (e.g., bird breeding season), have raised concerns about the scale, duration, and severity of impacts and their potential cumulative effects¹⁸. It is crucial, therefore, to establish an internationally agreed approach for monitoring the environmental impacts of tourism that integrates existing governmental and non-governmental initiatives, such as the site monitoring of Oceanites (<https://www.oceanites.org/>), observations and efforts by the tourism industry, and the work carried out through various NAPs^{22, 23}. With the tourist numbers growing, activities diversifying and new sites visited each year, there is a need for an agreed set of metrics for what we would be monitoring for, and how we would untangle the impacts of visitation from the impacts of climate change or other human activities.

Objectives

- To establish a monitoring framework for tourism activities and their environmental effects in Antarctica (incorporating current efforts) that could be consistently applied across Antarctica
- Developing an achievable and cost-effective framework for monitoring that can be consistently employed by different NAPs/IAATO operators at different scales and sites.

Potential indicators and data sources

Monitoring tourism visitor impacts builds on indicators for assessment tourism pressure (e.g., visitor numbers per site, number and types of operators, ships, activities, spatial and temporal distribution), environmental impact (e.g., changes in presence of breeding birds or other wildlife, soil erosion and compaction, changing condition and cover of shallow benthic communities, presence and spread of non-native species and pathogens, presence of litter, micro-plastics and pollutants, underwater noise), impacts on cultural and historic assets (e.g. condition of historical structures, integrity of cultural sites). In addition, monitoring should consider direct emissions from cruise ships, including atmospheric emissions, ballast water discharge, and waste release.

Proposed strategies

Many of the impacts that might be associated with tourism are cumulative and gradual changes in the biological or physical state of the system that unfold over years and even decades (e.g., moss recovery, wildlife population changes, changes to invertebrate community composition, soil compaction). For this reason, understanding the impact of tourism activities on time scales relevant for adaptive management likely requires a space-for-time substitution approach wherein sufficiently similar sites that experience different levels of tourism activity are identified to serve as matched case-control pairs. We will explore collaboration with National Antarctic Programmes located close to key sites, IAATO and member companies (vessels of opportunity), which would allow us to maintain the status of control sites as largely free from tourism-related impacts, including both the landing of passengers at the site and boat travel (including zodiac cruising) offshore. These case-control pairs would be monitored according to a suite of biological and physical criteria using in-situ methods, including wildlife surveys to assess population changes, vegetation and soil surveys, measurements of soil compaction, assessments of erosion and surface disturbance, invertebrate sampling to evaluate abundance and richness, and field-based wildlife counts during the breeding season. Chemical sampling (e.g., hydrocarbons, microplastics, or other pollutants) can further support the attribution of observed changes to human activities versus natural variability. Together, these complementary approaches provide a robust methodological basis for indicator development and long-term trend assessment across diverse Antarctic sites.

Topic D: Assessment and management of ecosystem effects of the krill fishery

General description

The Antarctic krill (*Euphausia superba*) fishery is the largest in the Southern Ocean in terms of harvested tonnage. It is currently concentrated in the southwest Atlantic sector of the Southern Ocean, known as CCAMLR Area 48. This region contains a significant proportion of the total krill biomass, which is estimated to be around 60–63 million tonnes (Mt), making it a vital ecological hotspot. Krill supports a wide range of predators, including penguins, seals, and baleen whales, and is therefore central to the Southern Ocean ecosystem.

Since 1991, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has set the operational annual catch limit (trigger level) for krill in Area 48 at 0.62 Mt. This limit was introduced as a temporary measure to replace the previous, higher precautionary catch limit of 5.61 Mt,

which was derived from a single large-scale krill biomass survey conducted in 2000²⁴. From 2009 until 2024, the operational catch limit was further subdivided among four subareas (48.1–48.4) to reduce the risk of concentrated fishing pressure. However, due to a lack of consensus among CCAMLR members regarding the revision of the fisheries management strategy, this measure expired in 2024. Consequently, there are currently no spatial restrictions on catching the 0.62 Mt limit in Area 48.

The removal of subarea catch limits has led to a rapid concentration in fishing pressure. For the first time, the operational catch limit was reached during the 2024/25 fishing season. Although the fishery normally runs from November to September, the catch limit was reached in August 2025 with 99.97% of the catch limit taken²⁵. Of particular concern was the increase in catch from 0.155 Mt to 0.355 Mt in subarea 48.1., the Antarctic Peninsula region. The concentration of fishing effort in this ecologically sensitive and rapidly changing region highlights the urgent need to determine the potential impact of the fishery on the ecosystem.

CCAMLR's mandate is to ensure that krill harvesting does not cause irreversible harm to target species, dependent predators, or the wider marine ecosystem. To this end, CCAMLR relies on information regarding krill biomass and distribution, as well as predator population dynamics and interactions within the ecosystem. However, the effectiveness of this approach depends on whether existing data and monitoring programs are sufficient to address these issues, or if there are significant knowledge gaps that require strengthened data collection and analyses²⁶.

As the krill fishery continues to grow alongside recovering whale populations in core fishing grounds²⁷, it is critical to enhance monitoring of major krill consumers, including penguins, fish, baleen whales, and crabeater seals²⁸ as well as of key drivers of krill stock dynamics, such as seasonal life-stage distribution, habitat connectivity, and recruitment. This will ensure sustainable ecosystem-based management.

Research gaps

Although the annual operational catch limit of 0.62 Mt for the entire southwest Atlantic fishery represents only around 1% of the region's estimated krill biomass, concerns about the sustainability of the fishery are growing, particularly regarding localized impacts. These concerns have become more pronounced since 2024, due to the lack of spatial restrictions on the distribution of the catch limit. The risks contributing to these concerns include:

- Fluctuating biomass: Krill biomass can vary dramatically from year to year, making it difficult to determine sustainable catch levels.
- Spawning stock vulnerability: In some years, the proportion of krill available for spawning is low, which could affect recruitment.
- Climate change impacts: Environmental shifts, such as the melting of sea ice and rising ocean temperatures, are expected to exacerbate these fluctuations, introducing additional uncertainty.
- Competition with wildlife: Intensive fishing in key foraging areas of krill-dependent predators could threaten the reproductive success of local wildlife.

Therefore, it is crucial to establish a data collection approach that integrates political bodies such as the CCAMLR Commission, the scientific community, both within and outside of CCAMLR, non-governmental initiatives, and the fishery, to monitor the impacts of the krill fishery on krill-dependent predators and the krill population itself.

Objectives

- Quantify the spatiotemporal overlap between krill fisheries and krill predators and assess whether this results in functional and numerical responses to fishery-induced changes in krill availability induced by the fishery.

- Investigate behavioural interactions between fisheries and predators, focusing on foraging behaviour, movement, and energetic costs.
- Develop coordinated, standardised, multi-platform monitoring protocols integrating predator tagging, krill surveys, and fisheries observations.
- Promote collaboration among scientists within and beyond CCAMLR.

Proposed strategies

A synchronised, interdisciplinary framework will integrate biological, oceanographic, and fisheries data, which will be collected through coordinated field campaigns and autonomous platforms. During the InSync period, predator-tagging campaigns and krill surveys will be coordinated across research and commercial vessels, gliders, and biologging devices. This will enable comparisons to be made across different scales regarding predator behaviour, krill availability and fishing effort. Collaboration with various research institutions and initiatives, including CCAMLR, SCAR, and the Association of Responsible Krill Harvesting Companies (ARK), will facilitate data integration on an unprecedented scale.

Topic E: Biosecurity and invasive species prevention

General description

Various anthropogenic activities can have devastating effects on the pristine and vulnerable ecosystem of Antarctica. Under Topic E, different important research areas are elaborated, specifically united by their potential negative effect on native Antarctic species (invasive species, diseases) or their importance in the understanding of global health threats (AMR). Each research area aims to gather data that will help to develop mitigation measures to either reduce anthropogenic effects in this ecosystem or use this pristine ecosystem to increase our understanding of global problems. Topic E is closely connected to Topic A as microplastic plays an important role in the dissemination of invasive species and pathogens by acting as a vector for organisms due to biofilm formation on microplastic particles. Furthermore, biofilms show increased resistance gene abundance, while heavy metals additionally accelerate the emergence of AMR.

Invasive species can be introduced to Antarctica via ships, cargo, or personnel, posing a major threat to the region's ecosystems. Non-native terrestrial (plants, insects, and microorganisms) and marine (metazoans, macroalgae and microorganisms) taxa may outcompete native species and alter ecosystem structure and function by disrupting food webs and altering nutrient cycling. Warming temperatures further exacerbate this issue by creating conditions conducive to the establishment of invasive species²⁹. Monitoring and prevention measures, such as biosecurity protocols and thorough inspections, are critical in mitigating this threat³⁰. Environmental DNA metabarcoding of a wide set of samples (e.g. water, soil, bulk and swabs) originating from ballast water, fouling organisms on ship hulls, ship and research station environments, as well as visitors/scientists themselves) will allow a comprehensive monitoring of microbial and eukaryotic/metazoan diversity for the detection of non-indigenous and invasive taxa³¹. This effort requires a harmonization of standard operation protocols for sampling, laboratory and bioinformatic analyses in a coordinated international effort.

Antimicrobial resistance (AMR) is a global health threat, both in human and veterinary medicine, in that certain bacteria successfully acquired mechanisms to resist antibiotics. Although antibiotics and AMR do occur naturally in the environment, different anthropogenic sources have been identified as the main drivers for the global increase in AMR. Especially aquatic environments are known to be impacted by different anthropogenic sources. Accordingly, AMR bacteria and genetic determinants have been found in various marine species, in seawater, and in pristine environments³², highlighting

AMR as another form of environmental pollution which is of specific interest for public health. Currently, transmission pathways and maintenance of AMR in the marine ecosystem are little understood. Microbial species carrying AMR may reach Antarctica by natural means, such as in association with migratory wildlife, and anthropogenic means, such as the sewage systems of visiting vessels and research stations³³. In addition, climate change may change the ocean microbiome composition, which will then also affect AMR dynamics³². To understand AMR pathways in the environment, it is of utmost importance to collect more data on AMR occurrence, especially in pristine environments. Here, Antarctica InSync offers the important opportunity to collect data year-round in different locations of Antarctica. The gained data set will increase our knowledge of AMR dissemination and transmission within the marine environment and may elucidate potential reservoirs. This information is highly needed to successfully combat AMR on a global scale.

Highly Pathogenic Avian Influenza (HPAI) is a highly contagious viral disease that causes mass die-offs in a wide range of domestic and wild bird species. Recently, cross-species transmission to various mammals has been reported in different areas of the world. The current H5N1 outbreak also affects sea birds, penguins, and marine mammals in Antarctica, drastically reducing their populations³⁴. Knowledge of current circulating subtypes and lineages, their hosts, and reservoirs is important to understand transmission pathways as well as to develop mitigation measures, specifically to prevent further spread of this disease by anthropogenic activities in Antarctica.

Research gaps

To gain new insights into AMR pathways in the marine environment, Antarctica InSync offers the unique opportunity to collect data in a partly still pristine environment. Determining the occurrence of AMR and AMR genes on a circumpolar scale including areas of varying anthropogenic activities, and during different seasons will identify regional and seasonal patterns. Moreover, this data may allow us to conclude dissemination, transmission, and potential reservoirs in this marine ecosystem. Additionally, the intended international cooperation will foster the harmonization of sampling and methods, thereby enhancing the gathering of comparable data. As for HPAI, continuous monitoring is essential to identify affected species, reservoirs, and transmission pathways.

Key essential variables

AMR occurrence, pheno- and genotype; regional and seasonal patterns; sample material (water, biota, soil, ice); sampling protocols; analytical methods; monitoring frequency; Occurrence of HPAI; HPAI subtype and lineage; affected species

Objectives

- Circum-Antarctic AMR surveillance – occurrence of AMR bacteria and AMR genes in different locations of various anthropogenic impact during different seasons
- Standardization in sampling and methodology
- Identifying indicator bacteria
- Link AMR to contaminants and microplastics to assess cumulative effects
- Targeted surveillance of wildlife populations

Proposed strategies

The year-round circum-Antarctic assessment of AMR bacteria and AMR genes will be based on sampling locations varying from pristine areas to areas of different anthropogenic activities resulting in a spatiotemporal mapping of AMR prevalence in Antarctica. Sampling material includes environmental samples like seawater, ice, soil, as well as biota samples like wildlife faeces and/or swabs.

Microbiological culturing of agreed indicator bacteria, antimicrobial susceptibility testing as well as metagenomic analysis will be used in this approach. Standardized methodology will produce comparable international data on the current occurrence of AMR in Antarctica. This data may elucidate dissemination pathways in the marine environment which will significantly contribute to AMR mitigation strategies and thus to public health. Circum-Antarctic sampling of wildlife populations via swabs for viral detection and blood for antigen detection. Year-round sampling may elucidate reservoir species.

Topic F: Effects of marine pollution on Southern Ocean phytoplankton and climate feedback

General description

This topic addresses how marine pollution, phytoplankton blooms, and atmospheric processes interact in the Southern Ocean near Antarctica. In view of the International Polar Year 2032-2033, this working subgroup aims to develop international, interdisciplinary research activities and design coordinated monitoring and experimental strategies. The overarching goal is to evaluate the role of marine pollutants within the coupled ocean-atmosphere system in a climate change context, using integrated in-situ and satellite measurements. Pollutants, interacting with phytoplankton bloom dynamics, can alter community composition, functions, phenology, and productivity and affect the concentration of biologically produced gases dissolved in oceanic waters and aerosol formation³⁵. These changes, in turn, can influence cloud properties^{36 37} linking biological responses and climate feedback.

Research gaps

A key research priority is to clarify how the different pollutants interact with, enter and accumulate within the lower marine trophic levels, such as phytoplankton. A major gap involves understanding how the phytoplankton community and its dynamics respond to marine pollutants, as different taxa can exhibit selective, and species- or size-specific sensitivities³⁸. Shifts in community structure can directly influence biogeochemical cycles, ecosystem functioning and climate processes, including the formation of climate-active aerosols³⁹. The role of the phytoplankton community and marine microorganisms in general in the formation of marine aerosols is not yet fully understood. Biogenic aerosols can modulate cloud microphysics, radiative forcing, and climate feedback over the Southern Ocean, but the underlying mechanisms, the regions of occurrence, the controlling factors and more, in general, the mechanisms linking community composition to atmospheric processes remain largely unclear. In turn, climate change-driven pressures could affect phytoplankton productivity and community composition in the Southern Ocean, with possible synergistic effects arising when combined with pollution impacts. Addressing these interconnected gaps is essential for improving our understanding of how phytoplankton blooms and their dynamics, impacted by inputs from land, atmosphere, and ocean and by their bidirectional exchange, influence climate-relevant processes in the Southern Ocean, shaping feedback loops within the coupled ocean–atmosphere–climate system.

Key essential variables

- Physical and Bio-Geo-Chemical properties of Atmosphere (with a focus on Aerosols and Clouds), Land and Ocean domains. Essential Climate Variables, ECVs, from Global Climate Observing System⁴⁰.
- Biological variables: Chlorophyll a, Phytoplankton community composition (abundance, taxonomic and functional/trait diversity), Ecosystem functioning (primary productivity); Environmental DNA (from different matrices). Variables from the ECVs, and the Essential Biodiversity Variables, EBVs⁴¹
- Concentrations and patterns of pollutants

Objectives

- To understand the main sources and pollutants by monitoring inputs from the atmosphere, ocean and land
- To understand how pollutants affect phytoplankton community composition and productivity
- To understand the role of phytoplankton and its composition and dynamics on climate feedback processes

Proposed strategies

Collection of in-situ and remote sensing data from ships, aircrafts and fixed stations and synergistic analysis of satellite data. Advancing this knowledge requires long-term, harmonized monitoring efforts, coordinated international sampling activities, and shared measuring platforms and data infrastructures.

Within the Antarctica InSync framework, dedicated measurement campaigns may be planned to observe key multi-domain variables through observational activities conducted from ships, airborne platforms and permanent observatories on the Antarctic continent.

Topic G: Encounters at the end of the world – Tracing Antarctic expedition legacies: Cultural signatures and evolving narratives

General description

Antarctica has long captured human imagination, inspiring exploration, storytelling and cultural production. Historic expeditions left tangible and intangible signatures, shaping perceptions of heroism, conquest, and human interaction with the environment⁴². Over time, literature, art, film, media, and tourism have reflected and transformed these narratives, influencing public understanding of Antarctica⁴³. Studying the cultural and historical impact of these expeditions provides insight into how human presence is remembered and communicated, how myths and narratives evolve, and how contemporary expeditions relate to and reinterpret this legacy^{44–46}. Nowadays we see more than ever that it has always been the images since the first photographs by Frank Hurley for Ernest Shackleton that have a massive influence on how an expedition is remembered and told. That is why the question of how old and new images function for expeditions is one central point for this topic. And then: it is also about the possible interactions between men, technique and wilderness and how images here are created or even made possible. Because our images shape the ways in which we understand and negotiate nature, wilderness and its ecosystems.

As a surplus from the cultural and social sciences and the environmental humanities to the question of anthropogenic signatures: There could be research on signatures of old expeditions in Antarctica, as well as a research on men-ocean-narratives on Antarctica via an investigation or a monitoring of international diverse cultural products, ideas and storytelling in the arts, especially in film & media. There should be a growing awareness of how to deconstruct Antarctic myths, with which, e.g. the tourism industry works, e.g. with old narratives of heroism & conquest. To raise awareness of how an expedition can be “translated” or negotiated for diverse publics and how its communication and stories changed throughout the centuries.

Research gaps

Despite growing interest in Antarctic cultural and historical narratives, research gaps remain systematically documenting the tangible and intangible signatures of historic expeditions⁴¹. Moreover, limited work exists on how “men–ocean” narratives and e.g. myths of heroism and conquest have evolved across film, literature, art, media and tourism. There is also a lack of comparative studies on

how contemporary expeditions relate to and reinterpret these legacies. Furthermore, strategies for effectively communicating expedition stories to diverse audiences and deconstructing persistent myths remain underexplored.

Key essential variables

The analysis focuses on key variables that illuminate the persistence and transformation of Antarctic legacies. These include the material and symbolic traces of historic expeditions; their representation in film, literature, art, media, and tourism; the evolution of “human-ocean” narratives within them; contemporary expedition practices; public perception; and communication strategies.

Objectives

- Document and analyze the cultural, social, and historical signatures of historic Antarctic expeditions
- Examine the evolution of expedition narratives and myths across film, literature, art, media and tourism
- Assess how contemporary expeditions relate to and reinterpret these historical legacies
- Explore strategies for public engagement with diverse audiences based on these insights.

Proposed strategies

The research strategy for Antarctica InSync integrates on-site fieldwork with collaborative and analytical methods to holistically study expedition legacies. This includes documenting physical and symbolic signatures at bases and heritage sites and collaborating with expedition personnel on expedition vessels in the Southern Ocean to observe contemporary practices in real time. Furthermore, we will observe evolving narratives also through the cultural products circulating within these communities and outside. Direct data on perception and engagement will be gathered via targeted surveys and interviews. Crucially, integrating field observations with archival, media and cultural analysis will facilitate a synthesized and comprehensive insight into Antarctic expedition legacies and its translations to and within a globalized world.

