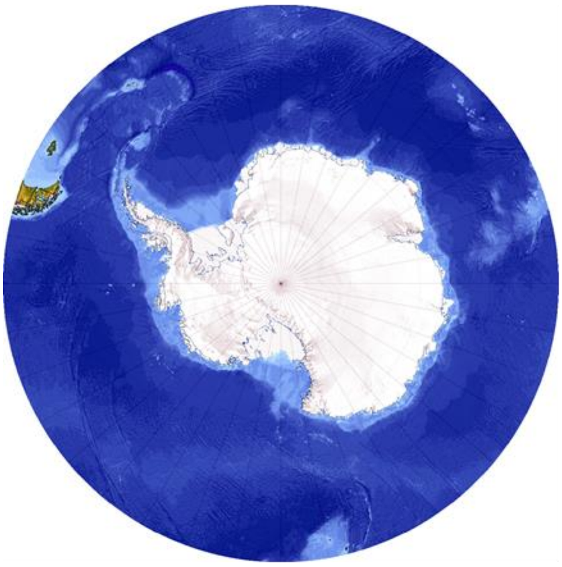
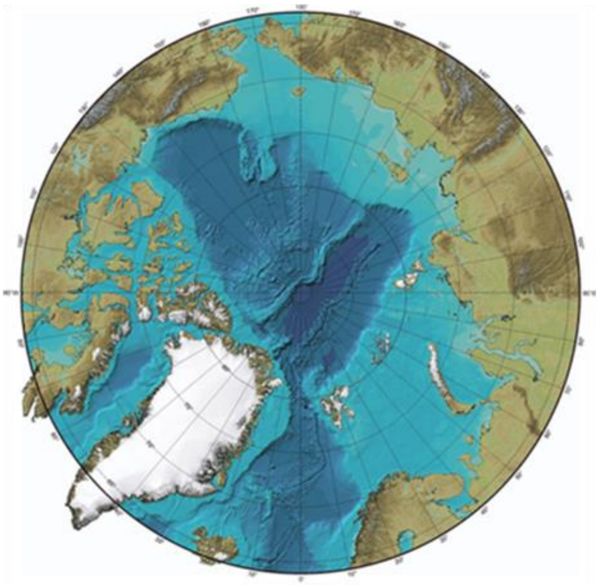
Renewal Proposal 2025-2030

Infrastructure Priority Program of the German Research Foundation
(DFG SPP 1158)

"Antarctic Research with Comparative Investigations in Glaciated Areas of the Arctic"





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DFG-SCHWERPUNKTPROGRAMM 1158
ANTARKTIS
FORSCHUNG
mit vergleichenden Untersuchungen in arktischen Eisgebieten

March 2023

4 Scientific Progress Report

The current SPP concept focused on four overarching research topics:

A) *“Dynamics of Climate System Components”*
B) *“Response to Environmental Change”*
C) *“Linkages with Lower Latitudes”*
D) *“Improved Understanding of Polar Processes and Mechanisms”*

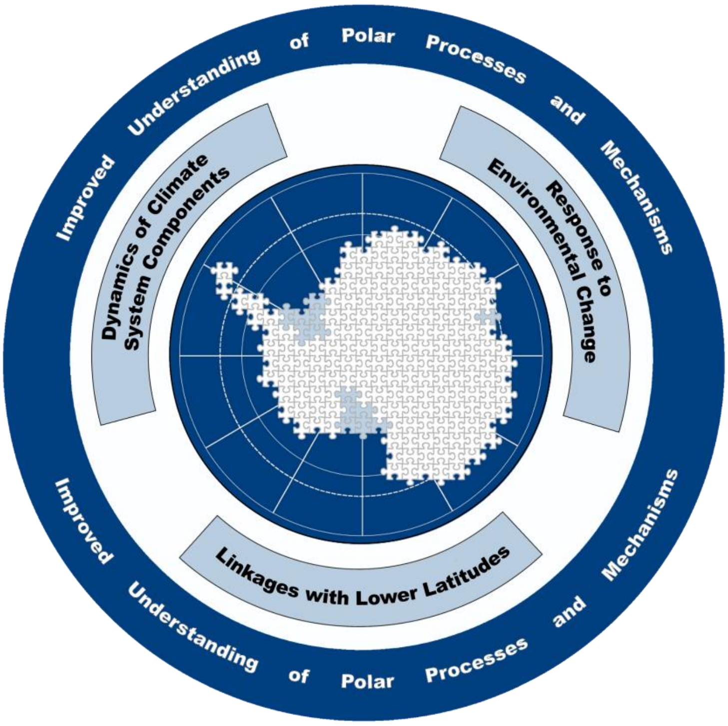


Fig. 4.1: Overarching interdisciplinary research topics for the current SPP phase 2019-2024 concerning the role of Antarctica in the Earth System.

This structure was very successful in the current SPP phase and each topic received applications from all relevant disciplines, biology, chemistry, physics and geology. Notably, some research topics received fewer applications than others. Although the main scientific focus of the SPP is Antarctica and the Southern Ocean, comparative studies between the Antarctic and the Arctic region are eligible and have also been funded. This includes, for example, bipolar distributed biota and their genetic and physiological traits to cope with global change.

During the next SPP phase, we propose to focus the research by strengthening two of the most successful transdisciplinary research topics from the current SPP phase (“Dynamics of Climate System Components”, “Response to Environmental Change”) along with the cross-cutting research topic “Improved Understanding of Polar Processes and Mechanisms” (**Fig. 3.1**). The overarching topic “Linkages with Lower Latitudes” will be replaced by “Connectivity and Exchange in Polar Systems” (see 3. **Concept Renewal Proposal 2025-2030**).

This conceptual structure of the current SPP phase focused on the most urgent issues in Antarctic sciences and resulted again in coordinated interdisciplinary research within the priority research program.

The four research topics were and still are of utmost importance for a better understanding of the role of Antarctica and the Southern Ocean in the Earth System. Their scope is very broad, and thus deserves further scientific attention in the upcoming SPP phase. Yet, we also saw excellent research results that made significant contributions and in some cases comprehensively answered long standing scientific questions. These ones are exemplarily outlined below.

Within the scope of the four major research topics, we defined key research priorities and > 50 key questions based on the input of the international research community concerned with Antarctic research and policy. The main research goals of the current SPP phase were aligned with the results of the SCAR Antarctic and Southern Ocean Science Horizon Scan, which outlined 80 key questions in all fields of Antarctic research for the next decade on an international scale (Kennicutt & Chown 2015, Antarctic Science 27), as well as the research questions identified by the German National SCAR committee. The research priorities within biological sciences and geosciences were fine-tuned based on an international review article in Frontiers in Marine Sciences (Xavier et al. 2016, Frontiers in Marine Science 3) and a publication of the working group "Geology and Geophysics of the Polar Regions" of the "German Society of Polar Research" (Melles et al. 2015, Polarforschung 85). This firmly placed the current SPP phase in the center of the top research priorities identified by the international scientific community, while taking advantage of the established strong German expertise in Antarctic research. Based on the success of previous SPP phases, we continued funding comparative studies of Antarctica and Arctic regions. Most of the German polar research is focused on the Atlantic sector of Antarctica and the Arctic, the main shipping routes of “Polarstern” as reflected in a review of the atmosphere and ocean research in the SPP in the previous phase had been published in Ocean Dynamics (***Hellmer et al., 2016***):

Hellmer H, Rhein M, Heinemann G, Abalichin J, Abouchami W, Baars O, Cubasch U, Dethloff K, Ebner L, Fahrbach E, Frank M, Gollan G, Greatbatch RJ, Grieger J, Gryanik VM, Gryschka M, Hauck J, Hoppema M, Huhn O, Kanzow T, Koch B, König-Langlo G, Langematz U, Leckebusch GC, Lüpkes C, Paul S, Rinke A, Rost B, van der Loeff MR, Schröder M, Seckmeyer G, Stichel T, Strass V, Timmermann R, Trimborn S, Ulbrich U, Venchiarutti C, Wacker U, Willmes S & Wolf-Gladrow D (2016) Meteorology and oceanography of the Atlantic sector of the Southern Ocean—a review of German achievements from the last decade. Ocean Dynamics 66: 1379-1413.

Given the same cruise track trajectories of RV Polarstern in the coming years, we anticipate a similar geographic focus in the next SPP phase (with a strong emphasis on Antarctic research), although fieldwork in other sectors of both polar regions will of course be possible.

The SPP also addresses research questions related to the geological evolution of the Antarctic continent since the time (~34 Ma) when the Antarctic Ice Sheet developed. Hereby, geological processes and structures that provide a boundary condition or feedback to the evolution of the ice-sheets should be addressed.

Widely used Key Performance Indicators to measure the success of DFG priority programs are the quality and quantity of peer-reviewed scientific publications as well as the number of B.Sc., M.Sc. and PhD thesis obtained by this funding source. For the current SPP reporting we reflect upon scientific progress achieved between Jan 2017 and Dec 2022. All peer-reviewed publications all qualification theses are summarized in **Attachments II to IV**.

Peer-reviewed publications 2017 until 2022

Physics/Chemistry	80
Biology	147
Geosciences	51
Total	278

Qualification theses 2017 until 2022

Physics/Chemistry	13 B.Sc.	10 M.Sc.	3 PhD
Biology	20 B.Sc.	28 M.Sc.	10 PhD
Geosciences	14 B.Sc.	8 M.Sc.	4 PhD
Total	47 B.Sc.	46 M.Sc.	17 PhD

Compared to other DFG funded SPPs, the scientific output of the SPP Antarctic Research with 278 peer-reviewed papers between 2017 and 2022 (c. 3 million € per year) can be rated as excellent. While the smaller SPP Earthshape (https://esdynamics.geo.uni-tuebingen.de/earthshape/) (c. 2.15 million € per year) published between 2017 and 2022 in total 68 peer-reviewed publications, the large infrastructure SPP Biodiversity Exploratories (https://www.biodiversity-exploratories.de/de/veroeffentlichungen/publikationen/) (c. 6.977 million € per year) between 2017 and 2022 in total 281 peer-reviewed papers.

Dr. Stefanie Arndt (AWI), who received SPP-funding for her first Postdoc and a follow-up project, got a highly prestigious DFG Emmy Noether proposal awarded. The Emmy Noether Program gives exceptionally qualified early career researchers the chance to qualify for the post of professor at a university by leading an independent junior research group for a period of six years. Dr. Arndt currently negotiates with the University of Hamburg as host institution.

Since not all scientific results from the current SPP phase can be acknowledged in this scientific progress report, we focus on some highlights in the following four chapters. In each chapter we present at least one example from Biology, Physics/Chemistry and Geosciences.

