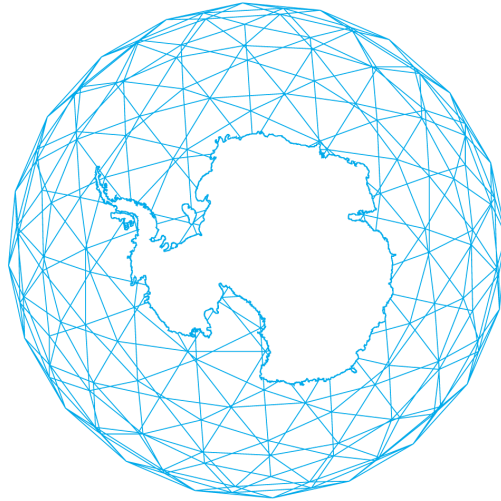




SOOS

SOUTHERN OCEAN
OBSERVING SYSTEM

Southern Ocean Observing System 2026-2030 Science and Implementation Plan

The Southern Ocean Observing System is an initiative of the Scientific Committee on Oceanic Research (SCOR) and the Scientific Committee on Antarctic Research (SCAR)



Alyce M. Hancock¹, Irene R. Schloss², Wolfgang Rack³, Andrew Meijers⁴, Sarat C. Tripathy⁵, Edward Doddridge^{6,7}, Clara Manno⁴, Kohei Mizobata⁸, Bhaskar V Parli⁵, Qinghua Yang⁹, Petra ten Hoopen¹⁰, Michaela E. Miller¹, Mohamed Adjou¹¹, Yue Bai¹², Emma J. D. Boland⁴, Carolina O. Dufour¹³, Marcel du Plessis¹⁴, Ruth Eriksen¹⁵, Pierpaolo Falco¹⁶, Denise Fernandez¹⁷, Blanca Figuerola¹⁸, Peter Fretwell⁴, Svenja Halfter¹⁷, Alexander Haumann^{18,19}, Katharine Hendry⁴, Sian F. Henley²¹, Nicole Hill⁷, Toru Hirawake²², Will Hobbs^{6,7}, Juan Höfer²³, Mathilde Jutras²⁴, Isobel Lawrence²⁵, Azwianewi Makhado²⁶, Martina Mascioni²⁷, Felicity McCormack²⁸, Cara Nissen²⁹, Antonio Novellino³⁰, Keyhong Park³¹, Luciano Ponzi Pezzi³², Ariaan Purich²⁸, Craig Stevens¹⁵, Sandy Thomalla³⁴, Andrew Thompson³⁵, Emily Twigg³⁶, Friederike Weith¹⁸, Kaihe Yamazaki³⁷

¹SOOS International Project Office, Institute for Marine and Antarctic Studies, University of Tasmania, Australia;

²Instituto Antártico Argentino, Centro Austral de Investigaciones Científicas y Técnicas (CADIC-CONICET) and Universidad Nacional de Tierra del Fuego, Argentina;

³School of Earth and Environment-Gateway Antarctica, University of Canterbury, New Zealand;

⁴British Antarctic Survey, UK;

⁵National Centre for Polar and Ocean Research (NCPOR), Ministry of Earth Sciences, India;

⁶Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania, Australia;

⁷Institute for Marine and Antarctic Studies, University of Tasmania, Australia;

⁸Tokyo University of Marine Science and Technology, Japan;

⁹Sun Yat-sen University and Southern Marine Science and Engineering Guangdong Laboratory, China;

¹⁰UK Polar Data Centre, British Antarctic Survey, United Kingdom;

¹¹Institut Supérieur de l'Electronique et du Numérique (ISEN OUEST), Brest, and Institut Universitaire Européen de la Mer (IUEM), Plouzané, France;

¹²University of California - San Diego, USA;

¹³University of Brest, CNRS Ifremer, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS), France;

¹⁴Department of Marine Sciences, University of Gothenburg, Sweden;

¹⁵Commonwealth Scientific and Industrial Research Organization, Australia;

¹⁶Marche Polytechnic University, Italy;

¹⁷Earth Sciences New Zealand, New Zealand;

¹⁸Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Germany;

¹⁹Ludwig Maximilian University of Munich, Germany

²⁰Institute of Marine Science (ICM-CSIC), Spain;

²¹School of GeoSciences, University of Edinburgh, United Kingdom;

²²National Institute of Polar Research, Japan;

²³Research Center Dynamics of High Latitude Marine Ecosystems, Pontificia Universidad Católica de Valparaíso, Chile;

²⁴Université du Québec à Rimouski, Canada;

²⁵University of Northumbria, UK;

²⁶Department of Environment Forestry and Fisheries, South Africa;

²⁷Universidad Nacional de La Plata, Argentina;

²⁸Securing Antarctica's Environmental Future, School of Earth, Atmosphere and Environment, Monash University, Australia;

²⁹Department of Freshwater and Marine Ecology, University of Amsterdam, Netherlands;

³⁰EMODnet [Physics]-ETT|DEDAGroup, Italy;

³¹Korea Polar Research Institute, Republic of Korea;

³²Instituto Nacional de Pesquisas Espaciais, Brazil;

³⁴Council for Scientific and Industrial Research, South Africa;

³⁵California Institute of Technology, USA;

³⁶Scientific Committee on Oceanic Research, College of Earth, Ocean and Environment, University of Delaware, USA;

³⁷Japan Agency for Marine-Science and Technology, Japan;

Citation:

Executive Summary

The Southern Ocean plays a disproportionately large role in the global Ocean including regulating the world's climate, weather systems and sea level. Yet, the Southern Ocean is currently undergoing rapid and unprecedented changes which could have cascading impacts on the broader Southern Ocean and global ecosystem. It is therefore more critical now than ever before to have a sustained, coordinated and integrated Southern Ocean observing system to understand the current changes, predict potential future states and the impacts of these on the global system.

Due to the size and complexity of the Southern Ocean, international coordination and collaboration is required to successfully deliver a sustained, coordinated and integrated observing system within the Southern Ocean, and this motivated the establishment of the Southern Ocean Observing System (SOOS). SOOS was initiated in 2011 to facilitate the enhanced collection and delivery of essential observations to all stakeholders. SOOS has been achieving this mission through alignment, advocacy and support of science priorities and challenges, and the observational needs to meet them, forming the fundamental first steps towards a cohesive and coordinated observing system in the Southern Ocean.

This Science and Implementation Plan articulates the scientific priorities for SOOS through the identification of key gaps in the observational network and by identifying the priorities in addressing them. The Plan covers the five-year period, 2026-2030, and provides an update on the previous SOOS Science Plan (2021-2025). The plan has an emphasis on the capabilities required to support data collection and delivery, and the objectives and actions that SOOS will implement.

Five Science Themes have been identified, each encompassing a number of Key Science Challenges. These Themes and Challenges incorporate many scientific drivers that are cross-disciplinary, reflecting the highly-interconnected nature of the Southern Ocean and the number of linkages amongst Themes. The Themes provide a framework for enhancing the coordination of international data collection and delivery efforts that will contribute to understanding and quantifying the state and variability of:

- Theme 1: Southern Ocean cryosphere
- Theme 2: Southern Ocean circulation
- Theme 3: Southern Ocean carbon and biogeochemical cycles
- Theme 4: Southern Ocean ecosystems and biodiversity
- Theme 5: Southern Ocean-sea ice-atmosphere fluxes

A cross-cutting list of Key Science Challenges has also been identified by the community which articulates specific priorities for the Southern Ocean community over the next five to ten years.

Addressing the data gaps across these inherently interconnected Themes sustainably and systematically requires parallel advances in coordination networks, cyberinfrastructure and data management tools, observational platform and sensor technology, and development of internationally agreed sampling and analytical standards and data requirements of key variables. In recognition of this, SOOS has also identified a number of Foundational Capabilities that will need to be developed or expanded.

The Science Plan is followed by a SOOS 2026-2030 Strategy and Implementation Plan which defines the key objectives, actions and deliverables that will provide the greatest benefit and impact to the SOOS mission to enhance the collection and delivery of essential observations from the Southern Ocean. The strategy is split into three sections;

- 1) High priority, core SOOS actions and deliverables which will be the main focus of SOOS's activities over the next five years,
- 2) SOOS supported actions and tasks in collaboration with the broader community which outlines activities that SOOS will conduct in collaboration with others if resources and capacity allow, and
- 3) SOOS governance and International Project Office operations which provides an overview on activities required to maintain the ongoing management of SOOS to be completed by the SOOS International Project Office.

Acknowledgements

The authors acknowledge the contribution of the whole SOOS and broader Southern Ocean community to the development of this Science and Implementation Plan. SOOS thanks the SOOS governing bodies - the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR); the SOOS International Project Office sponsors - Tasmanian State Government, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Australian Antarctic Program Partnership (AAPP), Swedish Polar Research Secretariat, Scientific and Technological Research Council of Turkey Marmara Research Centre Polar Research Institute (Türkiye), the National Centre for Polar and Ocean Research (NCPOR, India), EU Horizon Project OCEAN ICE, and the Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research (Germany); and SOOS International Project Office host - University of Tasmania's Institute for Marine and Antarctic Studies.

IN REVIEW

Table of Contents

Executive Summary	3
Acknowledgements	5
Table of Contents	6
Introduction	8
SOOS Mission, Vision and Values	9
SOOS Achievements 2011-2026	11
The SOOS Science Plan	13
Overview	14
Science Themes	15
Theme 1: Understanding and Quantifying the State and Variability of the Southern Ocean Cryosphere	15
Theme 2: Understanding and Quantifying the State and Variability of the Southern Ocean Circulation	18
Theme 3: Understanding and Quantifying the State and Variability of Southern Ocean Carbon and Biogeochemical Cycles	19
Theme 4: Understanding and Quantifying the State and Variability of Southern Ocean Ecosystems and Biodiversity	22
Theme 5: Understanding and Quantifying the State and Variability of Southern Ocean-Sea Ice-Atmosphere Fluxes	26
Key Science Challenges	29
Foundational Capabilities	36
Observing System Design, Key Variables and Modelling	36
Observing System Design	36
Key Variables	37
Modelling	37
Methods and Standards	39
Observational Technologies and Digital Infrastructure	39
Methodologies and Best Practices	42
Data Management and Delivery	42
Implementation Framework	45
Networks and Coordination	45
SOOS Networks	45
Externally Coordinated Observing Networks and Programmes	45
SOOS Collaborations and Partnerships with Large International Initiatives	47
Antarctica InSync	47
Synchronous Southern Ocean Observatory (SYNCHRONY)	47
5th International Polar Year (IPY-5)	47
Science, Policy and Management Programmes	48
Societal Impact	48
SOOS 2026-2030 Strategy and Implementation Plan	50

Overview of the plan structure and its establishment	50
SOOS Key Objectives	50
High Priority, Core SOOS Actions	51
Priority setting	51
Actions	51
Networks and Coordination	51
Actions:	52
SOOS Support for FAIR Data	53
Actions:	53
Knowledge Sharing	54
Actions:	54
High Priority, Core SOOS Deliverables	55
Publications, white papers, reports etc.	55
Networks and Coordination	55
SOOS Support for FAIR Data	56
SOOS Advocacy	56
SOOS Communications and Engagement	56
SOOS Supported Actions and Tasks in Collaboration with the Broader Community	57
SOOS Governance and International Project Office Operations	57
References	60
Acronyms	80

Introduction

The Southern Ocean is critically important in the Earth system as a major regulator of global climate, ocean circulation and heat uptake, modulator of Antarctica's contribution to sea level rise and moderator of primary productivity and carbon export. This vast ocean region is changing rapidly with warming waters, reduction in sea ice, melting of ice shelves and species population shifts among others, which will have cascading impacts not only within the Southern Ocean ecosystem but globally. Yet, it still remains one of the least observed regions in the world. To be able to detect, monitor, understand and potentially predict these changes it is more critical now than ever to have an integrated, coordinated and sustained observing system in the Southern Ocean.

A number of elements are required to upscale the current observing system within the Southern Ocean to address current and urgent needs (Figure 1):

- An **improved understanding of the current state of the observing system**, and identification of priority and highly influential regions and processes
- **Harmonisation and integration of in-situ, remote-sensing and autonomous observations** from both traditional and new observing and analysis techniques
- International coordination and collaboration, including utilisation of voluntary observing platforms and ships of opportunity
- **Inclusion and support across the entire Southern Ocean community** to allow equity in access to opportunities for research (e.g., fieldwork, infrastructure, data), policy influence and community building (e.g., conferences)
- **End-to-end open science and data** according to the FAIR data principles to ensure data are used to their full potential through leveraging existing and emerging cyberinfrastructure
- A **close feedback loop between observations and models** to ensure that observations continue to challenge and improve the models, and models inform observational gaps and uncertainties
- Clear, effective and efficient communication and collaboration between researchers and policymakers to ensure observations are translated into **policy-ready advice** to ensure the full value of observations is realised by society.

The Southern Ocean Observing System (SOOS), a joint initiative of the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR), is a well-established coordinating body with the established networks, systems and tools to meet these urgent needs.

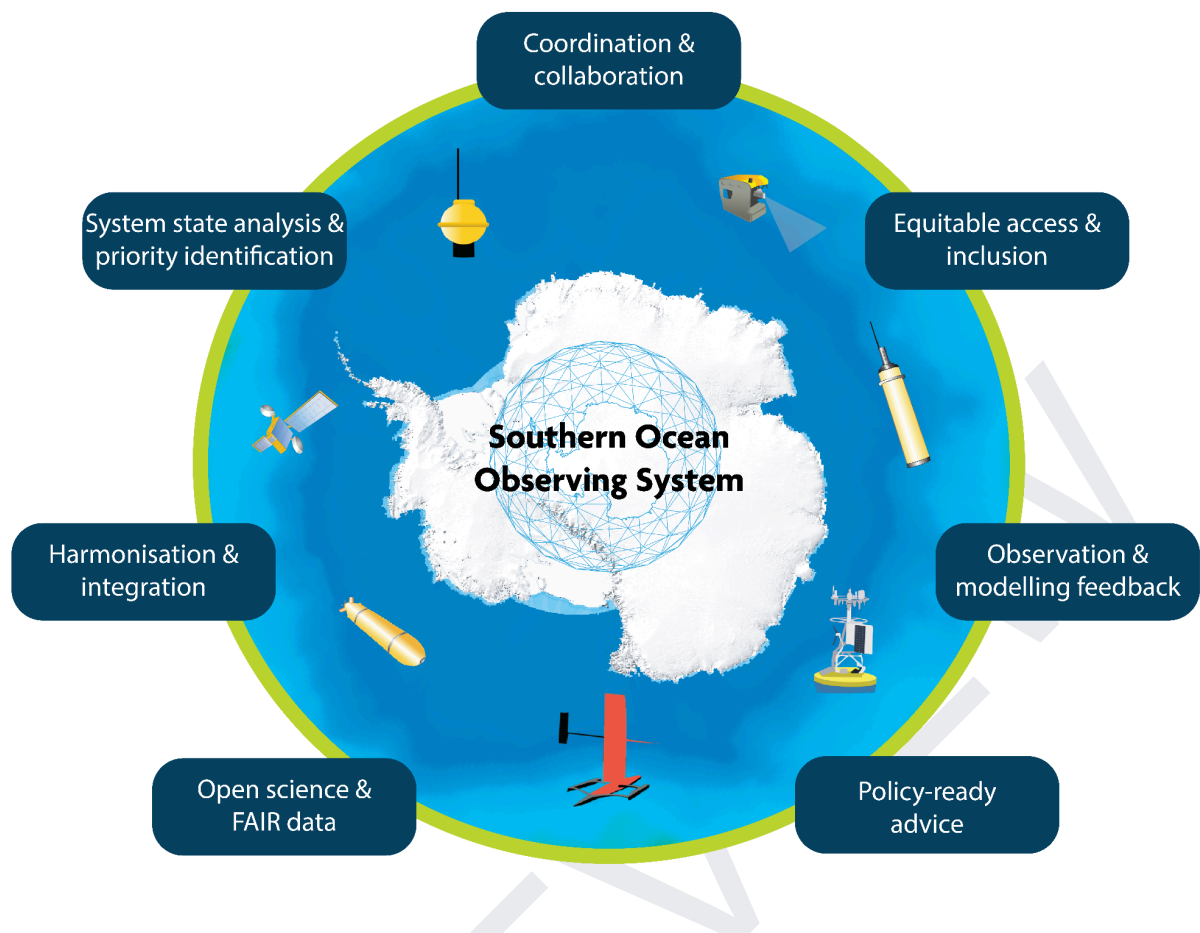


Figure 1: Key elements required to upscale the Southern Ocean observing system, including improved understanding of the state of the system, priority regions and processes, integration and harmonisation of diverse observing approaches, strengthened international coordination and collaboration, equitable and inclusive community participation, open science and FAIR data practices, feedback between observations and models, and effective science–policy communication. Background projection created using SOOSmap (soosmap.aq) displaying the CMEMS - CORA: Coriolis Ocean database for ReAnalysis – Temperature (Szekely et al., 2024, accessed via soosmap.aq on 2026-04-29).

SOOS Mission, Vision and Values

The SOOS mission is to:

“facilitate the sustained collection and delivery of essential observations of the Southern Ocean to all stakeholders, through the design, advocacy, and implementation of cost-effective observing and data delivery systems”

Working towards the overall vision for:

“sustained observations of physical, chemical, biological and geological processes and changes in the Southern Ocean system should be readily accessible to provide a foundation for enabling the international scientific community to advance understanding of the Southern Ocean and for managers to address critical societal challenges”

Specifically, SOOS enhances the collection and delivery of Southern Ocean observations by:

1. **Aligning, advocating, and supporting scientific and observational priorities, identifying gaps** to provide a clear message to funders, national programs, and intergovernmental agencies through publications, research endorsement, alignment of observing system requirements
2. **Enhancing collaboration and observational capabilities** by building integrative networks, developing collaborative tools, supporting capacity development opportunities, and facilitating the use of efficiencies in sensor, platform, and data technologies
3. **Ensuring the management and delivery of observational data** by connecting data repositories, integrating data, rescuing unpublished data, and encouraging the use of open science including FAIR data principles
4. **Sharing knowledge** within the Southern Ocean community and beyond, to provide visibility and enhance the impact of Southern Ocean research and the knowledge created from it, through communication strategies, workshops, publications, community coordination efforts

At each step of the Southern Ocean science life cycle (Figure 2), SOOS integrates between diverse communities to ensure greater impact.

Central to this mission is a set of values that are shared by SOOS and form the basis for our collaborations with and recommendations to the broader community. This includes our stakeholders within the research community, managers of marine resources, policy makers, local planners, ship operators, Antarctic tourism operators, weather and climate forecasters, educators, and international organisations, including the International Oceanographic Commission of UNESCO, the World Meteorological Organisation, SCAR and SCOR.