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Antarctica InSync Scientific Theme 6

Aerosol-cloud-precipitation interactions and radiative feedbacks

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Executive Summary and Key Recommendations

Insufficient understanding of the surface energy and mass budgets of the Southern Ocean and Antarctic Continent (SOAC) fundamentally limits our ability to estimate when, how fast and severely the region will respond to anthropogenic climate change. The recent abrupt sea ice decline raises a red flag. The SOAC surface energy and mass budgets are worryingly-inaccurately represented in predictive models. A key problem is the misrepresentation of aerosol-cloud-precipitation interactions and their impact on radiative feedbacks, systematically leading to gross surface temperature and precipitation biases.

To mitigate these important shortcomings, Theme 6 aims at closing five critical knowledge gaps: (i) Quantifying aerosol sources, properties and processes, (ii) Characterizing cloud and precipitation properties, (iii) Understanding the surface energy budget and boundary layer structure, (iv) Constraining cloud-circulation coupling, and (v) Advancing the modelling of clouds and aerosols. Together, these five elements describe both the continuum of atmospheric processes and their impacts on the entire SOAC, as well as the large regional variability of these processes.

We recommend an integrated ensemble of in situ and remote sensing observations targeted specifically at improving numerical representation and constraining model uncertainties. We emphasize the need for profile observations from the surface to low-level cloud altitude along latitudinal gradients, i.e., from the marginal sea ice zone towards the Antarctic plateau, while simultaneously covering East and West Antarctica as well as the Peninsula. Observations are categorized into three priority levels, where particularly priority 1 builds on existing long-term observations to build a strong legacy from existing efforts into future activities beyond Antarctica InSync. Priority 2 and 3 focus on process studies. Theme 6 will mitigate the present lack of structured data to constrain aerosol-cloud-precipitation processes and their radiative feedbacks.

Aerosol-cloud-precipitation processes and their feedbacks on the surface energy budget (SEB) have been identified as one of the key remaining uncertainties in climate science¹ and specifically over the Southern Ocean and Antarctic Continent (SOAC)². The impacts of these local to regional scale processes on the sea ice extent and Antarctic surface mass balance (SMB) are significant and comparable to climate-forcing at hemispheric and global scales through atmospheric circulation changes and greenhouse gas driven warming trends that have occurred in the recent decades³. However, major gaps in our understanding of the atmospheric drivers of accelerated Antarctic warming and ice loss limit our ability to use numerical models to reliably predict when and how rapidly Antarctic climate change will intensify, with profound implications for the stability of the Antarctic ice sheet and future sea level.

Due to its remoteness and extreme weather conditions, in situ observations in the SOAC are rare, especially during austral winter. Antarctica InSync is a unique opportunity to deliver unprecedented observational and modelling advances that will generate new understanding of the key atmospheric processes that control the SEB and SMB of the SOAC (links to **Themes 1-3**), which are fundamental to the functioning of the global climate system. The challenge of understanding these systems in the SOAC has become urgent over the past decade⁴. The post-2016 decline in Antarctic sea-ice extent, amplified warm-air intrusions, and accelerating changes in marine biogeochemistry raise critical questions about, if and how the continuum linking aerosols, clouds, and precipitation, and the resulting radiative feedbacks, is being altered, as these responses remain largely unknown^{5, 6}. Understanding

these processes is likely compounded by the spatial variability across diverse landscapes, including open ocean, sea ice, islands, coastal zones, and the Antarctic ice sheet.

Fig. 1 illustrates the spatial variability of long-term trends of selected climate variables around the Antarctic coast. A key point is that trends are inhomogeneous along the coast and can have opposite signs. They should be interpreted with caution, however, as the ability of ERA5 to accurately simulate cloud properties in the region is still limited.

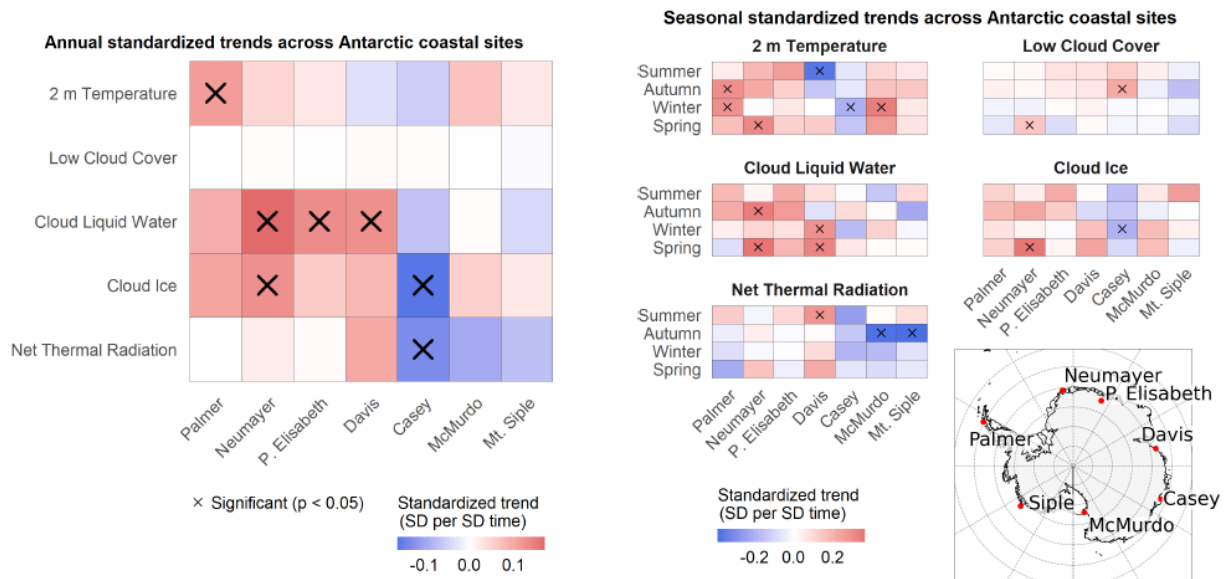


Figure 1: Trends derived from the nearest ERA5 (0.25×0.25°) grid cell (2000–2025). Seasons are defined as summer (DJ), autumn (MA), winter (MJJA), spring (SO). Linear regression is applied to 2 m temperature, net longwave radiation, cloud microphysics. Cloud liquid and ice water are column integrated amounts. SD per SD time means that the trend is expressed in standard deviations of the variable per one standard deviation of time (here 7.2 years). Monotonic trends in cloud cover are assessed using Mann–Kendall test with Sen’s slope. Magnitudes are standardized slopes for comparability; statistical significance is based on unstandardized trend estimates. This figure was created specifically for the Theme 6 whitepaper.

Theme 6 specifically focuses on aerosol-cloud-precipitation interactions and the resulting impacts on radiative feedbacks. Aerosols are small particles in the atmosphere that are required to initially form clouds by acting as seeds for cloud droplets and ice crystals. The relative abundance of cloud droplets versus ice crystals (and thus cloud phase) modulates the radiative cloud properties (e.g., albedo). Over the dark Southern Ocean, brighter clouds have a cooling effect⁷, whereas over reflective ice and snow surfaces, as well as in the absence of sunlight, clouds have a net warming effect⁸. Precipitation is formed in clouds and is a critical component of the SMB of the Antarctic ice sheet, ice shelves, and sea ice. Because we still lack a robust understanding of the SEB over ice- and snow-covered surfaces, it is challenging to quantify the SMB in the SOAC.

The community has identified five major **Knowledge Gaps (KG)** that must be addressed to advance understanding and predictive skills regarding the implications of aerosol-cloud-precipitation interactions and radiative feedbacks on the SEB and SMB over the SOAC along a full annual cycle:

- KG1 - Quantifying aerosol sources, properties and processes
- KG2 - Characterizing cloud and precipitation properties
- KG3 - Understanding the surface energy budget and atmospheric boundary layer structure
- KG4 - Constraining cloud-circulation coupling
- KG5 - Advancing the modelling of clouds and aerosols in the SOAC

Addressing these challenges cannot be achieved through any single approach. It requires sustained in situ observations of aerosol and cloud properties, precipitation, SEB, and atmospheric boundary layer (ABL) structure through dedicated airborne, ship-based, and ground-based campaigns and process studies; enhanced utilization of satellite observations; and advanced surface-based remote sensing and numerical modelling capable of resolving aerosol sources, cloud phase, precipitation, ABL mixing, and feedbacks across scales (**Fig. 2**). These activities must be coordinated through shared research infrastructures, open data, and jointly designed field and model experiments to capture the rapidly changing properties and feedbacks.

Antarctica InSync provides the framework needed to integrate these efforts, bridging communities of atmospheric chemistry, ocean and ice biogeochemistry, aerosol and cloud microphysics, precipitation processes, SEB, SMB, atmosphere-surface interactions, as well as remote sensing and modelling. By coordinating scientific activities around a unified set of questions, the community can work towards closing long-standing gaps in our understanding of a highly coupled and sensitive system. In designing and implementing activities, attention needs to be devoted to the long-term perspective (legacy) of observational and modelling efforts.

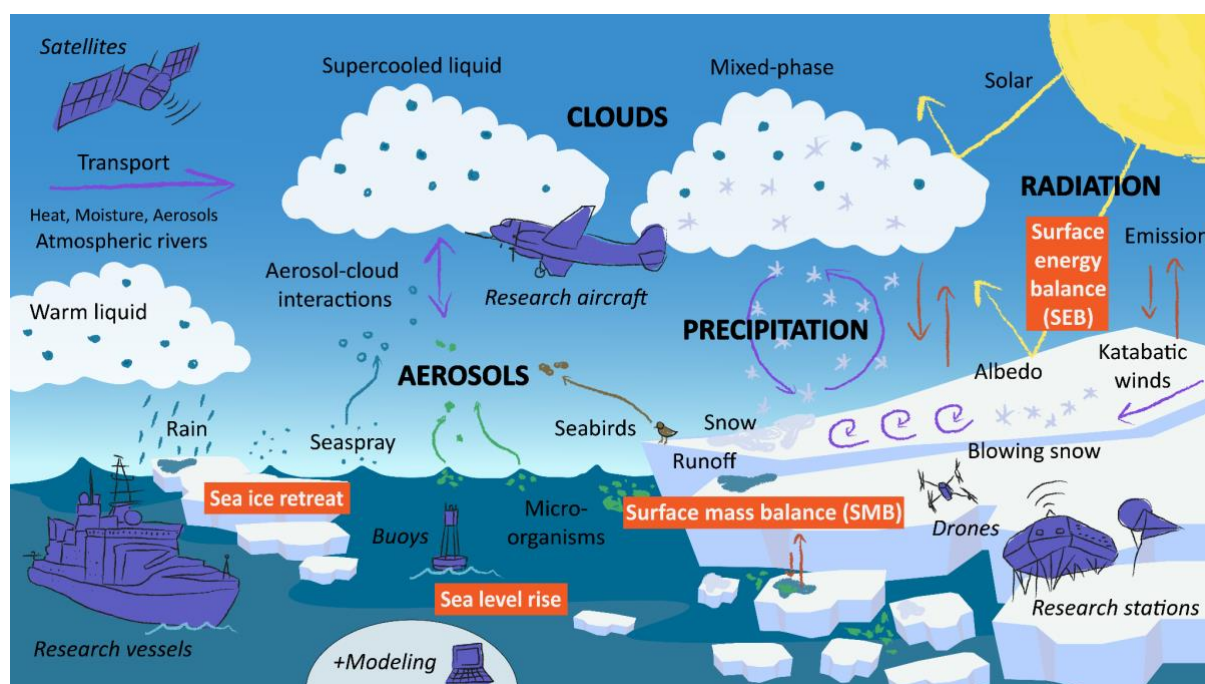


Figure 2: Schematic representation of the coupled atmosphere-ocean-ice climate system in the SOAC. Black capital words focus on elements to be addressed within Theme 6 on different platforms (purple). Orange highlights denote the endpoints that shall ultimately be better constrained.

2. Knowledge gaps and research needs

2.1 Quantifying aerosol sources, properties and processes (KG 1)

Aerosols are a key driver of the energy balance in the remote, pristine atmosphere in the SOAC. Aerosols interact with radiation directly through scattering and absorption, and indirectly by serving as cloud condensation nuclei (CCN) and ice nucleating particles (INPs) that modify cloud properties. The magnitude of these effects depends on aerosol abundance and properties – such as size, shape, chemical composition, and mixing state (i.e., the distribution of chemical components across the aerosol population) – which vary substantially across seasons and regions, including the open ocean, sea ice, islands, coastal zones, polynyas and the Antarctic ice sheet⁵. Although cloud properties and precipitation in the SOAC are highly sensitive to CCN and INPs, the region remains an observational

blind spot where aerosol abundance, formation, emission, and transformation are poorly constrained, limiting improvements in aerosol-cloud-precipitation interactions and radiative feedbacks in Earth system models^{9–11}. **Aerosol observations across multiple platforms spanning the full SOAC annual cycle are vital for assessing the aerosol-cloud-precipitation interactions and radiative feedbacks that affect Antarctic ice-sheet mass loss and the recent dramatic sea-ice decline.**

Primary aerosols are emitted directly into the atmosphere by wind-driven processes. In the SOAC, the main mechanisms for emission are blowing snow over sea ice and wave breaking, which release sea salt and organic material that act as CCN and INPs; both sources are strongly modulated by pronounced seasonal cycles across a broad latitudinal range¹². INPs initiate ice formation in cloud droplets at temperatures well above $-38\text{ }^{\circ}\text{C}$, and in the SOAC, marine and sea-ice microbiological sources (see Theme 4) may promote low-level cloud ice formation, while long-range transported dust likely contributes to colder-temperature INPs ($< -20\text{ }^{\circ}\text{C}$) at higher altitudes. However, the contribution of marine biological material to CCN and INP budgets remains poorly constrained because biogenic emissions vary widely with ecosystem state, air-sea exchange, and sea-ice seasonality. Changes in phytoplankton bloom dynamics, polynya activity, and marginal ice zone processes can therefore alter both the abundance and ice-nucleating efficiency of biological INPs and the CCN activity of sea salt aerosol, with implications for cloud phase partitioning and precipitation formation under ongoing sea-ice and biogeochemical change. Here, in situ measurements in combination with observations of ocean color from satellites for biogeochemical variables relevant to CCN and INP formation are important.

Beyond primary emissions, secondary aerosol processes – encompassing new particle formation, vapor condensation and the chemical transformation of existing particles – remain poorly constrained in the SOAC. CCN and cloud droplet number concentrations are highly sensitive to secondary aerosol formation^{9,10}, yet substantial uncertainties persist in the underlying mechanisms. Aerosol precursors arise from a combination of biogenic and abiotic sources, including highly productive Southern Ocean waters, sympagic ecosystems, coastal and island terrestrial biota, and heterogeneous chemistry on snow, ice, and aerosol surfaces (see Theme 4). Key precursors that can drive new particle formation and growth to CCN sizes include sulfuric and methanesulfonic acids derived from marine methylated sulfur compounds (e.g., dimethyl sulfide and methanethiol), ammonia from seabird colonies, iodine from sea ice and coastal regions, and alkylamines from plankton and sea-ice communities⁶. Ongoing reductions in sea- and land-ice cover are therefore expected to alter both primary aerosol emissions and secondary precursor fluxes, increasing uncertainty in aerosol-cloud responses to ice loss. **A key open question is how the aerosol and specifically CCN and INP populations are responding to changes in the SOAC system through shifts in aerosol precursors and processes (e.g., open ocean and sea-ice biological activity, long range transport, snow and ice loss, precipitation).**

Meteorological conditions strongly regulate the horizontal and **vertical distribution of aerosols** in the SOAC: wind speed controls sea spray and blowing snow emissions¹³, while temperature, solar radiation, and atmospheric stratification govern vertical mixing. Persistent temperature inversions over snow- and ice-covered surfaces can suppress mixing and trap surface-emitted aerosols, producing pronounced vertical concentration gradients similar to those observed in the Arctic¹⁴. Frontal systems and cyclones intermittently import aerosols from lower latitudes and the free troposphere and modulate aerosol abundance through precipitation scavenging¹⁵. Despite these insights, the seasonal balance between long-range transport and local sources, as well as the vertical structure of aerosol profiles, remains poorly constrained. Moreover, the scarcity of particle flux measurements over the many SOAC surface types and around clouds limits evaluation of model parameterizations of submicron dry and wet deposition and local source-sink processes. Source-sink processes also change over time, specifically during significant transition periods as we are observing currently in the SOAC. This is known from ice core research and linking these historic insights with present day process studies is critical to understanding the SOAC aerosol system on long timescales. In addition to sources, sink processes also

need to be considered to constrain the aerosol budget. CCN and INPs are efficiently removed by the ubiquitous shallow convection over the ocean, both through cloud scavenging and wet deposition¹⁶. **Systematic observations of both primary and secondary aerosol properties, their formation, and transport processes from ground-based stations, shipborne and airborne platforms, and remote sensing are urgently needed to improve their spatiotemporal representation in models.**

2.2 Characterizing cloud and precipitation properties (KG 2)

Clouds pose a major source of uncertainty in current climate projections. This is especially evident in the SOAC, where biases in simulated cloud cover and phase lead to shortwave radiative biases of up to 20 W/m^2 ⁵. These biases can be linked to our incomplete understanding of SOAC clouds: their microphysics linked to aerosols and radiative effects, are insufficiently constrained due to scarce observations, especially in austral winter, and complex processes of rain and snow formation. Observations frequently show a multi-layer structure of clouds over high latitudes, with distinct supercooled liquid and ice layers, further complicating their radiative effects and precipitation processes.