4.1 Overarching Research Topic - *Dynamics of Climate System Components*

The Earth climate system, and particularly that of Antarctica, is not in steady state, as observations and model results clearly show. The dynamics of the Antarctic climate system shapes Antarctica's unique ecosystems, revealing spatial and temporal variability on different scales (seasonal, annual, decadal to millennial). So far it is not fully understood, which of these variabilities are induced by natural or anthropogenic changes and how they influence the present and future Antarctic climate and the polar ecosystems.

In the frame of the current SPP phase, the focus was on improvement and development of new detection methodologies and tools. New possibilities emerged, for example, as new satellite data became available. Changes in oceanic and atmospheric properties were analyzed by taking into account new data sources, such as ocean drifters, gliders, ground-based and satellite-based remote sensing units. Analysis of the data obtained from these sources required support from numerical modelling, while the observations were needed for the verification of numerical models. Regional climate models for Antarctica or global climate models with a focus on Southern High Latitudes are useful tools for understanding and assessment of trends and variabilities for the past and for future scenarios.

Key Results from the current SPP Phase

Recent low summer sea ice extent in the Weddell Sea raises questions about the contributions of dynamic and thermodynamic atmospheric and oceanic energy fluxes. The roles of snow, superimposed ice, and snow ice are particularly intriguing, as they are sensitive indicators of changes in atmospheric forcing and as they could trigger snow–albedo feedbacks that could accelerate ice melt. To address this question ***Arndt et al. (2021)*** investigated snow depth data and ice core observations of superimposed ice and snow ice collected in the northwestern Weddell Sea in late austral summer 2019, supplemented by airborne ice thickness measurements. Texture, salinity, and oxygen isotope analyses showed mean thicknesses of superimposed and snow ice of 0.11 ± 0.11 and 0.22 ± 0.22 m, respectively, or 3 % to 54 % of total ice thickness. Mean snow depths ranged between 0.46 ± 0.29 m in the south to 0.05 ± 0.06 m in the north, with mean and modal total ice thicknesses of 4.12 ± 1.87 to 1.62 ± 1.05 m and 3.9 to 0.9 m, respectively. These snow and ice properties are similar to results from previous studies in 1980s and 1990s, suggesting that the ice’s summer surface energy balance and related seasonal transition of snow properties have changed little in past decades. This is supported by additional analyses of ***Arndt et al. (2021)*** on the summer energy balance using atmospheric reanalysis data and by melt onset observations from satellite scatterometry, all showing few recent changes (**Fig. 4.2**). These results support other studies showing that the low sea ice coverage in the northwestern Weddell Sea in February 2019 must have been the consequence of dynamic or oceanic processes rather than of thermodynamic atmospheric effects, i.e., of advection by winds and currents and increased ocean heat rather than of increased air temperatures, turbulent fluxes, or longwave radiation.

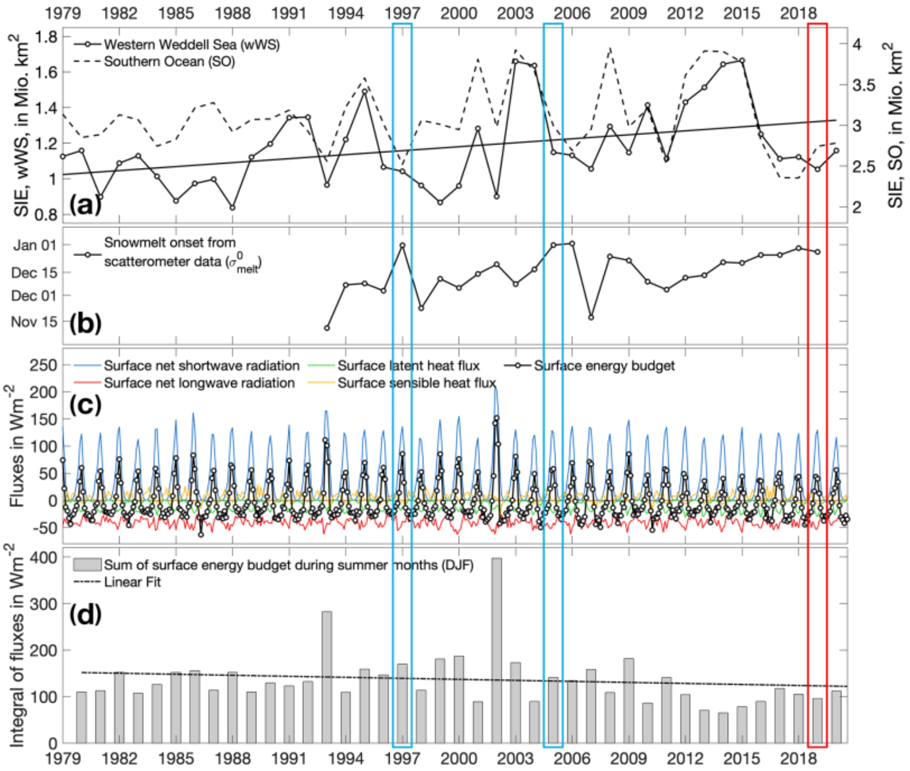


Fig. 4.2: Time series of ice extent, melt onset, and surface energy balance in the northwestern Weddell Sea (Sect. 2.4). (a) Sea ice extent (SIE) in the western Weddell Sea west of 30◦ W (wWS, solid line), and in the whole Southern Ocean (SO, dashed line), for February 1979–2020. Line shows linear fit to Weddell Sea data with a slope of +7000 km2 yr−1. (b) Snowmelt onset north of 69◦ S from scatterometer data.(c) Surface energy budget north of 69◦ S (black line) and its individual components (colored lines). (d) Annual total summer surface energy budget (sum from December to February). The dashed line shows the linear fit with a slope of −0.7 Wm−2 yr−1. The red box highlights the year of the WedIce expedition, 2019; blue boxes show years of field observations in 1997 and 2004/05 (ISPOL). Note that the year markers on the x axis represent 1 January of the respective year.

In a follow-up study ***Arndt (2022)*** investigated physical snowpack properties. The sensitivity of sea ice to the contrasting seasonal and perennial snow properties in the southeastern and northwestern Weddell Sea is not yet considered in sea ice model and satellite remote sensing applications. However, the analysis of physical snowpack properties in late summer in recent years reveals a high fraction of melt-freeze forms resulting in significant higher snow densities in the northwestern than in the eastern Weddell Sea. The resulting lower thermal conductivity of the snowpack, which is only half of what has been previously assumed in models in the eastern Weddell Sea, reduces the sea ice bottom growth by 18 cm during winter. In the northwest, however, the potentially formed snow ice thickness of 22 cm at the snow/ice interface contributes to additional 7 cm of thermodynamic ice growth at the bottom. The sensitivity study of ***Arndt (2022)*** emphasizes the enormous impact of unappreciated regional differences in snowpack properties on the thermodynamic ice growth.

Arndt S, Haas C, Meyer H, Peeken I, Krumpen T (2021) Recent observations of superimposed ice and snow ice on sea ice in the northwestern Weddell Sea. The Cryosphere 15, https://doi.org/10.5194/tc-15-4165-2021

Arndt S (2022) Sensitivity of sea ice growth to snow properties in opposing regions of the Weddell Sea in late summer. Geophysical Research Letters 49; https://doi.org/10.1029/2022GL099653

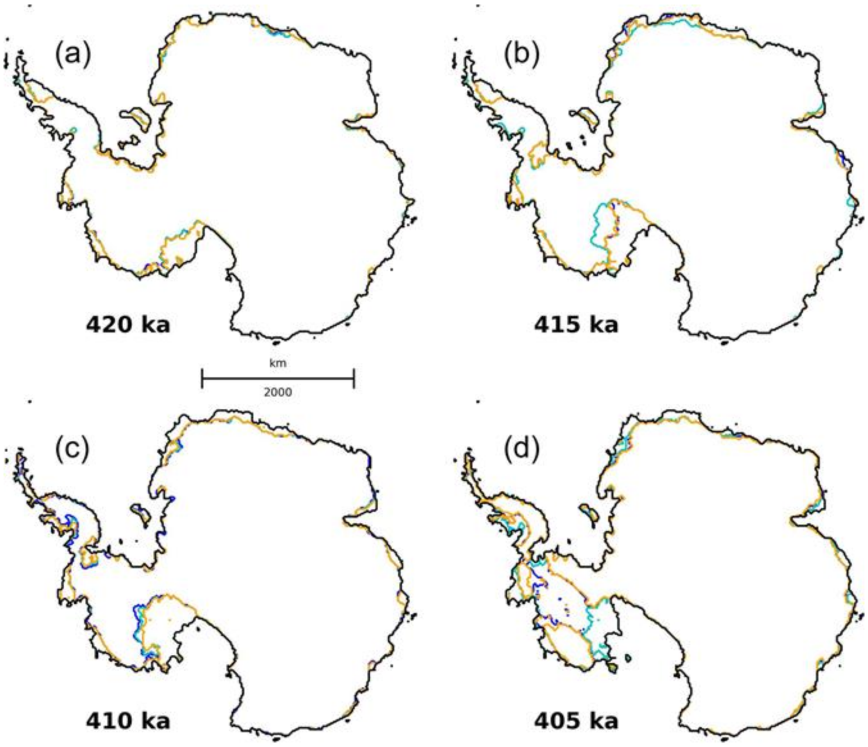


Fig. 4.3: Grounding lines of the Antarctic Ice Sheet during MIS 11c at 420, 415, 410, and 405 ka for different climate forcing scenarios (indicated by different line colors) as simulated by Mas e Braga et al. (2021).

Studying the response of the ice sheets during past periods of Earth history when climate conditions were similar to or warmer than the present can provide important insights into current observed changes and helps to identify natural drivers of ice sheet retreat. For this purpose, the marine isotope stage 11c (MIS 11c) about 425-395 ka ago offers a suitable scenario. For this interglacial a global sea level highstand of 6-13 m above the present-day level has been reconstructed. ***Mas e Braga et al. (2021)*** studied the response of the Antarctic ice sheets and their contribution to sea level rise for this period using a numerical model approach (**Fig. 4.3**). Their results indicate that the East and West Antarctic ice sheets contributed 4.0-8.2 m to the MIS 11c sea level rise. In the case of a West Antarctic Ice Sheet collapse, which is the most probable scenario according to far-field sea level reconstructions, the range is reduced to 6.7-8.2 m. The authors further found that the warmer regional climate signal captured by Antarctic ice cores during peak MIS 11c is crucial to reproduce the contribution expected from Antarctica during the recorded global sea level highstand. This climate signal translates to a modest threshold of 0.4 K oceanic warming at intermediate depths, which leads to a collapse of the West Antarctic Ice Sheet if sustained for at least 4,000 years.