SOOS commits to:

1. Support and advocate for active engagement with all interested nations, programs, organisations and projects across all relevant disciplines, industries, and stakeholders, including under-represented groups.
2. Appropriately invest resources, time, and effort to ensure engagement with and representation of the broader Southern Ocean community in SOOS, and actively contribute to efforts to improve equity, diversity and inclusion (EDI) in the community.
3. Contribute to and advocate for the development, adoption, and continual improvement of best practices in ocean observing and data management, including sharing of resources and knowledge and championing open and FAIR access to data and data products.

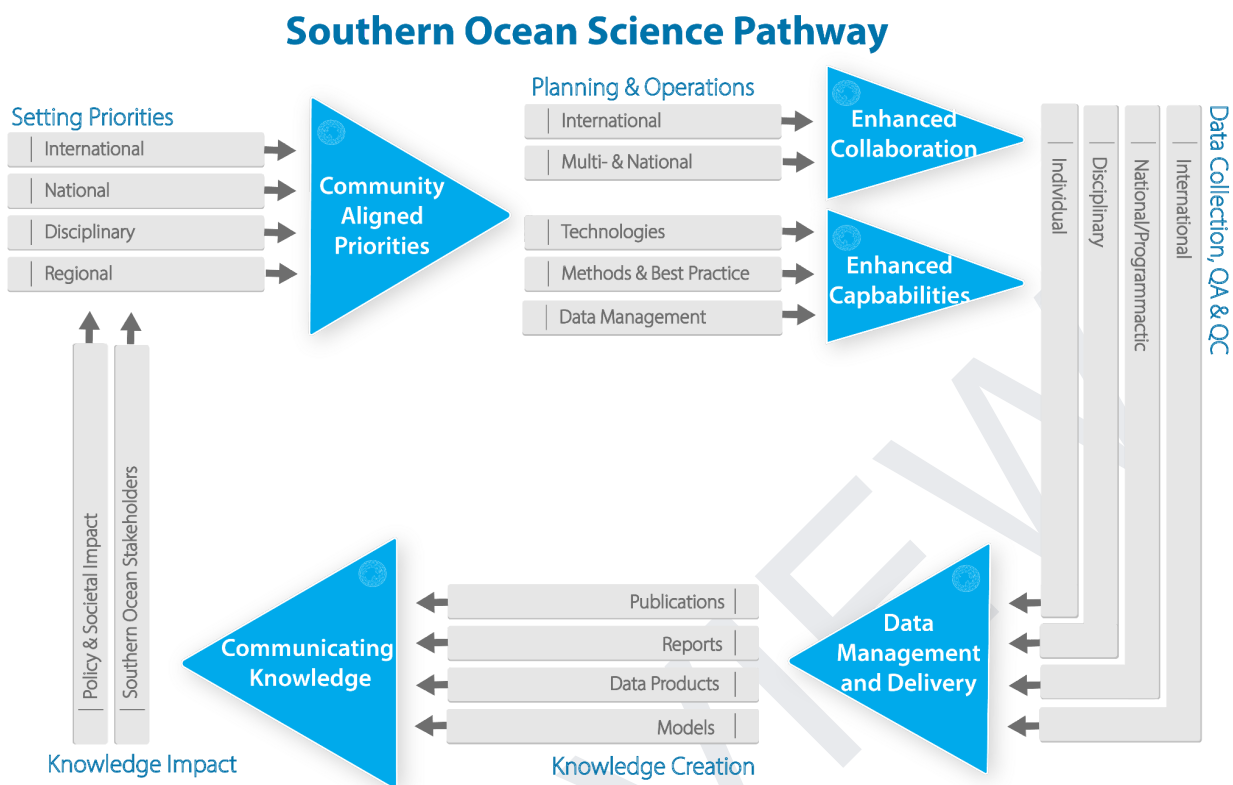


Figure 2: The steps in the Southern Ocean science life cycle, highlighting the major roles that SOOS plays facilitating collaboration and coordination across the community (blue triangles). SOOS enhances the collection and delivery of Southern Ocean observations by aligning priorities, enhancing collaboration, increasing ocean observing capabilities, delivering observational data, and sharing knowledge.

SOOS Achievements 2011-2026

Initiated in 2011 and having developed significantly over the last 15 years, SOOS has built strong global networks, community-driven initiatives, systems and tools that collectively deliver on the SOOS mission and vision. A summary of SOOS's achievements to date are listed in Figure 3.

SOOS Achievements (2011-2026)



21 Million + observations

from **60** data layers including physical, chemical, biogeochemical and biological observations



241 upcoming planned routes

including planned routes by National Antarctic Programs, tourism operators and fisheries



66 publications and **6** special issues

with **2,247** citations and uptake into **49** policy documents

108 reports, **42** were reports to policy



183 events

73 international in-person meetings, 69 online meetings, 44 webinars

representation at 300+ other meetings



1,029 international members

483 institutes from 55 nations

25 international networks + **7** partnerships

51 early career researchers in leadership positions



89 endorsed projects (53 funded)

54 acknowledgements of SOOS in publications

283 mentions of SOOS publications in policy documents

Figure 3: Summary of SOOS achievements. SOOS builds collaborative networks and products that align priorities, support sharing of resources and remove barriers to enhance the collection and delivery of Southern Ocean observations. Since its inception in 2011, SOOS has achieved the above successes working towards this goal.

The SOOS Science Plan

The Southern Ocean plays a critical role in the global climate system including the uptake of more than 75% of the excess global ocean heat and 40% of the total oceanic uptake of anthropogenic CO₂ emissions (Williams et al., 2024). Yet it is currently undergoing physical and biological changes, which are expected to continue and intensify as climate change proceeds. Since the development of the SOOS Science and Implementation Plan (2021-2025) (Newman et al., 2022), the Southern Ocean has undergone a period of rapid and unpredicted change in a number of key regional features such as sea ice coverage, ice sheet melt, ocean circulation, marine heat waves and atmospheric temperatures. Considered together, these point to potential large-scale abrupt changes in the Antarctic and Southern Ocean (Abram et al., 2025) and regime shifts (e.g., Hobbs et al., 2024). Further, these shifts are having cascading ecosystem impacts and suggest the region may be approaching critical tipping points.

The Southern Ocean is undergoing substantial warming, with ocean heat content reaching its maximum recorded value in 2024 (Thomalla et al., 2025). In addition to its long-term warming trend, the Southern Ocean is experiencing increasingly frequent marine heatwaves (Piñones et al., 2024). This warming is driving sea ice decline with Southern Ocean sea ice having undergone a rapid decline since 2015/16 and evidence it has undergone a regime shift to a new low sea ice state (Purich & Doddridge, 2023; Hobbs et al., 2024; Abram et al., 2025; Raphael et al., 2025). The severity of this rapid decline has led to a suite of studies into its drivers and consequences. Antarctic sea ice is now failing to recover during winter, its typical seasonal maximum, a phenomenon linked to poor regrowth following very low-ice summers (Purich & Doddridge, 2023), with severe implications for ocean heat loss, storms (Josey et al., 2024), and destabilisation of ice shelves by increased ocean swell due to sea ice loss (Massom et al., 2018).

These physical changes in Southern Ocean conditions have significant ramifications and flow-on effects across the entire Southern Ocean ecosystem, potentially resulting in tipping points that could have cascading effects, or regime shifts where one system triggers disruptions in others (Gutt et al., 2015; McQuaid, 2018; Kubiszewski et al., 2024). For example, declines in sea ice extent and season duration are having severe impacts on the breeding success of emperor penguins (Fretwell et al., 2023; Fretwell, 2024). Phytoplankton are also observed to exhibit shorter phytoplankton blooms, reduced summer biomass and changes in species dominance in years with low sea ice extent (Antoni et al., 2024). Marine heatwaves have been found to lead to parallel changes in plankton metabolism and community composition, signalling strong local ecological reorganisation during short-lived warming episodes (Latorre et al., 2023). Such shifts in phytoplankton community composition would potentially

affect the ecosystem transfer efficiency and the whole marine food web, especially Antarctic krill (*Euphausia superba*).

Without an integrated, sustained and coordinated observing system, the detection of these changes would not be possible. For example, long-term satellite observational data has allowed the detection of the regime shift which is underway in sea ice state, but to develop a mechanistic understanding of the drivers of this regime shift, further observations are required, including from the Argo array (Purich & Doddridge et al., 2023). Therefore, it is critical that we maintain and expand long-term, sustained observations in the Southern Ocean to detect and understand the changes occurring, and the ramifications of these changes not just within the Southern Ocean ecosystem but globally. It is within the light of these rapid changes that the SOOS Science Plan (2026-2030) has been developed.

Overview

To focus SOOS activities over the next five years, the SOOS 2021-2025 Science Plan has been updated below to incorporate the development of observations, research and understanding on the Southern Ocean, particularly in light of the rapid and unprecedented changes now occurring in the Southern Ocean. The SOOS 2026-2030 Science Plan follows a similar science structure to the SOOS 2021-2025 Science Plan with five community-agreed Science Themes, one of which is cross-cutting (Figure 4). These five Science Themes provide a balanced and integrated framework for coordination, collection and delivery of Southern Ocean data. In addition to the Science Themes, the community has agreed on a list of Key Science Challenges that articulate specific priorities of the Southern Ocean community (Table 1). These Key Science Challenges include both shorter (≤ 5 years) and longer (5-10 years) term challenges, and encompass scientific drivers across one or multiple Science Themes therefore reflecting the cross-disciplinary and interconnected nature of much of the science drivers within the Southern Ocean.

In addition to the community-agreed Science Themes and Key Science Challenges, the importance of enhancing our ability to collect, manage and use observational data is recognised. This includes addressing the data gaps across these inherently interconnected Themes sustainably and systematically through coordination networks, cyberinfrastructure and data management tools, observational platforms and sensor technology, and development of internationally agreed sampling and analytical standards and data requirements of key variables. In recognition of this, SOOS has also identified a number of Foundational Capabilities that will need to be developed or expanded (Figure 4).

Delivery of the knowledge and scientific outputs that will address the SOOS 2026-2030 Science Plan will not be carried out not only by SOOS, but by many community efforts, including the programs and projects of SCAR and SCOR, among

others. SOOS will not duplicate the efforts of these programs, but will support them where appropriate, to enhance the collection and delivery of the required data.

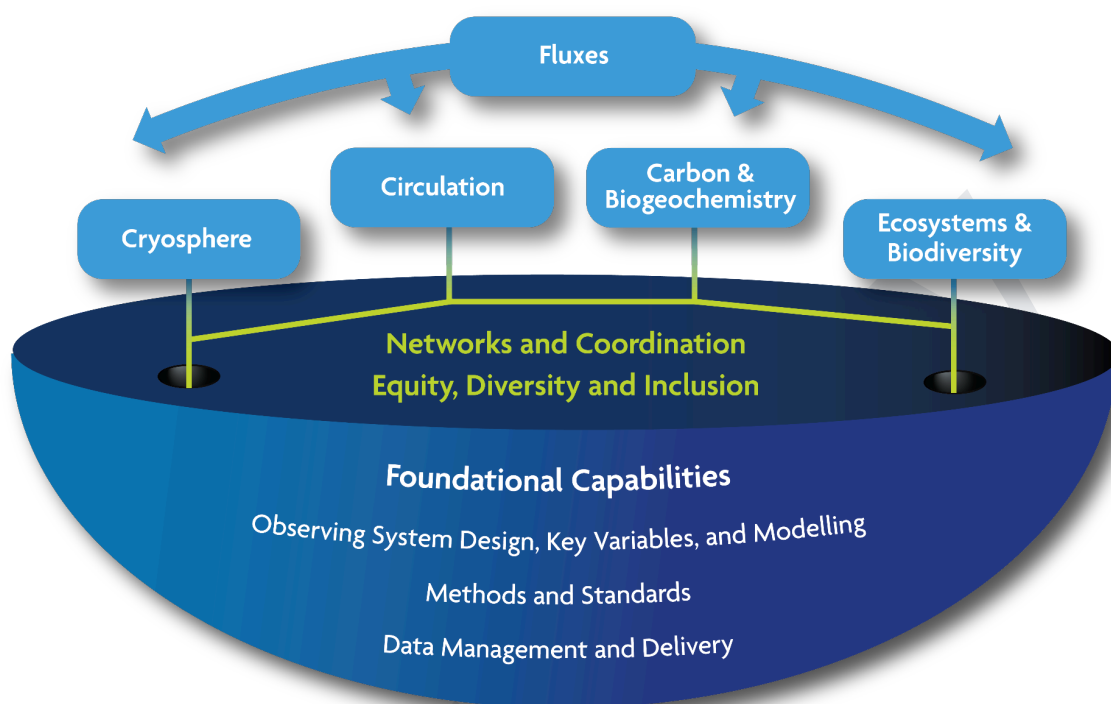


Figure 4. The SOOS Science Plan encompasses five Science Themes (top blue boxes and arrows for the cross-cutting theme) and Key Foundational Capabilities (base layers in the bowl at the bottom). Network development and international science coordination link across themes and capabilities, and are underpinned by principles of equity, diversity and inclusion that are woven through all SOOS activities (green line). Together, all of these elements provide the framework for SOOS to enhance the collection and delivery of the data needed by the international scientific community to deliver the Science Plan.

Science Themes

Theme 1: Understanding and Quantifying the State and Variability of the Southern Ocean Cryosphere

The components of the cryosphere that are present in or interact with the Southern Ocean are: the sea ice and its snow cover; icebergs; marine terminating glaciers; and ice shelves. Projections of future sea-level rise to 2100 range from 0.38 [0.28 to 0.55, likely range] (SSP1-1.9) to 0.77 m [0.63 to 1.01, likely range] (SSP5-8.5) (IPCC, 2021). These estimates consider only the processes which can be projected with reasonable confidence, and exclude poorly constrained ice sheet processes, including the marine ice sheet instability, that can accelerate ice loss and lead to significantly larger estimates. Quantifying the potential contribution of these processes to future sea level rise requires a better understanding of the ocean drivers of ice loss, including ice shelf-ocean interactions, and ice sheet dynamics that influence the timing of the onset of rapid retreat. Beyond sea level rise, ice loss from

Antarctica will affect the ocean through fluxes of heat and freshwater that occur throughout the water column to depths of more than one thousand metres.

Observations indicate a continuing increase in ocean-driven ice shelf basal melt and iceberg calving over the twenty-first century. The five largest ice shelves in the Amundsen Sea have already lost around 15% of their volume (The IMBIE Team., 2018). This is modulated by the Amundsen Sea Low (Dotto et al., 2019) which in turn is connected to and influenced by tropical Pacific atmospheric variability (Paolo et al., 2018; Dotto et al., 2019). Ice losses from the Antarctic Ice Sheet continue to be dominated by West Antarctica (82 ± 9 Gt yr⁻¹), driven by ocean-forced acceleration of outlet glaciers in the Amundsen Sea sector, with a smaller but significant contribution from the Antarctic Peninsula (13 ± 5 Gt yr⁻¹). East Antarctica remains close to a state of balance, though it is the most uncertain component of Antarctica's mass balance and the processes driving its variability remain poorly understood (Otosaka et al., 2023). Observed shoaling and poleward movement of warm Circumpolar Deep Water in the East Antarctic sector raises concerns for future ocean driven ice shelf melt (Herraiz-Borreguero & Naveira Garabato, 2022). Increased glacial meltwater input to the Southern Ocean has consequences for its stratification, growth and melt of sea ice, and heat transport onto the continental shelves (e.g., Bronselaer et al., 2018; Golledge et al., 2019). Regional ocean modelling suggests that rapid ocean warming in the Amundsen Sea at approximately triple the historical rate by 2100 is likely committed regardless of emissions scenario (Naughten et al., 2023). The projected increase in Antarctic meltwater over the next three decades is set to slow the abyssal overturning circulation by more than 40%, leading to warming and ageing of the deep ocean (Li et al., 2023)—a feedback not captured in most current coupled climate projections.

Sea ice, which until recently covered an area of the Southern Ocean ranging seasonally from about 3 million km² to 19 million km² (Parkinson, 2019) plays many key roles: it modulates ocean-atmosphere fluxes (Josey et al., 2024); impacts glacial ice discharge and ice shelf stability (Massom et al., 2018; Reid & Massom, 2022; Doddridge et al., 2025; Teder et al., 2025); mediates biogeochemical processes and provides an essential habitat for marine species (Fretwell et al., 2023; Krumhardt et al., 2026); and contributes to the formation of water masses that are key for ocean uptake of anthropogenic heat and carbon (Pellichero et al., 2018; Zhou et al., 2023). Following consecutive record high winter maximums between 2012 and 2014 (Reid & Massom, 2015), Antarctic sea ice reached record summer lows in 2017, 2022, and 2023, accompanied by a record-low winter in 2023 (Ionita, 2024; Liu et al., 2023; Purich & Doddridge, 2023; Turner & Comiso, 2017; Wang et al., 2022). This abrupt change and the observed transition to greater variability, longer persistence, and higher spatial coherence that began as early as 2007, likely indicates a regime shift in Antarctic sea ice (Purich & Doddridge, 2023; Schroeter et al., 2023; Hobbs et al., 2024; Abram et al., 2025; Raphael et al., 2025). The regime shift exemplifies the complexity of the ocean-sea ice-atmosphere system, which is not represented adequately in either

forecast or climate models (Hobbs et al., 2016; Holmes et al., 2019; Beadling et al., 2020). While atmospheric forcing is a well-known driver of sea-ice variability (Eayrs et al., 2021), recent atmospheric processes cannot fully explain these extremes, suggesting that warming Southern Ocean subsurface waters likely represent a key driver transitioning sea ice into a new state (Zhang et al., 2022; Purich & Doddridge, 2023; Espinosa et al., 2024; Hobbs et al., 2024).

Observing the cryosphere and ocean where they interact is key to understanding and modelling change, yet significant uncertainties remain across the ice shelf-ocean system. A survey of the Southern Ocean and Antarctic modelling community identified processes on the Antarctic margin, including in ice shelf cavities, as the most problematic bias in current ocean models (Martin et al., 2026), highlighting the key role for observations in this region. Advances in understanding ice-ocean interactions, including drivers of ice shelf melt (Kennicutt et al., 2014), requires progress on several fronts, including in observational advances, and reconciling observations and models of key processes. Satellite-derived observations are a vital component of the observational network, but in-situ observations from multiple regions and seasons are essential (Webster et al., 2018; Boisvert et al., 2020; Rignot, 2023). Under ice shelves in particular, the lack of bathymetric data, ice shelf draft measurements, observations of ocean-driven melt, and measurements of water mass modification and ocean circulation, limit the characterisation of ice-ocean interactions fundamental for predicting future change. Essential direct observations should therefore comprise: basal melt rates; ocean temperature, salinity, and circulation; high-resolution bathymetry on continental shelves and within ice shelf cavities; ice shelf geometry; subglacial topography; and improved characterisation of ice dynamic processes such as grounding zone migration and ice shelf calving. Addressing these needs will require the definition of essential state variables for each process, sustained investment in data assimilation approaches in both ocean and ice sheet models, and continued efforts to reconcile observations from different platforms and bridge the gap between models and observations (McCormack et al., 2024).