Supercooled liquid cloud water occurs frequently in the SOAC¹⁷. Causes for this high abundance are not fully understood; the extremely low concentrations of INPs observed might hamper the glaciation of clouds, but this process is not well parameterized in current models. Many in-cloud processes are not clear, e.g., persistent updrafts are thought to sustain the liquid phase. By means of case studies, gravity waves have also been reported to have a considerable impact on the phase partitioning in mid-level clouds over Antarctica¹⁸. Observed ice particle concentrations frequently exceed the estimated INP concentrations, which is likely related to secondary ice production (SIP) mechanisms¹⁹. However, it is unclear which SIP processes are most relevant. Given the abundance of supercooled liquid water over the Southern Ocean, it is unclear what the relative role of SIP processes compared to primary ice nucleation from INPs is, and how these interact with each other. **A better understanding of the interplay of INPs, SIP, and dynamics in the formation of ice in clouds is urgently needed to constrain their impact on the radiative budget.**

Furthermore, clouds regulate precipitation, which plays a crucial role in the SOAC climate system by regulating the SMB, ice sheet evolution, and freshwater fluxes to the ocean²⁰. Earth system models tend to overestimate precipitation over Antarctica, in particular over the inner plateau²¹. The spatial and temporal structure, frequency, intensity, trends and microphysical properties, such as phase and size distribution, of precipitation²² are insufficiently observed and understood components of the SOAC. Large discrepancies are found between reanalysis fields, satellite climatology and surface observations, where it is not even clear, if a certain property is over- or underestimated. This is due to challenges of surface observations in the region because of extreme conditions (wind, cold, blowing snow), combined with current limitations of satellite retrievals. Regional climate aspects and orography, frequent katabatic winds, and gravity waves²³ also impact cloud and precipitation amounts as well as prevailing snow particle habits. The pathways of how ice crystals grow into snow and how cloud properties and environmental conditions regulate snowfall rates are still incompletely understood. The relative importance of different ice growth processes, such as riming (supercooled liquid droplets freezing onto ice crystals upon contact) and aggregation (ice crystals sticking to each other forming larger flakes) is currently unclear. This leads to an incomplete representation in weather and Earth system models, which are not yet able to reproduce the structure of SOAC clouds from the Southern Ocean up to the Antarctic plateau. **To improve models, the microphysical pathways leading to precipitation need to be characterised and the frequency, intensity and phase of precipitation (liquid vs snow) reaching the surface quantified.**

The gradients in temperature and humidity conditions from the coast to the interior of Antarctica lead to gradients in cloud and precipitation properties and amounts²⁴. In coastal regions, synoptic features

are playing a key role in the transport of moisture, heat, and the associated clouds and precipitation. Extreme events, frequently associated with atmospheric rivers, have been shown to significantly contribute to the total annual precipitation amount. Over inner Antarctica, synoptically driven warm and moist air intrusions are less frequent, whereas phenomena such as ice fog and diamond dust (pristine ice crystals forming under clear-sky conditions) play significant roles. Escarpment regions, where the altitude of Antarctica changes significantly, further modulate the moisture transport from the coast and influence clouds and precipitation. **The regional variability of clouds and precipitation resulting from distant versus local moisture sources and orography must be quantitatively understood.**

Although most precipitation in Antarctica occurs in the form of snow, episodes of mixed-phase or (supercooled) liquid precipitation have been observed²⁵. In addition, according to IPCC AR6²⁶, there is high confidence that precipitation frequency and precipitation intensity will increase in the near future in Antarctica and that rainfall will increase over the coastal and ice shelves regions. When falling on snow or ice, rain and drizzle change the albedo, lead to warming through latent heat release during refreezing, and accelerate ice fracturing. **Hence, quantifying rain and drizzle and their spatial distribution is extremely important, especially for assessing their effects on snow and ice-covered surfaces.**

2.3 Understanding the surface energy budget and atmospheric boundary layer structure (KG 3)

The SEB, and the related atmospheric boundary layer (ABL) structure, are not well understood across the highly variable surfaces of the SOAC, and sometimes act as spatial process linkages (link to **Theme 1**). The SEB is governed by the complex interplay of solar insolation, longwave radiation, turbulent sensible and latent heat fluxes, and conductive heat transfer within snow and ice, many of which are intimately linked with the ABL, aerosols, clouds, and precipitation. High surface albedo and seasonal darkness limit the cloud cooling effect over ice-covered surfaces, while this effect is much larger over the adjacent ocean in summer. Thus, clouds typically radiatively warm the ice sheet and sea ice for most of the year through dominant longwave radiative trapping²⁷, while they can have an extended period of summer surface radiative cooling over the dark Southern Ocean. These spatially and temporally variable radiative effects are driven by cloud phase partitioning, microphysics, surface albedo, atmospheric water vapor, and temperature, all of which remain uncertain across the SOAC. As a result, large uncertainties persist in quantifying the net energy flux at the surface and its contribution to ice-sheet and sea-ice mass balances⁸. **Improving cloud and atmosphere representations in models therefore remains central to advancing predictions of energetic processes essential to SOAC climate evolution.**

At the same time, the ABL governs the interactions between large-scale atmospheric dynamics, cloud and precipitation development, aerosol transport, moisture and heat advection, vertical mixing, and local SEB processes. Over the Southern Ocean, the ABL is modulated by vigorous surface winds, large sea–air heat fluxes, and frequent cyclonic and frontal activity, producing deeper, dynamically active boundary layers²⁸. In contrast, the Antarctic continent is dominated by shallow, exceptionally stable ABLs that suppress vertical mixing and produce complex stratification aloft²⁹. Katabatic winds descending from the high interior introduce strong spatial heterogeneity, generate intermittent turbulent bursts that can modulate ABL stability, and serve to link complex land-ice sheet surfaces with the surrounding marine sea ice environment. Foehn winds generated by flow across the mountainous terrain can produce warm, dry, and turbulent conditions on the lee side, substantially modifying ABL structure, cloud formation, and precipitation, and enhancing surface energy fluxes that can promote snow and ice melt³⁰. Low-level clouds and precipitation can further modulate ABL stability, but their coupling with turbulence, inversion structure, and heat fluxes remains insufficiently understood³¹. These highly spatially variable ABL structures, along with large-scale advection of heat and moisture (KG4), affect turbulent surface heat exchange. Meanwhile, spatial heterogeneity in precipitation properties, sea-ice

types, sea-ice concentration, and surface roughness (link to **Theme 2**) complicate the modelling of turbulent fluxes. **The scarcity of year-round SEB and ABL observations representing the diverse conditions of the SOAC severely limits the ability to constrain these interacting processes and hinders model validation.**

These atmospheric processes have direct implications for atmosphere-surface exchange (KG1), perturbations in surface temperature, and further changes in the SMB. Atmospheric radiation and turbulence control the surface exchange of heat and moisture, ultimately driving processes like sea-ice formation and ice sheet surface melt (link to **Themes 2 and 3**). Sublimation of snow at the surface and of blowing snow also serves as a significant sink for the SMB³², further shaping the ABL structure and possibly acting as a source of aerosols. **Overall, improved representations of interacting energy and mass budget processes that are intimately tied to aerosol-cloud-precipitation interactions is critical for advancing predictive capabilities of Antarctic ice sheet instability and sea ice development.**

2.4 Constraining cloud-circulation coupling (KG4)

Atmospheric circulation modulates the Antarctic ice sheet SMB (link to Theme 3) by redistributing heat, moisture, and aerosols, thereby shaping clouds, precipitation, and radiative fluxes. Yet, current weather and Earth system models struggle to realistically represent cloud-circulation coupling processes, more specifically the diabatic heating and cooling of the atmosphere due to microphysical processes³³ related to cloud and precipitation formation, and their coupling to turbulence and convection over the SOAC. Furthermore, current reanalysis products exhibit systematic synoptically-dependent biases that fail to capture precipitation intensification driven by mesoscale substructures (such as shallow convection) within large-scale weather systems²².

Cloud-circulation coupling processes are especially critical during extreme weather events, and specifically if these extreme events occur in close succession. Cloud and below-cloud microphysical processes (in particular, those involving the ice phase) have been shown over the past 50 years of midlatitude meteorological research to play a key role in recycling moisture in the atmosphere. These processes may play a significant role in the hand-over mechanism of moisture from one cyclone to the next along the Southern Ocean storm track. This hypothesis should be further tested during Antarctica InSync with an unprecedented density of observations of the microphysics, dynamics, and thermodynamics of the atmosphere in and around Antarctica becoming available.

Atmospheric Rivers (ARs) are dominant contributors to the Antarctic SMB, accounting for most extreme snowfall events and occasionally triggering melt, rainfall, and ice-shelf weakening³⁴. ARs are closely linked to extratropical cyclones and often host warm conveyor belts (WCBs), i.e., rapidly ascending airstreams that generate strong latent heating through cloud formation at mid-levels and diabatic cooling below the WCB clouds due to precipitation evaporation and sublimation. This diabatic heating and cooling feeds back on the large-scale circulation, reinforcing blocking and sustaining poleward moisture transport. With warming-driven increases in atmospheric moisture, WCB-related heating is expected to intensify and extend higher into the troposphere, enhancing circulation impacts³⁵. AR- and WCB-associated mixed-phase clouds with high liquid water content further increase downwelling longwave radiation (KG 3), promoting surface melt (link to **Theme 3**). Furthermore, riming in clouds might become much more important, potentially strongly modulating the precipitation efficiency of AR and WCB cloud systems (link to **Theme 7**).

Recent Antarctic heat waves, such as the extreme March 2022 East Antarctic event, were driven by enhanced tropical convection promoting amplified Rossby waves and persistent blocking that advected warm, moist air anomalously deep into the continent³⁶. These events can precondition the ice sheet for enhanced impacts during subsequent ARs because they change the SEB, underscoring the importance of accurately representing diabatic processes embedded in the large-scale flow and their feedbacks on

the circulation also at timescales that extend beyond single events in the context of high-impact weather event sequencing (link to **Theme 7**).

Major open questions remain on how clouds interact with circulation patterns and influence ARs, WCBs and heatwaves³⁷, as well as how cloud-circulation coupling processes will evolve with global warming. Stable water isotopes provide a powerful tracer of moist diabatic processes embedded in the flow, directly linking cloud microphysics to the large-scale circulation³⁸. Water isotope measurements in ambient air and in high-resolution precipitation samples offer unique yet under-utilised constraints on cloud-circulation coupling. Integrating targeted observations with multi-scale modelling is essential to improve process understanding and modelling capabilities of cloud-circulation interactions and their consequences on Antarctic high-impact weather events. This is crucial to assess the far-reaching consequences of cloud-circulation coupling on sea ice extent, SEB and SMB.

2.5 Advancing the modelling of clouds and aerosols over the SOAC (KG5)

Accurate representations of atmospheric processes in the SOAC region, which underpin projections of Southern Ocean cloud feedbacks and Antarctic ice-sheet contributions to sea-level rise, are essential for global climate and Earth system models. Importantly, the equilibrium climate sensitivity of Earth system models is highly sensitive to how clouds over the Southern Ocean are represented³⁹. However, Earth system models show a strong warm bias in surface temperature over the SOAC, which has been traced to cloud model errors². The bias has been somewhat mitigated in recent models^{39,40}, but care needs to be taken as compensating errors mask a fundamental lack of cloud and aerosol process understanding. Accurately simulating Antarctic clouds is essential for estimating the Antarctic ice sheet surface mass balance through their influence on precipitation and surface melt⁴⁰. Targeted modeling studies using a hierarchy of models, ranging from high-resolution process-oriented Large Eddy Simulations and convection-permitting models to Earth System Models, are therefore essential for reducing persistent cloud and aerosol biases over the SOAC and for increasing confidence in Earth system model projections over the region. These studies will benefit from new observations collected during Antarctica InSync for model evaluation and calibration, while also guiding and supporting process-based understanding.

A key research gap concerns the representation of mixed-phase and ice clouds, specifically low-level clouds. Models are particularly sensitive to treatment of ice nucleation, with parameterizations based on SOAC in situ data leading to better Southern Ocean cloud properties in both global and regional models⁴¹. Other microphysical processes (riming, aggregation, vapour deposition, SIP, and interactions with blowing snow) continue to drive large model uncertainties both in terms of cloud radiative effect and precipitation, because they are insufficiently constrained observationally. Biases in cloud phase partitioning and structure⁴² as well as difficulties to capture the precipitation intensity distribution are also explained by improper parameterization of interactions between cloud microphysics and subgrid-scale dynamics such as turbulence, shallow convection and gravity waves. Shortcomings in the parameterization of turbulent fluxes also play a role, specifically across the highly variable boundary layer regimes (KG 3). The radiative effect of ice clouds also highly depends on the parameterization of ice crystals' optical properties which are still not well constrained in pristine Antarctic conditions, as well as on the parameterization of the spatial distribution of liquid and ice in clouds⁴³.

Another major gap in SOAC cloud modelling stems from insufficient parameterisations of aerosol sources and processes in this region. Models consistently underestimate aerosol and CCN concentrations over SOAC against surface observations⁴³, leading to low cloud droplet number concentrations compared with satellite data. Sensitivity studies suggest that several aerosol sources remain poorly quantified, with implications for the prediction of CCN and INPs (KG 1). Those include specifically the magnitude and spatial distribution of seawater dimethyl sulfide and methanethiol, their

fluxes to the atmosphere, and subsequent oxidation chemistry, marine isoprene emissions, primary marine organic emissions, sea spray and their dependence on marine biology and sea surface temperature, and downward mixing of secondary particles from the free troposphere. In addition, some potentially important aerosol sources are typically not described in global climate and Earth system models at all, such as emissions of primary sea salt aerosols from blowing snow, ammonia and nitrates from seabird colonies, alkylamines from plankton and sea ice communities, primary biological aerosols, and other precursor gases like iodic acid.

The numerous and complex process-interactions that determine the properties of SOAC aerosols and clouds continually raise the question of how much sophistication is actually needed in models, given that excessive complexity can hinder the interpretation of results and increase the models' degrees of freedom as well as the difficulty of tuning free parameters. **Research is therefore needed to identify the most critical processes that must be represented in global models as well as to set up regional modeling frameworks and intercomparison exercises to robustly evaluate models, help bridge global models and observations, and tune free parameters against observational references of SOAC clouds.** Perturbed Parameter Ensemble experiments and Artificial Intelligence techniques can be particularly relevant for this purpose⁴⁴. Machine learning approaches can also be leveraged to quantify the contributions of individual processes in complex cloud-aerosol modeling frameworks⁴⁵ and to emulate the effect of aerosol-cloud interaction processes in numerical models.

3. Observing strategies and essential variables supported by modelling

Addressing Theme 6 KGs requires synchronized, long-term, year-round and short-term intensified (e.g., summer and winter-focused) observations across the SOAC to capture the temporal and spatial variability of key processes specifically to continue the observations of climatological trends (**legacy**). The Theme 6 observing strategy achieves this by building on and significantly enhancing ongoing multinational scientific and logistical efforts. The aim is to maximize scientific output per unit of operational expenditure, thereby lowering the relative environmental footprint of field activities. This will be achieved by efficiently sharing capabilities across platforms, data, samples, satellite retrievals, and model products.

The observing strategy follows a multilevel approach, supported by models, to **target reductions in climate forecast uncertainties**. **Priority 1** measurements are provided year-round across all platforms and locations by sharing and expanding existing resources within a pan-Antarctic network. Advanced **priority 2** measurements during intensive observation periods deliver more detailed information, **particularly in the vertical dimension**. High-impact **priority 3** observations occur at dedicated supersites, during expeditions, ship cruises, and research flights. Machine learning approaches and proxies are employed to connect in situ and remote sensing data across different levels, enabling valuable extrapolation to other sites and seasons. **Table 1** recommends essential variables to address the outlined KGs. Parameters are classified by KG and priority, covering meteorology, aerosols, clouds, precipitation, radiation, surface exchange processes, and boundary layer structure. Data will be openly published and comply with the **FAIR principles** (Findability, Accessibility, Interoperability, and Reuse). A central metadata database is invaluable in enabling findability of data across the various data repositories where data are actually stored to ensure legacy of Antarctica InSync into the next International Polar Year (2032/33) and beyond. Beside databases, a sample bank shall provide community access to samples from targeted oversampling.

Theme 6 platforms include long-term observatories (Antarctica, Sub-Antarctic Islands, Southern Ocean region), ships (research vessels, sailing vessels, ships of opportunity), airborne systems (balloons,

drones, sondes, aircraft, helicopters), satellites, and autonomous networks on land, sea ice, and in the ocean. Integrating ground-based, airborne in situ, and satellite data enables multi-scale observations, point validation, and upscaling. Land based, ship- or sea-ice-based process studies yield realistic, environment-specific source profiles specifically for aerosols, heat, moisture and energy fluxes. Satellite products provide broad temporal and spatial coverage across the SOAC, retrieving trace gases, aerosols, clouds, precipitation, radiation, thermodynamic properties, and key surface data like ocean bio-optics and sea ice properties. In situ observations refine these products, enabling better validation and enhancement of Earth System Models.

The use of standard data collection procedures, formats and processing chains (such as those defined by e.g., ACTRIS) is a fundamental requirement for securing long-term use and reuse, enabling model implementation, and unlocking machine learning potential. Measurement procedures and quality control protocols should follow international standards (e.g., GAW, GUAN, ACTRIS). Traceability is key to improving data quality, reducing gaps, and enabling confident intercomparisons. Such standards for experimental setups and analysis procedures will enable scalable infrastructure for observations extendable beyond Antarctica InSync. Ensuring these standards suits the unique challenges of SOAC measurements, which require coordinated efforts before, during, and after the observational period. Specifically, during and after the observational period, coordinated efforts on value adding data products are planned, e.g., shared air mass back trajectory analysis or meteorological charts. **A key Theme 6 legacy will be improving, connecting, and harmonizing the observing network across the continent and surrounding oceans.**

Theme 6: Essential variables

ANTARCTICA INSYNC



Topic	Priority 1	Priority 2	Priority 3	Knowledge gap
Aerosol	Physical properties Total particle number concentration (> 10 nm) Particle number size distribution (10 nm to 10 µm)	Physical properties Particle number concentration (> 3 nm) Particle number size distribution (3 nm to 20 µm) Optical properties CCN number concentration and hygroscopicity INP number concentration (-10, -15, 20°C)	Aerosol physical properties Particle number size distribution (1 to 20 nm) INP number concentration (online) Hygroscopicity (sub-saturated) Cloud residual number size distribution Particle fluxes (at the surface and airborne)	Quantifying aerosol sources, properties and processes (KG 1, 3, 4)
	Chemical composition on total suspended particle (TSP) including major ions, organic carbon/elemental carbon	Chemical composition Size-resolved composition Major inorganics (TSP or PM10, PM2.5, PM1) Methane sulfonic acid (TSP or PM10, PM2.5, PM1) Vertical distribution from surface to above first cloud layer in situ particle number concentration in situ particle number size distribution in situ particle chemical composition Optical properties (remote sensing)	Aerosol chemical composition Organics and marine carbohydrates (TSP or PM10, PM2.5, PM1) Online aerosol, trace gas and ion chemical composition Fluxes of sea spray aerosols and VOCs	
Gases	Water vapour	gases Sulfur species Volatile organic compounds Iodine oxide Ozone (at the surface) ammonia, sulfuric acid, methane sulfonic acid	stable water isotopes (ground and vertical profile) ozone (vertical profiles) Nitrogen species (amines, amides...)	
Blowing Snow		particle size distribution	images, velocity, habit	
Biology	In situ sea-surface Chlorophyll-a General description of nearby animal population (e.g. bird colonies)	particulate organic carbon and total organic carbon of surface sea water taxonomic groups of phytoplankton	Sea-surface microlayer samples Ocean surface mixed-layer samples (<1 m depth)	
Clouds	Remote Sensing Cloud cover Fog identification Cloud base height Vertical profile of backscatter	Remote sensing Cloud phase, LWC, LWP, IWC, IWP (radar, lidar, radiometer) Cloud particle vertical velocity	Remote sensing Multi-frequency / dual-polarisation cloud radar In situ (balloons, aircraft) Cloud particle size distribution Cloud particle images	Determining cloud and precipitation properties and moisture sources (KG 2, 4)
Precipitation	At surface daily total, hourly rate, phase	Vertical profile Size distribution	Sampling chemical composition, INP and stable water isotopes of falling rain and snow, chemical composition, INP, salinity, pH of surface snow	
Meteorology	At 2 m height Barometric pressure Air temperature Air relative humidity	Daily in situ vertical profile of Barometric pressure Temperature Relative humidity Horizontal wind speed Wind direction	In situ vertical profiles with high spatial and temporal coverage of Barometric pressure Temperature Relative humidity 3D wind	Understanding the surface energy budget and atmospheric boundary layer structure (KG 3) Constraining cloud-circulation coupling (KG4)
	At 10 m height Horizontal wind speed Wind direction	At surface 3D wind speed Turbulent fluxes (momentum, sensible and latent heat) Remote sensing Vertical profiles of horizontal and vertical wind	At multiple heights on mast 3D wind speed Turbulent fluxes (momentum, sensible and latent heat)	
Radiation	At surface Total and diffuse	At surface Longwave up-/downward Shortwave up-/downward Direct Spectral	Vertical profiles Longwave up-/downward Shortwave up-/downward	

Table 1: Essential variables sorted by priority

Antarctica InSync will enable a step-change in our ability to test and improve our capability to model the SOAC weather and climate based on the suggested essential variables and observing program. On short timescales (i.e., from days to weeks), it will be critical to identify specific case studies of interest so that their occurrence can be targeted across the broad observational period of Antarctica InSync. Over longer time scales (months to years), it will be important to communicate hypothesis-driven model experiments for simulating different components of the SOAC system. Ensuring that this is done in conjunction with the efforts to standardise and share observational datasets will be critical. In addition, establishing modelling frameworks to support the interpretation of observations will be necessary to fully leverage model–observation synergy to make progress on SOAC uncertainties together. Developing targeted modelling experiments, including intercomparison and sensitivity exercises, and combining models of varying complexity applied to intensively observed case studies will also be essential to evaluate and improve model subgrid parameterizations, both physically-based and emulated. This will enable modelling efforts and be the basis for a framework for improving Earth System modelling capacity via observational constraints at different spatial and temporal scales over the SOAC.