Mas e Braga M, Bernales J, Prange M, Stroeven AP & Rogozhina I (2021) Sensitivity of the Antarctic ice sheets to the warming of marine isotope substage 11c, The Cryosphere, 15, 459–478, https://doi.org/10.5194/tc-15-459-2021

4.2 Overarching Research Topic - *Response to Environmental Change*

The detection and quantification of environmental changes in Antarctica under the present-day (i.e. known or measurable) boundary conditions are essential for predicting the changes to be expected in the future.

For the detection of changes in Antarctic biology, sites needed to be revisited and investigated with comparable, standardized methodologies. New techniques such as remote operating vehicles (ROVs) and permanent sea-floor observatories opened new opportunities. To compare the present environmental changes with changes in Earth history, geologists and glaciologists further developed geological and glaciological proxies for the settings in the past, and improved existing transfer functions for the quantification of environmental and climatic variables.

Polar regions are unique and highly prolific ecosystems characterized by extreme environmental gradients. Organisms in marine and terrestrial high latitudes are exposed to low temperatures, complete darkness in winter and continuous light and relatively high UV radiation during summer. Phototrophic and heterotrophic organisms adapt to strong environmental gradients and scarcity of key nutrients to maintain growth, reproduction, defense and metabolic activity despite abiotic conditions that would otherwise shut-down cellular processes in most temperate organisms. Understanding the molecular mechanisms of adaptation in Antarctic organisms is a prerequisite for assessing their vulnerability and resilience under climate change scenarios. In addition, polar communities and ecosystems have large inputs into global biogeochemical cycles. While knowledge on physiological and biochemical processes to cope with environmental extremes has emerged over the last decade, the genomic basis of adaptation in Antarctica and Southern Ocean organisms is still an open question. This was also the main conclusion of the SPP Topic Workshop in Bielefeld (16th till 18th of May 2022) on "Polar Genomics", which finally resulted in an invitation by Nature Communications for a perspective paper in 2023 tentatively entitled “Benchmarking polar biodiversity: Genomics approaches to predict the fate of polar ecosystems in a warming world”. Ecosystem resilience and adaptation are also poorly studied in Antarctica and Southern Ocean, which, however, is methodologically difficult to investigate because of its complexity.

In addition to modern observations, paleo-reconstructions of environmental conditions add to the understanding of current climatic variables and the response of Antarctic ecosystems to changing scenarios. The development and validation of environmental proxies, for example with regard to sea ice, temperature and biogeochemical cycles, from sedimentary records (e.g., from lipid biomarkers, isotopic compositions and (micro)paleontological observations) allows for assessing rates of changes beyond the observational period and under climate conditions different from present-day.

Key Results from the current SPP Phase

A scientifically important and interdisciplinary framework was recently developed and provided by ***Gutt et al. (2022)*** to observe, understand, and project ecosystem response to environmental change in the East Antarctic Southern Ocean (**Fig. 4.4**). The authors originate from the fields of biology, chemistry and physics, and they report that systematic long-term studies on ecosystem dynamics are largely lacking for the East Antarctic Southern Ocean, although it is well recognized that such investigations are indispensable to identify the ecological impacts and risks of environmental change. Consequently they developed a framework for establishing a long-term cross-disciplinary study and argued why the eastern Weddell Sea and the easterly adjacent sea off Dronning Maud Land is a well suited area for such an initiative. As in the Eastern Antarctic in general, climate and environmental change have so far been comparatively muted in this area. A systematic long-term study of its environmental and ecological state can thus provide a baseline of the current situation, an assessment of future changes, and sound data can act as a model to develop and calibrate projections. Only systematic long-term studies in so far less affected regions of Antarctica would allow the investigation of climate-driven ecosystem changes in ocean dynamics, biogeochemistry, biodiversity and ecosystem functions and services and their interactions with impacts arising from other anthropogenic activities, from their very onset. This approach would provide a level of long-term data availability and ecosystem understanding that are imperative to determine, understand, and project the consequences of climate change and support a sound science-informed management of future conservation efforts in the Southern Ocean.

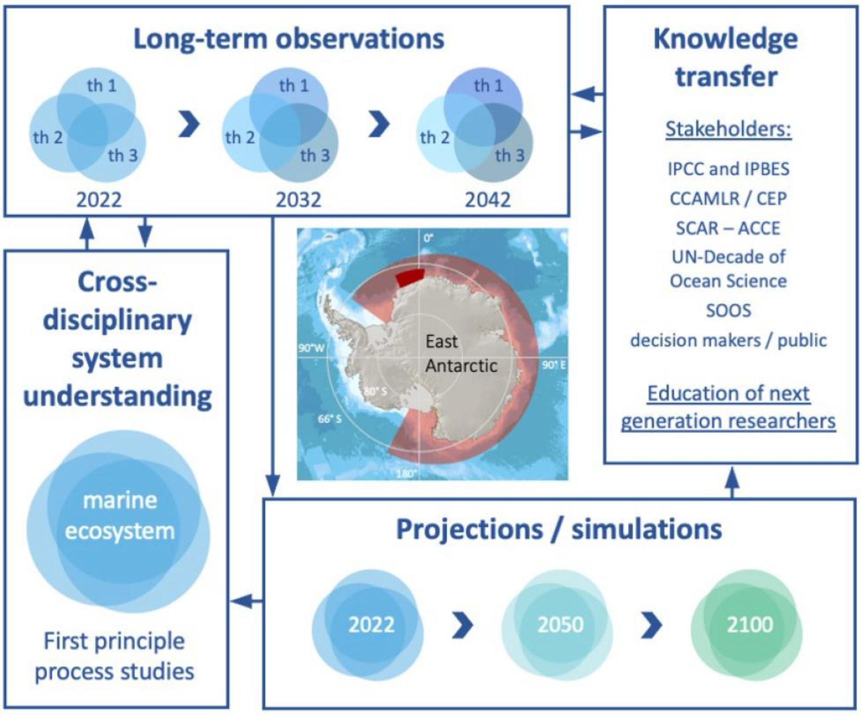


Fig. 4.4: Relationships between approaches, objectives and potential stakeholders of the proposed systematic long-term studies on ecosystem dynamics. The dark red rectangle in the map in the center indicates the proposed study region. th = Ecological research theme.

This paper also well documents the tight scientific collaboration of SPP members with other colleagues of other nations and with SCAR.

***Gutt J**, Arndt S, Barnes DK, Bornemann H, Brey T, Eisen O, Flores H, Griffiths H, Haas C, Hain S, Hattermann T, Held C, Hoppema M, Isla E, Janout M, Le Bohec C, Link H, Mark FC, Moreau S, Trimborn S, van Opzeeland I, Pörtner H-O, Schaafsma F, Teschke K, Tippenhauer S, Van de Putte A, Wege M, Zitterbart D, Piepenburg D (2022) Reviews and syntheses: A framework to observe,* *understand, and project ecosystem response to environmental change in the East Antarctic Southern Ocean. Biogeosciences Discussions, doi.org/10.5194/bg-2022-110*

In a mammalian project, ***Herr et al. (2022a,b)*** reported the return of huge aggregations of southern fin whales (*Balaenoptera physalus quoyi*) to the animals’ historical feeding grounds in Antarctica after a decades-long absence. Industrial whaling in the 20th century drove the southern fin whale population close to extinction. By the time fin-whale catches were banned in 1976, researchers were rarely sighting the animals around the Antarctic Peninsula, a former hotspot. ***Herr et al. (2022a,b)*** dedicated surveys confirmed their return to ancestral feeding grounds (**Fig. 4.5**), gathering at the Antarctic Peninsula in large aggregations (**Fig. 4.6**) to feed as documented by first ever video documentation. The authors interpreted high densities, re-establishment of historical behaviors and the return to ancestral feeding grounds as signs for a recovering population. Recovery of a large whale population has the potential to augment primary productivity at their feeding grounds through the effects of nutrient recycling, known as 'the whale pump'. A recovering fin whale population may lead to an increase of Southern Ocean productivity through enhancing iron levels in the surface layer. By stimulating primary production, whales act as a carbon sink in the Southern Ocean. This is of particular relevance, since the Southern Ocean is a major component of the coupled ocean–atmosphere climate system, crucial for atmospheric carbon regulation and the most important ocean region for the uptake of anthropogenic CO_2.

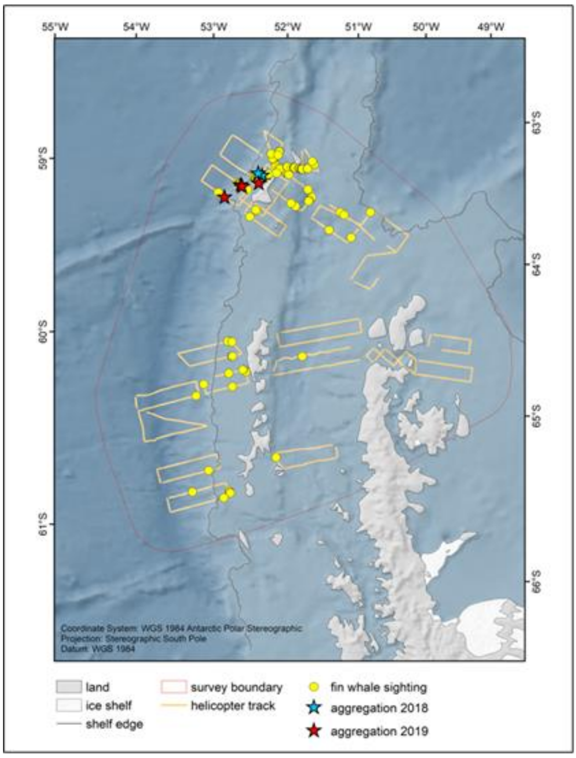


Fig. 4.5: Survey effort and fin whale sightings. Representation of transect lines covered by the aerial survey during RV Polarstern expedition PS112. Fin whale sightings recorded on-effort during the aerial survey are indicated as yellow dots. Positions of fin whale aggregations (stars) comprise sightings collected during both expeditions.

Fig. 4.6: Fin whale feeding aggregation at a distance. The horizon is covered by blows of a feeding aggregation numbering approximately 150 fin whales.