Knowledge gaps in sea ice thickness, motion, deformation, floe-size distribution, snow depth, and feedbacks between sea ice variability and glacial ablation inhibit reliable quantification and modelling of the interaction processes impacting the Southern Ocean and Antarctic Ice Sheet, reducing confidence in projections of sea ice distribution and thickness in coming decades (NAS, 2017). Understanding recent and near-future sea ice changes requires year-round, subsurface measurements of ocean temperature and salinity in the seasonal sea ice zone – variables that map directly onto WMO essential ocean variables – from a range of platforms including Argo floats, autonomous technologies, and satellite transmission systems to reduce the cost and effort of sustained monitoring. Routine evaluation of satellite-derived sea ice thickness and volume products, however, requires regular repeat in-situ observations of physical snow and ice properties from under-ice vehicles, sensors

within the sea ice and snow pack, and airborne sensors collocated beneath satellite altimeter or microwave radiometry overflights. Integrating these multi-platform observations into models remains a central challenge, and progress will depend on reconciling measurements across observational systems to deliver the consistent, long-term records needed to constrain sea ice model components.

Theme 2: Understanding and Quantifying the State and Variability of the Southern Ocean Circulation

The Southern Ocean plays a key role in regulating the global climate by controlling heat, carbon dioxide and other greenhouse gas exchanges between the atmosphere and the ocean (Rintoul, 2018). Yet, despite decades of research to develop an understanding of the underlying processes (Bennetts et al., 2024), the net exchange rates and other processes remain critically under-observed. The central element that impedes our ability to project decadal-to-centennial scale variability and change of ocean heat and carbon uptake and storage is our limited observational understanding of the rate at which oceanic water masses exchange heat and carbon with the atmosphere (Marshall and Speer, 2012). This limitation reflects a lack of sustained and process-resolving observations of key processes, including shelf circulation, ocean mixing, water mass transformation, deep water properties, and surface fluxes (Martin et al., 2026), which themselves depend sensitively on the strength of the overturning circulation, water mass transformation rates, and upper-ocean stratification and mixing. The Southern Ocean provides a preferential pathway for ventilation, with more than 70% of the world's ocean waters having had their last contact with the atmosphere in this region (Frölicher et al., 2015; Williams et al., 2024). Carbon and heat ventilation involve two main steps: ocean-sea ice-atmosphere fluxes at the ocean surface, and water mass circulation associated with the horizontal and vertical currents that form a three-dimensional overturning circulation. Both phenomena are sensitive to a range of complex dynamical processes, as well as to perturbations of Southern Hemisphere winds, sea ice dynamics and thermodynamics, and glacial melt patterns, including recent large-scale variability and events such as the 2016 and 2023 sea-ice anomalies, associated shelf freshening, and changes in Antarctic Bottom Water (AABW) formation. Recent observations suggest that these sensitivities are already manifesting as structural changes in Southern Ocean circulation, including changes in upper-ocean stratification, shifts in frontal systems, and changes in AABW formation (e.g., Silvano et al., 2023).

The Argo array has significantly advanced observations of the upper 2000 m of the Southern Ocean, leading to important progress in quantifying temperature and salinity changes and circulation dynamics, as well as in understanding and attributing those changes (Meredith et al., 2019; Suryawanshi et al., 2023), and increasingly supporting ocean state estimates and emerging data-driven approaches. However, many unknowns remain in documenting changes in the subpolar ocean, on the Antarctic continental shelf and at depths below 2000 m, and more generally in

understanding processes controlling the overturning circulation, such as interior mixing, subduction/upwelling processes, polynya dynamics, and the role of mesoscale/submesoscale eddies. In particular, many important interactions between the ocean and the cryosphere have been identified as central in controlling Southern Ocean water mass properties and circulation, but despite recent advances in observations in some regions (e.g., the Ross Sea; Falco et al., 2024), many of these processes remain poorly observed and understood (Abernathey et al., 2016; Haumann et al., 2016; Suryawanshi et al., 2023; Doddridge et al., 2025). Understanding how cryosphere-driven freshwater input modifies dense shelf water formation, lateral exchanges across the continental slope, meltwater transport pathways, inter-shelf sea exchange, and the strength of the overturning circulation is a critical priority for the coming decade. Recent analyses have documented a measurable decline and freshening of AABW in several sectors of the Southern Ocean (e.g., Shimada et al., 2022; Rintoul et al., 2025), underscoring the urgency of understanding the mechanisms driving these changes.

New satellite sensors and autonomous surface, airborne and subsurface instruments promise synoptic time-series observations of important aspects of the freshwater balance, including snow and ice thickness, ice shelf basal melt, and ocean circulation, which will provide substantial new information to advance our understanding of the Southern Ocean environment and fill in existing data gaps (Newman et al., 2019). However, these observations, particularly satellite-based ones, require validation and calibration against in situ observations, which places emphasis on the availability of a data system that provides access to curated observations. Sustained and integrated observing systems are therefore essential to detect and quantify climate-driven changes in dense shelf water formation, cross-shelf exchange, ice-shelf meltwater injection, coastal boundary currents, and abyssal ventilation. In particular, there is a critical and urgent need to expand observations beneath sea ice and during winter, where key processes remain largely unobserved. This includes the development and deployment of ice-capable platforms such as shelf-adapted floats, gliders, and other autonomous systems capable of operating under ice-covered conditions. These observational advances must be complemented by improved state estimates, data-assimilative modelling frameworks, and high-resolution simulations to reconcile observations with theory and quantify circulation variability and change.

Theme 3: Understanding and Quantifying the State and Variability of Southern Ocean Carbon and Biogeochemical Cycles

The Southern Ocean is the Earth's largest oceanic sink for natural and anthropogenic CO₂ (Khatriwala et al., 2009) and exerts a strong control on ocean fertility through macronutrient export and on global climate through CO₂ solubility and biological carbon pump (BCP) mechanisms (e.g., Sarmiento et al., 2004; Boyd et al., 2024). This role is underpinned by the combined action of the solubility pump, whereby cold, dense waters enhance CO₂ uptake and ventilate the ocean interior, and the BCP, which exports organic carbon to depth on climatically relevant timescales (Meredith

et al., 2025; Boyd et al., 2024). Yet the magnitude, variability and future trajectory of the Southern Ocean carbon sink remain uncertain under the combined effects of ice melt, winter outgassing, changing storm activity and climate variability (Bushinsky et al., 2019; Gray et al., 2018; Nicholson et al., 2022). Resolving these uncertainties requires a better understanding of how large-scale climate modes such as the Southern Annular Mode (SAM) and El Niño-Southern Oscillation (ENSO) teleconnections modulate Southern Ocean carbon uptake and biogeochemical variability over a range of timescales. These physical and climatic drivers interact with warming, enhanced upwelling and acidification may further alter CO₂ solubility, buffering capacity, carbonate saturation and calcifier-mediated carbon export (Bednaršek et al., 2012; Negrete-García et al., 2019; Figuerola et al., 2021). Iron (Fe) is a critical trace metal that limits productivity in large areas of the Southern Ocean. An increasing trend in photophysiological Fe stress has been observed that could reflect changes in mixed layer physics as well as complex biological and chemical feedbacks (Ryan-Keogh et al., 2023). As such, how the mode, magnitude and bio-availability of the Fe supply to Southern Ocean waters may change in the future needs quantification. Sea ice and glacial meltwater rates will impact Southern Ocean biogeochemistry differently depending on region (Arrigo et al., 2015; Hernando et al., 2015). Any adjustments in sea-ice dynamics (extent, thickness, snow cover, variability) that regulate stratification, light availability and nutrient supply (e.g., Fe) are likely to impact biogeochemistry. The co-location of nutrient fluxes and enhanced stratification from sea ice melt has long been hypothesised to drive marginal ice zone blooms (e.g., Sedwick & DiTullio, 1997). While some studies suggest substantial coastal Fe inputs from glacial meltwaters (Arrigo et al., 2015; Herraiz-Borreguero et al., 2016; Jones et al., 2025), other studies highlight sediment resuspension and Circumpolar Deep Water as primary sources of Fe to some regions (St-Laurent et al., 2017; Dinniman et al., 2020).

For a large part of the Antarctic shelf, studies have already shown a shift in phytoplankton community composition, including declines in diatom abundance associated with changing sea ice regimes (Hayward et al. 2025), with important implications for carbon cycling and energy transfer. Widespread changes in phytoplankton phenology have also been observed (Thomalla et al., 2023), which have the potential to de-synchronise trophic interactions negatively affecting higher trophic levels that rely on plankton as their principal food source. Community composition further shapes the fate of carbon and energy transfer with different taxa having specific ecological roles (Shadwick et al., 2025).

Dissolved organic matter (DOM) plays an important role in sustaining the microbial loop in the photic zone, including in the seasonally sea-ice covered regions of the Southern Ocean, impacting biogeochemical cycling e.g., through influencing trace metal bioavailability. Critical research priorities include improving our understanding of spatial and seasonal variability in the chemical composition of DOM, which regulates the availability of labile carbon, the turnover of organic matter, the

bioavailability of trace metals, photoreactivity, sea-ice properties, and optical characteristics of surface waters (Boye et al., 2001; Hirose, 2007; Norman et al., 2011; Müller et al., 2013; Ardiningsih et al., 2021; Bercovici et al., 2023). The role of organic gels such as transparent exopolymer particles (TEP) is also not clearly understood.

Marine microbes readily utilise most of the organic carbon being exported, producing CO₂ through the microbial loop. However, a small percentage (~5–7%) of microbially produced dissolved organic carbon is recalcitrant (RDOC), enhancing export by aiding the transfer of carbon to the oceans' interior (the microbial pump) (Jiao et al., 2024). However, the response of the microbial pump, and its interaction with the BCP, to Southern Ocean warming and acidification is uncertain (Jiao et al., 2010; Legendre et al., 2015). Microbes (including bacteria, fungi, and viruses) also play an important role in regulating biogeochemical processes of C, N, Si, P, Fe, and S, through e.g., production of ligands that bind with metals (Hassler et al., 2011; Sinha et al., 2019), which chelate trace metals (e.g., Fe) and impact their bioavailability.

Zooplankton also play a crucial role in the Southern Ocean BCP (Cavan et al., 2019; Halfter et al. 2020; Cavan et al., 2024). Zooplankton can enhance the export and sequestration of carbon in the ocean interior (Boyd et al., 2024) by converting surface phytoplankton production into fast-sinking particulate organic carbon (POC) via fecal pellet and moult production (Manno et al., 2020), carcasses (Halfter et al. 2021), and by actively transport via vertical migration (Baker et al, 2025, Yang et al., 2025). Conversely, zooplankton can reduce C export by remineralising POC in the upper ocean through grazing and respiration, fragmenting and slowing sinking particles, and retaining carbon within the food web. The role that fish play in oceanic carbon flux has yet to be quantified (Saba et al. 2021; Manno et al. 2024).

Biogeochemical measurements in the Southern Ocean are hampered by the remoteness and extreme conditions of the region resulting in data gaps at regional, seasonal and decadal scales. These data limitations are, in part, responsible for significant disconnects that have been identified between modelled and observational biogeochemical datasets (e.g., Gray, 2024) and need to be addressed for improved process-level understanding and future predictions (Boyd et al. 2024). For example, long-term monitoring of the biological fixation and removal of atmospheric CO₂ via sedimentation of particles to the deeper waters is crucial. Southern Ocean time series are sparse, and the Southern Ocean Time Series (SOTS, Shadwick et al, 2025) is the only program that includes long-term sedimentation datasets (Halfter et al. 2025). How primary productivity (e.g., Leung et al., 2015) and carbon export (Cabr   et al., 2015; Moore et al., 2018) will vary spatially and seasonally remains unclear, especially in ice-covered areas; this uncertainty is further complicated by knowledge gaps related to the cycling of nutrients (e.g., Fourquez et al., 2020; Mduyana et al., 2020) and potential shifts in phytoplankton dynamics (Deppeler & Davidson, 2017).

Autonomous platforms have greatly enhanced the availability and quality of biogeochemical data available for the Southern Ocean (Bushinsky et al., 2019; Sutton et al., 2021), including for important winter observations (Halfter et al., 2025). Sediment trap flux estimations are key to our understanding of climatically-driven changes in the composition and quantity of carbon export. However, the deployment and recovery of equipment in the Southern Ocean, particularly in the seasonal sea ice zone, is challenging, and only a few long-term observing platforms have been established in ice-covered areas, e.g., the Palmer Long-Term Ecological Research programme (Palmer LTER, Ducklow et al., 2007), the Scotia Sea Open Biological laboratories (SCOOBIES) and the Rothera Oceanographic Times Series (RaTS, Venables et al., 2023) west of the Antarctic Peninsula. The BGC-Argo programme (Johnson et al., 2017a), ice-capable floats (Johnson et al., 2017b), tagging of marine mammals by the Marine Mammals Exploring the Oceans Pole to Pole (MEOP) programme (Roquet et al., 2014), SOCCOM (Sarmiento et al., 2023), SO-CLIM and uncrewed surface vehicles (e.g., Saildrone; Sutton et al., 2021; Patterson et al., 2025), have vastly increased the number and temporal coverage of the available observations. The development and improvement of new satellites (e.g., Sentinel-3A OLCI sensor) and in situ sensors (e.g., nitrate) are necessary to enhance the quantity and quality of Southern Ocean data. Leveraging emerging tools, including machine learning, environmental genomics, compound-specific isotope techniques, and high-resolution regional modelling are crucial to advance understanding of Southern Ocean biogeochemistry.

Ship-based programmes like GO-SHIP and GEOTRACES also remain essential, both for providing full-depth, climate-quality reference measurements that underpin the calibration and validation of autonomous sensors (Sloyan et al., 2019; EuroGO-SHIP Deliverable 2.2, 2025), and for delivering intercalibrated trace-element and isotope datasets (Aguilar-Islas et al., 2024). In regions that remain difficult to access with autonomous platforms, sustained icebreaker-based observations in the marginal ice zones are also critical for validating autonomous sensors and ensuring a precise understanding of year-round biogeochemical dynamics in the Southern Ocean.

Theme 4: Understanding and Quantifying the State and Variability of Southern Ocean Ecosystems and Biodiversity

The circumpolar Southern Ocean is strongly affected by the seasonal advance and retreat of sea ice, which in turn contributes to the regional heterogeneity of Southern Ocean food webs (Ducklow et al., 2006; Massom & Stammerjohn, 2010; Ducklow et al., 2013). Variability in the physical environment can lead to changes in productivity through biogeochemical linkages (e.g., see Theme 3). During the past few decades, the oceanographic and cryospheric characteristics of the Southern Ocean have changed with consequences for ecosystems, such as declines in diatoms with a concomitant increase in gelatinous plankton and decreased Antarctic krill abundance in the Atlantic sector (Atkinson et al., 2004; 2019; Meredith et al., 2019), as well as

changes in phytoplankton phenology, primary production and phytoplankton size structure and composition (Montes-Hugo et al., 2008; 2009; Mendes et al., 2013; Schloss et al., 2014; Moreau et al., 2015; Schofield et al., 2017; Mendes et al., 2018; Ferreira et al., 2020; Thomalla et al., 2023; Ryan-Keogh et al., 2023; Hayward et al. 2025). Such changes have the potential to negatively impact the survival rate of zooplankton and larval fish populations (e.g. if prey availability decouples from critical life stages) with important implications for key species whose timing of spring migrations and breeding success relies heavily on the quantity and quality of marine food sources. The impact on higher predator populations has already been reported, e.g., the decline in penguin populations due to a decline in krill abundance in the West Antarctic Peninsula and Scotia Arc (Trivelpiece et al., 2011; Barbosa et al., 2012). Furthermore, upper trophic level predators are also directly impacted by the loss of habitat due to declining sea ice, e.g., Emperor penguins (Fretwell et al. 2025).

Microbes (including bacteria, fungi, and viruses) play an important role in regulating biogeochemical processes. The interplay between phytoplankton, bacteria, DOM, and microzooplankton fuels the microbial loop, which may be critical for the sustenance of zooplankton during austral summers (Evans et al., 2021). The bacterial diversity dataset is spatially patchy and temporally scarce. The impact of increased melting on marginal sea-ice microbial communities is not clearly understood. Similarly, marine fungi also have an important role in marine food webs (Breyer and Baltar, 2023), including the Southern Ocean where fungi seem to be key microorganisms in remineralization processes in intermediate-deep waters such as Circumpolar Deep Water (López-García et al., 2001; Mestre et al, 2026). However, the studies of marine viruses and marine fungi from the Southern Ocean are scarce. Addressing their diversity in the sea-ice, surrounding waters and sediments would help understand their role in the Southern Ocean. The data on microbial biomass, heterotrophy, turnover of organic matter, and trophic dynamics can feed the carbon dynamics (Theme 3) and would be useful in addressing cross-cutting challenges.

In addition to changes associated with sea-ice loss, benthic communities, which play a key role in blue-carbon storage, and provide habitat for commercially important species, are highly vulnerable to multiple drivers of change, including ocean warming, increased iceberg scour, ocean acidification, fishing pressure –through physical disturbance of the seabed, bycatch of habitat-forming species, and altered benthic food-web dynamics, pollution and the introduction of non-native marine species (Brasier et al., 2021, McCarthy et al., 2019). Particularly sensitive regions include the rapidly warming West Antarctic Peninsula (Steig et al. 2009), subantarctic islands and high-traffic tourist areas (e.g., West Antarctic Peninsula), as well as intensively fished regions such as South Georgia and the Heard and McDonald Islands (Brasier et al., 2021). Vulnerable taxa include species with narrow thermal tolerance ranges and limited acclimation capacity (e.g., Morley et al., 2009), calcifiers susceptible to acidification (Figuerola et al., 2021), and slow-growing habitat-forming organisms such as sponges, bryozoans and corals. Accurate estimates of biomass

and biodiversity and patterns across all trophic levels are essential to assess the impacts and responses of climate change (Murphy et al., 2012; Rogers et al., 2020). For benthic systems, this challenge is amplified by the high spatial heterogeneity of seafloor habitats, which makes large-scale assessments particularly complex (Brasier et al., 2021, Halfter et al., 2025).