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Antarctica InSync Scientific Theme 7

Variability, extremes, and tipping in a changing Antarctic climate

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Executive Summary and Key Recommendations

Antarctica is changing faster than our current observation networks can robustly assess or predict. Recent extreme events – major ice-shelf collapse, unprecedented heatwaves and abrupt, record-low winter sea ice – show that rare extremes can rapidly reshape the Antarctic system. These changes matter well beyond the polar regions: Antarctica influences global sea level, ocean circulation, and the whole climate system. This white paper sets out the case for **Antarctica InSync (2027–2030)** to deliver a **four-year, coordinated observational baseline** ahead of the **International Polar Year 2031/32**, so it is possible to distinguish **temporary anomalies** from **long-term shifts**, detect early warning signs of **tipping points**, and improve the evidence base for risk management.

The result is **more reliable projections**, better attribution of drivers, and earlier detection of destabilising trajectories – directly supporting policy decisions on climate adaptation, coastal planning, and the design of international monitoring commitments, specifically targeting the following four focus areas bridging ocean-atmosphere-ice interactions and climate variability:

- **Snow, firn and SMB:** Fund coordinated field and satellite-calibration measurements to reduce the largest uncertainty in sea-level projections: how snowfall, melt, refreezing and runoff will change.
- **Atmosphere and water cycle:** Expand weather, precipitation and water-isotope observations to track storms and moisture transport inland – essential for forecasting extremes and future snowfall/rainfall shifts.
- **Ocean–sea ice–atmosphere coupling:** Invest in marginal-ice-zone and ice shelves fronts observations to understand how sea-ice loss and ocean warming amplify extremes, alter heat/moisture exchange, destabilise ice shelves and weaken deep-water formation.
- **Variability and warming detection:** Combine new observations and ice-core and marine records to separate human-driven trends from natural variability and identify early warning signals of irreversible change.

1. Background and motivation

Antarctica is currently witnessing a sustained warming, associated with sea-ice decline, accelerating mass loss, grounding-line retreat of ice shelves, and a measurable slowdown of the Antarctic overturning circulation¹. In the atmosphere, recurrent atmospheric river intrusions – transporting warm, moist air from the mid-latitudes and subtropics – have driven a series of major heatwaves across Antarctica^{2,3}.

As a precursor to the International Polar Year 2031/32, **Antarctica InSync (2027–2030)** will deliver a four-year baseline of the Antarctic climate and provide essential context for disentangling natural variability from long-term trends obtained from paleoclimate proxies, for identifying extreme events, and for assessing their role in Antarctic climate processes (see Box 1).

Three recent Antarctic events illustrate some extreme changes (see also Fig. 1):

- **In 2002**, over just a few weeks, ~3,250 km² of the Larsen B Ice Shelf collapsed following several intense summer melt seasons and an atmospheric river prior to the final collapse, with widespread surface meltwater ponding triggering hydrofracture.
- **In 2022**, Antarctica experienced the most extreme atmospheric heat wave ever recorded worldwide⁴.
- **In 2023**, Antarctic sea-ice extent fell abruptly to a record winter low, reaching ~2.5 million km² below the satellite-era average⁵.

Such extreme events, and the associated large snow accumulation, influence the Antarctic energy and surface mass balance (SMB) in ways that may either partially compensate for ice-sheet mass loss or, conversely, amplify loss by preconditioning ice shelves for collapse. Taken together, the emerging pattern of extremes, trends, and feedbacks indicates an increasing risk that parts of Antarctica may be approaching *tipping points* – thresholds beyond which change could trigger abrupt and potentially irreversible shifts in the coupled cryosphere-ocean-climate system, with global consequences⁶.

Box 1: Definition of extreme events

Definitions of extreme events in Antarctica vary by discipline and by spatial and temporal scales. In this white paper, we follow the Intergovernmental Panel on Climate Change (IPCC) definition: an extreme event occurs when a climate variable exceeds a high-impact threshold for a given region and season (typically the 95th or 99th percentiles).

Rare events may have a return period of a century or more, while glaciological extremes can build over decades to centuries but be triggered by short-lived episodes; consistent metrics of frequency, duration and intensity are therefore essential for detecting future trends.

However, assessing the significance and true extremity of recent and ongoing Antarctic changes remains challenging without sustained improvements in observations^{1,4}. **Theme 7 therefore aims to characterise natural and anthropogenic Antarctic climate variability and the drivers of change across the continent, providing the essential context needed to interpret extremes, identify emerging tipping behaviour, and distinguish transient anomalies from long-term shifts.**

Theme 7 activities aim to be informed by existing and new observation networks and will focus on the coupled processes that underpin Antarctic climate change: atmospheric circulation, extremes, and the hydrological cycle that drive accumulation and melt; the response of snow and firn processes in regulating SMB and ice-shelf vulnerability; the interplay between sea ice and the Southern Ocean, and atmospheric forcing and variability; and the resulting patterns of climate variability and emerging signatures of Antarctic warming across timescales. It links particularly closely also to Antarctica InSync Themes 1, 2, 3 and 6.

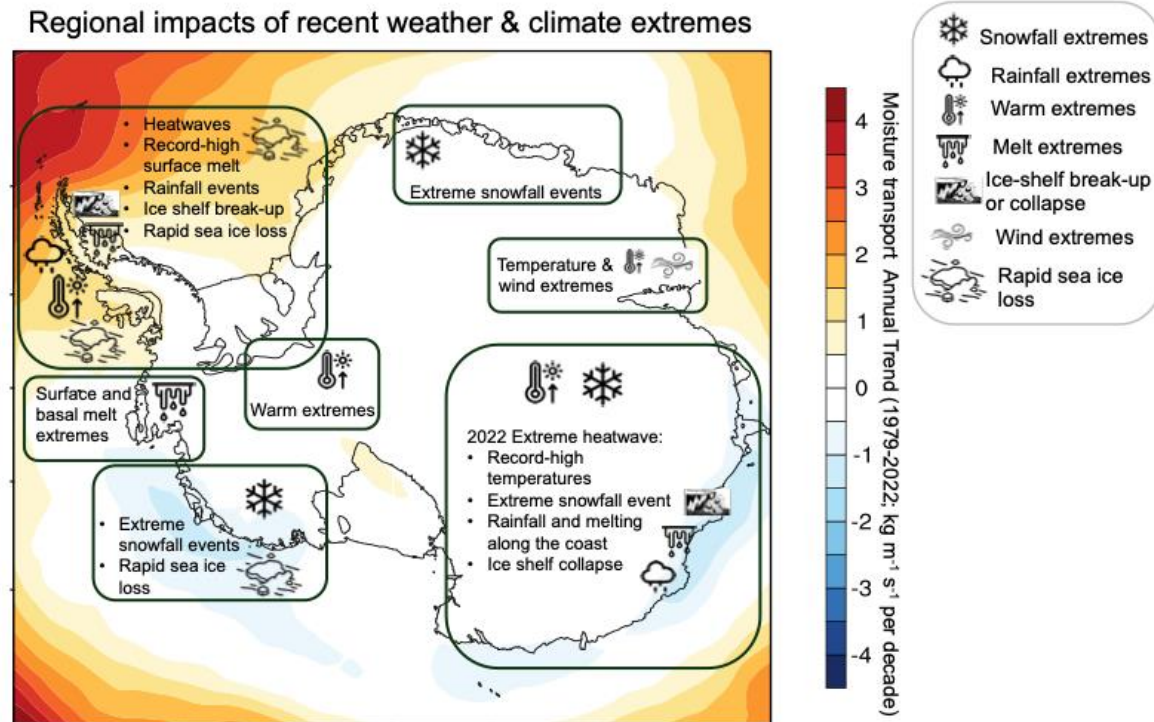


Figure 1: Examples of recent weather and climate extremes and their impacts across Antarctica (selected events; not exhaustive). Background shading shows the annual trend in atmospheric moisture transport based on ERA5 reanalysis from 1979 to 2022. Modified from Zou et al. (Front. Earth Sci., 2026)³³.

1.1 Uncertain future in surface mass balance and role of extremes

Current Earth System and climate models, regional climate models, and reanalysis products however do not agree on Antarctic SMB contributions, including the key accumulation, snowmelt, and runoff terms⁷. This represents a critical limitation, as an accurate assessment of the SMB response to climate change is essential for reliably projecting the future mass of the Antarctic Ice Sheet and its contribution to global sea-level rise.

At the continental scale, climate projections show that snowfall will increase in a warming climate⁸. This is because a warming climate increases the atmosphere's moisture-holding capacity, alongside modifications of large-scale circulation patterns. Warming also tends to increase the frequency and intensity of atmospheric storms and extreme events, including atmospheric rivers, that deliver pulses of heat and moisture to Antarctica, driving increased snowfall alongside increased surface melt in coastal regions^{2,3}.

Recent Antarctic surface mass balance changes reflect these shifts in atmospheric circulation, particularly in stronger and poleward shifting westerlies, which favour warm-air advection towards the Antarctic Peninsula⁹ as well as foehn effects, and which can enhance the delivery of relatively warm circumpolar deep water to Antarctic margins, thus driving regionally variable surface, hydrofracture, and basal melt of ice shelves¹⁰. Changes in large-scale atmospheric circulation can also affect the formation of Antarctic Bottom Water (AABW), ocean circulation and the Southern Ocean carbon cycle¹¹.

1.2 Surface ocean - sea ice - atmosphere interactions: from variability to regime change

Against a backdrop of Southern Ocean warming, Antarctica's recent sea-ice decline is reshaping the atmosphere-ocean interactions and the hydrological cycle. The recent record-low sea ice reflects long-term oceanic warming, reduced upper-ocean stratification¹², and short-term atmospheric forcing, such

as circulation anomalies and storm episodes¹³ – suggesting a structural shift including diminished coastal polynya formation¹⁴. As sea ice retreats, expanding open-ocean areas modify air–sea heat and moisture fluxes, alter boundary-layer conditions, and shift the source regions and transport pathways of moisture reaching the continent. These changes influence large-scale atmospheric circulation and extreme events through modified surface forcing, altered planetary-wave generation, and changes in troposphere–stratosphere coupling. In turn, these atmospheric changes have the potential to reduce sea ice formation and brine rejection, which may slow AABW formation.

1.3 Climate variability and emerging warming signals

Polar amplification, the ratio of polar to global temperature change, is expected to be weaker in Antarctica than in the Arctic. Recent studies report an amplified warming signal even on the East Antarctic Plateau¹⁵ and emerging evidence of rapid transformations in the atmospheric circulation¹. The role of climate change on modifying extremes and natural variability is poorly quantified, with detection and attribution studies suggesting intensified amplification, especially over the Antarctic Peninsula¹⁶.

Climate variability strongly influences Antarctica’s contribution to future sea-level rise. Satellite observations show accelerating mass loss from marine-based sectors of the ice sheet, largely driven by intrusions of warm Circumpolar Deep Water (CDW)¹⁷. High-resolution marine sediment records along shelf-to-open-ocean transects extend this perspective from decades to millennia, providing essential context for modern changes and the long-term interplay between ocean forcing and ice-sheet dynamics.

2. Knowledge gaps and research needs

2.1 Snow, firn and the Antarctic SMB

Despite the central role of snow and firn processes in controlling Antarctic SMB, substantial knowledge gaps remain that limit our ability to quantify present-day SMB and project its future evolution. These gaps arise from sparse observations, incomplete representation of key processes in models, and weakly constrained linkages between atmospheric forcing, firn evolution, and ice-sheet dynamics. We identify the following two key knowledge gaps:

2.1a What will be the overall Antarctic SMB changes under uncertainty in its components? Major uncertainties in SMB stem from the sparse ground-based SMB measurements, notably the remote interior and low-accumulation and melt-prone zones, directly hindering the development and calibration of satellite SMB products⁷. These chronic under-sampling compounds errors in snowfall, snow/firn density or wind-driven snow transport and sublimation in climate models¹⁸. Expanded, synchronised arrays of automatic weather stations (AWS), snow stakes, snow pits, firn cores, and accumulation radar are urgently needed, ideally sustained through IPY5.

2.1b How do atmospheric drivers and firn processes affect susceptibility to hydrofracture? Firn densification, refreezing, and liquid-water retention determine meltwater storage or runoff in Antarctica, yet current models fail to capture spatial heterogeneity in firn responses – especially on ice shelves – during melt events. This affects their ability to predict saturation and ponding, both of which can precondition surface-lake formation and, in turn hydro-fracture and destabilisation¹⁹. SMB patterns are highly sensitive to both atmospheric forcing and firn evolution, underscoring the need for improved firn property observations²⁰. Firn processes, also studied in Theme 3, are here linked to atmospheric drivers, extremes, variability, and compound multi-year effects potentially shaping tipping-point behaviour.

Coupling between atmospheric changes, SMB variability and ice dynamics remains poorly understood. Surface forcing can affect ice viscosity, grounding-line stress regimes, and the likelihood of meltwater-driven processes that can accelerate ice flow.

2.2 Atmospheric circulation, extremes and the water cycle

Fewer than thirty weather stations, mostly located in coastal regions, comprise the totality of Antarctica's long-term (>50 years) weather records. Antarctica InSync provides an excellent opportunity to address key gaps in data coverage and process understanding by enhancing synchronous, process-based observations through the integration of existing and newly established measurement networks. This coordinated framework will enable for example the tracking of air and water vapour as weather systems progress inland, improving understanding of how Antarctic atmospheric circulation and water cycle respond to anthropogenic climate change. We identify the following two knowledge gaps:

2.2a How will climate change affect atmospheric circulation and the hydrological cycle in Antarctica? The current sparsity of weather and precipitation observations in Antarctica seriously hinders the identification of ongoing changes in the Antarctic hydrological cycle. This applies both to climatological trends and to changes in extreme snowfall and rainfall events^{2,21}. Fundamental questions about Antarctic atmospheric dynamics, including cyclone–anticyclone interactions, cloud processes, and boundary-layer dynamics, remain unanswered²². Further, despite its critical importance for Antarctic climate variability, the future evolution of the Southern Hemisphere storm track, its teleconnections with the tropics, and its sensitivity to uncertainties in the pace of ozone recovery remain under-explored.

2.2b How will the Antarctic precipitation origins and pathway processes change under anthropogenic forcing? The origins and the pathways of moisture leading to precipitation in Antarctica is going to be a key parameter to understand future projection of increase of precipitation amounts, and is particularly characterised by distinct sources regions for high- and low-elevation Antarctic sites. Water isotopes permit the origin and transport pathways of the vapour contributing to Antarctic precipitation to be traced²³. The inclusion of isotope diagnostics in regional and Earth system models, alongside the development of a more comprehensive observational network, can substantially improve understanding of the drivers of change in the Antarctic hydrological cycle, for both climatological trends and extremes²⁴. However, we currently lack both a coordinated isotope observational network and the capability to track water isotopes in most climate models. Addressing these deficiencies would transform our ability to perform near-real-time tracking of vapour during Antarctic precipitation events and enable more rigorous evaluation of modelled circulation, water-cycle, and precipitation processes. Together, these advances would enable direct links between Southern Ocean surface changes and the mass and energy exchanges that shape Antarctica. Crucially, improved understanding of water vapour isotopes in the present-day Antarctic hydrological cycle is also essential for interpreting ice-core and other climate archives, providing the basis for reconstructing long-term variability, trends, and extremes in atmospheric circulation and precipitation on centennial and longer timescales (see also 2.4 and 2.5).

2.3 Sea surface interactions with the atmosphere

Recent, significant losses of Antarctic sea ice have highlighted major gaps in our understanding of air-sea-ice interactions, particularly in the marginal ice zone. Limited process-level knowledge constrains our ability to quantify how sea-ice loss and Southern Ocean surface warming alter heat and moisture fluxes, boundary-layer dynamics, cloud formation, and cyclogenesis. Persistent model biases – especially in clouds and sea-ice–atmosphere representation and coupling – undermine confidence in projections, motivating the following interrelated knowledge gaps linking atmospheric dynamics, surface mass balance, and the production of brines and deep-water.

2.3a How does sea-ice loss modify marginal-ice-zone fluxes and boundary-layer dynamics? Substantial uncertainty remains in the atmospheric dynamical response to the recent Antarctic sea-ice loss¹⁴. While emerging evidence suggests that reduced sea ice can influence planetary-wave forcing and

large-scale circulation, it remains poorly constrained how strong surface-forcing anomalies affect air-sea fluxes, boundary-layer structure, and stratosphere-troposphere coupling, including their influence on the Southern Annular Mode.

2.3b Are Southern Ocean warming and sea-ice loss already reshaping Antarctic SMB and extremes? Process-level understanding of air–sea–ice interactions in the marginal ice zone remains limited, particularly regarding how changes in sea-ice concentration and snow-covered sea ice modify heat and moisture fluxes, boundary-layer dynamics, and cyclogenesis. In addition, there is a paucity of attribution studies that robustly link recent and emerging Southern Hemisphere extremes to sea-ice loss. As a result, the extent to which regional sea-ice anomalies can trigger or amplify extremes – through altered storm tracks, moisture-transport pathways, or large-scale circulation changes – remains poorly quantified.

2.3c Can the ongoing atmospheric changes to cause abrupt changes in AABW formation and the Southern Ocean overturning circulation? Recent observations indicate that AABW formation rates may have declined by up to ~30% in some regions since the 1990s, with significant implications for the global overturning circulation and deep-ocean carbon storage. Determining whether these changes reflect a gradual response or an approach to a critical threshold requires sustained, multi-platform observations of the coupled system including the feedback mechanisms between atmosphere, sea ice, ice shelves, and ocean (in collaboration with Theme 2). A further challenge is disentangling the influence of sea-ice loss on AABW formation from other major climate forcings, including ozone recovery, increasing greenhouse gas concentrations, and tropical teleconnections.