***Herr H**, Viquerat S, Devas F, Lees A, Wells L, Gregory B, Giffords T, Beecham D, Meyer B (2022a) Return of large fin whale feeding aggregations to historical whaling grounds in the Southern Ocean. Scientific Reports, https://doi.org/10.1038/s41598-022-13798-7*

***Herr H**, Hickmott L, Viquerat S, Panigada S (2022b) First evidence for fin whale migration into the Pacific from Antarctic feeding grounds at Elephant Island. Royal Science Open Science, doi.org/10.1098/rsos.220721*

Many regions of Antarctica are classified as high nutrient low chlorophyll (HNLC) areas. Here, iron availability is limiting primary productivity and subsequent carbon export. Which iron ligands facilitate primary production in Antarctic waters is enigmatic to date. ***Geuer et al (2020)*** approached this topic with on board incubation experiments on RV Polarstern. Domoic acid (DA) has previously been detected in the Southern Ocean and suggested to act as a ligand that facilitates iron assimilation in the diatom *Pseudo-nitzschia* spp., a prominent bloom forming Antarctic species. An incubation experiment using the non-toxic species *Pseudo-nitzschia subcurvata* was performed in Antarctic seawater at low and high iron concentrations. Dissolved DA was added to one set of each of the two treatments. This was done to verify whether DA positively affected the growth of *P. subcurvata* and increased its cellular iron content, particularly under low iron conditions. ***Geuer et al (2020)*** hypothesized that (i) DA is taken up under low iron conditions (ii) that more iron is taken up if DA is available and (iii) that the growth rate increases in the presence of DA. ***Geuer et al (2020)*** showed that *P. subcurvata* did not take up any added DA, even under low iron conditions. Additionally and contrary to their hypothesis, the cells were not positively influenced by the addition of dissolved DA in terms of growth rate, cellular iron and carbon content (Table 3). Hence, there was no significant difference in iron content between the different treatments. Their study suggests that dissolved DA in naturally occurring concentrations does not increase bioavailability of iron to *P. subcurvata* and that only species producing DA might benefit from it. While being a first discrete step in this direction, this study confirms the great need for further research into the nature, abundance and ecological role of iron binding ligands which promote algal blooms and carbon export in Antarctic waters.

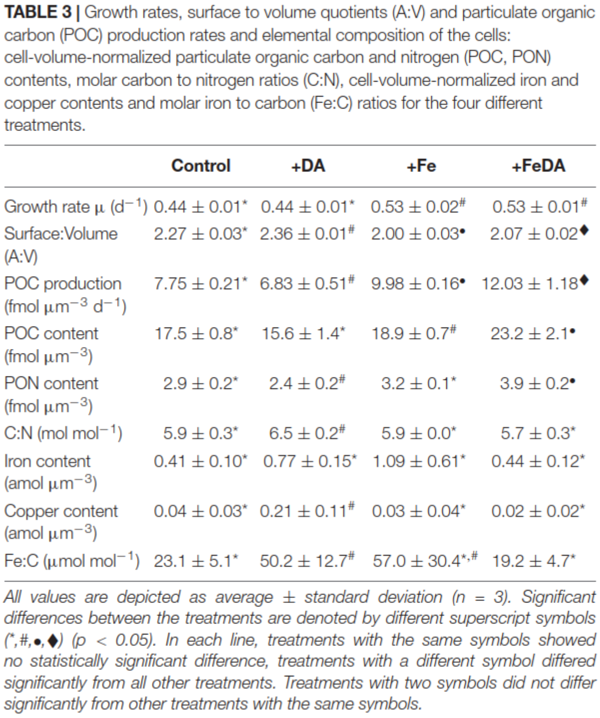


TABLE 3 | Growth rates, surface to volume quotients (A:V) and particulate organic carbon (POC) production rates and elemental composition of the cells: cell-volume-normalized particulate organic carbon and nitrogen (POC, PON) contents, molar carbon to nitrogen ratios (C:N), cell-volume-normalized iron and copper contents and molar iron to carbon (Fe:C) ratios for the four different treatments.

	Control	**+DA**	**+Fe**	**+FeDA**
Growth rate μ (d^{-1})	$0.44 \pm 0.01^{*}$	$0.44 \pm 0.01^{*}$	$0.53 \pm 0.02^{\#}$	$0.53 \pm 0.01^{\#}$
Surface:Volume (A:V)	$2.27 \pm 0.03^{*}$	$2.36 \pm 0.01^{\#}$	$2.00 \pm 0.03^{\bullet}$	$2.07 \pm 0.02^{\blacklozenge}$
POC production (fmol μm^{-3} d^{-1})	$7.75 \pm 0.21^{*}$	$6.83 \pm 0.51^{\#}$	$9.98 \pm 0.16^{\bullet}$	$12.03 \pm 1.18^{\blacklozenge}$
POC content (fmol μm^{-3})	$17.5 \pm 0.8^{*}$	$15.6 \pm 1.4^{*}$	$18.9 \pm 0.7^{\#}$	$23.2 \pm 2.1^{\bullet}$
PON content (fmol μm^{-3})	$2.9 \pm 0.2^{*}$	$2.4 \pm 0.2^{\#}$	$3.2 \pm 0.1^{*}$	$3.9 \pm 0.2^{\bullet}$
C:N (mol mol^{-1})	$5.9 \pm 0.3^{*}$	$6.5 \pm 0.2^{\#}$	$5.9 \pm 0.0^{*}$	$5.7 \pm 0.3^{*}$
Iron content (amol μm^{-3})	$0.41 \pm 0.10^{*}$	$0.77 \pm 0.15^{*}$	$1.09 \pm 0.61^{*}$	$0.44 \pm 0.12^{*}$
Copper content (amol μm^{-3})	$0.04 \pm 0.03^{*}$	$0.21 \pm 0.11^{\#}$	$0.03 \pm 0.04^{*}$	$0.02 \pm 0.02^{*}$
Fe:C (μmol mol^{-1})	$23.1 \pm 5.1^{*}$	$50.2 \pm 12.7^{\#}$	$57.0 \pm 30.4^{*,\#}$	$19.2 \pm 4.7^{*}$

All values are depicted as average ± standard deviation ($n = 3$). Significant differences between the treatments are denoted by different superscript symbols (,#,●,◆) ($p < 0.05$). In each line, treatments with the same symbols showed no statistically significant difference, treatments with a different symbol differed significantly from all other treatments. Treatments with two symbols did not differ significantly from other treatments with the same symbols.*

***Geuer JK**, Trimborn S, Koch F, Brenneis T, Krock B, Koch B (2020) Dissolved Domoic Acid Does Not Improve Growth Rates and Iron Content in Iron-Stressed Pseudo-Nitzschia subcurvata. Frontiers in Marine Science; https://doi.org/10.3389/fmars.2020.00478*

Stomach oil deposits of snow petrels can be used as geological paleoclimate archives. Sea ice affects the marine ecosystem in the coastal zone of the Southern Ocean, but also influences climate-relevant physical/chemical processes, such as the exchange of gas and heat between ocean and atmosphere, biogeochemical cycling, water mass formation and ocean circulation. Three consecutive projects investigate/ed a novel geological archive for sea-ice and environmental reconstructions in the coastal Southern Ocean - fossil stomach oil deposits of snow petrels (*Pagodroma nivea*), also called "Antarctic mumiyo" (**Fig. 4.7**, ***Berg et al. 2019, 2023 (in review), McClymont et al. 2022***).

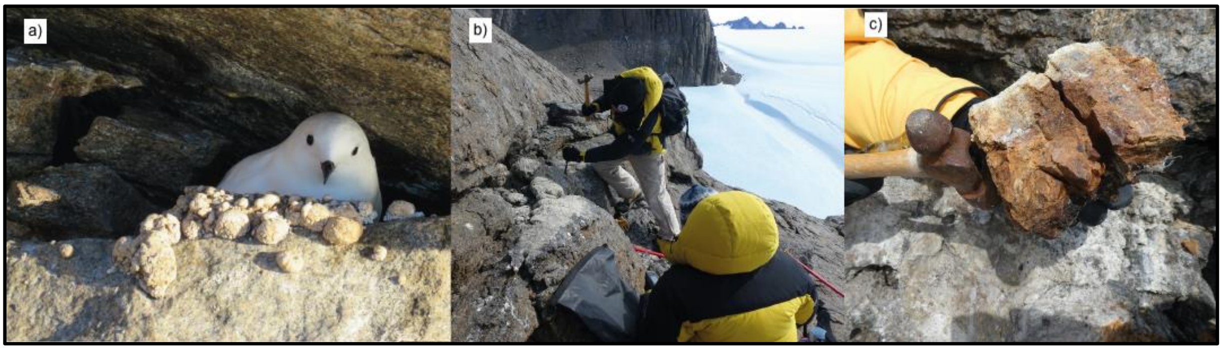


Fig. 4.7: a) Snow petrel (*Pagodroma nivea*) in nesting cavity. Globular encrustations in front of the bird are from regurgitated stomach oil. b) and c) Ornithologists from the Australian Antarctic Division are sampling stomach oil deposits (Photos by Tanja Fromm, Marcus Salton and Anna Lashko). The stomach oil deposits can be as thick as several decimeters.

The organic-rich deposits form from regurgitated, dietary stomach oil at snow petrel nesting sites on land (**Fig. 4.7**). Radiocarbon dating of mumiyo from various sites in East Antarctica showed that the stratigraphic range of single deposits can comprise several thousand years (***Berg et al. 2019***). The hitherto oldest stomach oil deposits have been reported from central Dronning Maud Land, indicating the presence of breeding snow petrels for more than 55 ka (***Berg et al. 2019***). A detailed reconstruction of changes in snow petrel diet over time was obtained on a deposit from central Dronning Maud Land that covers the time interval from 30.3 to 24.3 ka, highlighting the presence of open water (polynyas) within the more extensive summer sea-ice cover during MIS 2 (***McClymont et al. 2022***). These results add to a growing body of evidence which shows that polynyas were likely important drivers of sea ice–climate feedbacks during glacial stages (***McClymont et al. 2022***).

To progress the concept of inferring past environmental conditions from the diet of snow petrels, modern observations were combined with paleo-data obtained on fossil stomach oil deposits (***Berg et al. 2023***). Based on lipid biomarker and stable isotope data from modern and fossil stomach oil ***Berg et al. (2023)*** suggest that the composition of snow petrel diet can be derived from fossil deposits in a paleo-ecological sense, by distinguishing on-shore and off-shore prey assemblages. Future mumiyo-based reconstructions will now allow for characterizing the paleo-ecological diet and to investigate regional and long-term variability of snow petrel foraging strategies.

These interdisciplinary projects provide a basis to improve the understanding of ecosystem response to changing climate conditions, and to provide information on regional sea-ice and climate histories in coastal East Antarctica.