Models have shown changes in biomass estimates can have cascading impacts on dependent predators (Xavier et al., 2013). Improved observations of key mid-trophic level species that have a major influence on food web structure and biogeochemical processes are fundamental for projecting impacts of change (Murphy et al., 2016; McCormack et al., 2021). Upper-trophic-level predators are among the most effective biological indicators of Southern Ocean ecosystem change because they integrate environmental variability across large spatial and temporal scales. Seabirds and marine mammals respond to changes in prey abundance, oceanographic conditions, and habitat availability, making them valuable sentinels of ecosystem status and productivity. Observations of top predators as sentinels of change (Bestley et al., 2020) remain critical to assess these changes in community structure derived from environmental stressors, using measures such as diet composition, foraging success, habitat use, reproductive success, phenology, growth rates, and population stability (e.g., Ducklow et al., 2013; Hinke et al., 2017; Colominas-Ciuró et al., 2021). Indeed, regional diversity of environmental stressors and their impacts and differences in thermal tolerance and plasticity create a complex field of "winners and losers" with respect to faunal abundance and distributions (Clucas et al., 2014; Griffiths et al. 2017).

Human activities in Antarctica have increased substantially over recent decades, leading to a growing direct human footprint associated with fisheries, tourism, scientific research, and the expansion of coastal research infrastructure. Ship traffic represents one of the main pathways through which Antarctica is connected to global ecosystems, with vessels supporting tourism, fishing operations, cargo supply, and scientific research increasingly traversing Antarctic waters (Stark et al., 2023). These activities generate multiple environmental pressures, including the introduction of non-native species through ballast water and hull fouling, underwater noise, wildlife disturbance, atmospheric emissions, operational discharges, and marine debris such as plastics (McCarthy et al., 2021). Similarly, fisheries activities can have ecosystem-wide consequences through bycatch, and alteration of Southern Ocean food-web dynamics. Past and current harvesting of Southern Ocean living resources and subsequent recovery of some species, such as whale and seal populations, further introduce confounding effects in determining cause and direction of change (e.g., Murphy, 1995). Although environmental management practices have improved substantially under the Antarctic Treaty System and the Protocol on Environmental Protection, contamination and ecological disturbance can persist for decades in Antarctic environments due to slow degradation rates and limited ecosystem recovery (Senigaglia et al., 2026). Understanding and monitoring the direct human footprint in Antarctica is therefore critical for supporting evidence-based

conservation, environmental management, and sustainable governance of the Southern Ocean region. The combination of increasing human activities, together with rapid climate change, is likely to intensify cumulative pressures on Antarctic ecosystems (Hunter et al. 2024).

Addressing these challenges requires sustained observations that capture population changes of key species, their spatio-temporal changes and/or the overall food web structure. Therefore, long-term monitoring of predator populations can reveal ecosystem shifts that may not be immediately detectable through lower-trophic-level observations alone. A major limitation is that environmental and biological datasets are still patchy in space and time, making it difficult to derive reliable estimates of many ecosystem processes (Brasier et al., 2021). Beyond these spatial and temporal gaps, a further challenge lies in the limited standardisation of what should be collected at broad scales. The definition and adoption of biological Essential Ocean Variables (eEOVs) provide a framework for guiding coordinated and sustained observing efforts. However, reaching community-wide agreement on priority variables remains a complex and ongoing process, and one that is fundamental to the development of any truly integrated biological observing system. More sustained and intensive data collection and inclusion of newer forms of datasets addressing (i) better standardisation of net sampling for mid-trophic players (Kaartvedt et al., 2020), (ii) improved models to convert acoustic backscatter data into biomass (Proud et al., 2019), and (iii) complexities identified in developing integrated modelling frameworks, including distribution models, process-based models, and food-web models (Murphy et al., 2012) are important. Understanding and predicting ecosystem responses to change will require a suite of complementary modelling approaches, each with their respective strengths and limitations. The key challenge lies in integrating these complementary tools that draw on physical, chemical and biological information and explicitly account for species' physiological limits and their capacity to adjust to shifting conditions, to build a holistic, weight-of-evidence picture of ecosystem dynamics across multiple trophic levels. Close coordination among disciplines will also be essential to ensure that observations are collected in compatible ways and at scales that allow ecosystem change to be interpreted more holistically (Brasier et al., 2021).

Key gaps to be addressed in biological observations also include production in the habitats beneath and within sea ice, temporal expansion of observations (year-round and winter series), co-located and coincident sampling (e.g., net & core sampling, acoustics, profiles, predator observations), and measures of diversity and relative biomass of key taxa, links and nutrient flux rates. Identifying priority regions and representative taxa or functional groups that can serve as early indicators of change, together with the adoption of consistent performance metrics, will greatly improve our capacity to detect and understand ecological functions and responses. Monitoring of biodiversity in areas subjected to high variations in both terrestrial and marine environmental conditions is crucial for understanding the impact of rapidly

progressing changes. Such efforts should be paired with sustained observations in areas of comparatively low variability, which serve as essential reference baselines against which the magnitude and direction of change can be contextualised and interpreted. Observation systems must work towards being integrated end-to-end, from virus, bacteria, archaea and primary producers through zooplankton, and fish to top predators and seafloor fauna, aiming to provide a quantitative understanding of the impacts of change on Southern Ocean ecosystems. Such observation systems are integral for developing and constraining models for Southern Ocean ecosystems. Strengthening the bidirectional link between observations and models across all trophic levels is essential both to improve model performance and to guide observational priorities identifying key drivers in these ecosystems. This necessitates integrated and joint modelling approaches capable of synthesising diverse data sources, including the growing body of historical observations alongside data from new platforms, methods and evolving survey designs. Fostering such integration should be developed in close coordination with the modelling approaches discussed below.

Theme 5: Understanding and Quantifying the State and Variability of Southern Ocean-Sea Ice-Atmosphere Fluxes

Theme 5 integrates across the other Themes through its focus on fluxes (e.g., heat, freshwater, momentum, carbon and other climate-active gases) across the ocean-sea ice-atmosphere-land interfaces and the implications for physical, biogeochemical and biological exchanges. These fluxes manifest in each of Themes 1-4, as well as throughout this cross-cutting theme, reflecting the integrated nature of the system. Southern Ocean fluxes of heat, momentum, freshwater, carbon are key components of the global ocean and climate system. The Southern Ocean heat uptake now accounts for $83 \pm 33\%$ of the total oceanic heat uptake and $\sim 43 \pm 3\%$ of the global oceanic uptake of anthropogenic CO_2 (Williams et al., 2024). The Southern Ocean also regulates the uptake and emission of other climate-active gases such as methane (CH_4), nitrous oxide (N_2O), halocarbons, isoprene and dimethyl-sulphide (DMS) (e.g., Curran and Jones, 2000; Nevison et al., 2005; Römer et al., 2014). However, there are significant regional and seasonal differences as well as considerable uncertainties in our estimations and understandings of them (Bushinsky et al., 2019).

Several studies suggest that Southern Ocean CO_2 uptake declined in recent decades (e.g., Yoshikawa-Inoue & Ishii, 2005; Le Quéré et al., 2007; Takahashi et al., 2012; Lenton et al., 2013), followed by a reinvigoration in 2012 (Landschützer et al., 2015). However, estimates of the Southern Ocean carbon sink derived from different methods and datasets, such as bulk air-sea flux calculations, eddy covariance measurements, and interior carbon accumulation, often disagree substantially (Hauck et al. 2023a; Zhong et al., 2025; Friedlingstein et al., 2025). At the same time, discrepancies between models and observations continue to increase (Hauck et al., 2020; Hauck et al., 2023a; Gregor et al., 2024), and the drivers of this divergence remain unclear. It highlights the need to better constrain the processes controlling

ice-ocean-air exchange and to improve the methods used to measure and parameterise surface carbon fluxes in models. Physical climate variability further complicates the Southern Ocean air-ocean carbon and anthropogenic carbon flux. Strengthened winds and enhanced upwelling can increase CO₂ outgassing from carbon-rich deep waters, while ocean warming reduces CO₂ solubility and ocean acidification weakens buffering capacity. The influence of large-scale climate modes, including the SAM, ENSO, and shifts in Antarctic Circumpolar Current dynamics, on carbon uptake across multiple timescales also remains uncertain.

A major limitation causing these challenges is the scarcity of direct observations. The available measurements are concentrated in the ice-free areas during austral summer, while observations in other seasons and environments, including areas covered by sea ice in winter, the ice-melting season, the marginal sea ice zone, polynyas/leads, and storms remain extremely limited (Gray et al., 2018; Monteiro et al., 2020; Nicholson et al., 2022; Carranza et al., 2024; Zhang et al., 2024). This lack of systematic monitoring hinders process understanding and leads to seasonal biases that limit our ability to accurately quantify annual air-sea carbon fluxes across the Southern Ocean (Bushinsky et al., 2019; Fay et al., 2025; Zhong et al., 2025). This poses a challenge for investigating the behavior of the carbon flux between the atmosphere and the ocean at complex interfaces, as well as its responses to extreme events, long-term trends, and future evolution. No less important is understanding how the fluxes of CO₂ and other climate-active trace gases and aerosol precursors (e.g., N₂O, CH₄, DMS, VOCs) behave at the ocean-sea ice-atmosphere interface of the Southern Ocean (Thomas et al., 2019). Recent observations suggest that the Southern Ocean may act as a methane source (Workman et al., 2024; 2025; Seabrook et al., 2025; Holthusen et al., 2025). A growing array of autonomous platforms (wave gliders, uncrewed surface vehicles, BGC-Argo floats) and sensor integration onto sailing boats, are aimed at helping to close these observational data gaps. In addition, recent years have seen an explosion in the amount of machine learning-based air-sea fluxes reconstructions (e.g. DeVries et al., 2023; Zhang et al., 2025; Zhong et al., 2025), the performance and limitations of which are being assessed in the coming years.

Major challenges exist to understand the behaviour of turbulent fluxes and reduce the uncertainties in knowledge obtained through studies based on physical parameterisations and through satellite data. In situ measurements of heat, moisture, and momentum are required to determine accurate estimates of the ocean-sea ice-atmosphere turbulent fluxes, yet are sparse and often non-existent over the Southern Ocean (Villas Bôas et al., 2015; Santini et al., 2020; Swart et al., 2023). At present, many of the transfer coefficients used in these flux parameterisations are from studies based on the observations in the tropical regions, but their applicability in the polar regions remains questionable (Fairall et al., 2003; Wanninkhof, 2014; Hackerott et al., 2018; Bharti et al., 2019; Santini et al., 2020; Pezzi et al., 2021). This has constrained the development of remote sensing products, parameterization schemes, and emerging AI models for turbulent fluxes (Bourassa et al., 2013; Pinker et

al., 2014; Swart et al., 2019), leading to persistent gaps in understanding ocean-sea ice-atmosphere interactions and their trends in the Southern Ocean (Meredith et al., 2019; Newsom et al., 2023; Prend et al., 2025). The influence of sea ice processes (e.g., formation or melting) on turbulent heat and gas fluxes is also generally overlooked in parameterisation schemes (Butterworth & Miller, 2016; Bharti et al., 2019; Loose & Schlosser, 2011; Rutgers van der Loeff et al., 2014). Furthermore, the short time- and length-scale variability of air-sea fluxes makes quantifying exchanges challenging (Lenton et al., 2006; Monteiro et al., 2015), particularly in regions with varying ocean-atmosphere dynamics (e.g., Boundary Currents; Villas-Bôas et al., 2015), regions of higher energetics (e.g., Drake Passage; Song et al., 2016), and the complex marginal sea ice zone (Butterworth & Miller, 2016; Zhang et al., 2025). Poorly constrained air-sea exchange in these regions is likely to have consequences for our projection of long-term heat and CO₂ uptake in the Southern Ocean.

Progress in addressing these challenges requires international agreement on effective and best practice methodologies, priorities on observations (essential climate variables and sites) and observational strategies (Swart et al., 2019; Prend et al., 2025). The emerging consensus on the significant role for short-term (or extreme) events calls for a measurement strategy that resolves those scales, which are often missed by bulk formulae for the Southern Ocean based on wind products that underestimate strong wind events (Nickford et al., 2024; Russel et al., 2021). These will ultimately lead to reduced bias between direct observations and bulk formulas (Santini et al., 2020; Pezzi et al., 2021) and improvements in the long-term air-sea exchange projections due to an improved time-integrated view of these short-term events. Improved flux estimates across both the ice-free and ice-covered Southern Ocean will need to identify and improve observing system design (e.g., Mazloff et al., 2018; Wei et al., 2020; Zhang et al., 2025) as well as taking advantage of ships, coastal research stations, surface moorings, and the growing capabilities of autonomous platforms such as Saildrones, Wave Gliders, Argo-like floats, drifting spar buoys, and drones with eddy covariance systems (Monteiro et al., 2015; Swart et al., 2020; Sutton et al., 2021; Edholm et al., 2025). These technological advancements have created the opportunity for process studies under various atmospheric conditions and at times of the year otherwise not suited for ship expeditions. These comparatively low-cost platforms justify targeted field campaigns that measure flux variables at length scales of order 1 km and time scales of hours (e.g., Swart et al., 2020). Data practices for data handling and quality assurance for these low-cost platforms are developing alongside these technological developments; for example, Saildrone data is now available in SOOSmap.

Key Science Challenges

Specific priorities for the Southern Ocean community are outlined as Key Science Challenges (Table 1). These Key Science Challenges include both shorter (≤ 5 years) and longer (5-10 years) term challenges, and encompass the scientific drivers of a Southern Ocean observing system. Many of these drivers are cross-disciplinary across multiple Science Themes, thus within the table below many Key Science Challenges cross-cut across two or more Science Themes.

IN REVIEW

Table 1: Key Science Challenges with the Science Theme(s) it addresses and key international initiatives contributing to addressing each challenge (darker blue is directly contributing and lighter blue is less directly benefiting but still contributing). International initiatives include other international programs, coordinating bodies or large projects. Acronyms at the end of the document.

Key Challenges	Theme 1: Cryosphere	Theme 2: Circulation	Theme 3: Carbon & Biogeochemical Cycles	Theme 4: Ecosystems & Biodiversity	Theme 5: Ocean-Sea Ice -Atmosphere Fluxes	International Initiatives Addressing Challenges
Understand changes in the Antarctic Ice Sheet, especially movement of the grounding zone, and its impact on global sea level to improve projections and predictions of future states						Antarctica InSync Theme 3 (WG Ice Shelf-Ocean Interaction; Past Present & Future SMB of Antarctic Ice Sheets), Theme 7; grounding line retreat rates; JCIOL, ice sheet mass balance estimates; IODP and ice sheet drilling projects; IMBIE; modelling community; SCOR ORCAS Working Group; SCAR RINGS Action Group and INSTANT SRP
Increased coverage of subglacial and continental shelf bathymetry to improve: - Understanding of ocean heat pathways to ice shelves - Antarctic ice sheet and ocean modelling capabilities - Understanding of cross-shelf exchange of heat, salt, and biogeochemical tracers by the ocean - Quantification of ocean-driven ice shelf melt						Antarctica InSync Theme 1 (WG Surface Salinity, Carbon Cycling, Coastal Connection, Antarctic coastal hotspots), Theme 3 (WG Ice Shelf-Ocean Interaction; Past Present & Future SMB of Antarctic Ice Sheets); AniBOS; Argo; IBCSO; JCIOL; NECKLACE; Seabed2030;

						SCAR Bedmap3 Action Group and RINGS Action Group
Understand cryosphere–ocean interactions beneath Antarctic sea ice and ice shelves, with emphasis on: - Spatial and temporal variability in under-ice ocean properties, circulation, and mixing, including the role of polynyas and leads - Ocean heat access to ice-shelf cavities and grounding zones, and its influence on basal melt and ice-sheet mass balance - Heat and freshwater exchange between the ocean, sea ice, and ice shelves, including the impacts of sea-ice loss and meltwater input						Antarctica InSync Theme 1 (WG Surface Salinity, Carbon Cycling, Coastal Connection, Antarctic coastal hotspots), Theme 2, Theme 3 (WG Ice Shelf-Ocean Interaction; Past Present & Future SMB of Antarctic Ice Sheets and OASIS WG); Argo; AniBOS; CLIVAR; CMEMS; JCIOL; NECKLACE; CLIVAR SOFIA; CLIVAR/CliC/SCAR SORP; SCAR ASPeCt and FRISP Expert Groups; INSTANT and AntClimNOW SRPs; SCOR SOLAS Research Project and ORCAS Working Group