2.4 Characterising climate variability and warming in the recent past

As above, the long recurrence length and paucity of Antarctic observations severely limit our ability to robustly quantify recent temperature trends, climate sensitivity, and the magnitude of natural variability across Antarctica²⁵. Addressing these limitations requires integrating modern observations with paleoclimate archives to place recent change in a longer-term context of the last hundreds of years. We identify the following key knowledge gaps:

2.4a What will be the magnitude and trajectory of climate warming amplification over Antarctica? Recent observations from parts of Antarctica, including the Antarctic Peninsula and the East Antarctic Plateau, indicate emerging signatures of warming and changes in accumulation that may represent early expressions of Antarctic polar amplification²⁶. However, these sparse observations are cannot yet be assessed robustly against the background of natural variability. Climate models tend to underestimate Antarctic temperature variability²⁷, complicating attribution of observed trends. Quantifying Antarctic amplification therefore requires extending temperature and accumulation records beyond the observational period using paleoclimate archives, particularly shallow ice cores, to establish robust baselines of variability against which recent change can be evaluated.

2.4b How will climate variability across timescales evolve as Antarctica warms? Understanding how climate variability – from interannual to centennial timescales – will evolve with global climate mean warming remains a major challenge. Water-isotope observations of the atmospheric hydrological cycle, combined with shallow snow and firn cores, offer powerful tools to trace atmospheric processes and extend climate records into the pre-instrumental period, providing both information on Southern Ocean surface changes and on local temperature²⁸. However, how synoptic-scale variability and extreme events are preserved in snow and firn remains poorly understood. Detecting past extremes in short firn cores and identifying Antarctic regions where the ice archive retains sufficient temporal resolution therefore represent critical research frontiers and require advances in proxy-model integration, completing the database of PAGES Antarctica 2k²⁹ and expanding the study of climate variability both spatially to a tighter network of sites and temporally beyond 2005¹⁵.

2.5 Setting the current change in a longer, paleo context

The synchronous measurements of Antarctica InSync can benefit from studies over a longer temporal context by understanding the underlying mechanism or obtaining past analogues. This paleo point-of-view means targeting a comprehensive, pan-Antarctic reconstruction of the climate and ice sheet evolution since the Mid-Pleistocene transition.

2.5a How can paleoclimate archives be better used to constrain Antarctic and Southern Ocean variability and warming? Current ice-core reconstructions are often affected by high noise levels that obscure decadal variability³⁰, while systematic biases such as post-depositional processes introduce uncertainties across timescales³¹. Recent studies demonstrate that statistically optimised sampling strategies and replication can overcome these limitations¹⁵. Applying such approaches across the East Antarctic Plateau and revisiting deep ice core drilling sites is essential for quantifying Antarctic sensitivity to climate change, in particular, past warm and cold periods could provide a key context to understand whether climate variability will increase or not under a warmer mean climate state³².

Beyond firn and ice cores, the relationship between sea ice, ocean circulation, and climate variability prior to the satellite era remains poorly constrained. Marine sediment records south of the Polar Front are sparse, and quantitative reconstructions of sea-surface temperature and salinity remain highly uncertain. Blue ice areas can be an interesting way to obtain records from past interglacial with only shallow drilling. Overall dedicated efforts are needed to better connect atmospheric, oceanic, and cryosphere information from ice-core and marine archives, supported by targeted modern observations to constrain proxy system models. Without such advances, our ability to benchmark climate models against independent evidence and to place recent Antarctic changes in a long-term context will remain limited.

2.5b What Can Paleo-Proxies and High-Resolution Mapping Reveal About Antarctic Ice Sheet Evolution and Ocean-Driven Instability? High-resolution bathy-morphological mapping and geological records have advanced our understanding of Antarctic ice sheet dynamics, yet critical gaps remain: vast areas of the continental shelf – particularly grounding zones – and the continental rise and slope are still unmapped or unexplored. These regions are vital, as sedimentary and erosional features (e.g., sediment drifts, glacial troughs) trace the flow of warm Circumpolar Deep Water (CDW) toward the ice sheet base, accelerating basal melting and influencing glacier stability.

To address the vulnerability of marine-grounded glaciers, in particular to extreme marine and atmospheric heatwaves, a multidisciplinary approach is essential – combining high-resolution mapping, geophysical data, sediment cores, and robotic surveys in challenging areas like grounding zones. The goal is to integrate past and present ice-earth-ocean interactions, improving predictions of ice sheet stability and sea-level rise in a warming climate.

3. Key variables and an observational strategy

A coordinated Antarctic observing strategy must directly target the dominant sources of uncertainty identified in Sections 1 and 2, including uncertainties in SMB arising from accumulation and atmospheric forcing (Sections 2.1, 2.2), weakly constrained couplings between atmospheric circulation and the hydrological cycle (Section 2.2), and limited process-level understanding of how ocean and sea-ice changes influence atmospheric circulation, extremes, and climate variability (Section 2.3, 2.4). Characterising Antarctic climate variability and emerging signatures of warming requires placing recent changes in a longer-term context using palaeoclimate constraints (Section 2.4). Observations must therefore span the coupled atmosphere-surface-firn-ocean system and resolve both spatial contrasts and variability across timescales, including rare extreme events.

3.1 Key variables

The key variables required to address these uncertainties are summarised in **Table 1**, which to map scientific questions, timescales, observing platforms, and climate archives.

Together, these variables support four linked objectives:

- (i) quantifying accumulation, precipitation characteristics, and wind-driven snow redistribution;
- (ii) constraining firn structure, thermal state, hydrology, and signal preservation that regulate meltwater storage, runoff, and ice-shelf vulnerability;
- (iii) diagnosing how atmospheric circulation, moisture transport, ocean–sea-ice interactions, and extremes propagate inland and affect SMB and ice-sheet stability; and
- (iv) characterising Antarctic climate variability and polar amplification across timescales by integrating modern observations with palaeoclimate constraints.

3.2 Observing platforms, climate archives, and implementation

The observing strategy emphasises a dual approach: broad spatial coverage through an expanded, coordinated network of stations, traverses, and marine observations to detect continental-scale circulation- and ocean-driven change, and long, continuous, high-resolution time series from well-chosen palaeoclimate archives at a limited number of sites to quantify rare, high-impact extremes, variability, and emerging warming signals.

Implementation must build on the existing Antarctic station network, together with coordinated deployments in under-sampled regions. Priority platforms include expanded snow-stake networks, accumulation radar surveys, blue ice, and firn-core programmes (including shallow coring and ice cores), alongside enhanced automatic weather stations in both accumulation- and melt-dominated regimes capable of measuring full surface energy balance, near-surface meteorology, and subsurface firn temperature, density, and liquid water content. Sites with deep ice cores covering at least the last interglacial (like Kohnen or Concordia) could be priority sites to improve climate reconstruction and connect the current change with past analogues. For instance, within the framework of IPICS, an expert group of SCAR, a new priority project, “Ice Core Context for Current Change” is expected to be proposed.

System domain	Key variables on short time scales	Key variables on long time scales	Key question	Primary observing platforms	Why this matters
Precipitation & accumulation	Snowfall rate	Thickness/density of annual layers	2.1a, 2.2a	AWS (precip sensors), precipitation, disdrometers, radar, satellite, ice cores, stake networks, GPR, firn cores, sounding	Dominant mass-gain term; largest SMB uncertainty Controls firn saturation and runoff onset Calibration of satellite SMB; trend detection Links circulation and orography to snowfall
	Rainfall rate & phase	Ice lenses/crusts	2.1b, 2.2a		
	Accumulation	Accumulation	2.1a, 2.4a		
	Vertical precipitation structure		2.2a		
Wind-driven snow processes	Blowing/drifted snow flux		2.1a	AWS, snow particle counters, satellite, flux tower, water isotopes, ice chemistry	Major redistribution and sublimation loss Often missing SMB term in models
	Sublimation rate	Metamorphism	2.1a, 2.4c		
Near-surface meteorology	Air temperature	Temperature reconstruction	2.1b, 2.4a	AWS, automatic	Melt threshold; firn thermal state

	Humidity Wind speed & direction Turbulence	Dust particles	2.1a, 2.2a 2.1a, 2.2a 2.1b	stations, flux towers, eddy covariance, masts, ships, water isotopes, dusts	Sublimation and surface fluxes Snow transport; circulation signal Controls sensible/latent heat exchange
Surface energy balance	SW & LW radiation ($\downarrow\uparrow$) Sensible & latent heat fluxes	Insolation	1.1, 2.1b, 2.2a, 2.3a 2.1a, 2.1b, 2.3a	AWS, flux towers, radiometers, satellite, models	Primary control on melt and refreezing Close surface energy and water budgets
Cloud properties	Cloud fraction, phase, optics		2.2a, 2.3a	Satellite, cloud radar, lidar	Radiative forcing; precipitation formation
Atmos. structure & circulation	Boundary-layer profiles (T, q, wind) Vertical wind profiles Integrated moisture transport		2.2a, 2.3a 2.2a, 2.3a 2.2b, 2.4	Radiosondes, UAVs, AWS towers, wind profilers, reanalysis, models	Coupling circulation to SMB response Moisture transport pathways Source regions of future snowfall
Water-isotope tracers	Precipitation isotopes Vapour isotopes (continuous)	snow pit and ice core isotopes	2.2b, 2.3b, 2.4a 2.2b, 2.3b, 2.4a	Precip collectors, firn cores, stations, ships	Identify moisture origin and pathways Real-time tracking of extremes (e.g. ARs)
Surface melt & runoff	Melt rate Refreezing rate Runoff occurrence	Melt layers Refrozen ice lenses	2.1b 2.1b 2.1b	AWS, satellite, firn cores, thermistor strings, satellite, ground survey	Firn saturation and hydrofracture risk Firn buffering capacity Ice-shelf destabilisation
Firn thermal state	Firn temperature profiles	Firn temperature profiles	2.1b	firn cores	Controls refreezing depth and water storage
Firn structure & density	Firn density Stratigraphy	Firn and ice density Stratigraphy	2.1a, 2.4a 2.1b, 2.4b	Firn and ice cores, snow pits, radar	Height–mass conversion uncertainty Permeability and ice-layer formation
Near-surface firn (0–2 m)	Grain size Specific surface area (SSA) Albedo Microstructure	Crystalline structure Albedo Physical properties	2.1b 2.1b 2.1b 2.1b, 2.4b	Snow pits, optical sensors, field spectroscopy, snow pits, AWS radiometers, snow micro-CT,	Albedo and melt sensitivity Energy absorption; wind effects Strong feedback on melt Liquid water retention
Firn hydrology	Liquid water content Permeability	Firn properties and lockin depth	2.1b 2.1b	Firn cores, dielectric probes	Saturation and ponding Runoff vs storage

Surface–ice coupling	Meltwater at grounding lines		2.1c	Satellite, GPS, field surveys	Flow acceleration risk
Sea ice–ocean–air coupling	Sea surface temperature and salinity	Sea surface temperature and salinity	2.3a, 2.3b	Ships and autonomous profiles; satellite; sediment and ice cores (stable oxygen isotopes; Mg/Ca ratios, chemical proxies), airborne sampling	Surface ocean warming
	Sea ice concentration	Sea ice concentration	2.3a, 2.3b		Boundary conditions; sea ice loss
	Fluxes over heterogeneous surfaces	Sea ice chemistry	2.3a		Bridging point observations and model grid scales
	upper-ocean heat content and surface stratification		2.3c		Ocean preconditioning and ice shelf destabilisation
Integrated outcomes	Net SMB	Ice sheet thickness	1.1, 2.1c	Integrated obs + models	Sea-level contribution
	Spatial SMB variability		2.1a, 2.2a	Radar, satellite, models	Circulation-driven contrasts
	Atmospheric extreme events	Frequencies of extreme events	2.2a, 2.4b	Stations, satellite, reanalyses	Risk-relevant change
	Marine heatwaves		2.3a, 2.3b	Stations, satellite, reanalyses	Risk-relevant change
	Positions of wind systems and currents	Atmospheric circulation	2.3	satellite, reanalysis	Atmospheric and oceanic circulation changes
System domain	Key variables on short time scales	Key variables on long time scales	Key question	Primary observing platforms	Why this matters
Precipitation & accumulation	Snowfall rate	Thickness/density of annual layers	2.1a, 2.2a	AWS (precip sensors), precipitation, disdrometers, radar, satellite, ice cores, stake networks, GPR, firn cores, sounding	Dominant mass-gain term; largest SMB uncertainty
	Rainfall rate & phase	Ice lenses/crusts	2.1b, 2.2a		Controls firn saturation and runoff onset
	Accumulation	Accumulation	2.1a, 2.4a		Calibration of satellite SMB; trend detection
	Vertical precipitation structure		2.2a		Links circulation and orography to snowfall
Wind-driven snow processes	Blowing/drifted snow flux		2.1a	AWS, snow particle counters, satellite, flux tower, water isotopes, ice chemistry	Major redistribution and sublimation loss
	Sublimation rate	Metamorphism	2.1a, 2.4c		Often missing SMB term in models
Near-surface meteorology	Air temperature	Temperature reconstruction	2.1b, 2.4a	AWS, automatic stations, flux towers, eddy	Melt threshold; firn thermal state
	Humidity		2.1a, 2.2a		Sublimation and surface fluxes

	Wind speed & direction		2.1a, 2.2a	covariance, masts, ships, water isotopes, dusts	Snow transport; circulation signal
	Turbulence	Dust particles	2.1b		Controls sensible/latent heat exchange
Surface energy balance	SW & LW radiation ($\downarrow/\uparrow$)	Insolation	1.1, 2.1b, 2.2a, 2.3a	AWS, flux towers radiometers, satellite, models	Primary control on melt and refreezing
	Sensible & latent heat fluxes		2.1a, 2.1b, 2.3a		Close surface energy and water budgets
Cloud properties	Cloud fraction, phase, optics		2.2a, 2.3a	Satellite, cloud radar, lidar	Radiative forcing; precipitation formation
Atmos. structure & circulation	Boundary-layer profiles (T, q, wind)		2.2a, 2.3a	Radiosondes, UAVs, AWS towers, wind profilers, reanalysis, models	Coupling circulation to SMB response
	Vertical wind profiles		2.2a, 2.3a		Moisture transport pathways
	Integrated moisture transport		2.2b, 2.4		Source regions of future snowfall
Water-isotope tracers	Precipitation isotopes	snow pit and ice core isotopes	2.2b, 2.3b, 2.4a	Precip collectors, firn cores, stations, ships	Identify moisture origin and pathways
	Vapour isotopes (continuous)		2.2b, 2.3b, 2.4a		Real-time tracking of extremes (e.g. ARs)
Surface melt & runoff	Melt rate	Melt layers	2.1b	AWS, satellite, firn cores, thermistor strings, satellite, ground survey	Firn saturation and hydrofracture risk
	Refreezing rate	Refrozen ice lenses	2.1b		Firn buffering capacity
	Runoff occurrence		2.1b		Ice-shelf destabilisation
Firn thermal state	Firn temperature profiles	Firn temperature profiles	2.1b	firn cores	Controls refreezing depth and water storage
Firn structure & density	Firn density	Firn and ice density	2.1a, 2.4a	Firn and ice cores, snow pits, radar	Height–mass conversion uncertainty
	Stratigraphy	Stratigraphy	2.1b, 2.4b		Permeability and ice-layer formation
Near-surface firn (0–2 m)	Grain size	Crystalline structure	2.1b	Snow pits, optical sensors, field spectroscopy, snow pits, AWS radiometers, snow micro-CT,	Albedo and melt sensitivity
	Specific surface area (SSA)		2.1b		Energy absorption; wind effects
	Albedo	Albedo	2.1b		Strong feedback on melt
	Microstructure	Physical properties	2.1b, 2.4b		Liquid water retention
Firn hydrology	Liquid water content	Firn properties and lockin depth	2.1b	Firn cores, dielectric probes	Saturation and ponding
	Permeability		2.1b		Runoff vs storage
Surface–ice coupling	Meltwater at grounding lines		2.1c	Satellite, GPS, field surveys	Flow acceleration risk

Sea ice-ocean-air coupling	Sea surface temperature and salinity	Sea surface temperature and salinity	2.3a, 2.3b	Ships and autonomous profiles; satellite; sediment and ice cores (stable oxygen isotopes; Mg/Ca ratios, chemical proxies), airborne sampling	Surface ocean warming
	Sea ice concentration	Sea ice concentration	2.3a, 2.3b		Boundary conditions; sea ice loss
	Fluxes over heterogeneous surfaces upper-ocean heat content and surface stratification	Sea ice chemistry	2.3a 2.3c		Bridging point observations and model grid scales Ocean preconditioning and ice shelf destabilisation
Integrated outcomes	Net SMB	Ice sheet thickness	1.1, 2.1c	Integrated obs + models	Sea-level contribution
	Spatial SMB variability		2.1a, 2.2a	Radar, satellite, models	Circulation-driven contrasts
	Atmospheric extreme events	Frequencies of extreme events	2.2a, 2.4b	Stations, satellite, reanalyses	Risk-relevant change
	Marine heatwaves		2.3a, 2.3b	Stations, satellite, reanalyses	Risk-relevant change
	Positions of wind systems and currents	Atmospheric circulation	2.3	satellite, reanalysis	Atmospheric and oceanic circulation changes

Table 1: Antarctic Key Variables including links to key questions, time scales (short, daily to seasonal, long interannual to multi-millennial), observing platforms, and climate archives.

Precipitation radar arrays are required to capture the strong spatial and temporal variability of Antarctic snowfall and extreme events. A limited number of coordinated supersites should be established where atmosphere-surface-firn-ocean interactions, water isotope measurements, and firn thermometry can be measured synchronously, including during extreme melt and precipitation episodes. These observations should help improve the retrieval of snowfall, melt extent, blowing snow, SMB, sea-ice conditions, and surface roughness from satellite products, via systematic calibration and validation against these in-situ measurements.

Finally, coordinated measurements from research vessels and coastal and terrestrial sites are essential to connect atmospheric, oceanic, and cryospheric processes across the land-ocean interface and to provide context for climate variability and extremes beyond the observational period. All instrumental data must be tightly integrated with global or regional climate models, reanalyses, and isotope- and proxy-enabled simulations to reduce accumulation and circulation biases, improve process representation, and translate observations into robust projections of Antarctic mass change and climate evolution.

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Cross-Cutting Theme Earth Observation

Unleashing the potential of Earth Observation to improve monitoring and understanding of Antarctica and the Southern Ocean

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Executive Summary

Advances in satellite Earth Observation (EO) have enabled comprehensive and continuous monitoring, and characterisation, of Antarctica and the Southern Ocean. EO data products provide essential information to tackle the scientific priorities of Antarctica InSync, including crucial spatial and temporal context for in-situ campaigns and modelling. The wealth of EO data products enables scientific research priorities to be addressed, such as understanding impacts of climate change and variability across ice sheets, ice shelves, sea ice, ocean, atmosphere and ecosystems, investigating trends, extremes and feedbacks.