__Berg S__, Emmerson L, Heim C, Buchta E, Fromm T, Glaser B, Hermichen W-D, Rethemeyer J, Southwell C, Wand U, Zech M, Melles M (2023) Reconstructing the paleo-ecological diet of snow petrels (Pagodroma nivea) from modern samples and fossil deposits - implications for Southern Ocean paleoenvironmental reconstructions. JGR Biogeosciences (under review)

McClymont E, Bentley M J, Hodgson D A, Spencer-Jones C L, Wardley T, West M D, Croudace I W, __Berg S__, Gröcke DR, Kuhn G, Jamieson SSR, Sime L, Phillips RA (2022). Summer sea-ice variability on the Antarctic margin during the last glacial period reconstructed from snow petrel (Pagodroma nivea) stomach-oil deposits. Climate of the Past doi.org/10.5194/cp-18-381-2022

__Berg S__, Melles M, Hermichen W-D, McClymont E L, Bentley M J, Hodgson D A, Kuhn G (2019). Evaluation of mumiyo deposits from East Antarctica as archives for the Late Quaternary environmental and climatic history. Geochemistry, Geophysics, Geosystems doi.org/10.1029/2018GC008054

4.3 Overarching Research Topic - *Linkages with Lower Latitudes*

The atmospheric and oceanic circulation separates the Antarctic continent from the rest of the Earth system. However, several linkages allow the transport of chemical substances, particles and heat, as well as organisms in and out of the Antarctic continent, the surrounding Southern Ocean, and the overlying Southern atmosphere. In this context, geological processes that enhance or reduce such linkages must also be considered in order to understand fundamental Earth system processes, driving forces and interconnections, in present times as well as during the major climate changes in the past. The interlinked influences of the physical, chemical, geological and biological parameters on the climate system need to be better understood to allow improved predictions of future climate scenarios.

Key Results from the current SPP Phase

Rapid Transport Mechanisms and Invasions

Due to its long cold-water history and extreme environmental conditions, Antarctica and the Southern Ocean are home for many endemic species in marine and terrestrial habitats. Antarctic communities are currently challenged not only by increasing temperature and ocean acidification, but also by invading biota from temperate regions. The introductions of new taxa into Antarctica are likely related to geological cycles of ice sheet and oceanic front movement and to short-term natural dispersal such as rafting and hitch-hiking on migrants. In recent years, anthropogenic influences led to increased introductions, both, directly by transporting organisms (e.g. fouling organisms on tourist vessels) and indirectly as a consequence of climate change. Rising water temperature around the Antarctic Peninsula provide better habitat conditions for less cold-adapted biota. Changing climate in Antarctica also leads to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events as well as to changes in atmospheric circulation patterns.

Laeseke et al. (2020, 2021) investigated the ecology and invasive potential of macroalgae (**Tab 4.2**). These seaweeds are highly important ecosystem engineers and provide invaluable ecosystem services to coastal marine habitats throughout all ecoregions. Antarctica, the “final frontier for marine biological invasions”, is highly isolated latitudinally from other continental masses by natural physical barriers, such as the Antarctic Polar Front (APF) and the Antarctic Circumpolar Current (ACC), and has the harshest climatic conditions on Earth. Therefore, non-native species have to cross a major biogeographic barrier across a large latitudinal range and face highly contrasting environmental conditions on either side of this barrier. These factors have led to a high level of endemism in Antarctica, and the APF has been perceived as an almost impenetrable protective barrier against invasions into Antarctic ecosystems. However, in recent decades, the continent's isolation has decreased as shipborne activities, scientific research, and the amount of long-lasting floating litter reaching Antarctica have increased. In addition, natural rafts like the kelps *Durvillaea antarctica* and *Macrocystis pyrifera* frequently reach Antarctica and offer the possibility for attached species to hitchhike to Antarctica. Simultaneously, global warming is leading to higher suitability of Antarctic habitats for non-native species, and the reduction of the impact of ice and ice-scouring along the coasts will increase substrate availability to intertidal species such as seaweeds.

Laeseke et al. (2021) applied correlative Ecological Niche Models (ENMs) to identify invaders and invasion sites in Antarctica (**Fig. 4.8**). They reconstructed pre- and post-introduction niches for numerous introduced seaweed species, calculated relative niche sizes and overlap between pre-Antarctic and Antarctic sites, and evaluated increase in niche size due to inclusion of Antarctic habitats. In seven species, the absolute occupied temperature range was strongly enlarged, with minimum sea surface temperature (SST) being 2-5°C lower than in the pre-Antarctic ranges. In all species except one, summer SST was 5-20°C lower than in the pre-Antarctic ranges. As a result, several species' niches increased massively (**Fig. 4.9**). The authors highlighted that non-native Antarctic species likely originated from climatically non-matching and distant habitats, and that shifts in realized niches might be common during introductions to Antarctica. In addition, Southern Hemisphere seaweeds in particular, and perhaps other intertidal organisms, in the Southern Hemisphere exhibit non-equilibrium distributions and might be "invaders in waiting". ***Laeseke et al. (2021)*** argued that from a precautionary standpoint, not only seaweeds from climatically matching regions pose an invasion threat for Antarctica, but that also species from other, climatically non-matching regions, might be potential invaders. In light of higher connectivity of the Antarctic continent with other continents these results significantly increases invasion risk for Antarctica.

Tab. 4.2: Pre-Antarctic distributions of the newly recorded Antarctic seaweeds with northern & southern latitudinal limits and number of global records from www.gbif.org and literature used for analyses. Categories based on distribution (Category I = cosmopolitan or amphiequatorial, category II = Pacific coast of North America, category III = Southern Hemisphere).

Species (Phylum – Order – Genus)	Category	Pre-Antarctic distribution	Pre-Antarctic northern limit [°]	Pre-Antarctic southern limit [°]	Number of global records	Reference
Blidingia minima (Chlorophyta – Ulvales – Blidingia)	I	Cosmopolitan or amphiequatorial	76.96	-54.04	752	Gallardo et al. (1999), Wiencke and Clayton (2002)
Monostroma grevillei (Chlorophyta – Ulotrichales – Monostroma)	I	Cosmopolitan or amphiequatorial	70.38	- 40.58	502	Pellizzari et al. (2017)
Petalonia fascia (Phaeophyta – Ectocarpales – Petalonia)	I	Cosmopolitan or amphiequatorial	74.71	-54.54	1074	Clayton et al. (1997), Pellizzari et al. (2017)
Ulva compressa (Chlorophyta – Ulvales – Ulva)	I	Cosmopolitan or amphiequatorial	70.37	-51.54	1004	Clayton et al. (1997), Pellizzari et al. (2017)
Ulva intestinalis (Chlorophyta – Ulvales – Ulva)	I	Cosmopolitan or amphiequatorial	71.29	-55.21	2383	Clayton et al. (1997), Pellizzari et al. (2017)
Callophyllis pinnata (Rhodophyta – Gigartinales – Callophyllis)	II	Pacific coast of North America	60	30.43	81	Yoneshigue-Valentin et al. (2013)
Asteronema ferruginea (Phaeophyta – Scytothamnales – Asteronema)	III	Southern Australia, Tasmania, Argentina, Macquarie Island	-37.17	-54.61	16	Pellizzari et al. (2017)
Cladodonta lyallii (Rhodophyta – Ceramiales – Cladodonta)	III	South America, Subantarctic Islands	-42.36	-55.53	25	Pellizzari et al. (2017)
Dictyota decumbens (Phaeophyta – Dictyotales – Dictyota)	III	Macquarie Island	-54.62	-54.62	(*)	Pellizzari et al. (2017)
Microzonia velutina (Phaeophyta – Syringodermatales – Microzonia)	III	New Zealand, Subantarctic Islands, Argentina	-34.13	-54.79	45	Pellizzari et al. (2017)
Rhizoclonium ambiguum (Chlorophyta – Cladophorales – Rhizoclonium)	III	South America, Subantarctic Islands	-3.6	-54.77	26	Pellizzari et al. (2017)
Rhodophyllis centrocarpa (Rhodophyta – Gigartinales – Rhodophyllis)	III	New Zealand, South America	-35.25	-54.76	38	Pellizzari et al. (2017)

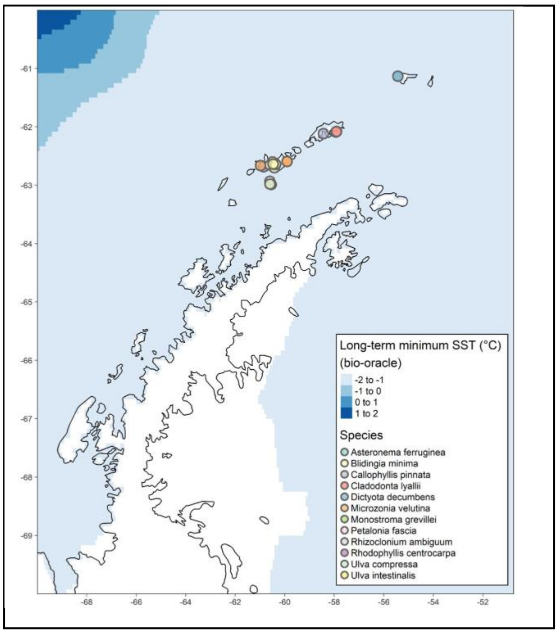


Fig. 4.8: Locations where the novel species were reported at the South Shetland Islands (references in **Tab. 4.2**) and long-term minimum sea surface temperature from bio-oracle v2.0 (Assis et al. 2020).

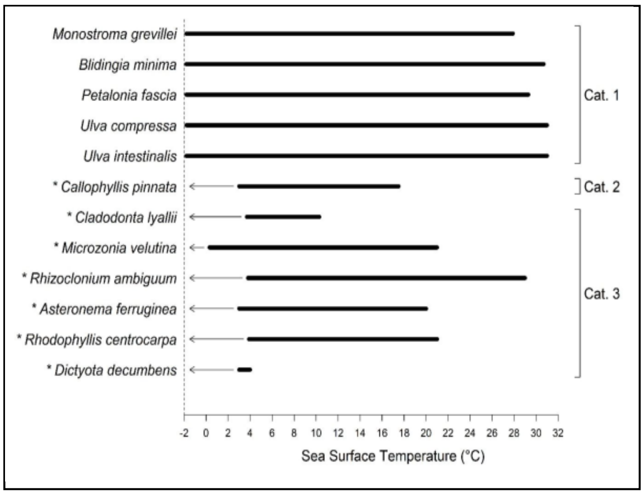


Fig. 4.9. Absolute pre-Antarctic SST ranges (black lines) as sampled from bio-Oracle v2.0 layers with all available distributional data from www.gbif.org and the literature. Minimum sea surface temperature at the Antarctic sites is c. -1.9°C (y-axis, dashed). Species with range extensions are marked with an asterisk and arrows indicate shift of the minimum SST. Categories based on native latitudinal distribution as in **Tab. 4.2** (Category I = cosmopolitan or amphiequatorial; Category II = endemic to Pacific coast of North America; Category III = distributed only in the Southern Hemisphere).