Understand dynamical processes in the Southern Ocean and their likely future changes, with emphasis on: - Water-mass transformation, upwelling and subduction, and the roles of isopycnal/diapycnal mixing and mesoscale to submesoscale processes - Lateral exchanges between the continental shelf, slope, and deep basin, including heat and freshwater transports by major marginal current systems such as the Antarctic Coastal Current and Antarctic Slope Current, and processes controlling dense shelf water export - Stability and variability of the Southern Ocean overturning circulation, frontal systems, and subpolar gyres in response to changes in winds, sea ice, surface buoyancy forcing, ice-shelf melt, and ocean warming - Responses of Southern Ocean circulation, water-mass transformation, and ventilation to extreme atmospheric and oceanic forcing, including atmospheric rivers, persistent wind anomalies, and freshwater pulses					Antarctica InSync Theme 1 (WG M&M's, Surface Salinity, Carbon Cycling, Coastal Connection, Antarctic coastal hotspots), Theme 2, Theme 3 (WG Ice Shelf-Ocean Interaction; Past Present & Future SMB of Antarctic Ice Sheets), Theme 6; AniBOS; Argo; CLIVAR/CliC/SCAR SORP; CLIVAR SOFIA; CMEMS; ; DBCP; GO-SHIP; OceanSITES; SCAR AntClimNOW SRP
Resolve the Southern Ocean freshwater budget and understand how climate-driven changes in cryosphere-derived freshwater input and surface fluxes affect ocean stratification, sea-ice formation, water-mass formation, circulation, and ventilation. This includes: - Spatial distribution, seasonal cycle, and interannual variability of Antarctic freshwater sources - Modification of surface freshwater and heat budgets under the post-2015 low sea-ice regime - Impacts of freshwater inputs from different source regions on stratification, sea-ice formation, dense shelf water formation, Antarctic Bottom Water properties, and abyssal ventilation - Climate-driven changes in stratification, convection, vertical exchange, and extreme ocean surface conditions					Antarctica InSync Theme 1 (WG M&M's, Surface Salinity, Carbon Cycling, Coastal Connection, Antarctic coastal hotspots , Theme 2, Theme 3 (WG Ice Shelf-Ocean Interaction; Past Present & Future SMB of Antarctic Ice Sheets), Theme 6; AniBOS; Argo; CLIVAR/CliC/SCAR SORP; CLIVAR SOFIA; CMEMS;

such as marine heatwaves, particularly during winter and under sea ice - Changes in winds, surface buoyancy forcing, horizontal circulation, frontal systems, and shelf-slope exchanges, and their implications for regional circulation and heat/carbon redistribution						DBCP; GO-SHIP; OceanSITES; SOFIA; SCAR AntClimNOW and INSTANT SRPs; ASPeCt, BEPSII and FRISP Expert Groups; SCOR SOLAS Research Project
Understand Southern Ocean heat, freshwater and carbon exchange and storage under global warming, and their effects on the global ocean. This includes: - Large-scale structure and variability of Southern Ocean heat, freshwater, and carbon storage and circulation - Production and export of Antarctic Bottom Water and its role in abyssal ventilation and deep-ocean heat and carbon uptake - Upwelling and onshore transport of deep water and their implications for heat, freshwater, and carbon exchange. - Formation and subduction of Subantarctic Mode Water and Antarctic Intermediate Water - Oceanic implications of spatial and temporal variability in polynyas						Antarctica Insync Theme 1 (WG M&Ms, Surface Salinity, Carbon Cycling, Coastal Connection, Antarctic coastal hotspots); AniBOS; Argo; CMEMS; CLIVAR/CliC/SCAR SORP; CLIVAR SOFIA; DBCP; GO-SHIP; IBCSO; OceanSITES; Seabed2030; SOCAT; SOCCOM; SOCONet; SCAR AntClimNOW SRP; SCOR SOLAS Research Project
Greater emphasis is required on how large-scale climate modes such as the Southern Annular Mode (SAM), ENSO teleconnections, and shifts in Antarctic Circumpolar Current dynamics modulate Southern Ocean carbon uptake and biogeochemical variability						Antarctica Insync Theme 1 (Carbon Cycling); Argo; CLIVAR/CliC/SCAR SORP; Global Carbon Project; IOCCG; IOCCP; SOCAT; SOCCOM; SOCONet; SCAR AntClimNOW SRP; SCOR SOLAS Research Project
Assess the extent and impact of ocean acidification across the Southern Ocean and the influence on the Carbonate Pump						Argo; Global Carbon Project; GOA-ON; SOCAT;

						SOCOM; SOCONet
Evaluate the contribution of seasonally ice-covered areas to carbon uptake and export						Antarctica InSync Theme 1 (WG Carbon Cycling); Argo; Global Carbon Project; IOCCG; IOCCP; SOCAT; SOCOM; SOCONet SCAR BEPSII Expert Group; SCOR SOLAS Research Project;
Determine the key drivers of primary productivity, community composition, phenology and the Biological Carbon Pump (temperature, light, stratification, circulation, and supply of micro- and macronutrients) and assess ongoing changes in these parameters						Antarctica InSync Theme 1 (WG Coastal Connection, Carbon Cycling, M&M's, Surface Salinity); AniBOS; Argo; BIOPOL; Global Carbon Project; GO-SHIP, GEOTRACES; IOCCG; SOCAT; SOCOM; SOCONet
Quantify the impact of recycling and remineralisation, including via the Microbial Loop and Microbial Carbon Pump, on nutrients, trace metals, and carbon cycling						Antarctica InSync Theme 1 (WG M&M's, Carbon Cycling); Argo; GEOTRACES; SOCOM
Quantify the role of zooplankton and fish community structure and behaviour in regulating carbon export efficiency and understand how climate-driven changes alter this zooplankton-mediated carbon export						Antarctica InSync Theme 4; CCAMLR; ICED; JGOFS; PHOCIS; SO-CPR; SCAR Ant-ICON SRP; SCAR SCARFISH Action Group
Improve model parameterizations for phytoplankton and zooplankton by integrating observations of phytoplankton photophysiology, size structure, and stoichiometry, along with zooplankton grazing, migration, and loss rates, to enhance						Antarctica InSync Theme 1, Theme 4; Argo; IOCCG; ICED; SCAR Ant-ICON SRP

representation of biological processes in carbon cycle models						
Identify and quantify the key drivers of change and their impacts on Southern Ocean ecosystems, including vulnerable taxa, food webs and biogeochemical cycling, at circumpolar and regional scales, with emphasis on the effects of changing Southern Ocean conditions on key species that are central to Southern Ocean food webs (e.g., Antarctic krill, Antarctic silverfish, upper trophic level species)						Antarctica InSync Theme 1 (WG Coastal Connection, M&Ms) Theme 4 (WG SO-BEDS, PREDYCT, ECOSENT); AniBOS; BGC-Argo; CCAMLR; ICED; MAPPPD; PHOCIS; SO-CPR; SCAR Ant-ICON SRP; AntOBIS/SCAR Antarctic Biodiversity Portal; SCARFish Action Groups; SKEG and EG-BAMM Expert Groups
Determine how changes in phytoplankton productivity, timing and community composition, and associated shifts in zooplankton and microbial communities, impact carbon export, benthic communities, alter food-web structure and energy transfer to higher trophic levels, with consequences for their nutritional condition, reproductive success and survival.						Antarctica InSync Theme 1 (WG Coastal Connection, M&Ms), Theme 4 (WG SO-BEDS, PREDYCT, ECOSENT, MESO); SO-CPR; SOTS; AntOBIS/ SCAR Antarctic Biodiversity Portal; SCAR SKEG Expert Group
Constrain the multi-scale variability of the Southern Ocean CO ₂ sink and Essential Climate Variables across diverse regions and timescales, including seasonal biases, while quantifying the role of sea-ice variability in ocean–sea ice–atmosphere fluxes and regional heat and carbon budgets, and reducing uncertainties in associated physical and biogeochemical processes						Antarctica InSync Theme 1 (WG Carbon Cycling , M&M's, Coastal Connection, Antarctic coastal hotspots); AniBOS; CATCH; CMEMS; Global Carbon Project; GO-SHIP; Global Carbon Project; SOConet; IOCCP;

					SOCAT; SOLAS; SORP; SOTS; SCAR AntClimNOW SRP; ASPeCt and BEPSII Expert Groups
Assess the spatial, seasonal and interannual distribution of climate-active gases and halogens in ice-covered and ice-free waters, and increase the coverage of measurements of fluxes in climate relevant gases other than CO ₂ (e.g., N ₂ O, CH ₄ , DMS, halogens, isoprene)					Antarctica InSync Theme 1, Theme 5, Theme 6; CMEMS; CATCH, WCRP; SCAR AntClimNOW SRP; ASPeCt and BEPSII Expert Groups; SCOR SOLAS Research Project
Characterize biodiversity patterns in response to climate change and human activities across benthic and pelagic ecosystems, accounting for regional heterogeneity, multiple stressors (warming, acidification, fishing, pollution, non-native marine species), and differences in species' thermal and acidification tolerance and plasticity					Antarctica InSync Theme 4 (WG PREDYCT, ECOSENT), Theme 5, Theme 7; AniBOS; CMEMS; ICED; MAPPPD; SO-CPR; SCAR Ant-ICON SRP; SPEG and EG-BAMM Expert Groups; AntOBIS/SCAR Antarctic Biodiversity Portal
Assess past, present and projected distributions of species and habitats in relation to Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Marine Protected Area (MPAs) and climate change, integrating historical baselines, ongoing environmental change and future scenarios					Antarctica InSync Theme 4 (WG SO-BEDS, PREDYCT, ECOSENT), Theme 5; AniBOS; CCAMLR; ICED; PHOCIS; SO-CPR; SCAR Ant-ICON SRP; AntOBIS/SCAR Antarctic Biodiversity Portal; EG-BAMM Expert Group

Quantifying the cumulative impacts for the ecosystem of direct (fishery, tourism, research) and indirect (climate change) activity, and understanding ecosystem sensitivity and resilience						Antarctica InSync Theme 5; AniBOS; CCAMLR; ICED; PHOCIS; SO-CPR; SCAR Ant-ICON SRP; AntOBIS/SCAR Antarctic Biodiversity Portal; EG-BAMM Expert Group
Evaluate and optimize observational sampling strategies, including instrument configuration, platform motion corrections, and sampling frequency. Increase long-term and extreme event observations of air-sea flux with emphasis on process understanding: - Varying conditions imposed by wind patterns, storms, sea ice and sea state (including polynyas/leads) - Regions and times (winter) of high uncertainty in reanalysis products - Frontal regions with elevated ocean small-scale dynamics						Antarctica InSync Theme 1, Theme 2, Theme 3, Theme 6, Theme 7; CATCH; CMEMS; OceanSITES; SOLAS; CLIVAR/CLiC/SCAR SORP; SCAR ASPeCt Expert Group
Improve satellite-derived air-sea flux measurement capabilities: - Develop reliable retrievals of ocean-sea ice-atmosphere turbulent heat and gas fluxes, especially in high winds and sea state - Improve freshwater and gas dissolution flux retrievals for regions with variable ice-induced freshwater inputs - Combining AI techniques to enhance turbulent flux estimates in numerical models and remote sensing products						Antarctica InSync Theme 1, Theme 2, Theme 6, Theme EO; CMEMS
Improve understanding of atmosphere-ocean-sea ice boundary-layer processes and reconcile discrepancies among air-sea flux estimation methods (observational, bulk, model-based, and machine-learning), reducing uncertainties in weather and climate model predictions, including ocean waves, ocean mixed-layer turbulence, atmospheric boundary layer physics, cloud condensation nuclei and ice nucleating particles						Antarctica InSync Theme 1, Theme 2, Theme 6, Theme EO; AniBOS; CATCH; CMEMS; PHOCIS; CLIVAR/CLiC/SCAR SORP; WCRP; SCAR AntClimNOW SRP;

						BEPSII Expert Group; SCOR SOLAS Research Project
Integrated efforts are needed that combine multi-platform observations (from autonomous platforms, animal borne sensors, ships, ice-based measurements, and remote sensing) with advances in modelling and data synthesis aimed at detecting emerging climate and ecological signals.						Antarctica InSync Theme 1, Theme 2, Theme 4, Theme 6, Theme EO; AniBOS; SCAR Ant-ICON SPR; ANTOS Expert Group

IN REVIEW

Foundational Capabilities

In support of the above science priorities, SOOS recognises the importance of enhancing our ability to collect, manage and use observational data. The SOOS Foundational Capabilities (shown in Figure 4) provide the framework to enable these efforts.

Observing System Design, Key Variables and Modelling

Observing System Design

Observing activities require specialised infrastructure, equipment, expertise, and sustained access to the field, making observations particularly costly to acquire and maintain. It is therefore essential that available resources are deployed strategically and that observing activities are demonstrably aligned with clearly defined scientific and societal requirements. Robust observing system design is fundamental to ensuring that the Southern Ocean observing system is scientifically effective, operationally feasible, sustainable, and capable of delivering the knowledge required by the research, operational, and policy communities.

Effective observing system design requires careful consideration of the quantities to be measured, the capabilities of the equipment to be deployed, and any operational constraints. Different quantities can have different optimal strategies, and indeed the same quantity may have different optimal strategies for different science goals. Objective and transparent approaches are therefore needed to compare alternative observing strategies, identify critical observing gaps, assess trade-offs, and prioritise investment.

For quantities that can be modelled to reasonable fidelity for the relevant process, Observing System Simulation Experiments, or OSSEs, can be used to quantitatively assess the efficacy of a particular design, or to find optimal strategies under given constraints. Other tools include self-sensitivities, ensemble techniques, and adjoint-based methods (Oke & O'Kane 2011). Emerging artificial intelligence and machine learning techniques (e.g. Mignot et al. 2023) provide new opportunities to integrate observations and models, optimise sampling strategies, identify information-rich locations and periods, and support adaptive observing systems.

In the five years covered by this Science and Implementation Plan, the SOOS Observing System Design Capability Working Group (OSD CWG) will coordinate and deliver SOOS contributions to advance this Foundational Capability. The group aims to facilitate the development of new strategies for observing system design, and to develop methodologies for objectively assessing the effectiveness of different observing system designs, through community engagement and stakeholder consultation. In particular, the group aims to improve the interaction between the observational and modelling communities, primarily through cooperative activities

such as OSSEs, with a particular focus on planning for Antarctica InSync (Arndt et al., 2026) and the Fifth International Polar Year 2032/2033.

This working group also plays an advisory role within SOOS and the broader Southern Ocean community on the selection and application of observing system design methods, promoting interoperability and complementarity among observing networks, and supporting initiatives seeking to improve the use and impact of Southern Ocean observations. This may include collaboration with programmes such as the Animal-Borne Ocean Sensor (AniBOS - previously MEOP) network (GOOS-252), the Observation system design with AI for Sea Ice Surveillance (OAISIS) Antarctica InSync working group, and other initiatives developing or applying innovative observing system design methodologies (e.g., Wei et al., 2020).

Key Variables

The Framework for Ocean Observing (Lindstrom et al., 2012) provided an internationally agreed collaborative mechanism for prioritising and integrating efforts to observe the global oceans. The global oceanographic community (led by the Global Ocean Observing System, GOOS) has worked to identify Essential Ocean Variables (EOVs) that are relevant to addressing key societal issues (e.g., climate, operational ocean services, ocean health), technically feasible to observe using proven methods, and are cost effective to collect, manage and deliver through existing data archiving processes (Tanhua et al., 2019a; Balvanera et al., 2022; GCOS, 2022). SOOS was involved in several of these efforts; providing input into global surveys, workshops and advocating for inclusion of air-sea flux variables into the Essential Climate Variables (ECVs) scheme that aligns with EOVs. Many of the GOOS-derived EOVs are also central to SOOS, however, the global scale of the GOOS perspective means some Southern Ocean-specific aspects are missing. This is especially true for ecosystem variables, and resulted in a SOOS co-led initiative to identify a process for determining ecosystem EOVs and sea-ice ECVs for the Southern Ocean (e.g., Constable et al., 2016; Milsolavich et al., 2018; Lavergne et al., 2022; Plasman et al., 2026).

Looking forward, SOOS will work collaboratively with international initiatives such as Antarctica InSync (Arndt et al., 2026), SYNCHRONY and the International Polar Year to identify Southern Ocean relevant essential variables. SOOS will prioritise its support for data collection, management and delivery around a set of key variables that are required to address the Science Themes, which will include the GOOS EOVs, the global ECVs and some Southern Ocean specific variables. These key variables will be identified through iterative, community engagement, driven predominantly by the SOOS working groups.

Modelling

Over the past decades, the ocean modelling community has made significant advances in simulating Southern Ocean processes. High-resolution ocean circulation

models coupled with sea ice and ice shelf models have been implemented at regional (Graham et al., 2016; Naughten et al., 2018) and circumpolar scales (Mazloff et al., 2010; Dinniman et al., 2020). Biogeochemical models, coupled with ocean circulation models, have been implemented at regional (Salmon et al., 2020; Twelves et al., 2021) and circumpolar scales (Lovenduski et al., 2015; Verdy & Mazloff, 2017; Nissen et al., 2022, Chang et al., 2025). These models have been used to reproduce and project regional circulation and biogeochemical responses to changes in environmental forcing (e.g., Gwyther et al., 2014; Smith et al., 2014; Dinniman et al., 2018, Nissen et al., 2024).

Even with advances in dynamical understanding and increased observations, many processes included in circulation models of the Southern Ocean remain poorly represented, including mesoscale and sub-mesoscale eddy fluxes, bottom water formation and export, convection in open ocean, and oceanic circulation and basal melting within ice shelf cavities (Dufour et al. 2017; Utolia et al., 2019; Beadling et al., 2020). This is especially the case in coupled climate models which struggle to resolve (or completely exclude) processes over the continental shelf, sea ice dynamics (Roach and Polvani, 2026), the impact of ice sheet melt (Siahaan et al., 2022), convection and bottom water properties/export (Huezé et al., 2021). Concerted efforts (Schmidt et al., 2025) have been made to provide realistic historical boundary ice sheet melt conditions to those climate models that do not include coupled ice sheets (almost all of them), but these still do not permit feedback between the ocean-ice system, or provide for future scenarios. Away from the coast progress has been made in reducing persistent air-sea heat flux biases (Hyder et al., 2018), though precipitation biases persist (Blanco et al., 2026), as do the warm biases in almost all water masses noted in CMIP5 (Sallée et al., 2013), possibly due to biases in remote formation sites (Luo et al., 2025).

Increased spatial resolution in circulation models permits resolution of eddy fluxes (e.g., Stewart et al. 2018, $1/48^\circ$ resolution) and improved simulation of Antarctic Bottom Water formation (e.g., Morrison et al. 2020, 0.1° resolution). Yet, the representation of stratification and convection in models remains a challenge that the increase in resolution alone cannot address. A particular challenge is the uncertainty in local bathymetry, which has a big influence on coastal circulations and ocean-ice shelf interactions (Liu et al, 2024), with implications for projecting sea level rise. Moreover, the intertwined carbon–climate–ecosystem feedbacks are poorly represented in climate models, where major uncertainties arise from sparse observations, unresolved mixed-layer dynamics, difficulties in simulating seasonal cycles, simplified iron cycling, and poorly constrained biological loss processes such as zooplankton grazing (Henson et al. 2022, Hauck et al., 2023b). Observations are still required for simulation verification and process parameterisation.

The regional and circumpolar circulation models have also provided the basis for understanding current and historical changes in the distribution of species, simulating

population connectivity (Piñones et al., 2013; Piñones et al., 2016; Thorpe et al., 2019) and for assessing projected changes in species and ecosystems (Pinones and Federov, 2016). A range of complementary modelling approaches—including food-web, process-based, and species distribution models—also contribute to understanding Southern Ocean ecosystem dynamics, each with distinct strengths and limitations, and together supporting integrated, weight-of-evidence assessments of change.

Coupling food webs, especially upper trophic levels, with circulation and biogeochemical models, and is ongoing work (Murphy et al., 2025). Modelling of Southern Ocean food webs tends to focus on regional implementations because of the heterogeneity of these systems and because of the extensive data requirements of these models (Murphy et al., 2012; Constable et al., 2014).

Even with the many advances in models developed for Southern Ocean systems, understanding of key coupled physical, chemical and biological drivers of change and their impacts is limited or lacking. Understanding and quantifying the impacts of multiple and synergistic drivers are critical for parameterisation, calibration and validation of modelling studies (Constable et al., 2016; Asay-Davis et al., 2017; Russell et al., 2018; Malyarenko et al., 2020). While the mandate of SOOS does not explicitly include model development and implementation, SOOS recognises the critical need to integrate observations with models and target the needs of modelling approaches (Martin et al., 2026). Development and extension of observational networks should be mindful of the aspirational needs of the modelling community, notably the desire to have easier access to gridded observational products and data from winter and over the continental shelves. (e.g. Martin et al., 2026).