However, there remain many areas for improvement. In the context of Antarctica InSync the EO scientific community have identified the following priorities:

- It is vital to continue to improve satellite EO of Antarctica and the Southern Ocean. Efforts should target:
 - o Extending the observational record,
 - o Increasing the range of measured variables,
 - o improving spatial and temporal resolution,
 - o quantifying and reducing measurement uncertainties,
 - o increasing data accessibility,
 - o creating new satellite EO capabilities.
- Integrated EO and campaign data should form the core observational baseline for InSync.
- Antarctica InSync provides a valuable opportunity to advance science through EO-led science investigations and collaboration with:
 - In-situ, ship-based and airborne campaigns:
 - o In-situ observations are a critical resource for validation and calibration of EO data. Coordination with fieldwork teams is vital to ensure all possible opportunities for EO cal/val are maximised. Ideally, in-situ observations should be maintained for longer periods (i.e. years) to enable ongoing cal/val activities through multiple seasons.
 - o EO data provides valuable information on where to target in-situ activities, such as significant areas of change and regions where key physical processes are exemplified. These regions should be coordinated across Antarctic InSync science themes as supersites.
- Modelling community:
 - o EO data provides crucial information for model initialization, assimilation and validation.
 - o Improved process understanding, driven by analysis of EO data, leads to improved representation of complex processes in models and more accurate future projections.
- International, national and commercial EO capability:
 - o There is strong interest within the EO community for improved coordination between space agencies and substantial scientific potential in high-resolution commercial data products. Access to these data could be achieved through strengthened collaboration with commercial providers.

1. Introduction

Antarctica InSync is a global initiative aimed at coordinating and synchronizing scientific observations across Antarctica and the Southern Ocean to address critical knowledge gaps and connect ice, ocean, climate, and life systems to better understand and protect the Antarctic region and its global impacts.

The initiative focuses on seven interconnected research themes:

- **Southern Ocean and Antarctic heat, freshwater, carbon and elements cycles and their response to climate change.**
- **Rapid sea ice decline and its causes and consequences.**
- **Antarctic Ice Sheets and Ice Shelves: Processes driving rapid change, from observation to prediction.**
- **Improving knowledge and protection of the unique Antarctic life: from land to the ocean and into the deep sea.**
- **Anthropogenic signatures in Antarctica: the race against pollution and other pressures.**
- **Aerosol-cloud interactions and radiative feedbacks.**
- **Variability, extremes and tipping in a changing Antarctic climate.**

The timeline for Antarctica InSync consists of:

- **Preparatory Phase (2024–2026):** for planning, coordination, and community engagement.
- **Field Phase (2027–2030):** Implementation of joint science missions and synchronous observations.

Satellite Earth Observation (EO) is uniquely placed to contribute to Antarctica InSync across all themes, providing region-wide coverage of a wide range of variables with long temporal records. These data can provide a foundation for targeted in-situ observations and modelling activities, as well as enabling EO-driven science investigations. Synchronizing in-situ campaigns with satellite observations improves calibration and validation of EO datasets, thereby increasing accuracy and reducing uncertainty in EO data products. The long temporal coverage of EO data also ensures the impact and context of the Antarctica InSync activities extend beyond the field phase.

In this whitepaper we outline the contributions EO datasets, space agencies and the EO science community can make to achieve the goals of Antarctica InSync. We highlight the research priorities identified by the EO community and propose a set of actions to be implemented to maximise EO usage, increase coordination with in-situ and modelling activities to address Antarctica InSync Science Theme priorities, and develop EO-led science investigations.

2. Overview of EO capabilities

Before the satellite era, monitoring the remote and inhospitable regions of Antarctica and the Southern Ocean relied heavily on sparse in-situ observations and limited aerial surveys, offering only fragmented insights into this vast and dynamic system. The launch of the first Earth Observation satellites enabled large-scale, and increasingly detailed and frequent monitoring of polar environments. Over the decades, advancements in satellite sensors—from optical imagers and radar systems to altimeters and gravimeters—have provided critical data on this crucial region including ice sheet dynamics, sea ice variability, ocean circulation, ecosystems and atmospheric conditions. This has transformed our ability to track environmental change, assess and understand climate impacts, and inform global climate models with increasing accuracy and temporal coverage.

Satellite Earth Observation can contribute data relevant to all the Antarctica InSync Science Themes. A comprehensive list of the available EO capabilities and datasets is provided in Annex: A. To

demonstrate the wealth and diversity of EO data available, here we provide a brief and consolidated example of the EO datasets that could be used to understand interactions between the Antarctic Ice Sheet, sea ice and the Southern Ocean, split by sensor type.

- **Optical, multispectral, hyperspectral and Infrared Imaging, Moderate resolution ocean colour radiometry:** sea ice extent, floe size distribution and lead fraction, polynyas, calving front locations, supraglacial hydrology, ice surface properties (albedo, temperature), organic carbon pools, primary production and phytoplankton biomass and diversity, clouds and aerosols.
- **Synthetic Aperture Radar (SAR):** ice sheet dynamics, grounding line location and migration, pinning point area, solid Earth deformation monitoring, ice shelf rifting, damage and fracturing, ice shelf basal melt, iceberg calving, surface melt and refreeze, firn properties, supraglacial hydrology, subglacial meltwater outlet locations, sea ice motion, iceberg mapping, sea ice type, ridge and lead fraction, ocean surface currents and winds.
- **Altimetry:** ice sheet elevation and elevation change, mass loss, surface density and roughness; ice shelf thickness, basal melt, calving front locations, grounding line locations; sea ice freeboard, thickness, concentration, extent, topography and lead fraction; snow depth on sea ice; sea surface height, ocean circulation patterns, ocean fronts and eddies.
- **Gravimetry:** ice sheet mass change.
- **Passive Microwave Sensors (PMW):** sea ice concentration and extent, sea-ice type, sea ice motion, snow depth on sea ice, surface melt, sea surface salinity, atmospheric moisture and temperature.
- **Scatterometry (SCAT):** sea-ice concentration, classification of sea-ice types, sea ice motion, ice sheet surface melt and refreeze extent, duration and melting phase (e.g. freezing, refreezing), firn properties, ocean surface winds.

Together this collection of datasets can be used to monitor change and investigate the interconnectedness of the system, understanding complex feedbacks and responses to changing climate. This list is not intended to be exhaustive, but an example of the potential offered by EO datasets for a specific scenario. Readers are encouraged to review the complete list of EO data products presented in the **Annex A**.

3. Importance of Earth Observation for Antarctica InSync activities

EO datasets provide the essential foundation for integrating and advancing Antarctica InSync activities. Its unique capability to deliver consistent, pan-Antarctic measurements across spatial and temporal scales makes EO central to the vision of coordinated Antarctic research. Moreover, the EO data record has become sufficiently long to investigate links to climate.

EO data provides the only feasible way for cost-effective, long-term and comprehensive mapping of a wide range of environmental variables on pan-Antarctic scale. These measurements fill the spatio-temporal gaps of observations between fixed ground-based or campaign-oriented measurements, thereby providing context to interpret field measurements and model outputs. EO data can also provide observations of variables not quantified by in-situ campaigns such as ice damage, large-scale sea ice motion, sea ice area and ice type distribution, active crack/rift propagation, iceberg calving rates or subglacial lake filling and drainage.

The use of EO data products allows key locations for in-situ observations to be identified, based on observed changes or poorly understood dynamics. This information could potentially be provided at near real time, enhancing the probability of measuring events in-situ and observing short-lived processes of scientific interest. Therefore, the preparation of routes for scientific traverses and airborne

acquisitions can be optimized. EO data is also important for weather forecasting with accurate weather prediction an essential resource for safe and efficient campaign activities.

The generation and curation of EO data products is highly complementary to in-situ activities. Firstly, in-situ observations are essential for validation of EO data products and characterisation of uncertainties. Furthermore, in-situ observations can investigate processes unobservable from satellite EO (such as properties beneath the surface, e.g., ocean properties) or on smaller spatial scales beyond the resolution of EO, while EO provides the spatiotemporal context for in-situ observations.

EO data is also an important resource for modelling efforts through provision of real-world data for boundary conditions, model initialization, assimilation and process parameterization, training of Machine Learning-based algorithms, as well as model evaluation.

Moreover, EO products and EO-based indicators will continue monitoring beyond the InSync campaigns. Through sustained satellite missions and the development of standardized EO-based indicators, the legacy of Antarctica InSync will extend into the future, towards and beyond IPY5, supporting continuous assessment of environmental change and providing open, interoperable datasets for the scientific community and decision-makers alike.

4. Earth Observation Priorities for Antarctica InSync

We have identified a number of key aspects in relation to Earth Observation that should be prioritized during Antarctica InSync.

4.1 Coordinate with fieldwork teams to maximise potential for EO calibration and validation with in-situ observations

Coordination between fieldwork activities and EO is mutually beneficial. EO data is of great benefit to in-situ campaigns, for identifying key locations, planning routes, and contextualising field observations in space and time. Collaboration with in-situ observations allows creation of integrated products, moving from point measurements to pan-Antarctic scale.

In order to calibrate and fully exploit EO data, year-round in-situ observations are required, not only during the spring/summer season, which is currently heavily biasing the observations. Autonomous instrumentation may therefore play a key role in achieving sustained, all-season coverage. Unmanned Aircraft Systems also have considerable potential for providing medium-scale coverage for targeted regions and providing information on variability of observations within a satellite footprint.

Ideally in-situ observations should be coincident with satellite overpasses. Furthermore, to improve the spatial representativeness of the in-situ measurements, observations should not be limited to a single point but, where possible, should sample the small-scale variability within the satellite footprint. This helps ensure that the in-situ data better reflect the heterogeneity captured by the EO sensor.

In-situ cal/val is particularly important for new satellite missions, for instance CRISTAL, ROSE-L, CIMR, CHIME, EnMAP, PACE, FLEX, Harmony, EarthCARE, BIOMASS, WIVERN, NISAR, EDGE. There also remains a need for in-situ cal/val over the full lifetime of the missions, especially for under-sampled environments like Antarctica and the Southern Ocean.

The development of multiple Antarctic cal/val supersites would maximise the coordination of cal/val campaigns for multiple sensors and provide robust validation datasets with broader spatial coverage and context to observations, with observations over multiple years/seasons providing improved understanding of temporal change.

Planned expedition routes and locations should be identified and shared to allow the request of observations for the benefit of EO. Equipment could then be provided to the campaign team to be deployed in the field. As examples this could include: corner reflectors or GNSS, ASD field spectrometers to calibrate spectral reflectance, protocols for snow sampling, on-ice drifters, shipborne surface (e.g. snow) and atmosphere radars and radiometers, drones with lidar and snow radar to deploy from scientific stations or icebreakers, terrestrial laser scanners and radar instruments such as Ground Penetrating Radars (GPR), Electro Magnetic (EM) sensors over sea ice, ApRES to calibrate and validate ice shelf basal melting.

Here we provide a list of the in-situ (ground-based, shipborne and airborne) datasets that have been identified as priorities for EO cal/val and product development:

Parameters to be observed	Target EO sensor	Instrument	Location	Domain (ice sheet, ocean, atmosphere, sea ice)
Sea Surface Salinity	SMOS and SMAP	CTD casts, Thermosalinographs (TSG), Argo floats, sensors mounted on marine-mammals	Everywhere, preferably close to Marginal Ice Zone and ACC frontal zones	Ocean
Sea Surface Temperature	Infrared radiometers, microwave	TSG, CTD, Argo floats, autonomous surface vehicles	Everywhere, preferably close to Marginal Ice Zone and ACC frontal zones	Ocean
Surface wind	Scatterometer, SAR	Anemometers, wavegliders		Ocean
Steric height, total ocean currents	Altimeter, SAR, scatterometer	moorings		Ocean
Ocean currents	Altimeter currents	Drifters, S-ADCP, ADCP on autonomous surface vehicles		Ocean
Phytoplankton Functional Types / Community Composition, diffuse attenuation (K_d , also spectral)	PACE-OCI, S3A/B/C-OLCI and HARP See full list at: https://ioccg.org/resources/missions-instruments/	HPLC analysis (water samples), Above-water radiometry (e.g., DALEC (Dynamic Above-water Radiance (L) and Irradiance (E) Collector), or SeaPRISM), or in-water radiometry and inherent optical properties (e.g., HyperPRO and BGC-Argo floats), FDOM EEMs. Hypernet NetworkAERONET	Southern Ocean	Ocean

		and AERONET-OC		
Waves (height, spectra, period, direction)	Altimeter, diffusiometer	Wave drifter		Ocean
Sea surface height	Altimeter	Bottom pressure recorders, tide gauges	Ice-covered ocean	Ocean
Sea ice draft	Altimeter	Moored or UAV or marine mammal with Upward Looking Sonars (ULS)		Sea ice
Snow depth on sea ice, sea ice freeboard	Altimeter	Surface-based/ airborne/drone snow radar. Should be combined with an altimeter or an eletroc-magnetic sonar. Laser Scanner	Where possible	Sea ice
Sea ice thickness	Altimeter / Passive Microwave	EM-Bird (electro-magnetic sensor for ice thickness + snow-radar) Or lidar altimeter/scanner + snow-radar.	Where possible	Sea ice
Sea ice thickness plus snow depth on sea ice	Altimeter / Passive Microwave	EM bird or lidar+snow-radar or Sea Ice Monitoring System (SIMS) + snow radar		Sea ice
Sea ice drift vector, sea ice strain rates (deformation)	Passive Microwave, SAR	Ice-tethered drifters	MIZ, pack-ice conditions	Sea-ice
Sea ice age, sea ice type	Passive Microwave, Scatterometer, SAR	Ice trackers	Everywhere; regions where sea ice survives summer, e.g. Weddell Sea; Ross Sea	Sea ice
Snow / ice micro-physical properties for microwave emission and backscatter modelling	Passive Microwave, all radars	SnowImager, SMP, permittivity probe, salinity, temperature, ice cores, surface and interface roughness	Everywhere	Sea ice
Firn density, snow pit stratigraphy	SAR, Altimeter	Corner reflectors, GNSS	Where possible, continuous multi-year deployment	Ice sheet

Ice sheet surface radiance, irradiance, and reflectance	Optical	ASD field spectrometers	Where possible, coincide with satellite overpass. Ideally mid-season and start or end of season (ie. range of sun angles)	Snow/ice
Ice shelf basal melt rate, ice divergence, and ocean tides.	Basal melt from Altimetry + SAR	ApRES radar, GNSS, snow/firn density, AUV	See Figure 1. Continuous, multi-year deployment	Ice shelves, Ocean
Subglacial water transport, ocean intrusion in grounding zones, and short-term grounding zone migration	Interferometric SAR	ApRES, ground-based radar, GPS, ice penetrating radar (ground-based, UAV or plane-mounted)		Ice sheet, ice shelves
Ice sheet surface elevation and radar penetration	Altimetry, and Bistatic SAR	Snow/firn density and stratigraphy, liquid water content, GNSS	Where possible, coincide with satellite/airborne overpass	Ice sheet, ice shelves
3D ice velocity	Ice velocity and speed change from SAR	GPS (3D)	Where possible, Evans Ice Stream has been identified as a possible target site. Continuously, several years	Ice sheets, ice shelves
Evolution of fractures, basal motion, calving, subglacial lake drainage events, grounding lines, ice thickness, internal structure, and mechanical properties.	Many: SAR, altimetry,	Seismic and infrasound observations	Where possible	Ice sheets, ice shelves
Supraglacial Meltwater Volume (lake depth, storage, stream discharge)	ICESat-2 (laser altimetry), optical sensors (Sentinel-2, Landsat), SAR (C-/L-band), high-resolution commercial optical/SAR	Lake bathymetry measurements (sonar, pressure transducers), water-level loggers, stream discharge measurements	Ice-shelf supersites with recurrent melt (e.g., Larsen C, George VI, Amery; wet ice shelves of the Antarctic Peninsula)	Ice sheets, ice shelves
Surface roughness at microwave-relevant scales (mm–dm scale variability)	SAR, scatterometer, passive microwave radiometers	Terrestrial laser scanning, close-range photogrammetry, UAV-based lidar, ground-based multi-frequency microwave measurements	Representative wet and dry ice shelves (e.g., Larsen C, Ross Ice Shelf), East Antarctic Plateau reference sites; repeat	Ice sheets, ice shelves

			observations	
Vegetation distribution, species (flora and fauna) distribution	Optical, infrared, SAR	Vegetation distribution, species (flora and fauna) distribution	Terrestrial, sea ice, ice shelves, ocean	Ecosystems
Aerosol, Cloud and precipitation properties	Optical and microwave imager, sounders, radar, lidar	Airborne, ballon-borne, surface and ground based remote-sensing	Southern Ocean & Antarctica (super-sites + targeted campaigns)	Atmosphere

4.2 Improved observations

There is considerable potential for improving the current set of Earth Observation data products covering Antarctica and the Southern Ocean. Firstly, it is important to continue to extend the observational record by fully utilising past, present and future data acquisitions and to ensure there is sustained monitoring as part of the legacy of Antarctica InSync to IPY. This includes continuation of existing missions where possible (i.e. continuation of SWOT). Further advances in scientific understanding and operations could be achieved with the systematic production of near real time data.

There is a continued need to quantify and reduce uncertainties and improve resolution of observed variables. This can be achieved through well-designed calibration and validation campaigns, as well as the development of new sensor technologies and application of innovative AI methods. New and existing sensors, as well as sensor synergy also provides significant potential for developing new EO data products. Known observational gaps, such as in the critical ice marginal zone, and those identified as part of Antarctica InSync can be used to define the next generation of Earth Observation missions and products.

Furthermore, efforts should be made to fill the spatial and temporal gaps in EO data. For example, ocean colour satellite remote sensing is only possible during daylight and under ice-free and cloud-free conditions, with observations for the first optical depth only. High-resolution in-situ data would enable observations at greater depths, under clouds and close to the ice edge, filling the observational gaps and allowing optimal model development of simulation of ocean ecosystem or biogeochemistry. Data fusion techniques for combining in-situ and satellite data, including the use of AI, can enhance the capabilities substantially.

4.3 EO-driven research projects

EO datasets are now sufficiently long, detailed and varied across multiple parameters that they can address research priorities and stimulate scientific advances. A major advantage of EO data is that research can start prior to the InSync observing period, link into the observing period, be deployed at pan-Antarctic scale and extend to IPY. Furthermore, there is also potential to address research priorities that go across Antarctica InSync science themes.

We provide details of EO-driven research opportunities within Antarctica InSync science themes in Annex B.

4.4 Coordinating activities of space agencies and commercial satellite operators

There is a clear need for improved coordination between international and national space agencies and commercial satellite operators to maximise the quality, continuity, and coverage of EO data in support of Antarctica InSync, including the coordination of in-situ cal/val measurement campaigns.

Furthermore, there is also a need to expand the participation in the EO cross-cutting group, which is currently largely dominated by European-based scientists and with focus on Ocean, Sea Ice and Ice Sheet Science Themes.

Coordination among international and national space agencies should be facilitated through the WMO Task Team on Cryosphere and Polar Observations from Space (TT-CPOS, formerly the Polar Space Task Group). Commercial satellite operators, particularly SAR (e.g. ICEYE, Cappella Space, Umbra Space) and high-resolution visible (e.g. WorldView, Planet) providers, should be invited to contribute to and align with a shared observing strategy for polar regions.

With regard to commercial satellite operators, there is strong interest within the EO community and substantial scientific potential in accessing high-resolution commercial data products. Opportunities to strengthen collaboration with commercial providers and improve data access should be explored. One possible approach is the establishment of a mechanism to request and task high-resolution acquisitions for events of high scientific or validation activities.