Laeseke P*, Martínez B, Mansilla A, Bischof K (2021) Invaders in waiting? – Non-equilibrium in Southern Hemisphere seaweed distributions may lead to underestimation of Antarctic Invasion Potential. Frontiers of Biogeography, https://doi.org/10.21425/F5FBG50879*

Laeseke P*, Martínez B, Mansilla A, Bischof K (2020) Future range dynamics of the red alga Capreolia implexa in native and invaded regions: contrasting predictions from species distribution models versus physiological knowledge. Biological Invasions DOI 10.1007/s10530-019-02186-4*

The sub-Antarctic, and with it the remote island South Georgia, is very sensitive to Southern Hemisphere climate variability due to its geographical position between the fronts of the Antarctic Circumpolar Current and within the core of the Southern Westerlies’ wind belt (**Fig. 4.10a**). Climate change induced latitudinal shifts of these oceanographic and atmospheric systems affect this region and its ice caps presumably stronger and faster than the more isolated continent of Antarctica. South Georgia Island is a remote fragment of South American continental crust, rich in wildlife, far away from continental influence, and features an extensive continental shelf with glacially incised trough systems that trap sediments and therefore, inter alia, archive glacier advances, current variability and biological activity (**Fig. 4.10b**). This makes the island an important target to study Southern Hemisphere climate since at least the Last Glacial Maximum (LGM). However, the ice cap extent during the LGM is still not fully resolved, lacking dated evidence from the marine realm, even though numerous studies suggested that it reached the continental shelf edge (***Graham et al., 2017***; ***White et al., 2017***). This would not only have impacted trough evolution, sedimentation and shelf currents, but also the distribution of biota and the availability of biological refugia during the last glacial. ***Lešić et al. (2022)*** investigated the Drygalski Fjord system, a coupled fjord-trough system in the southeast of South Georgia on the continental shelf (**Fig. 4.10b**). They studied the respective submarine geomorphology based on bathymetric data, as well as the trough evolution since the LGM with sub-bottom profiler data and dated glacimarine sediments from the outer Drygalski Trough. Introducing the first continuous marine record

(PS199_5-1, **Fig. 4.10b,c**) from the LGM to modern environmental conditions, they found ice-marginal sediments (Dmst, **Fig. 4.10c**) from the last glacial on the mid-continental shelf,

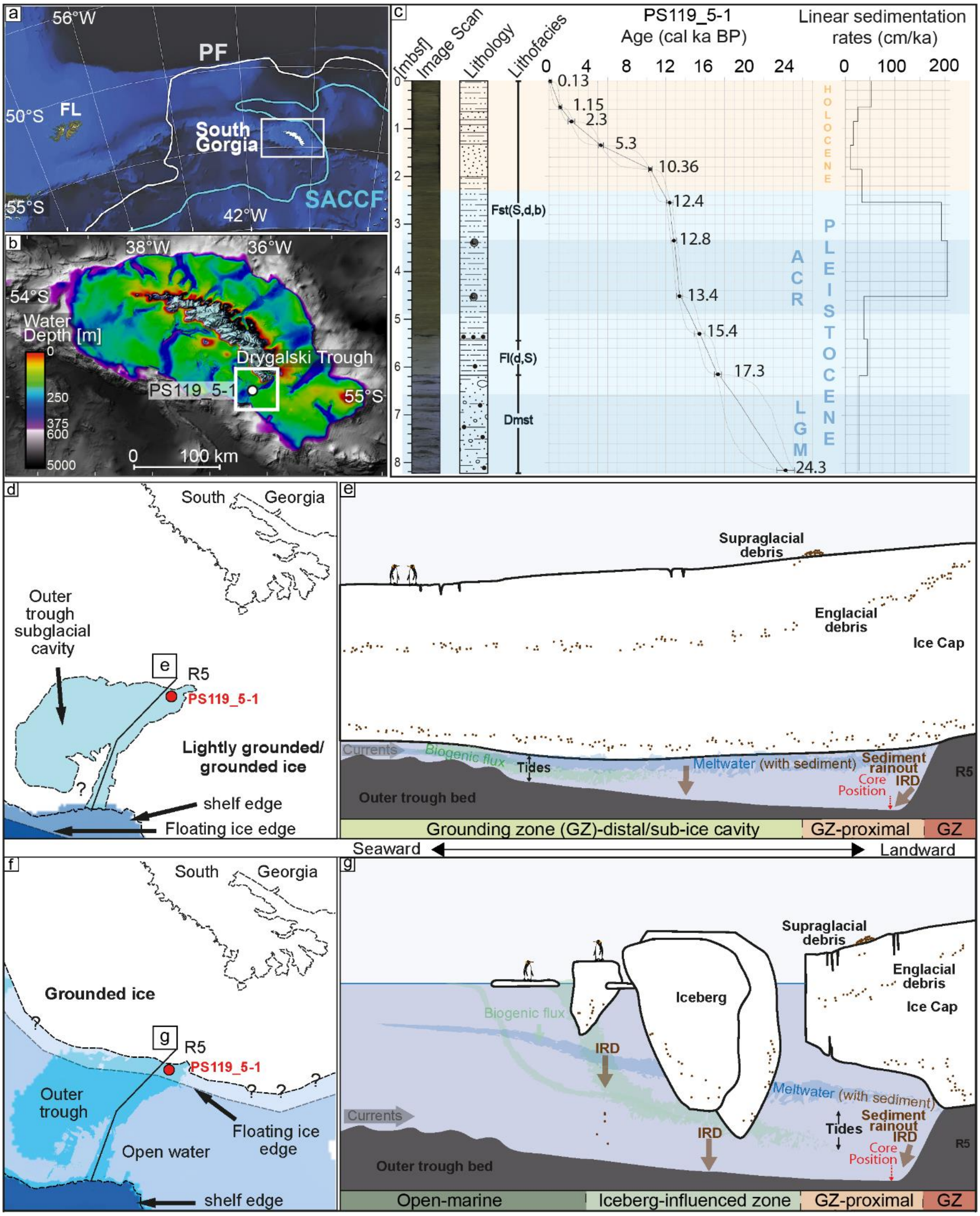


Fig. 4.10: modiefied after Lešić et al. (2022) a) overview map of the South Atlantic sector where South Georgia island is located southeast of Falkland Islands (FL) between the Polar Front (PF) and the Southern Antarctic Circumpolar Current Front (SACCF) b) a close-up map on South Georgia and its continental shelf with the glacial troughs. Drygalski Fjord system and Drygalski Trough are indicated by a white box. The sedimentcore PS119_5-1 is indicated by a white dot c) Agemodel and sedimentation rates along the core PS119_5-1 d,f) birds-eye view of outer Drygalski Trough and the core position, showing the possible extent and configuration of the ice cap during LGM and during its retreat before 17.3 cal ka BP, respectively e,g) show cross-sections through the grounding zones towards the shelf edge and correspond to d and f, respectively

which they interpret to be deposited in a water-filled subglacial cavity with restricted seawater access (**Fig. 4.10d,e**). This sediment core is the first dated evidence that South Georgia’s ice cap, at least in this region, extended far onto the continental shelf during the LGM, possibly all the way to the shelf edge (**Fig. 4.10d**). Further, the subsequent early deglaciation history can be reconstructed from its record, suggesting that until before 17.3 cal ka BP, the cavity had vanished and the ice margin started to retreat from a bathymetric high (R5, **Fig. 4.10f,g**) on the mid-shelf. Further retreat is indicated by changing sedimentary facies that show progressively ice-distal conditions with a declining iceberg influence over time. Still, the sediment core archived glacier-advance driven hinterland erosion during the Antarctic Cold Reversal (ACR), which resulted in a significant increase in sedimentation rates at the core site (**Fig. 4.10c**). This supports findings from the northern side of the island, where ***Graham et al. (2017)*** reconstructed a major glacier re-advance during the ACR. The subsequently deposited Holocene sediments are characterised by increased sand content but low sedimentation rates, rather indicating exposure to shelf currents than glacial influence, creating some sort of “bypass environment” for fine fractions at the core site. This is in accordance with previous studies who described ice-free coastal areas for the Holocene and proposed glacier fluctuations within the fjords (***Graham et al., 2017***; ***Bakke et al., 2021***). These findings by ***Lešić et al. (2022)*** significantly contribute to the understanding of sub-Antarctic vulnerability to Southern Hemisphere climate change, proving expansive glacier extent during the LGM on South Georgia and a rapid following deglaciation. However, the low sedimentation rates at the core site do not securely allow reconstructing the deglaciation history, shelf current exposure and connected climate changes on a higher temporal resolution. Current investigations aim to close this gap for the southern shelf within the SPP framework, based on sediment cores from the inner continental shelf.

Bakke J*, Paasche Ø, Schaefer JM, Timmermann A (2021). Long-term demise of sub-Antarctic glaciers modulated by the Southern Hemisphere Westerlies. Scientific Reports 11(1): 8361.*

Graham AG*, Kuhn G, Meisel O, Hillenbrand C-D, Hodgson DA, et al. (2017). Major advance of South Georgia glaciers during the Antarctic Cold Reversal following extensive sub-Antarctic glaciation. Nature Communications 8(1): 14798.*

Lešić N-M*, Streuff KT, Bohrmann G, Kuhn G (2022). Glacimarine sediments from outer Drygalski Trough, sub-Antarctic South Georgia–evidence for extensive glaciation during the Last Glacial Maximum. Quaternary Science Reviews 292: 107657.*

White DA*, Bennike O, Melles M, Berg S, Binnie SA (2018). Was South Georgia covered by an ice cap during the Last Glacial Maximum? Geological Society, London, Special Publications 461(1): 49-59.*

4.4 Overarching Research Topic - *Improved Understanding of Polar Processes and Mechanisms*

As described in the research topics A (*Dynamics of Climate System Components*), B (*Response to Environmental Change*) and C (*Linkages with Lower Latitudes*), Antarctica and the Southern Ocean reveal a complex relationship between physical, chemical, biological, and geological phenomena and processes, which are so far poorly understood. Due to the continent’s remoteness and difficulties for in situ observations, our knowledge of the basic processes and linkages is still limited. An improved understanding is a prerequisite to answer the relevant research questions. New and interdisciplinary approaches comprising the biological, chemical, physical and geological Antarctic system and their interactions were applied in the current SPP phase by mainly developing conceptual or numerical models and their validation in the field (e.g. ***Reese et al. 2020***). Such models can help to improve our deep understanding of complex fundamental processes in the Antarctic system beyond the currently known isolated phenomena, and hence is pivotal for understanding the changes and linkages outlined in A to C. In addition, several multi-disciplinary review articles were published with strong contributions of the SPP community, as exemplarily shown by ***Gutt et al. (2017)*** and ***Ingels et al. (2020)***.