To this end, SOOS's role and priority for the next phase is the provisioning of observations with sufficient space and time resolution to validate process parameterisations, constrain models, particularly climate models, and the development of scenarios. Further, SOOS recognises the potential for model findings to be used to guide observational needs and to optimise OSD. SOOS will continue to work with programmes such as ICED (Integrated Climate and Ecosystem Dynamics) and SORP (CLiC/CLIVAR/SCAR Southern Ocean Regional Panel), SCAR AntClimNow, ongoing research projects (e.g. SYNCHRONY), and other networks to facilitate integration between the Southern Ocean observational and modelling communities.

Methods and Standards

Observational Technologies and Digital Infrastructure

The difficulties associated with observing the Southern Ocean are well recognised (e.g., Newman et al., 2019) and necessitate a broad suite of technologies to capture the complexity of the system. Yet, the rapid development of technological and digital infrastructure is providing new opportunities to collect spatiotemporal observations

that were previously challenging to sample (Hancock et al., in review). Additionally, these new technologies provide high frequency data streams through recent developments in satellite and data transfer technologies, allowing near-real time data.

The urgent need to address the spatio-temporal data gaps in traditional ship-based sampling is driving technology development, resulting in a global focus on autonomous platforms, such as profiling floats (e.g. Argo), and international programmes dedicated to advancing the maturity and use of these autonomous platforms. Recent developments in the Argo program, including BGC-Argo and DeepArgo, are allowing a rapid expansion on the observations that can be collected from these floats (Zilberman et al., 2023). Additionally, the expansion of the use of Argo floats under sea ice through advances in under ice position estimation and tracking and bottom landing of floats is offering opportunities to improve our understanding of seasonal sea ice cycles (Chamberlain et al., 2018; Wallace et al., 2020; Oke et al., 2022). However, it is critical that shore and ship based sampling are maintained to provide sensor calibration, as well as a method to merge the new sensor based data streams with traditional lab-based approaches. Through the combination of these observing methods, the collation of datasets will be possible allowing improvements in time-series length and applicability. Despite these advances, the seasonal sea-ice zone remains difficult to sample. Autonomous surface platforms such as uncrewed surface vehicles and wave gliders are susceptible to ice damage and are constrained by limited solar energy during the polar winter, underscoring the need for further development of ice-avoidance algorithms, intelligent navigation systems, and alternative power solutions.

Satellite-based remote sensing of ocean colour is the only observational capability that can provide synoptic views of upper ocean phytoplankton characteristics at high spatial and temporal resolution (~1 km, ~daily) and high temporal extent (global scales, for years to decades). In many cases, these are the only systematic observations available for chronically under-sampled marine systems such as the Southern Ocean making it necessary that we maximise the value of remote sensing observations for this globally critical region. This is particularly important in the Southern Ocean, where regionally tuned algorithm development is required to accurately represent the unique optical and ecological characteristics of Southern Ocean phytoplankton communities and their environment. The emergence of new hyperspectral satellite missions, such as the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, provides unprecedented opportunities to advance the retrieval of phytoplankton functional types, physiological status, and biogeochemical properties. Realising this potential will require coordinated efforts to expand in situ bio-optical observations, develop regionally appropriate algorithms that can be validated.

Increasing volumes of data are being collected, which has led to the need to improve processing capabilities. Rapid developments in artificial intelligence and machine learning are allowing the upscaling of processing and automation of data. For example, automation is critical for the effective use of earth observation datasets which have rapidly increased in temporal frequency, spatial accuracy, quantity and size (e.g., Copernicus Sentinel-2A and -2B satellites and downstream processing chains generate 1.7 terabytes of data daily, Sudmanns et al., 2020). All parts of the data pipeline, including data ingestion, standardisation, visualisation and analysis require automation to reduce post-processing times, limit human error and allow machine to machine reading capabilities. Typically, analysis methods of earth observation data have been based on spectral indices and classification models, but new developments in artificial intelligence and machine learning are increasing the capacity and accuracy of remote sensing observations. Recent advances in computer vision, including developments in Convolutional Neural Networks (CNNs) and Foundation Models have improved the capacity of detection and classification of satellite and aerial imagery, from ocean scale to single animals. Solutions can be tailored to user needs including fully automated, semi-automated or human-driven methods. However, large, frequent image datasets and complex artificial intelligence routines require large training datasets and efficient high performance processing pipelines which, in many cases, still require development. Such developments in the use of satellite imagery to detect and count air breathing predators in the Southern Ocean through medium and very high resolution (VHR) earth observation platforms which has been effective to track predator populations in coastal areas and at sea; this work is being coordinated by the SOOS CAPS CWG.

These observational technology and digital infrastructure developments have led a step-change in Southern Ocean observational capabilities (Schofield & Kohut, 2018). Observational technologies directly impact the ability to collect sustained, integrated and cost-effective multidisciplinary data. For this reason, SOOS supports activities that:

- Enhance the efficiency and effectiveness of existing platforms/sensors; communicate technological requirements
- Support platform/sensor-specific networking
- Transition networks towards being a sustained and operational network such as the [GOOS Global Ocean Observing Networks](#)
- Support data technology development developing data discovery technologies, including artificial intelligence/machine learning effort

SOOS will continue to support activities that contribute to enhanced technological capabilities, through continuation of the aforementioned activities and development of new activities as needed. Artificial intelligence and machine learning are new areas of focus for the global community, and SOOS is open to supporting initiatives of relevance that use these approaches (e.g., SCOR ORCAS Working Group).

Methodologies and Best Practices

The high cost, scientific imperative, and the logistical and technological difficulty associated with collecting observations from the Southern Ocean means that every observation is important and should be leveraged for the greatest impact for society. This requires that observations be collected employing standardised sampling, analytical protocols and reference materials, and the resulting data be interoperable and accessible using well-defined and reproducible methods. The international ocean observing community recognises the importance of standard methodologies and best practice for all aspects of the ocean observing value chain (Pearlman et al., 2019), and provides an important framework for the development and discovery of best practices, through the Ocean Best Practices System (OBPS).

SOOS supports Southern Ocean community efforts to develop and implement new observational and analytical methods, and the actions required for acceptance of these and other aspects of the observing system value chain as best practice through OBPS, where appropriate. Examples of SOOS efforts to-date include: development of new algorithms for the census of seal and penguin populations from space (CAPS CWG); advocating the development of standards for the collection and management of emerging data types, including acoustic moorings and ice shelf melt data (NECKLACE programme); the development of standardised data policies for polar regions (Tronstad et al., 2021); and involvement in the OBPS Collaboration and partnerships working group.

SOOS will continue to advocate for use of standardised methodologies and best practices, and to support community efforts to develop new methodologies and documentation of best practices. For example, community initiatives such as the GOOS supported Surface Ocean CO₂ Observing Network (SOCONET) provide an important example of coordinated international efforts to develop best practices, methodologies and observing strategies for high-quality measurements of surface ocean and atmospheric CO₂ needed to constrain air-sea fluxes and deliver user-driven data products. Some SOOS working groups will continue to deliver into this capability, and all groups will be encouraged to utilise best practices where possible.

Data Management and Delivery

Enhanced observations of the Southern Ocean will be of limited value unless the resulting data (in situ, satellite-derived, and model outputs) are open and FAIR, "Findable, Accessible, Interoperable, and Reusable" (the FAIR Principles, Wilkinson et al., 2016; Tanhua et al., 2019b). The variety of data types, barriers to the widespread adoption of data and metadata standards, and limitations of data discovery tools are major challenges for researchers (van de Putte et al., 2021). Supporting efforts to address these challenges is the core objective of the SOOS data strategy (see Newman et al., 2019). The SOOS Data Management Sub-Committee (DMSC) has

contributed to a set of aligned data principles for the polar regions (Tronstad et al., 2021; Bricher et al., 2023) and developed a data policy to govern and advocate for best practice approaches to data management for all SOOS partners (SOOS Data Management Sub-Committee, 2022).

SOOS data management efforts have led to the development of data tools for the community. Well-structured and curated data generated by Antarctic research programmes from many nations and marine science disciplines can be discovered and downloaded via the online data discovery tool, [SOOSmap](#), managed by European Marine Observation and Data Network Physics (EMODnet Physics) (ten Hoopen et al., 2025). Many more existing datasets, including those with limited curation, are findable and, generally, accessible via the SOOS Metadata Catalogue, hosted by the NASA International Directory Network. These tools have significantly changed the way Southern Ocean researchers discover data, as evidenced by the over 8,000 monthly visits to SOOSmap.

SOOS will continue to utilise and improve these data tools, including developing interoperable web services on SOOSmap to satisfy the emerging needs of users of bulk data, and adding new aggregated data layers when they become available and technical resources allow. Additionally, SOOS will continue to encourage best practices in data management (e.g., Tronstad et al., 2021 and Bricher et al., 2023), inform the community of external data products (e.g., model outputs, remote sensing, and gridded data aggregations), and broker data management relationships between scientists and data centres. This approach also strengthens transparency and reuse for community synthesis and assessment outputs (i.e., not only original observational or modelled data, but also derived material such as indicators and assessment reporting) by promoting deposition of underlying datasets with persistent identifiers in trustworthy repositories adhering to TRUST principles (Transparency, Responsibility, User focus, Sustainability, and Technology) with clear and standardised metadata. On top of this advocacy, selected derived data layers can be harvested, where appropriate, and served through SOOSmap for consistent visualisation and open access. By implementing these best practices and applying community driven standards (e.g., Open Geospatial Consortium Web Services, CF Conventions), it improves the capacity of SOOS to feed data from data tools (e.g., SOOSmap), up to technologies like the Digital Twins of the Ocean and AI supported data discovery tools. In all these areas, SOOS data efforts will focus on facilitating access to existing and new data to address the Science Themes and Challenges identified in this plan (see the SOOS values for developing data tools in Box 2).

As with all aspects of SOOS implementation, the degree to which these activities can be undertaken will be contingent on available resources, such as technical hosting and support of SOOSmap and other tools, and sustained capacity within the SOOS International Project Office to continue data input and oversight. Activities in this space will be a mix of strategic and opportunistic, to make best use of available

resources and the activities of other community organisations. Since data management is key to the SOOS Vision, all contributing projects should consider how the resulting data will be managed at all stages of the data life cycle.

Box 2: SOOS Values for Developing Data Tools

The SOOS data community is a federation of data professionals bridging nations and scientific disciplines, with the aim of developing data sharing and discovery tools that meet the needs of Southern Ocean researchers, and that are nested in a global network of data management systems. The following values provide a decision-making framework for all SOOS data activities:

Free and FAIR data: Data should be freely shared for reuse by other members of the community in ways that maximise the Findability, Accessibility, Interoperability, and Reusability (FAIR Principles) of the data, so far as is ethically responsible ("as open as possible; as closed as necessary"). A single authoritative copy of the data should be preserved in a trusted, long-term, well-curated, and publicly accessible repository.

Local But Global Tools: Data sharing and discovery tools for the Southern Ocean community should be interoperable with similar tools elsewhere and should not duplicate existing efforts, where possible.

Flexible Networks: Networks are stronger than single pillars. Tools that are collectively owned and supported by multiple agencies have more opportunities for ongoing support than those relying on a single agency.

Mobile Tools: To support the value of Flexible Networks, it is important that, where possible, new tools should be built in "containerised" ways that allow them to be separated from the internal infrastructure of a given host, to allow them to be moved if necessary.

Adaptability: Tools and services should be able to be changed as SOOS's needs grow and as technologies develop.

Open Standards: The use of open standards, open source software, and openly documented tools support the interoperability of SOOS tools and systems with those in other regions and disciplines.

Implementation Framework

Networks and Coordination

Delivering the breadth of observations required by all end-users is an enormous task, greater than can be achieved by a single forum or nation alone – a key driver for the development of SOOS. Over the last decade, SOOS has worked with all stakeholders to build networks and connections that will support the delivery of the required data, founded on a network of Regional Working Groups (see SOOS Implementation section) that incorporate all overlapping end-user requirements where possible and implement these observing systems in an integrated and flexible way.

SOOS Networks

The development of networks is fundamental to achieving the SOOS mission. The ability to collect and deliver Southern Ocean observations, to enhance observing and data capabilities, and to coordinate national plans and resources, are only achievable through the development of international, coordinated, inclusive, and well-supported networks.

SOOS networks are developed through either bottom-up initiatives, proposed by the community to address specific issues (e.g., CAPS CWG), or directly by SOOS to address a gap in our capabilities (e.g., SOFLUX, OSD and SO-OA Hub CWGs), define priorities in order to align strategies, support our ability to implement the observing system required to address the Science Themes (e.g., SOOS Regional Working Groups), or facilitate FAIR data management practices (e.g., POLDER, DMSC). Since its initiation in 2011, SOOS has established 25 international networks (including SOOS Working Groups and Task Teams) and has been centrally involved in 7 partnership projects/programmes.

Looking forward, SOOS will continue to support these existing networks, whilst also identifying gaps that require new collaborative partnerships or networks to be built. SOOS also works to build tools and products that support collaboration. For example, [DueSouth](#) is the Database of Upcoming Expeditions to the Southern Ocean and is a platform that enables the community to share planned expeditions, observational projects and logistics in an openly accessible way. Hosted for SOOS by the European Polar Board as part of their polar infrastructural and logistics database, [PolarDEX](#), DueSouth provides information on upcoming research vessel expeditions, flights, fishing vessel plans and tourist expeditions. DueSouth is delivered in collaboration with the Council of Managers of National Antarctic Programs (COMNAP), the CCAMLR and the International Association of Antarctica Tour Operators (IAATO).

Externally Coordinated Observing Networks and Programmes

There are many international programmes and projects that facilitate and coordinate aspects of the planning, organisation, collection and management of specific observational data or platforms. Combined, these individual programmes form the

backbone of SOOS and are integral to efforts to deliver sustained observing systems. Global observing programmes ensure sustained data delivery of a core set of variables, using prescribed platforms, methods and standards across all steps of the data lifecycle, from planning and collection of observation through their inclusion in knowledge exchange products. These include global programmes such as Argo, GO-SHIP, OceanSITES, Integrated Marine Observing System Southern Ocean Time Series (IMOS-SOTS), OceanGliders, Animal Borne Ocean Sensors Network (AniBOS), Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM), GEOTRACES and BioGEOTRACES (a list of SOOS connected international programs and observing initiatives is available via the [SOOS website](#)). Similarly, other programmes are important observing systems for SOOS, although these are limited by some combination of being not fully operational, reliant on project-based funding, have limited data sharing capacity, or have not yet published standard best practice documentation. These include programmes such as CCAMLR Environmental Monitoring Program, Continuous Plankton Recorder (CPR), Antarctic Fast Ice Network (AFIN), Antarctic Sea Ice Processes and Climate (ASPeCt), International Programme for Antarctic Buoys (IPAB), NECKLACE and satellite remote sensing. SOOS will work to advocate for the continuation of these programmes in the Southern Ocean, and support implementation of their observing programmes where required.

Further to these internationally coordinated programmes, there are many national and multinational projects and programmes that collect observations of the Southern Ocean. These vary from long-term observational efforts (>10 years); through the mid-length, science question-focused observing efforts (>4 years); to the short, more process-focused studies (<4 years). SOOS is developing a list of long-term observing programmes to provide a database to facilitate enhanced coordination and collaboration amongst these programmes, and new programmes starting (<https://soos.aq/community/long-term-observing-programmes>). However, to create a sustained and coordinated network these long, medium and short-term monitoring programmes need to be coordinated to create an integrated observing system (Hancock et al., in review; Heil et al., 2023).

To support proposals for new research projects, large national and international collaborative and coordinated programmes, and data initiatives, SOOS provides project and programme endorsement, a list of SOOS-Endorsed Projects is available on the SOOS website (<https://soos.aq/activities/endorsed-projects>).

This broad range of projects complements the international operational observing efforts, addresses spatio-temporal gaps in observations and delivers a more comprehensive observing system. SOOS supports these programmes through endorsement and advocacy, data management support, networking and communication support, and through our working groups, provides an international framework for alignment of programme strategies and greater leverage and impact of the data and outputs.

SOOS Collaborations and Partnerships with Large International Initiatives

Much of SOOS's work over the next five years will be involved in large international initiatives that align with the mission of SOOS. Collectively, these initiatives are providing an opportunity to enhance the coordination, integration and collaboration required to enhance the Southern Ocean observing system to meet current needs. However, ongoing efforts need to continue past these programmes to provide the sustained observations needed to deliver a fully integrated, sustained and coordinated observing system. The large international initiatives below will be delivered into the UN Decade of Ocean Science for Sustainable Development (2021-2030) (Ocean Decade) and the UN Decade of Action for Cryospheric Sciences (2025-2034) (Cryospheric Decade). Additionally, SOOS remains engaged with the Ocean Decade Collaborative Centre for the Southern Ocean region (DCC-SOR) which is hosted by SCAR.

Antarctica InSync

Antarctica InSync is a regional programme of both the Ocean and Cryospheric Decades with the mission to develop international science and infrastructure for synchronous observation of Antarctica to create a circumpolar assessment of the connections between ice, ocean, climate, environment and life. SOOS is an institutional partner of Antarctica InSync and has endorsed the programme (Arndt et al., 2026). SOOS will work centrally with Antarctica InSync to facilitate enhanced coordination across Antarctica InSync activities using well established SOOS networks and tools including DueSouth. Additionally, SOOS, as a co-lead of the Antarctica InSync Data Cross-Cutting Theme, will work to ensure that all data from Antarctica InSync is as open and accessible as possible via SOOSmap.

Synchronous Southern Ocean Observatory (SYNCHRONY)

SYNCHRONY is an EU Horizon Project, 2026-2030, which aims to establish a coordinated, internationally synchronized observatory in the Southern Ocean and around Antarctic ice shelves. This observatory will monitor rapid changes in ocean-ice-atmosphere systems, and their impacts on climate and biodiversity. SOOS will be involved in the SYNCHRONY project through delivering work towards developing standardised shared essential polar variables, coordinating DueSouth/Polardex entries to support Antarctica InSync logistical coordination, convening a SOOS Symposium in 2027, and ensuring international connections and impact for SYNCHRONY.

5th International Polar Year (IPY-5)

The 5th International Polar Year (IPY-5), scheduled for 2032-2033, aims to address urgent global challenges advancing polar research, focusing on the impacts of climate change in the Arctic and Antarctic. SOOS is centrally involved in this coordinated effort as a member of the International Planning Committee and will work to ensure that the activities and legacy from Antarctica InSync continue to be developed and implemented through to the IPY-5. This includes work on data

management and delivery which SOOS will be working to ensure alignment between the two programs as a co-lead of the IPY-5 Data Task Group.