At the time of writing, due to inactivity and unknown status of WMO TT-CPOS, it is suggested that alternative options are explored, such as direct contact between scientists and space agencies interested in contributing to Antarctica InSync. Priorities for these activities should be to develop an observing strategy for polar regions, comprising two complementary components: (i) continuous, routine monitoring of polar areas to deliver sustained, operational as well as scientific and experimental products; and (ii) targeted, on-demand acquisitions of very high-resolution satellite data activated case by case to capture regions and events undergoing significant change. A dedicated activation procedure (including triggers, decision roles, and tasking workflows) need to be developed to allow this on-demand component.

4.5 Closer collaboration with modelling teams to ensure maximum use of EO data

There is a need to create and enhance dialogue between modelling and EO communities to ensure the accurate use of EO data for model initialisation and assimilation, including uncertainties and range of variables available. The EO community should ensure the most state-of-the-art EO data is easily findable and accessible for scientists using EO data in numerical models, by updating relevant data portals and communicating latest data releases. This shall ensure EO knowledge is being fully exploited by models. Furthermore, EO data should be maximised to improve process understanding and representation in models.

Combined with this, improved coordination with modelling teams could ensure modelling is used to fill in gaps in space and time in EO datasets. The quality and quantity of EO data also suggests there is significant additional potential for the use of EO in AI models. EO datasets are detailed and extensive enough to potentially allow training of AI representation of the system.

4.6 Data Management Principles and Coordinating EO data products across domains

The Antarctica InSync EO cross-cutting group supports data management principles outlined by the efforts of the Antarctica InSync Data Management Cross-Cutting group. Advanced data management is highly relevant for the EO community, due to the large volumes of data produced from EO. The underlying principle is that all scientific results from Antarctica InSync activities shall be verifiable and reproducible through ethical open access to all data and workflows necessary to produce those results. Data shall be preserved, accessible, and used in accordance with scientific norms of FAIR attribution and use.

Furthermore, synchronous, international and cross-domain aspects of Antarctica InSync should be maximised, which prompts the EO community to work across traditional domains. This should focus

on linking datasets across domains (i.e. land ice, sea ice, ocean, atmosphere). In particular, further work is needed to improve datasets at boundaries (i.e. marginal ice zone, close to coastlines).

To enable the linkage of datasets across observation domains EO data should be easily accessible, interoperable and analysis ready for integration into an array of data systems, including digital twins, to reveal new knowledge and insights. Standardising the organisation of EO data through formats and metadata is the first step towards achieving this goal. To this end, good progress has been made for geospatial data through initiatives including the open geospatial consortium (OGC), Committee on Earth Observation Satellites (CEOS), the SpatioTemporal Asset Catalogs (STAC), the Open Data Cube (ODC) and standardised nested grids like MGRS. When combined with standardised data, tiered cloud-optimised formats like COGs and (Geo-) Zarr allow data to be easily queried, accessed and synthesised using API's, cloud computing and geospatial tools like the Geospatial Data Abstraction Library (GDAL). This makes EO data accessible for analysis with a range of software hosted on high-performance computing, desktop machines and visualisation services or data portals. Still, to fully realise this potential in polar regions, improved solutions for nested gridding for polar projections (preferably EPSG:3031) and querying across the antemeridian need to be found.

Satellite observations at the poles are constrained by the extreme conditions of ever-changing terrain, limited ground control and large atmospheric effects. Efforts to pre-process polar observations can provide consistent, analysis-ready data for the community, particularly focusing on the atmospheric correction of low solar angles for optical imagery, the aerosol and BRDF (Bidirectional Reflectance Distribution Function) corrections applied in optical imagery, polar cloud masking, consistent processing of SAR data at high incidence angles close to the pole, multi-temporal or dynamic digital elevation models and geolocation of older and very high-resolution satellite imagery. When improvements are realised, these can be used to compare with, inform and adjust global processing efforts. Collaborating in this way will work towards delivering consistent, analysis ready data at the poles within existing EO data delivery programs.

5. Summary

Satellite Earth Observation provides comprehensive and continuous monitoring, and characterisation, of Antarctica and the Southern Ocean. These EO data products are essential to address the scientific priorities of Antarctica InSync.

Continued and improved EO datasets of Antarctica and the Southern Ocean are essential. Efforts should target; extending the observational record, increasing range of measured variables, improve spatial and temporal resolution, quantify and reduce measurement uncertainties, increase data accessibility, and create new satellite EO capabilities. Furthermore, strengthened collaboration with commercial providers may allow the use of high-resolution data products which have substantial scientific potential.

The wealth of EO data products available enables scientific research priorities to be addressed with EO-driven research projects targeting the science priorities of Antarctica InSync, such as understanding impacts of climate change and variability across ice sheets, ice shelves, sea ice, ocean, atmosphere and ecosystems.

During Antarctica InSync it is vital that the EO community collaborate effectively with in-situ, ship-based and airborne campaigns to form the core observational baseline. These in-situ observations are a critical resource for validation and calibration of EO data and coordination should be maximised. Ideally, in-situ observations should be maintained for longer periods (i.e. years) at supersites to enable ongoing cal/val activities through multiple seasons and for a range of sensors. In turn, EO data, in

particular when produced in near real time, can provide valuable information on where to target in-situ activities, such as key locations of change or interactions between elements (ice sheet, ice shelf, sea ice, ocean, atmosphere, ecosystems).

In addition to coordination with in-situ observations, EO data provides crucial information for model initialization, assimilation, validation and improved process understanding. Maximising the use of EO data in models should be prioritized as an activity within Antarctica InSync.

Annex A: Satellite Earth Observation capabilities for Antarctica and Southern Ocean

Data product	Sensor (type & name)	Temporal and Spatial extent	Temporal and Spatial resolution	Primary Science Theme
Global Low Resolution Sea Ice Drift data record, release 1. OSI455	SSM/I and SSMIS from CM SAF R4, AMSR-E (NSIDC) and AMSR2 (JAXA)	1991-2020; Global	24 hr, 75 km	Rapid sea-ice decline and its causes and consequences
a. OSI405d	GCOM-W/AMSR2 and Metop/ASCAT	2009-ownwards; Global	24 hrs, 62.5 km	Rapid sea-ice decline and its causes and consequences
Swath-to-swath (s2s) sea-ice drift.	GCOM-W1 AMSR2 36.5 GHz	Antarctic: 15-13 July 2019. Spatial extent limited to swath overlap.	1-48hrs, 62.5 km	Rapid sea-ice decline and its causes and consequences
High resolution sea ice drift and deformation	Sentinel-1 / RCM SAR	2014–present	Regional coverage, <1 km	Rapid sea-ice decline and its causes and consequences
Sea ice thickness (ESA CCI v4)	Satellite altimetry	1995-2024	Monthly, 25km	Rapid sea-ice decline and its causes and consequences
Sea ice thickness (ESA S3MPC and Cryo-TEMPO)	Satellite altimetry	2010-present 2016-present	Along-track	Rapid sea-ice decline and its causes and consequences
Sea ice thickness (NASA)	Satellite altimetry	2018-present	Along-track	Rapid sea-ice decline and its causes and consequences
Sea ice thickness (ESA SIN'XS)	Satellite altimetry	1993-2025	Monthly, 12.5km	Rapid sea-ice decline and its causes and consequences
Sea ice thickness (SO-SIMBA)	Satellite altimetry	2018-present	Daily/Monthly, 12.5 km	Rapid sea-ice decline and its causes and consequences
Snow Depth (SO-SIMBA)	Satellite altimetry Passive Microwave	2018-present (1978) 2002–present	Monthly, 25km Daily (winter months only), 25 km	Rapid sea-ice decline and its causes and consequences
Snow Depth (ESA Cryo-TEMPO)	Satellite altimetry	2018-present + climatology	Monthly, 25 km	Rapid sea-ice decline and its causes and consequences

Snow Depth (SIN'XS)	Satellite altimetry	2013-2015	Monthly, 25 km	Rapid sea-ice decline and its causes and consequences
Snow depth from PMW	(AMSR-E/AMSR2)	2002-06-01 to 2011-10-04 & 2012-07-02 to present	12.5 km daily resolution	Rapid sea-ice decline and its causes and consequences
Sea ice concentration (OSISAF, NSIDC, ...)	Passive Microwave	1978-present	Monthly, daily; 25 km	Rapid sea-ice decline and its causes and consequences
Sea ice type (OSISAF, NSIDC, ...)	Passive microwave and scatterometry; SAR	1978-present 2014-present	daily/monthly (winter months only), 25 km	Rapid sea-ice decline and its causes and consequences
Melt season length	Passive microwave and scatterometry	1978-present	daily	Rapid sea-ice decline and its causes and consequences
Land Ice Velocity (derived products: velocity change, strain rate, discharge)	Sentinel-1 SAR L-C-X Band SAR	AIS margins, peripheral glaciers + ice shelves (north of 78.5°S); Oct 2014 - present	Monthly, annual, 6/12 days; 200 m (100 m)	Melting ice sheets and ice shelves and coastal impacts
(High resolution) Land Ice Velocity (derived products: velocity change, strain rate, discharge)	TerraSAR-X/TanDEM-X, CSK, ICEYE	AIS selected locations; 2007 - present	11 d; 50 m	Melting ice sheets and ice shelves and coastal impacts
Surface Melt Extent (derived products: melt onset, end, phase)	Metop ASCAT	2007-2021, AIS	Daily; 4.5 km	Melting ice sheets and ice shelves and coastal impacts
Surface Melt Extent	Sentinel-1 SAR L-C-X Band SAR	AIS margins + ice shelves (north of 78.5°S); Oct 2014 - present	6/12 days; 200 m (100 m planned)	Melting ice sheets and ice shelves and coastal impacts
Surface refreeze depth	L-C Band SAR	AIS margins + ice shelves (north of 78.5°S); Oct 2014 - present	6/12 days; 200 m	Melting ice sheets and ice shelves and coastal impacts Experimental product
Grounding Line Location (GLL)	Sentinel-1 SAR, L-C-X Band SAR	AIS north of 78.5°S		Melting ice sheets and ice shelves and coastal impacts
Ice shelf damage (fractures)	Sentinel-1 SAR	ice shelves (north of 78.5°S); Oct 2014 - present	6/12 days	Melting ice sheets and ice shelves and coastal impacts
Surface Elevation Change	Satellite Altimetry	AIS; 1992 - present	Monthly; 5 km	Melting ice sheets and ice shelves and coastal impacts
Surface Elevation Change	Satellite Altimetry	AIS; 2010 - present	Monthly; 2 km	Melting ice sheets and ice shelves and coastal impacts

Ice shelves basal melt rate	Satellite Altimetry / SAR / Optical	AIS; 2010 - present	Monthly; 2 km	Melting ice sheets and ice shelves and coastal impacts
Subglacial lake locations and activity	CS2 altimetry	AIS (2011 - 2021)		Melting ice sheets and ice shelves and coastal impacts
Subglacial water routing and outlet locations	Sentinel-1 SAR	Selected locations (2014 - present)	6/12 days	Melting ice sheets and ice shelves and coastal impacts
Calving Front Location (CFL)	Sentinel-1 SAR	ice shelves (north of 78.5°S); Oct 2014 - present	6/12 days; 200 m	Melting ice sheets and ice shelves and coastal impacts
Ice Sheet mass balance	GRACE/GRACE-FO	AIS, 2002-present	Monthly, >150 km Melting Ice Sheets and Ice Shelves and coastal impacts	Melting Ice Sheets and Ice Shelves and coastal impacts
Surface hydrology (meltwater lake extent)	SAR/optical	AIS, 2000-present	Sub-weekly; 10-30 m	Melting Ice Sheets and Ice Shelves and coastal impacts
Firm aquifer presence	SAR/radiometry	AIS, 2014-present	Sub-weekly; 1 km	Melting Ice Sheets and Ice Shelves and coastal impacts
Iceberg locations/iceberg drift (SCAT)	SCAT	1978 & 1992-present	daily	Melting Ice Sheets and Ice Shelves and coastal impacts
Iceberg locations/iceberg drift (SAR and optical)	SAR and optical	2013-present	weekly	Melting Ice Sheets and Ice Shelves and coastal impacts
Iceberg decay (area change)	SAR and optical	2024-present	weekly	Melting Ice Sheets and Ice Shelves and coastal impacts
Iceberg thickness	Altimetry	2020-present	irregular	Melting Ice Sheets and Ice Shelves and coastal impacts
Volume of ice, probability of presence of icebergs and mean iceberg area for smaller icebergs (ALTIBERG)	Altimetry	1991-present	monthly, 100 km grid	Melting Ice Sheets and Ice Shelves and coastal impacts
Mixed phase cloud classification and retrievals	Sentinel-3 SLSTR, PACE	2017- present; pan-Antarctic	Daily, 1 km	Aerosol-Cloud interaction
Mixed phase cloud classification and retrievals	EarthCARE, ICESat-2, Metop-SG and NOAA-PO			Aerosol-Cloud interaction

Aerosol Optical Depth	Sentinel-3 SLSTR, PACE	2017- present; Antarctic snow-covered areas	Daily, 1 km	Aerosol-Cloud interaction
Aerosol retrievals	EarthCARE, ICESat-2	pan-Antarctic		Aerosol-Cloud interaction
Precipitation	EarthCARE	2024-present; pan-Antarctic	500m, 25-day repeat cycle	Aerosol-Cloud interaction
Sea Surface Salinity	L-band radiometers, SMOS, SMAP	2010 - present; 2015 - present	Every 4 days 25 km Daily 25 km	Southern Ocean and Antarctic heat, freshwater, carbon
Sea level anomalies and geostrophic surface currents	Multi-mission altimetry	1993 - present	Daily ~80 km Improved with SWOT ~10 km	Southern Ocean and Antarctic heat, freshwater, carbon
Sea Surface Temperature	Infrared and microwave radiometers	1981 - present	Daily ~10km	Southern Ocean and Antarctic heat, freshwater, carbon
Ocean surface winds	SAR (Sentinel-1, RADARSAT), scatterometers (ASCAT, QuickSCAT)			Southern Ocean and Antarctic heat, freshwater, carbon
Phytoplankton pigments, inherent optical properties, K _d , PFT/PCC, R _{rs} , AOT, FCHL, phytoC, POC, PIC	Moderate resolution ocean colour radiometry (OCR): MODIS, Sentinel-3 (OLCI), PACE (OCI), VIIRS, EnMAP, S2 (MSI), LANDSAT	1997- present	1-16 days, 300 m (with lower temporal coverage ~30m)	Southern Ocean and Antarctic heat, freshwater, carbon pools, ecosystem functioning (biodiversity)

Annex B: EO-led Science Research Opportunities

In the context of the Antarctica InSync initiative, there are a number of scientific research opportunities that can be addressed through activities with Earth Observation at their core. These activities can be enacted through dedicated Working Groups. This is not intended to be an exhaustive list, but rather a starting point for future project development. As such, please find Points of Contact for each opportunity, who can be contacted for further information and discussion.

Science Theme: Southern Ocean and Antarctic heat, freshwater, carbon and other elements cycles and their response to climate change.

Quantify and monitor air-sea exchanges of heat and freshwater in the Southern Ocean, and understand their role in driving climate variability and change. Adapting methodologies from the ESA projects ARCTIC-FLOW and CCI-OSHF, by combining satellite Earth Observation (sea surface salinity, temperature and currents) with in situ measurements of mixed layer depth, and applying conservation principles to estimate surface fluxes in the upper ocean. Extending this framework to the Southern Ocean will allow us to monitor flux variability and its climate impacts, while close collaboration with in-situ networks and modelling teams will improve accuracy, enable robust validation, and enhance predictive skill. [Estrella Olmedo, olmedo@icm.csic.es]

Determine how the Southern Ocean's three dimensional upper-ocean circulation regulates the transfer of heat and carbon in the open ocean and close to the marginal ice zone and how these exchanges shape regional climate sensitivity. We will estimate vertical velocities, heat and carbon budgets in the Southern Ocean from satellite altimetry, including SWOT high-resolution SSH observations, and integrate these fields with targeted in-situ records from Argo and dedicated observational campaigns. These derived quantities will be combined with dynamical modelling to close heat and carbon budgets and isolate the mechanisms controlling vertical exchange [Elisa Carli, elisa.carli@esa.int]

Evaluate the impacts of the extent, seasonality and dynamics of recurring coastal and open-ocean polynyas on Southern Ocean overturning and biogeochemical cycles. We will use high-resolution satellite Earth Observation (e.g. SAR, passive microwave, optical/IR and sea-ice products) to monitor polynya extent, opening/closing rates and associated surface fluxes. We will combine these with in situ observations (moorings, floats, gliders) and ocean, sea-ice, biogeochemical models. This integrated framework will quantify polynya-driven dense-water formation and its downstream effects. [Giuseppe Aulicino, giuseppe.aulicino@uniparthenope.it]

Quantify the role of mesoscale eddies associated with different Antarctic Circumpolar Current (ACC) fronts in redistributing heat, freshwater and carbon in the Southern Ocean and assess their impacts. We will characterise eddy properties by combining eddy detection from satellite altimetry with information on their vertical structure from in situ observations (e.g. Argo profiles). Eddies will be classified by ACC front of origin and their spatial and temporal variability will be analysed. This analysis will identify seasonal cycles in eddy properties and evaluate the extent to which they are influenced by recent changes in sea-ice regime and salinity, as well as by large-scale climate drivers such as ozone depletion. [Antonino Ian Ferola, antoninoian.ferola@esa.int]

Science Theme: Rapid sea-ice decline and its causes and consequences.

What is the relative contribution made by dynamical processes (advection, deformation, divergence, etc) to sea-ice variability over a wide range of spatial and temporal scales? Robust EO sea-ice drift fields are required to quantify these processes, ultimately yielding input data for sea-ice mass budgets, ice transport, air-ice-ocean (AIO) flux estimates, data assimilation for sea-ice thickness using divergence information, snow-depth retrievals. Ice motion data is necessary to interpret extreme sea-ice extent decline/variability observed in the Southern ocean due to the unconstrained dynamics associated with the Southern Ocean environment. Delivering these requires continuous, holistic tracking of sea-ice motion and deformation from formation to melt. Strengthening the two-way link between EO products and in-situ observations is essential: e.g. buoy trajectories test retrieval accuracy, while EO-derived motion histories guide the design and interpretation of in-situ sampling by informing on sample history. A key scientific need is to reduce the substantial uncertainty in Southern Hemisphere motion retrievals relative to the Arctic. Optimizing swath-to-swath use of passive-microwave and SAR measurements and merging multiple EO sources to recover long, coherent sea-ice trajectories are ways to improve our understanding of sea-ice motion contributions to aforementioned processes, notably across multiple scales (global, regional from PMW) and mesoscale, individual floes from SAR). Maximizing SAR coverage and overlap would aid resolving deformation and maintaining trajectory continuity across the ice pack and marginal ice zone where ice heterogeneity is difficult to resolve in PMW. [Thomas Lavergne, thomasl@met.no, and Wayne de Jager, wayne.dejager@uct.ac.za]

What is the impact of the recently observed drop in Antarctic sea ice extent on the sea ice mass balance and freshwater fluxes? To address this, it is crucial to provide and maintain a near-real-time dataset that integrates information on sea ice thickness and snow depth, as well as the volume and mass of snow and sea ice, through the synergistic use of multiple satellite missions, building on ESA SO-SIMBA. Such a system would also enable the calculation of sea-ice volume fluxes across key gateways, providing direct constraints on freshwater export and its influence on ocean circulation. Eventually, we can provide pan-Antarctic, uncertainty-quantified EO reference records to benchmark models and complement/upscale InSync's circumpolar observing strategy. It needs to be highlighted that there is a strong mutual link between EO-derived sea-ice thickness and snow datasets and in-situ and airborne observations: EO products identify spatial and temporal anomalies of interest for coordinated investigation, while in-situ measurements provide essential validation and process understanding that, in turn, our EO retrievals. [Robert Ricker et al., rori@norceresearch.no]

How are recent Antarctic sea-ice anomalies linked to changes in the age and type of the sea-ice cover, and what does this imply for sea-ice resilience and its response to atmospheric and oceanic forcing?