Key Results from the current SPP Phase

The Antarctic Ice Sheet comprises an ice mass equivalent to 58 m of global sea-level rise. Its future evolution and the associated sea-level change are therefore of profound importance to coastal populations, ecosystems and economies. Over the past decades, the ice sheet has been losing mass at an accelerating rate. Although the current net mass loss from Antarctica is small compared to the other sea-level rise contributions, it is likely to increase with progressing global warming. Snowfall can be expected to increase in a warming atmosphere, but this additional accumulation is likely to be counteracted and eventually overcompensated by ice dynamical effects. Compared to the Greenland Ice Sheet, different physical processes make the much less studied West Antarctic Ice Sheet susceptible to tipping dynamics (***Rosier et al. 2021***). As large parts of West Antarctica are grounded in marine basins, abiotic changes in the ocean are key in driving the evolution of the ice sheet. The marine ice sheet instability can trigger self-sustained ice loss where the ice sheet is resting below sea level on retrograde sloping bedrock (***Wunderling et al. 2021***, and references therein). This destabilizing mechanism is possibly already underway in the Amundsen Sea region. Once triggered, a single local perturbation via increased sub-shelf melting in the Amundsen region could lead to wide-spread retreat of the West Antarctic Ice Sheet. Further, a recent study has shown strong hysteresis behavior for the whole Antarctic Ice Sheet, identifying two major thresholds that lead to a destabilization of West Antarctica around 2°C of global warming and large parts of East Antarctica between 6 and 9°C of global warming (***Garbe et al. 2020***) (**Fig. 4.11 and 4.12**). These authors showed in their modelling approach that the ice sheet's temperature sensitivity is 1.3 meters of sea-level equivalent per degree of warming up to 2 degrees above pre-industrial levels, almost doubling to 2.4 meters per degree of warming between 2 and 6 degrees and increasing to about 10 meters per degree of warming between 6 and 9 degrees.

Floating ice shelves, which fringe most of Antarctica's coastline, regulate ice flow into the Southern Ocean. Their thinning or disintegration can cause upstream acceleration of grounded ice and hence also contribute to global sea levels. So far the effect has not been quantified in a comprehensive and spatially explicit manner. Therefore ***Reese et al. (2017)*** applied a finite-element model and diagnosed the immediate, continent-wide flux response to different spatial patterns of ice-shelf mass loss. The authors showed that highly localized ice-shelf thinning can reach across the entire shelf and accelerate ice flow in regions far from the initial perturbation. They further reported that the integrated flux response across all grounding lines was highly dependent on the location of imposed changes: the strongest response was caused not only near ice streams and ice rises, but also by thinning, for instance, well-within the Filchner–Ronne and Ross Ice Shelves. ***Reese et al. (2017)*** concluded that the most critical regions in all major ice shelves were often located in regions easily accessible to the intrusion of warm ocean waters, stressing Antarctica's vulnerability to changes in its surrounding ocean.

Another aspect is related to the fact that the land ice contribution to global mean sea level rise has not yet been predicted using ice sheet and glacier models for the latest set of socio-economic scenarios, nor using coordinated exploration of uncertainties arising from the various computer models involved. Therefore ***Edwards et al. (2021)*** estimated probability distributions for previously published projections using statistical emulation of the available ice sheet and glacier models. These authors reported that limiting global warming to 1.5°C would halve the land ice contribution to twenty-first-century sea level rise, relative to current emissions pledges. The projected Antarctic contribution did not show a clear response to the optimistic emissions scenario, owing to uncertainties in the competing processes of increasing ice loss and snowfall accumulation in a warming climate. However, under risk-averse (pessimistic) assumptions, Antarctic ice loss could be five times higher, with massive consequences for coastal regions.

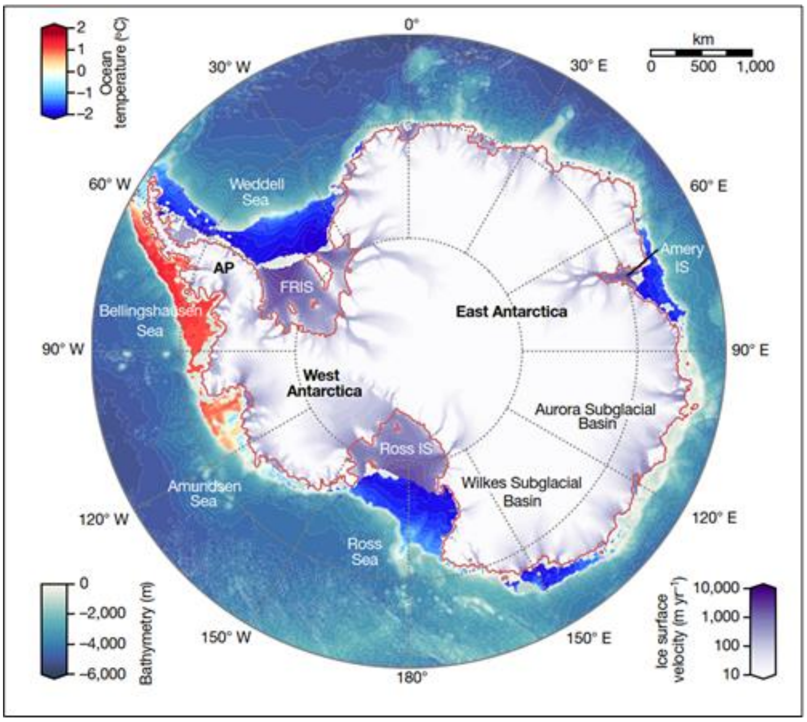


Fig. 4.11: Antarctic ice velocities and surrounding ocean temperatures. Simulated ice surface velocities (in metres per year) of the reference ice-sheet state revealing the fast-flowing ice streams (purple shadings). The simulated grounding-line locations are shown in red. AP, Antarctic Peninsula; IS, ice shelf; FRIS, Filchner–Ronne Ice Shelf.

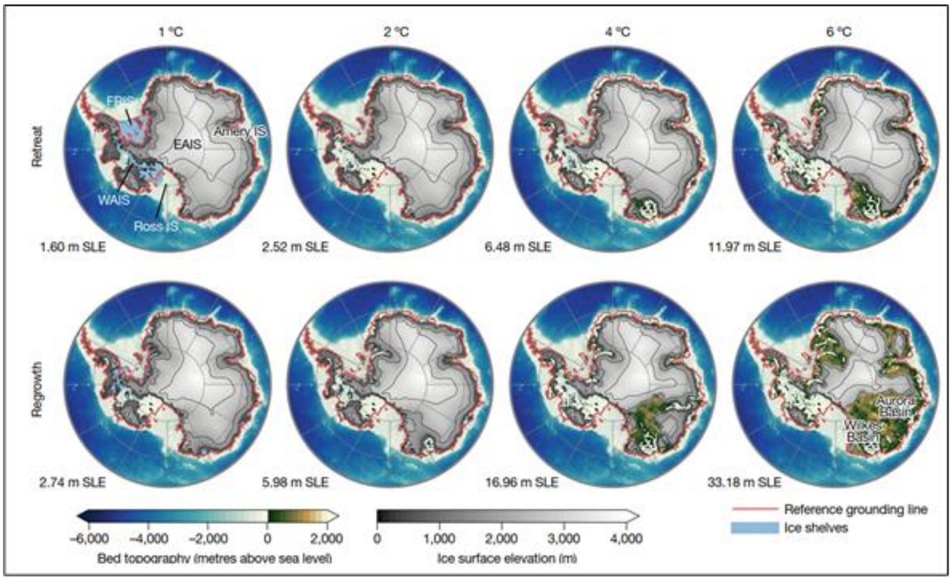


Fig. 4.12: Long-term ice loss for different warming levels. The equilibrium ice-sheet surface elevation is shown in meters for different warming levels (1°C, 2°C, 4°C and 6°C GMT anomaly above pre-industrial level), comparing the retreat (upper panels) and regrowth (lower panels) branch of the hysteresis curve. Ice surface-height contours are delineated at 1,000-m intervals. Grounding-line locations of the reference state are shown in red; ice shelves are marked in light blue. The absolute sea-level relevant ice-volume anomaly compared to the reference state (in m SLE), that is, the committed sea-level rise, is given for each panel. Blue shadings illustrate the bedrock depth in metres below the present-day sea level; brown shadings illustrate the bedrock elevation in meters above the present-day sea level. EAIS, East Antarctic Ice Sheet; WAIS, West Antarctic Ice Sheet.

Reese R*, Gudmundsson GH, Levermann A, Winkelmann R (2017) The far reach of ice-shelf thinning in Antarctica. Nature Climate Change, DOI: 10.1038/s41558-017-0020-x.*

Reese R*, Levermann A, Albrecht T, Seroussi H, Winkelmann R (2020) ISMIP-6: The role of history and strength of the oceanic forcing in sea-level projections from Antarctica with the Parallel Ice Sheet Model. The Cryosphere, DOI: 10.5194/tc-14-3097-2020.*

Garbe J*, Albrecht T, Donges JF, Levermann A, Winkelmann R (2020) Hysteresis of the Antarctic Ice Sheet. Nature, DOI: 10.1038/s41586-020-2727-5.*

Rosier SHR*, Reese R, Donges JF, De Rydt J, Gudmundsson GH, Winkelmann R (2021) The tipping points and early-warning indicators for Pine Island Glacier, West Antarctica. The Cryosphere, DOI: 10.5194/tc-15-1501-2021.*

Edwards TL*, Nowicki S, Marzeion B,……Winkelmann R, et al. (2021) Projected land ice contributions to twenty-first-century sea level rise. Nature 593, DOI: 10.1038/s41586-021-03302-y*

Wunderling N*, Donges JF, Kurths J, Winkelmann R (2021) Interacting tipping elements increase risk of climate domino effects under global warming. Earth System Dynamics, DOI: 10.5194/esd-12-601-2021.*

Gutt et al. (2017) described in their interdisciplinary review biodiversity, ecosystem services and climate variability of the Antarctic continent and the Southern Ocean as major components of the whole Earth system. In addition, Antarctic ecosystems are driven more strongly by the physical environment than many other marine and terrestrial ecosystems. Therefore, the authors strongly argued that for the fundamental understanding of ecological functioning, cross-disciplinary studies are especially important in Antarctic research, and as a consequence they developed a conceptual study, which focused on challenges in identifying and applying cross-disciplinary approaches in Antarctica (**Fig. 4.13**). New approaches to bridge knowledge gaps in Antarctic ecosystem research included multi-disciplinary monitoring, linking biomolecular findings and simulated physical environments, as well as integrative ecological modelling. The authors were also convinced that results of advanced cross-disciplinary approaches can contribute significantly to deeper knowledge of Antarctic and global ecosystem functioning, the consequences of climate change, and to global assessments that ultimately benefit humankind.