Science, Policy and Management Programmes

In addition to the programmes and projects that collect, manage and deliver Southern Ocean observations, there are those that are focused on delivering scientific outputs to address key science issues or deliver into policy and management. The scientific initiatives of SCAR and SCOR, the World Climate Research Programme (e.g., Climate and Ocean-Variability, Predictability, and Change; CLIVAR, Climate and Cryosphere; CliC), the World Meteorological Organisation (e.g., Year of Polar Prediction; YOPP, Executive Council Panel of Experts on Polar and High Mountain Observations, Research and Services; PHORS, Antarctic Regional Climate Centre; Ant RCC) and co-sponsored initiatives that contribute to Future Earth are all important collaborators and/or stakeholders for SOOS. In instances where these communities are already engaged in activities that will address SOOS objectives, SOOS will not duplicate efforts, but rather identify ways to support the existing enterprise, where required. Where existing efforts require a level of modification to deliver against SOOS objectives, SOOS will work with the community to augment them and tailor outputs to SOOS requirements. In instances where no active efforts exist but SOOS has identified a requirement, SOOS Working Groups or a Task Team will work with any relevant community to address the issue, or initiate development of a community if none such exists.

The connection between SOOS and policy or management organisations is predominantly through SCAR and SCOR into programmes such as CCAMLR and the ATS's CEP. The CEP provides recommendations to manage the impact of human activities in Antarctica, including climate change, and as such requires sustained observations of environmental conditions. SOOS publications have also contributed directly to policy documents, for example, publications and strategic policies of the World Meteorological Organisation (WMO), and the Intergovernmental Panel on Climate Change (IPCC) Special Report on the Oceans and Cryosphere in a Changing Climate. Further, SOOS working groups may deliver data or knowledge directly to policy organisations, such as the Censusing Animal Populations from Space (CAPS) Capability Working Group, which contributed information which has led to the reclassification of emperor penguins and Antarctic seal species by IUCN, and the proposal to the ATS's CEP for emperor penguins to be a specially protected species. SOOS outputs also deliver into the UN Sustainable Development Goals 13 (Climate Action) and 14 (Life Below Water).

Societal Impact

Addressing the SOOS Science Themes and Challenges within and across Themes, and delivering into the Southern Ocean science pathway (Figure 2) will lead to tangible societal impacts. For example, SOOS activities will support evidence-based decision-making within the Antarctic Treaty System (ATS), in particular its Committee

for Environmental Protection (CEP) and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) through providing circumpolar-scale coordination and collaboration for the collection and delivery of Southern Ocean observations. SOOS publications have been used in over 49 policy documents including the IPCC AR6 Synthesis Report and the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019; IPCC, 2022). SOOS will also be delivering large international initiatives as described above that will deliver in the UN Decade of Ocean Sciences for Sustainable Development (2021-2030) and the UN Decade Action for Cryospheric Sciences (2025-2034).

SOOS objectives are well-aligned with the vision and priorities arising from its governing bodies including the SCAR Horizon Scan (Kennicutt et al., 2014), and the overarching purpose and defined functions of SCOR, both of which have a strong focus on delivering science for global societal benefit. SOOS activities also support national priorities in Southern Ocean observing, science and environmental management. The broad, multidisciplinary and integrated approach promoted and coordinated by SOOS will continue to facilitate the efficient and effective delivery of high-priority observational data and translation of science outputs into genuine societal outcomes. These outcomes will be delivered from each of the SOOS Science Themes, and will include, for example, the role of Southern Ocean processes in global climate regulation (including clouds, aerosols and ocean stratification), sea level rise, the Antarctic cryosphere in the functioning of the Earth System, the connection of Southern Ocean/atmosphere processes (e.g., Southern Annular Mode) and climate variability and change in the Southern hemisphere nations (e.g., drying of south-west Western Australia), and the impacts of Southern Ocean ecosystems on food security.

SOOS 2026-2030 Strategy and Implementation Plan

Overview of the plan structure and its establishment

SOOS 2026-2030 Implementation Plan focuses on the key actions of SOOS for the 2026 to 2030 period that will provide the greatest benefit and impact to enhancing the collection and delivery of Southern Ocean observations. The four key areas in which SOOS provides benefit and impact to the Southern Ocean science life cycle are outlined in "SOOS Vision, Mission and Values" above and in Figure 2, which provides the background for the five key objectives, actions and deliverables presented below to focus SOOS activities over the next five years (Figure 5). The actions and outputs of SOOS are split into three sections:

- **High Priority, Core SOOS Actions and Deliverables:** core SOOS actions and deliverables, which will be high-priority activities of SOOS and where most resources will be committed
- **SOOS Supported Actions and Tasks in Collaboration with the Broader Community:** actions and tasks which SOOS will conduct in collaboration with the broader community if there is sufficient capacity and resources
- **SOOS Governance and International Project Office Operations:** actions and deliverables associated with the ongoing management and maintenance of SOOS's Governance and operations of the SOOS International Project Office

SOOS Key Objectives

1. **Align, advocate, and support observational priorities, gaps and inefficiencies** to provide a clear message to funders, national programs, and intergovernmental agencies
2. **Enhance collaboration and observational coordination** by facilitating inclusive and resilient networks
3. **Ensure the management and delivery of observational data** by connecting data repositories, providing synthesis activities/products, integrating data, and encouraging the use of open science, FAIR data principles and enabling tools
4. **Develop and deliver interactive maps of observational coverage** and summary visualisations of Southern Ocean available data
5. **Sharing knowledge** with all stakeholder groups, including policymakers, to provide visibility and enhance the impact of Southern Ocean research and the knowledge created from it, through summary reports, communication strategies, workshops, publications, and community coordination efforts

High Priority, Core SOOS Actions

Priority setting

The first step towards a coordinated Southern Ocean Observing System is identifying and aligning priorities. This includes defining key science priorities the system needs to address, as well as recognising gaps and/or inefficiencies that need to be filled. These community-developed priorities enable a clear message to funders, national programs and intergovernmental agencies.

Actions

A1. Science Plan: Maintain an up-to-date and relevant SOOS Science and Implementation Plan with the current status of the observing system, gaps, key priorities and challenges
(Associated deliverable: D5)

A2. Priority White Papers: Support or coordinate the alignment of priorities for Southern Ocean observations, identification of key gaps and inefficiencies in the observing system and/or future directions for the Southern Ocean observing system, including to support Antarctica InSync and OceanObs'29 in collaboration with other initiatives
(Associated deliverables: D1, D2, D3, D4, D5)

A3. Essential Variables: Support identification and development of global essential variables (including EOVs, ECVs, EBVs, eEOVs) developed by other groups, to identify and fill any gaps and/or adjustments required for the Southern Ocean and polar waters in collaboration with other initiatives (including Antarctica InSync and SYNCHRONY)
(Associated deliverables: D3, D4)

Building Networks and Coordination

Delivering the breadth of observations required by all end-users is an enormous task, greater than can be achieved by a single forum or nation alone – a key driver for the development of SOOS. The development of networks is fundamental to achieving the SOOS mission, founded on a network of Regional Working Groups. The ability to collect and deliver Southern Ocean observations, to enhance observing capabilities, and to coordinate national plans and resources, are only achievable through the development of international, coordinated, inclusive, and well-supported networks and collaborative tools. DueSouth, SOOS's Database of Upcoming Expeditions, is a key logistical product developed by SOOS and available through the European Polar Board's logistical tool, Polardex, to facilitate open access to Southern Ocean logistical information and improve collaboration within Southern Ocean research. SOOS networks (Capability Working Groups, Task Teams or projects in partnership with SOOS connected programs) and collaborative tools are developed through either bottom-up initiatives proposed by the community to address specific issues, or

directly by SOOS to address a gap in our capabilities, define priorities to align strategies, support our ability to implement the observing system required to address the Science Themes or facilitate FAIR data management practices.

Actions:

A4. SOOS Existing Implementation Groups: Build and maintain regional or capability specific networks of interested members to facilitate collaboration and coordination, address gaps and inefficiencies towards ensuring a sustained and coordinated Southern Ocean observing and data delivery system. These networks are built with international engagement and recognition that provides a mechanism for network correspondence and information sharing.

(Associated deliverables: D6)

A5. SOOS New Implementation Groups: Identify, review and manage proposals for new SOOS networks to address gaps and inefficiencies in the observing system.

(Associated deliverables: D6, D7)

A6. SOOS Connected Community: Ensure two-way engagement with allied networks across the broader Southern Ocean and ocean observing community with support for collaborative efforts where SOOS and other programs share specific priorities to leverage impact/benefit. This includes collaboration with UN Decade programmes (e.g., Ocean and Cryosphere), Antarctica InSync, SYNCHRONY, and preparations for IPY-5, where SOOS can both contribute to and benefit from coordinated international observing efforts.

(Associated deliverables: D8)

A7. Equity, Diversity and Inclusion: Ensure a culture of equity, diversity and inclusivity across all SOOS networks, activities and practices.

(Associated deliverables: D11, D12, D13)

A8. Capacity Development: Invite engagement of early career professionals and emerging National Programs in SOOS activities and leadership roles

(Associated deliverables: D10, D11, D12, D13)

A9. SOOS Endorsement: Maintain SOOS project endorsement process

(Associated deliverables: D10)

A10. DueSouth: Maintain functionality of DueSouth through collaboration with the European Polar Board (responsible for hosting and maintaining DueSouth as part of Polardex), and continuously populate DueSouth with upcoming expeditions and projects, and support community uptake, use and input into DueSouth

(Associated deliverables: D8, D9)

SOOS Support for FAIR Data

Enhanced observations of the Southern Ocean will be of limited value unless the data is Findable, Accessible, Interoperable and Reusable (FAIR). Improving the findability and accessibility of Southern Ocean data is core to SOOS. SOOS's data efforts have led to the development of data tools for the community, including metadata discovery portals and SOOS's key data product, SOOSmap. SOOSmap is a gateway to physical, biogeochemical and biological open-access data free for anyone to use. SOOSmap was developed in collaboration with the European Marine Observations and Data Network (EMODnet) Physics to provide an easy one-stop shop for Southern Ocean data held in repositories around the world. SOOS also works to rescue unpublished data and encourage the use of FAIR data principles. The data activities of SOOS overseen by the SOOS Data Management Sub-Committee who provide guidance on cost effective collaborative mechanisms for managing and publishing data from the Southern Ocean (and is one of the SOOS Implementation Groups outlined above).

Actions:

A11. SOOSmap Functionality: Ensure continuity and growth in functionality of SOOSmap, including population with key datasets (including essential variables identified in A3), identifying and resolving challenges in the delivery of datasets, and working to identify and deliver aggregated datasets
(Associated deliverables: D4, D14, D15, D17)

A12. SOOSmap Stakeholders: Engage with SOOSmap stakeholders to maintain service and use, and encourage new and existing users to explore and use SOOSmap.
(Associated deliverables: D14, 15, 16, 17)

A13. SOOSmap Filtering: Develop and deliver a filter matrix tool in SOOSmap for agreed Southern Ocean essential variables and temporal ranges, and develop interactive maps of observational coverage for SOOS Regional Working Group areas and CCAMLR regions.
(Associated deliverables: D4, D15)

A13. Data FAIRness via SOOSmap: Work with the data community to ensure that data is curated, standardised and aggregated in ways suitable for sharing through SOOSmap or other data portals
(Associated deliverables: D14, D15)

A14. Metadata Portals: Maintain, develop and promote the SOOS NASA EarthData metadata portal and the Polar Federated Search portals
(Associated deliverables: D18)

A15. Essential Variable Summary Visualisations: Develop and deliver summary visualisations and communications product(s) of Southern Ocean essential variables (Associated deliverables: D1, D4)

Knowledge Sharing

Sharing knowledge within the Southern Ocean community and beyond is critical to providing visibility and enhancing the impact of Southern Ocean research to the broader research community, stakeholders, policy and global society. This knowledge is critical to understanding current Southern Ocean conditions, informing predictions of future states, and supporting policies and regulations for the benefit of society.

Actions:

A16. Publications: Coordinate delivery of publications that align with working group or SOOS objectives, including the SOOS contribution to BAMS State of Climate Report (Associated Deliverables: D1, D2)

A17. Stakeholders Reports: Coordinate delivery of stakeholder reports that align with working group or SOOS objectives (Associated Deliverables: D1, D2, D4, D20, D22)

A18. SOOS Symposium 2027: Convene a large international conference, SOOS Symposium 2027, in 2027 to build on the inaugural SOOS Symposium 2023 (Associated Deliverables: D6, D7, D8, D9, D11, D12, D13, D16, D19, D21, D25)

A19. SOOS Workshops and Meetings: Convene SOOS workshops and meetings to meet working group and SOOS objectives. (Associated Deliverables: D11, D12, D13, D19, D25)

A20. Advocacy: Advocate for the sustained and coordinated observations of the Southern Ocean through advocacy pieces such as community statements (Associated Deliverables: D1, D5, D8, D9, D19, D20, D21, D22, D23, D24, D25)

A21. SOOS Community Communications and Engagement: Maintain and deliver a SOOS Communications and Engagement Strategy including through engagement, presentations and communication at relevant meetings, conferences, townhalls, etc. to promote SOOS, SOOS's objectives and achievements; advocate for the aligned priorities for the Southern Ocean observing system; support and build collaborative efforts between SOOS and other programs; and ensure two-way engagement with allied networks (Associated Deliverables: D1, D2, D3, D4, D5, D19, D20, D21, D22, D23, D24, D25)

A22. Policy Efforts: Coordinate engagement with and delivery into relevant policy forums to advocate for the importance of the Southern Ocean in the global Earth system and aligned priorities for the Southern Ocean observing system, as well as SOOS tools and products that improve evidence-based decision making (Associated Deliverables: D1, D2, D4, D5, D20, D21, D22)

High Priority, Core SOOS Deliverables

Publications, white papers, reports etc.

D1. Publication/White papers/Reports: Community-lead publications, white papers, synthesis documents and reports that deliver aligned priorities against working group or SOOS objectives

D2. BAMS SOTC: Southern Ocean section contributing annually to the BAMS State of the Climate Report

D3. Southern Ocean EOVs List: Product (report or publication) mapping already established global essential variables relevant to the Southern Ocean

D4. Southern Ocean EOV Report Card: Summary visualisation product (e.g., report card) of Southern Ocean essential variables

D5. SOOS SIP: Develop a future SOOS Science and Implementation Plan for 2031 and beyond, including science priorities, key objectives, actions and deliverables for SOOS

Networks and Coordination

D6. SOOS Membership: Continued growth and engagement across the SOOS network including SOOS both existing and new Implementation Groups

D7. SOOS New Implementation Groups: Establish new SOOS Implementation Groups where there is both need and community support

D8: SOOS Connected Community: SOOS deliverables in collaboration and support of allied networks and initiatives including UN Decade Programmes (Ocean and Cryosphere), Antarctica InSync, SYNCHRONY and IPY-5

D9. DueSouth: Continued use, engagement and growth of DueSouth including delivery of user guides and tutorials

D10. SOOS Endorsement: Continued support and increased projects endorsed through SOOS Endorsements

D11. EDI: Continued support and implementation of equity, diversity and inclusion initiatives to reduce barriers to equal participation to all with SOOS

D12. National Reps: Continued growth and engagement of SOOS National Representatives, particularly those with developing Antarctic National Programs

D13. ECRs: Support and opportunities provided to Early Career Researchers, including SOOS leadership opportunities

SOOS Data Products

D14. SOOSmap Datasets: Increase in datasets made available through SOOSmap, including the use of bulk data-products that are ready to be integrated

D15. SOOSmap User Functionality: Increased user functionality of SOOSmap to visualise and access aggregated data for Southern Ocean variables over various spatial and temporal scales

D16. SOOSmap Advocacy: Promote usage to increase the impact of SOOSmap

D17. SOOSmap Resources: User guides and tutorials for SOOSmap

D18. SOOS Metadata Portals: Increased usage and functionality of the SOOS NASA EarthData Metadata Portal and the Polar Federated Search Portal

SOOS Advocacy

D19. Meeting Advocacy: Attendance, presentations, engagement and advocacy at meetings, workshops, conference sessions etc.