This requires consistent and long-term datasets that capture how Antarctic sea ice transitions between first-year and older ice, and how these shifts relate to its physical state, mechanical strength, and susceptibility to rapid retreat events. Mapping of sea-ice age/type classes in the Antarctic remains immature, and methodologies developed for the Arctic must be adapted to Antarctic conditions, building on capabilities developed in ESA SAGE. To address this science priority, multi-frequency passive microwave and scatterometer observations should be used to produce pan-Antarctic climate data records of sea-ice age/type. Here, EO-derived sea-ice drift data (see above) will support tracking of ice persistence and type transitions. Because age/type retrievals depend on tracking of individual ice parcels, it is crucial that EO observations and derived products provide full spatial and temporal coverage; gaps lead to abrupt tracking interruptions and reduced accuracy. Variations in age and drift influence energy balance, ecosystem habitats, and the occurrence of extreme breakup or retreat events, and are relevant to several InSync themes, including “rapid sea-ice decline” and “ocean heat, freshwater, ... cycles”, and “Antarctic life...”. Validation through GPS-tracked ice buoys and in situ measurements of sea-ice physical properties, thickness, and snow, as well as model-data integration, will be key to improving the accuracy of satellite-derived sea-ice age. [Signe Aaboe et al., signeaa@met.no]

What is the response of phytoplankton productivity to interannual and longer-term changes of sea ice extent? A significant interannual variability of sea ice extent around the Antarctic continent is revealed by satellite observations, with an unusual large drop post-2015. An impact of these changes on phytoplankton productivity in the vicinity of the ice edge or at larger scale in the Southern Ocean is expected. However, the reasons for this possible connection between sea ice melt and phytoplankton growth remain to be elucidated and the potential impact quantified (e.g., micronutrient release, rapid change in underwater light availability and spectral quality, changing mixing conditions). Whether this impact is limited to transient ice-edge blooms forming when sea ice melts or extends further north away from the sea ice margin is also unclear. EO data can help address these questions by providing the required long-term observations of most parameters into play (phytoplankton, SST, ice cover, wind, SLA, irradiance). Boosting the acquisition of relevant field data is an important role that InSync can play, when these data can complement satellite observations or help to make them more accurate or better suited to addressing these questions (e.g., improving atmospheric correction in the vicinity of ice, better disentangling the effect of phytoplankton and other particles and dissolved substances on the remote-sensing reflectance). [David Antoine, david.antoine@curtin.edu.au]

How has sea ice decline impacted phytoplankton spring bloom dynamics in the marginal ice zone of the Southern Ocean? The marginal ice zone (MIZ) and open waters along the south-eastern Scotia Arc encompass some of the most productive areas in the Southern Ocean. Despite its potential significance for krill stocks and the biological carbon pump, this area and season is largely under-sampled, and phytoplankton blooms remain underestimated by satellites. This is because the maximum biomass develops at depths in the water column below satellites can sense their influence on the backscattered sunlight. Due to global warming, the importance of melting ice as a potential trace metal carrier will increase and the MIZ, which acts as critical growth habitat for krill larvae, will not extend as far north in the future. This poses a potential threat to the productivity in this region which is driven by phytoplankton community composition and growth. An intense field program within InSync, including bio-optical automated sampling together with many more biological, chemical and physical measurements during late winter to spring, can serve to assess the development of spring blooms in the highly productive MIZ and adjacent open ocean along the South Scotia Ridge. The study will fill a critical knowledge gap on the magnitude and timing of carbon uptake and export in a region and at a time where almost no measurements exist. The combination of satellite observations with the InSync-

coordinated ship-based survey and process studies will provide an unprecedented process understanding of sea ice melting on primary productivity and phytoplankton community composition which impacts ecosystem functioning, biogeochemical cycles, and broader climate feedback. The EO data will help to upscale the process to other MIZ regions within the Southern Ocean and assess the interannual variability [Astrid Bracher, astrid.bracher@awi.de].

Science Theme: Melting ice sheets and ice shelves and coastal impacts

Identify the processes controlling ocean ice melting of the Antarctic ice sheet:

How is ocean, sea-ice and wind variability driving melting of Antarctic ice shelves? How do local conditions and processes (e.g. at grounding zone, channels, shear zones, pinning points, ice-ocean boundary regime) modulate ocean melting? E.g. Sea-ice variability vs wind as drivers of undercurrent supplying CDW to ice shelves cavities, leading to melting?

How does variability in basal melt impact ice sheet stability? How does freshwater input impact coastal ocean processes? How to best parametrize basal melt in projection of future ice sheet contribution to sea level change?

Addressing these questions requires a combination of synchronised observation of sub-shelf basal melting (from EO from ice elevation and ice velocity, in-situ ApRES and integrated oceanographic melt), and of sea ice, ocean and atmospheric conditions across the Antarctic climate system.

This activity requires accurate basal melt determination, but currently there are disagreements between methods based on EO, in-situ (on-ice or oceanographic). This calls for a dedicated synchronized experiment associating EO, in-situ (on ice and oceanographic), modelling groups, with a target to improve the accuracy of basal melt and to explore the sources of differences, whether related to physical processes or to uncertainty. In the frame of Insync, ice shelf(ves) “supersites” could be established, the choice of which should be both driven by feasibility, in particular from in-situ and oceanographic perspectives, and likely processes driving melt. See also RECOIL, 2025 - <https://doi.org/10.5281/zenodo.17469856>.

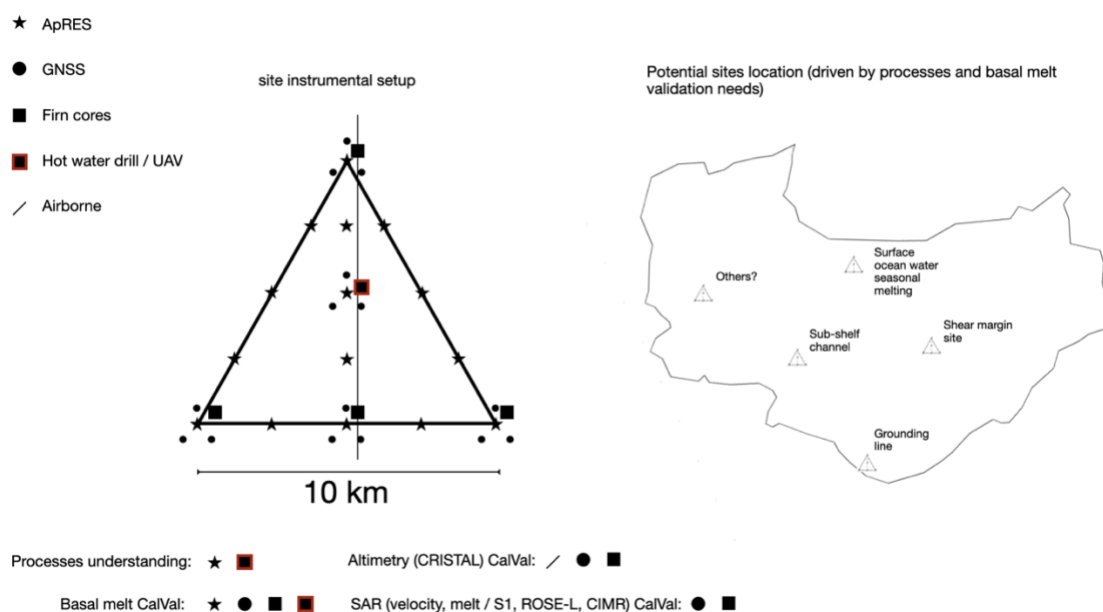


Figure 1: Suggested field setup for validation and calibration of EO-derived basal melting at various key ice shelves locations, and validation and calibration of individual satellite measurements entering into the basal melt mass conservation approach. ApRES and GNSS would require continuous, multi-year, acquisition. [Noel Gourmelen, noel.gourmelen@ed.ac.uk]

Quantifying the impact of fast ice buttressing on ice shelves calving rates: Investigating the role of landfast sea ice on ice shelves' calving rates and land ice buttressing capacity is critical to fully assess the stability of Antarctica's ice shelves. This requires the extensive use of EO datasets to monitor calving rates from satellite imagery, ice shelf and fast ice thickness from satellite altimetry, and ice velocity of the grounded ice upstream, but also in-situ measurements to improve these EO retrievals especially at the sea ice/land ice boundary. Finally, these observational datasets can be used in an ice sheet numerical model to formally quantify the impact of fast ice variability on ice dynamics and further our understanding of how changes in fast ice will impact future rates of sea level rise. [Inès Otosaka, ines.otosaka@northumbria.ac.uk]

Detecting atmospheric rivers to improve ice sheet mass balance estimates: The past few years have been marked with strong variability in snowfall in Antarctica, masking the ongoing dynamic mass loss signal and modulating Antarctica's contribution to sea level rise. This also presents a challenge for EO estimates of ice sheet mass balance with radar and laser altimeters sensing snow differently and gravimetry estimates not being able to resolve ice and snow mass changes separately, leading to large differences between geodetic estimates in regions with strong snowfall variability. To overcome this, there is a need to develop a new EO capability for detecting atmospheric rivers that bring large amounts of snow to the continent using satellite altimetry data as well as improve our current satellite elevation retrievals using airborne radar/laser surveys and in-situ measurements of snow properties. [Inès Otosaka, ines.otosaka@northumbria.ac.uk]

The impact of meltwater on ice dynamics, ice shelf stability and primary productivity: How does meltwater move on, within, and beneath the AIS, and why does this freshwater matter for ice flow, sea level rise, and ocean ecosystems? To understand how basal- and surface meltwater is routed, how it interacts with the bed and overlying ice, what the influence is of bed properties, and how its release into the ocean affects ice shelf stability and marine life, a tight coupling between EO observations, in-situ measurements and modelling is essential. EO provides large-scale, time-resolved views of meltwater routing, ice dynamics, and ocean response, but in-situ observations (e.g. ApRES, GPR) and close collaboration with modellers are necessary for process understanding and improved prediction of changes in this part of the freshwater cycle. [Jelte van Oostveen, jeoo@norceresearch.no]

Constraining ice shelf evolution and ice mass loss on the Antarctic Peninsula: The Antarctic Peninsula (AP) has experienced substantial warming during the 20th century, with many of its fringing ice shelves having retreated or collapsed. The climate and geometric configuration of this region makes it vulnerable to future atmospheric and oceanic warming, yet the abundance of relatively small, marine-based glaciers, often situated within complex topographic settings, and subject to multiple different environmental forcing mechanisms, presents a challenge to scientific understanding; both in terms quantifying of the magnitude of ice mass loss from the Antarctic Peninsula, and better constraining the processes that will drive future change in this region. Discoveries such as the presence of widespread seasonal ice speed variability on the peninsula has shown that new modes of ice dynamic variability still require detection and characterisation. Antarctica InSync has the potential to make significant progress against this challenge, through a coordinated set of synchronous EO and in situ activities, aimed at delivering a comprehensive EO dataset detailing the magnitude and drivers of AP mass loss, spanning ice, ocean, and atmosphere. It is anticipated that this would be achieved through a 2-stage approach. The first objective would be to use existing and new EO approaches to optimise monitoring of a set of key AP variables (e.g. AP mass loss, ice shelf basal melt, surface mass balance, basal hydrology, ice discharge etc) for individual glaciers, including the exploitation of altimetry, velocity, Digital Elevation Model, and interferometry data; and complementing this with new in situ observations from InSync campaigns to calibrate and validate these approaches within the challenging AP setting. The second objective would be to scale these EO approaches to develop a new InSync pan-AP baseline dataset that would serve to underpin future activities, with a particular focus initially on preparations

ahead of IPY5. More broadly, this would establish a monitoring framework ready to track and diagnose the response of the AP to the significant environmental changes that are expected to occur over the coming decades. During the scale up phase, observations from other InSync in situ campaigns around the Peninsula would be utilised to test and complement the new EO datasets, to provide the most comprehensive snapshot of the AP's state, to date. The work has links to Theme 2 Rapid Sea Ice Decline. [Mal McMillan, m.mcmillan@lancaster.ac.uk]

Characterising the rate of ice sheet mass loss and the processes driving it: Mass loss from the Antarctic Ice Sheet contributes to present day sea level change, with accelerating ice discharge from the ice sheet offset in part by snowfall into the ice sheet. Satellite observations have shown that the rate of ice sheet mass loss is changing over time, as do the relative importance of the physical processes driving it which vary with region. Ice dynamic change through ice discharge has accelerated since the 1990's and is particularly pronounced in West Antarctica and on the Antarctic Peninsula. In East Antarctica surface mass processes dominate, and extreme snowfall from atmospheric rivers has become increasingly important in recent years. [Anna Hogg, a.e.hogg@leeds.ac.uk]

Supraglacial Lake Volume: Current EO products focus primarily on supraglacial lake occurrence and area, whereas lake volume governs hydrostatic loading, hydrofracture likelihood, and chain-reaction drainage events. Optical approaches can substantially underestimate lake depth and volume, potentially biasing assessments of meltwater-driven ice-shelf vulnerability. ICESat-2 provides an important calibration pathway for lake bathymetry along ground tracks, but upscaling of the ground-track measurement to lake-wide bathymetry, as well as to lakes not covered by ICESat-2, requires robust cross-calibration with optical sensors (e.g., Sentinel-2, Landsat) and improved uncertainty quantification. To enable this, targeted field measurements are required, including:

- Direct lake bathymetry measurements (e.g., sonar or pressure sensors in representative lakes)
- Coincident spectral reflectance measurements in relevant optical bands
- Water-level monitoring to capture temporal evolution
- Measurements of supraglacial stream discharge and meltwater flux into lakes
- UAV or airborne photogrammetry/laser scanning to resolve fine-scale lake geometry

Including such measurements at InSync supersites would enable the development of calibrated, continent-wide supraglacial lake volume products, directly supporting assessments of hydrofracture risk and freshwater routing. [Bert Wouters, bert.wouters@tudelft.nl]

Firn Microstructure and Firn Air Content: Firn air content and grain size control meltwater buffering capacity and thus determine whether excess meltwater is retained, refreezes, or ponds at the surface. These processes directly influence hydrofracture susceptibility and long-term ice-shelf stability. Active and passive microwave observations provide the only feasible continent-scale monitoring tool for firn microstructure. However, retrievals depend critically on assumptions about surface roughness and the partitioning between surface and volume scattering.

Field measurements needed to support operational EO retrievals include:

- Firn cores to quantify density/grain size profiles and quantify air content
- Repeat measurements of microwave-scale surface roughness (e.g., terrestrial laser scanning or close-range photogrammetry)
- Ground-based multi-frequency microwave observations to characterise scattering behaviour

Seasonal and multi-year repeat observations are essential to capture temporal evolution driven by snowfall, wind redistribution (sastrugi), melt events, and refreezing. Such measurements are critical to reducing ambiguity in satellite-based firn retrievals and to enabling continent-wide monitoring of firn vulnerability. [Bert Wouters, bert.wouters@tudelft.nl]

Surface Melt Rates: Satellite observations are highly sensitive to the presence of liquid water but much less sensitive to melt intensity or total melt volume. Wet snow can persist after melt events, making it

difficult to distinguish newly generated melt from stored or refrozen water. Yet melt rates - rather than melt occurrence alone govern firn air depletion, meltwater production, and freshwater export to the ocean. Improved melt-rate estimation requires multi-frequency synergy across passive microwave radiometers and active C-, L-, and P-band radar/scatterometer observations, ideally integrated with firn and surface energy-balance models.

Field measurements required to support this development include:

- Automatic Weather Stations (AWS) providing full surface energy-balance components
- Direct melt measurements and ablation stakes
- Repeated vertical profiles of liquid water content in the upper firn
- Multi-frequency ground-based microwave measurements to monitor sensor sensitivity through melt-storage-refreezing cycles
- Snow temperature profiles and thermal conductivity measurements

These datasets are essential to calibrate satellite retrievals, disentangle melt intensity from melt presence, and constrain model-observation integration. Including surface melt rates as a dedicated EO research priority would strengthen the linkage between atmospheric forcing, firn evolution, and ice-shelf stability. [Bert Wouters, bert.wouters@tudelft.nl]

Science Theme: Aerosol-cloud interactions and radiative feedbacks.

Cloud properties, in particular their phase and the abundance of aerosols, are practically not observed in Antarctica from satellites: The atmosphere plays an important role in the surface mass balance of the Antarctic ice sheet through precipitation and evaporation processes. The atmosphere-sea ice fluxes of heat and moisture, together with large scale dynamics can drive sea ice extent. Applying novel methods developed and refined for the Arctic shall be applied to Antarctica as well. These involve aerosol retrievals using the SLSTR/AATSR instrument over relatively fresh snow, i.e., a regime that cannot yet be evaluated from satellites in terms of aerosols. Furthermore, we identify mixed-phase clouds using SLSTR. The approaches need to be adapted, tested, or validated for Antarctica. The resulting data sets can support the planned InSync campaigns on synoptic or larger scales and, for the first time, reveal spatial Antarctic patterns that go far beyond the scales of previous measurements. In a further step, R_{TOA} measurements (not retrieved but purely measured) by space-based instrumentation are used to perform statistical analyses on a pan-Antarctic scale. [Marco Vountas, vountas@iup.physik.uni-bremen.de]

Science Theme: Climate variability: from extremes, to weather, long-term variability, and global teleconnections.

Understand impacts of climate change and variability, across ice sheets, sea ice, ocean, atmosphere and ecosystems. Consolidate and extend EO record across all domains to investigate trends, extremes and feedback mechanisms. For example, EO data plays a crucial role in monitoring the evolution of the Antarctic Circumpolar Current (ACC) and changes in sea ice extent and concentration. Long-term datasets have identified significant shifts, such as the regime change in sea ice extent observed around 2015-2016, with the minimum extent now consistently being reached almost every year. This shift underscores the importance of continuous monitoring to better understand the feedback loops between ocean dynamics, sea ice changes, and climate variability. EO data supports improved prediction of extreme events and seasonal outlooks by linking historic (satellite era) sea-ice age distributions to susceptibility to rapid retreat, anomalous break-up, or record-high/low extent. Older, mechanically stronger ice behaves differently under extreme forcing than young ice. Age-based metrics help quantify how past states influence future behaviour (e.g., forecast skill derived from “memory” in the ice cover).

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