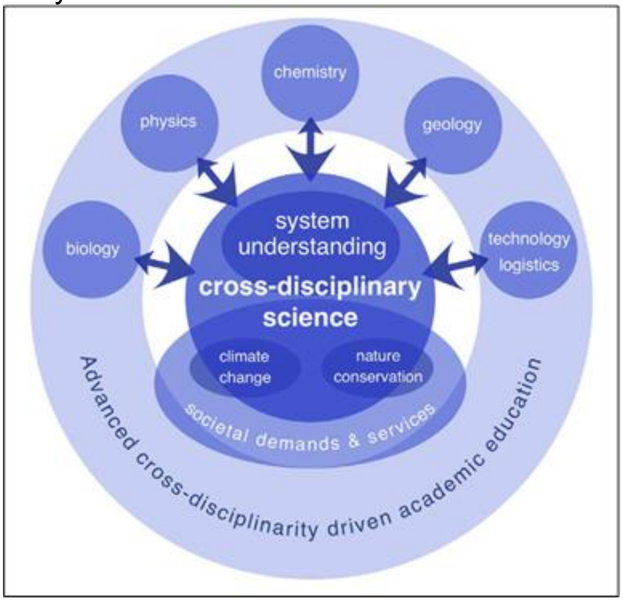


Fig. 4.13: Schematic overview of how to achieve advanced cross-disciplinary research on Antarctic ecosystems. Different scientific disciplines can contribute through cross-disciplinary coordination and management to improved scientific and societal approaches. This strategy includes modern cross-disciplinary academic education.

Gutt et al. (2017) also nicely summarized the strong interactions between the chemical-physical environment and biota. Most ecosystems on the Antarctic continent and in the Southern Ocean are rather unique, and vary greatly in their connectivity to other ecosystems on Earth. However, they all are exposed to the high spatial and temporal variability of the physical climate environment. The complexity of these relationships is illustrated in **Fig. 4.14**, and reflects the great potential for focused research on these interactions or aspects of them. The connection between Antarctic biological and non-biological systems can be divided into the exposure of biota to environmental impact and the response of organisms to it, which contributes significantly to the functioning of the entire Earth system, for example, via biogeochemical processes.

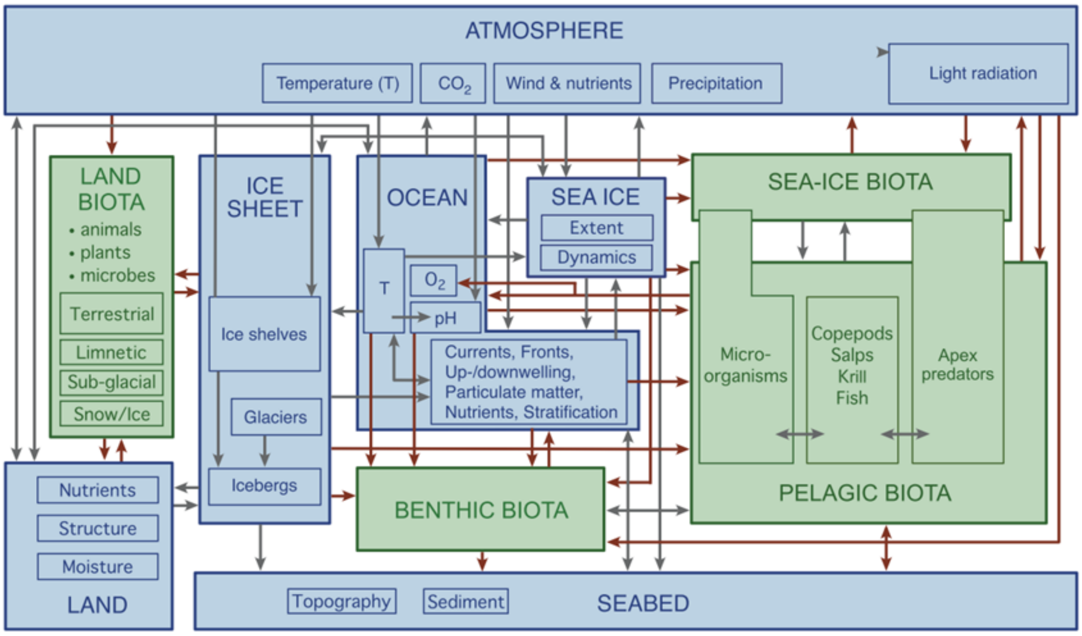
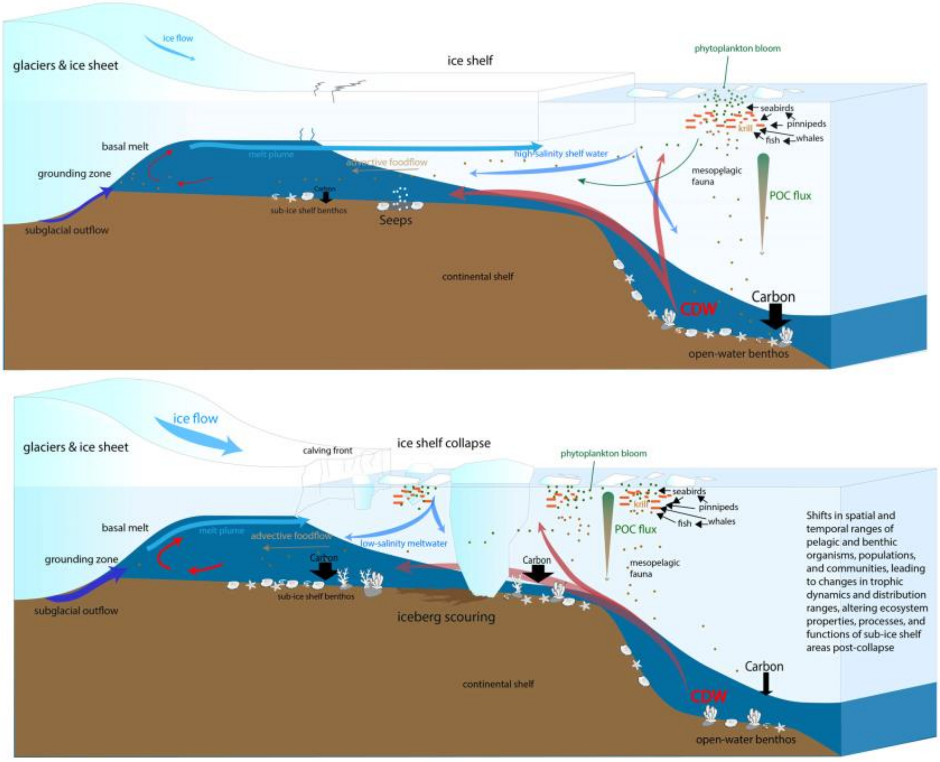


Fig. 4.14: Interactions between the chemical-physical environment and biota. This generalized and simplified schematic focuses on the main components of Antarctic ecosystems and their interactions, including with the non-living environment. Blue boxes represent physical-chemical conditions/variables, green boxes the biota. Interactions between living and non-living components are shown by red arrows.

Gutt J*, Isla E, Bertler AN, Bodeker GE, Bracegirdle TJ, Cavanagh RD, Comiso JC, Convey P, Cummings V, De Conto R, De Master D, di Prisco G, d'Ovidio F, Griffiths HJ, Khan AL, López-Martínez J, Murray AE, Nielsen UN, Ott S, Post A, Ropert-Coudert Y, Saucède T, Scherer R, Schiaparelli S, Schloss IR, Smith CR, Stefels J, Stevens C, Strugnell JM, Trimborn S, Verde C, Verleyen E, Walla DH, Wilson NG, Xavier JC (2017) Cross-disciplinarity in the advance of Antarctic ecosystem research. Marine Genomics, doi.org/10.1016/j.margen.2017.09.006*

Ingels et al. (2021) evaluated in their multi-disciplinary review the effects of ice-shelf collapse and iceberg calving on Antarctic ecosystems (**Fig. 4.15**). The authors outlined the current knowledge on I.) geo-physical and glaciological aspects, such as processes mediating ice-shelf melt, volume loss, retreat, and calving, on II.) ice-shelf-associated ecosystems through sub-ice, sediment-core, and pre-collapse and post-collapse studies, and on III.) ecological responses in pelagic, sympagic, and benthic ecosystems. The overarching question was how these ecosystems might change over a range of time scales under climate-change scenarios, which predict further ice-shelf retreats and calving icebergs. Therefore, the current knowledge was summarized and important research gaps identified (***Ingels et al. 2021***), such as exemplarily listed:

- Knowledge of the timescales and spatial reach of iceberg advection, melting, and scouring, drop-stone and scouring frequencies and magnitude, and the effects of mass calving events on higher trophic levels, carbon sequestration and the biological pump, nutrient and sediment exports, and stratification of pelagic ecosystems far from the ice-shelf collapse.
- Better predictions of ice-shelf retreat, disintegration, and collapse to be able to assess the ecological consequences;
- Comprehensive knowledge on the diversity of organisms that inhabit sub-ice-shelf and similar habitats;
- Understanding of the response-times of pelagic and benthic organisms to ice-shelf disintegration and collapse, including how these responses may vary seasonally and across size, taxonomic, and functional/trophic groups;
- Knowledge of the quantity and quality of food sources that feed the pelagic fauna and are exported to the benthos, their remineralization during transit through the water column, and how the quantity and quality will change under ongoing ice-shelf changes;
- Understanding of advective and other processes feeding sub-ice-shelf communities, and how they will be affected by changes in ice-shelf coverage;



Shifts in spatial and temporal ranges of pelagic and benthic organisms, populations, and communities, leading to changes in trophic dynamics and distribution ranges, altering ecosystem properties, processes, and functions of sub-ice shelf areas post-collapse

Fig. 4.15: Top, pre-collapse. **Bottom**, post-collapse. Shifts in the spatial and temporal ranges of pelagic and benthic organisms and communities. Post-collapse leads to changes in trophic dynamics and species ranges, altering ecosystem properties, processes, and functions of sub-ice-shelf areas. Thin black arrows between pelagic and surface biota indicate trophic interactions. The color gradient of the particulate organic carbon flux indicates the change from fresh to more degraded/refractory material. Thicker arrows indicate higher fluxes.

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