D20. Policy Impact: Representation and presentation at key policy forums, including ATCM, CCAMLR, COP Climate Change Conferences, UNOC

SOOS Communications and Engagement

D21. SOOS Communications and Engagement Strategy: Maintain SOOS Communication and Engagement Strategy

D22. SOOS Stakeholder Communications: Communications products and key messages to all relevant Southern Ocean stakeholders, including relevant policy forums

D23. SOOS Community Communications: Community newsletters and social media posts to communicate SOOS objectives, priorities, activities, opportunities, achievements and connected program updates

D24. SOOS Symposium in 2027

D25. SOOS Meetings: Thematic and/or Specialised Workshops and Meetings

SOOS Supported Actions and Tasks in Collaboration with the Broader Community

- Support collaborative efforts where SOOS and other programs share specific priorities to leverage impact/benefit and reduce duplication of effort
- Support efforts to design or quantify observational requirements
- Facilitate integration between Southern Ocean observational and modelling communities, and work with the modelling community to ensure appropriate observations for modelling requirements
- Advocate for the implementation of best practices in all areas of ocean observing, including promotion of relevant best practice documentation to the Southern Ocean observing community
- Support joint field campaigns, project funding proposals, and encourage ongoing campaigns and collaborative efforts
- Working with allied data communities on advocacy and support for FAIR and CC-CY (or equivalent) data, including sharing of training guides, resources, etc.
- Deliver a layered map of Southern Ocean Essential Variables (physical, biogeochemical, cryospheric, ecosystem/EBVs) and associated observing platforms, aligned with other international initiatives

SOOS Governance and International Project Office Operations

Governance

- All working groups maintain leadership following Terms of Reference and EDI expectations
- SSC and EXCOM governance structure maintained and supported

Objectives Coordinated

- Monitor and track progress of objectives as per the SOOS Impact Framework
- Provide support to SOOS groups for implementation of actions
- Issues with progression of plan are identified and solutions agreed
- Risk assessment finalised, monitored and updated as required

Communications and Engagement Strategy

- Develop an engagement and communication strategy
- Deliver communication products (newsletters, posters, presentations)

- Keep website up-to-date
- Maintain social media presence

Impact metrics

- IPO and SOOS groups to maintain a monitoring process and deliver impact metrics
- EXCOM to maintain reporting schedule and templates
- WGs and TT to collate information and provide progress reporting to IPO
- IPO to collate information and provide progress reporting to all stakeholders

IPO Funding

- Deliver requirements of existing sponsorship
- Advocate for continued and enhanced funding
- Maintain an up-to-date business case for IPO hosting

IPO Administration

- IPO staff contracts and IPO administration are managed as according to host requirements
- IPO work plan is developed and delivered
- SOOS finances are administered
- IPO staff work in a safe, collegial, and supported environment with clear and realistic workload expectation

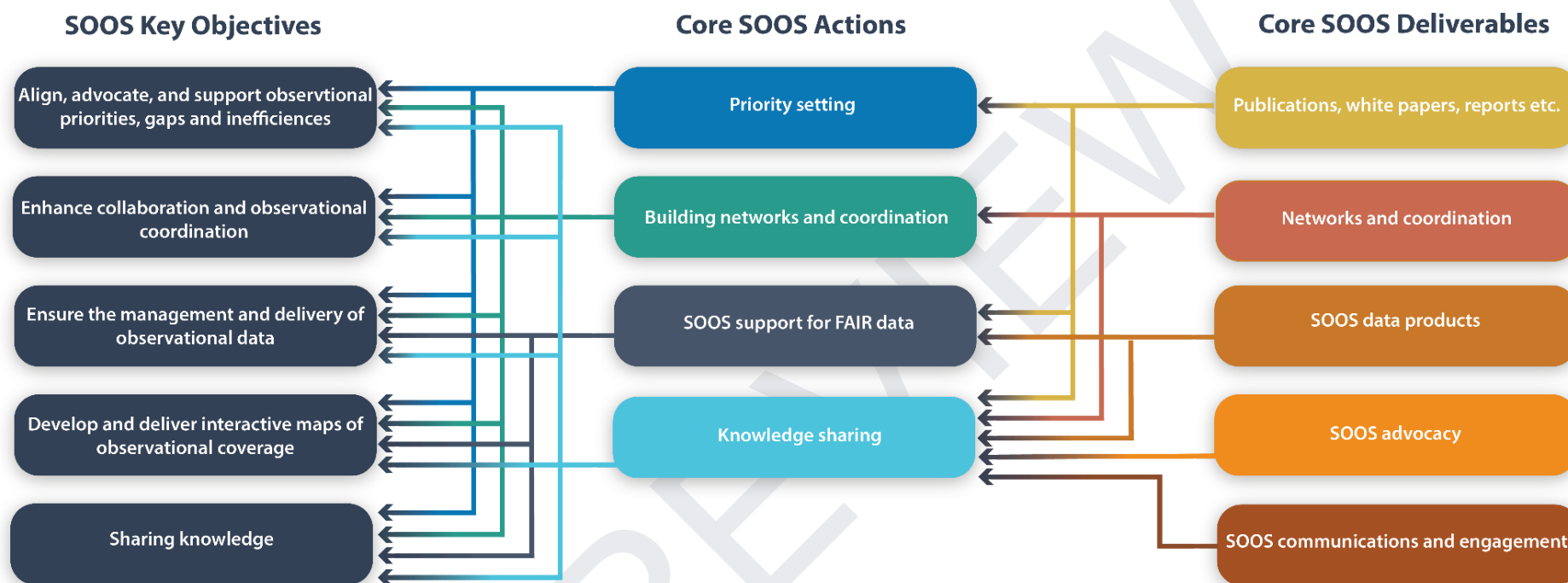


Figure 5: Summary figure of the SOOS Implementation Plan 2026-2030 High Priority, Core SOOS Actions and Deliverables and how they link to the SOOS Key Objectives.

References

- Abernathy, R.P., Cerovecki, I., Holland, P.R., Newsom, E., Mazloff, M., & Talley, L.D. (2016). Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geoscience*, 9(8), pp 596-601. DOI: 10.1038/ngeo2749.
- Abram, N. J., Purich, A., England, M. H., McCormack, F. S., Strugnell, J. M., Bergstrom, D. M., Vance, T. R., Stål, T., Wienecke, B., Heil, P., Doddridge, E. W., Sallée, J.-B., Williams, T. J., Reading, A. M., Mackintosh, A., Reese, R., Winkelmann, R., Klose, A. K., Boyd, P. W., Chown, S.L., & Robinson, S. A. (2025). Emerging evidence of abrupt changes in the Antarctic environment. *Nature*, 644 (8077), pp 621-633. <https://doi.org/10.1038/s41586-025-09349-5>
- Antoni, J.S., Almandoz, G.O., Goldsmit, J., Garcia, M.D., Flores-Melo, X., Hernando, M.P., & Schloss, I.R. (2024). Long-term studies on West Antarctic Peninsula phytoplankton community structure: A review of environmental drivers and potential responses to climate change. *Global Change Biology*, 3 (3), e17238. DOI: 10.1111/gcb.17238
- Ardiningsih, I., Seyitmuhammedov, K., Sander, S.G., Stirling, C.H., Reichart, G.J., Arrigo, K.A., Gerringa, L.J.A., & Middag, R. (2021). Fe-binding organic ligands in coastal and frontal regions of the western Antarctic Peninsula. *Biogeosciences*, 18, pp 4587-4601. DOI: 10.5194/bg-18-4587-2021.
- Arndt, S., Haumann, F. A., Boetius, A., Abram, N., Aemisegger, F., Aikaterini, T., Alexander, S., Amblas, D., Amory, C., Antoine, D., Arata, J. A., Arun, B. S., Aulicino, G., Auger, M., Baldini, L., Baldry, K., Babula, J., Bahlburg, D., Bamford, C., Barbante, C., Bartak, M., Beck, I., Behrens, E., Bengtson Nash, S., Berne, A., Biebow, N., Blok, D., Boersma, M., Braakmann-Folgmann, A., Bracher, A., Bracci, A., Brekke, C., Buzzard, S., Cajiao, D., Calace, N., Campana, G. L., Carli, E., Casado, M. G., Casassa Rogazinski, G., Castagno, P., Catany, R., Chaffron, S., Chandra Tripathy, S., Colesie, C., Colleoni, F., Corsolini, S., Cordero, R. R., Crabeck, O., Creamean, J. M., Cusick, A., Dadic, R., Darelius, E., Datta, R., Davis, P., Decesari, S., Delille, B., Deregibus, D., Di Ciccio, A., Di Liberto, L., Dierssen, H., Dimitris, E., Dimri, A. P., Dommergue, A., Donda, F., Doroteaciro, I., Droste, E. S., Ebinghaus, R., Ebbing, J., Eisen, O., Eléaume, M., Esquete, P., Fabris, R., Falco, P., Ferraccioli, F., Ferola, A. I., Favier, V., Filiciotto, F., Filún, D., Flemming, A., Fleury, S., Flocco, D., Fretwell, P., Frey, M. M., Friedlander, A., Fuchs, N., Gabarró, C., Galvez-Serna, J., Garbarini, E., Gerland, S., González-Herrero, S., Gorodetskaya, I., Gourmelen, N., Grotti, M., Gross, S., Guglielmin, M., Guarino, M. V., Halfter, S., Handorf, D., Hassler, C., Hattermann, T., Havermans, C., Heil, P., Henley, S., Hendrikx, J., Herraiz-Borreguero, L., Herr, H., Herrera, I., Hogg, A., Holmes, C., Hörhold, M., Hobbs, W., Höfer, J., Hrbáček, F., Huang, Y., Humphries, R. S., Huwald, H., Im, U., Jamieson, S., Jahnke, A., Jin, E. K., Johnston, N. M., Kaiser, T., Kalesse-Los, H., Kallenborn, R., Kapler, P., Kittel, C., King, C. K., Klocker, A., Köhler, R., Krüger, K., Krüger, L., Krzemińska, M., Kucera, P., Küster, A., Laepple, T., Landais, A., Langet, N., Laverigne, T., Lawrence, I., Le Bohec, C., Leckie, R. M., León, R., Li, X., Liu, X., Lohse, J., Lonardi, M., Londoño, P., López Lara, A., Lucchi, R. G., Lund, M. P., Lynche, H., Maestriau, C., Maignan, L., Maksym, T., Mallet, M. D., Manno, C., Marshall, G., Martin, T., Marzocchi, A., Massom, R., Massonnet, F., Matsuoka, K., Mayot, N., McClymont, E., McMillan, M., Meijers, A., Meiners, K., Meloth, T., Merkouriadi, I., Meyer, A., Meyer, H., Middag, R., Miloslavich, P., Mizobata, K., Moreau, S., Nagler, T., Nakayama, Y., Neder, C., Neely III, R. R., Olmedo, E., Olivier, L., Oliviera, L., Otsuka, I., Panda, P. P., Park, K., Patara, L., Patrolecco, L., Pattyn, F., Pezzi, L. P., Pfander, M., Picard, G., Pilz, C., Pillon, E., Pohl, B., Post, A., Poulin, E., Prend, C. J., Price, R., Quartino, M. L., Quesada, A., Radenz, M., Rampal, P., Rebecq, M., Reisinger, R., Ricker, R., Rod, D., Ropert-Coudert, Y., Sanders, R., Sangiorgi, F., Saeedi, H., Samrat, N., Schmale, J., Schulte, Schumacher, K., Schulz, A., Sciacca, V., Scardilli, A. S., Serrão, E., Shupe, M. D., Siems, S., Silvano, A., Simó, R., Simonsen, S. B., Sime, L., Singh, Smith, I. J., Souza, H. T., Soutullo, A., Spagnoli, F., Spolaor, A., Spreen, G., Steen, H., Steen-Larsen, H. C., Stephenson, L., Stevens, C., Stroeve, A. P., Strugnell, J., Sutton, A., Swart, S., Swiggs, A., Tamura, T., Tang, H., Talley, L., Tebben, J., Tedesco, L., Tetzner, D., Thomas, J. L., Thomisch, K., Thompson, A., Torricella, F., Treasure, A., Tripathy, S. C., Trimborn, S., Uitz, J., Urgeles, R., van de Berg, W. J., van Oostveen, J., van Opzeeland, I., Vancoppenolle, M., Vieira, G., Vignon, É., Vountas, M., Vrettou, A., Wahl, S., Warwick-Evans, V., Weiss, A., Weith, F., Werner, M., Wietz, M. P., Willatt, R., Willis, M. D., Winton, H., Wouters, B., Wuite, J., Wolfgang, R., Xie, Z., Yang, X., Yaneva, R.,

- Zhou, L., Zou, X. (2026). Antarctica InSync Science Plan. Scientific Committee on Antarctic Research (SCAR). <https://doi.org/10.67382/EACD5221>
- Arrigo, K.R., van Dijken, G.L., & Strong, A.L. (2015). Environmental controls of marine productivity hot spots around Antarctica. *Journal of Geophysical Research: Oceans*, 120 (8), pp 5545-5565. DOI: 10.1002/2015JC010888.
- Asay-Davis, X.S., Jourdain, N.C. & Nakayama, Y. (2017). Developments in Simulating and Parameterizing Interactions Between the Southern Ocean and the Antarctic Ice Sheet. *Current Climate Change Reports*, 3, pp 316–329. DOI: 10.1007/s40641-017-0071-0.
- Atkinson, A., Siegel, V., Pakhomov, E., & Rothery, P. (2004). Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*, 432, pp 100-103. DOI: 10.1038/nature02996.
- Atkinson, A., Hill, S.L., Pakhomov, E.A., Siegel, V., Reiss, C.S., Loeb, V.J., Steinberg, D.K., Schmidt, K., Tarling, G.A., Gerrish, L., & Sailley, S.F. (2019). Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. *Nature Climate Change*, 9, pp 142-147. DOI: 10.1038/s41558-018-0370-z.
- Balvanera, P., Brauman, K.A., Cord, A.F., Drakou, E.G., Geijzendorffer, I.R., Karp, D.S., Martin-López, B., Mwampamba, T.H., & Schröter, M. (2022). Essential ecosystem service variables for monitoring progress towards sustainability. *Current Opinion in Environmental Sustainability*, 54, 101152. DOI: 10.1016/j.cosust.2022.101152.
- Baker, K., Halfter, S., Scouling, B., Swadling, K. M., Richards, S. A., Bressac, M., Sutton, C.A., & Boyd, P. W. (2025). Carbon injection potential of the mesopelagic-migrant pump in the Southern Ocean during summer. *Frontiers in Marine Science*, 12, 1461723. DOI: 10.3389/fmars.2025.1461723.
- Barbosa, A., Benzel, J., De Leon, A., & Moreno, J. (2012). Population decline of chinstrap penguin (*Pygoscelis antarctica*) in Deception Island, South Shetlands, Antarctica. *Polar Biology*, 35, pp 1453-1457. DOI: 10.1007/s00300-012-1196-1.
- Beadling, R. L., Russell, J. L., Stouffer, R. J., Mazloff, M., Talley, L. D., Goodman, P.J., Sallée, J-B., Hewitt, H.T., Hyder, P., & Pandde, A. (2020). Representation of Southern Ocean Properties across Coupled Model Intercomparison Project Generations: CMIP3 to CMIP6. *Journal of Climate*, 33 (15), pp 6555-6581. DOI: 10.1175/JCLI-D-19-0970.1.
- Bednaršek, N., Tarling, G.A., Bakker, D.C.E., Fielding, S., Jones, E.M., Venables, H.J., Ward, P., Kurzirian, A., Lézé, B., Feely, R.A., Murphy, E.J. (2012). Extensive Dissolution of Live Pteropods in the Southern Ocean. *Nature Geoscience*, 5 (12), pp 881–85. DOI: 10.1038/ngeo1635.
- Bennetts, L.G., Shakespeare, C.J., Vreugdenhil, C.A., Foppert, A., Gayen, B., Meyer, A., Morrison, A.K., Padman, L., Phillips, H.E., Stevens, C.L., Toffoli, A., Constantinou, N.C., Cusack, J.M., Cyriac, A., Doddridge, E.W., England, M.H., Evans, D.G., Heil, P., Hogg, A.M., Holmes, R.M., Huneke, W.G.C., Jones, N.L., Keating, S.R., Kiss, A.E., Kraitzman, N., Malyarenko, A., McConnochie, C.D., Meucci, A., Montiel, F., Neme, J., Nikurashin, M., Patel, R.S., Peng, J-P., Rayson, M., Rosevear, M.G., Sohail, T., Spence, P., & Stanley, G.J. (2024). Closing the loops on Southern Ocean dynamics: from the circumpolar current to ice shelves and from bottom mixing to surface waves. *Reviews of Geophysics*, 62, 3, e2022RG000781. DOI: 10.1029/2022RG000781.
- Bercovici, S.K., Wiemers, M., Dittmar, T., & Niggemann, J. (2023). Disentangling biological transformations and photodegradation processes from marine dissolved organic matter composition in the global ocean. *Environmental Science & Technology*, 57, 50, pp 21145-21155. DOI: 10.1021/acs.est.3c05929.
- Bestley, S., Ropert-Coudert, Y., Bengtson Nash, S., Brooks, C.M., Cotté, C., Dewar, M., Friedlaender, A.S., Jackson, J.A., Labrousse, S., Lowther, A.D., McMahon, C.R., Phillips, R.A., Pistorius, P., Puskic, P.S., de A. Reis, A.O., Reisinger, R.R., Santos, M., Tarszisz, E., Tixier, P., Trathan, P.N., Wege, M., & Wienecke, B. (2020). Marine Ecosystem Assessment for the Southern Ocean: Birds and Marine Mammals in a Changing Climate. *Frontiers in Ecology and Evolution*, 8, 566936. DOI: 10.3389/fevo.2020.566936.
- Bharti, V., Fairall, C.W., Blomquist, B.W., Huang, Y., Protat, A., Sullivan, P.P., Siems, S.T., & Manton, M.J. (2019). Air-sea heat and momentum fluxes in the Southern Ocean. *Journal of Geophysical Research: Atmospheres*, 124 (23), pp 1242-12443. DOI: 10.1029/2018JD029761.

- Blanco, J.E., Siems, S.T., & Alexander, L.V. (2026). Precipitation biases over the Southern Ocean in CMIP6, reanalyses and satellite-based products. *JGR Atmospheres*, 131 (2), e2025JD044145. DOI: 10.1029/2025JD044145.
- Boisvert, L., Webster, M., Petty, A.A., Markus, T., Cullather, R.I., & Bromwich, D.H. (2020). Intercomparison of Precipitation Estimates Over the Southern Ocean from Atmospheric Reanalyses. *Journal of Climate*, 33 (24), pp 10627–10651. DOI: 10.1175/JCLI-D-20-00441.
- Bourassa, M.A., Gille, S.T., Bitz, C., Carlson, D., Clayson, C.A., & Cerovecki, I. (2013). High-latitude ocean and sea ice surface fluxes: challenges for climate research. *Bulletin American Meteorological Society*, 94, pp 403–423. DOI: 10.1175/bams-d-11-00244.
- Boyd, P.W., Arrigo, K.R., Ardyna, M., Halfter, S., Huckstadt, L., Kuhn, A.M., Lannuzel, D., Neukermans, G., Novaglio, C., Shadwick, E.H., Swart, S., & Thomalla, S. (2024). The role of biota in the Southern Ocean carbon cycle. *Nature Reviews Earth & Environment*, 5, pp 390–408. DOI: 10.1038/s43017-024-00531-3.
- Boye, M., van den Berg, C.M.G., de Jong, J.T.M., Leach, H., Croot, P., & de Baar, H.J.W. (2001). Organic complexation of iron in the Southern Ocean. *Deep Sea Research I*, 48, pp 1477–1497. DOI: 10.1016/S0967-0637(00)00099-6.
- Brasier, M., Barnes D., Bax, N., Brandt, A., Christianson, A., Constable, A.J., Downey, R., Figuerola, B., Griffiths, H., Gutt, J., Lockhart, S., Morley, S.A., Post, A., Van de Putte, A., Saeedi, H., Stark, J.S., Sumner, M., & Waller, C. (2021). Responses of Southern Ocean seafloor habitats and communities to global environmental changes. *Frontiers in Marine Science*, 8 (622721). DOI: 10.3389/fmars.2021.622721.
- Breyer, E., & Baltar, F. (2023). The largely neglected ecological role of oceanic pelagic fungi. *Trends in Ecology & Evolution*, 38, 9, pp 870–888. DOI: 10.1016/j.tree.2023.05.002.
- Bricher, P., Verhey, C., Dueer, R., Rebekah, I., Pulsifer, P., Collins, J., Jones, M., de Bruin, T., Manley, W., Christoffersen, S., Budden, A., Van de Putte, A., Gaylore, A., Tacoma, M., Fremand, A., Aulicino, G., Gao, A., Minch, W., Tronstad, S., Hayes, A., Godøy, Ø., & Schneider, O. (2023). POLDER best practice guide to implementing schema.org for data discovery. DOI: 10.5281/zenodo.7787160.
- Bronselaer, B., Winton, M., Griffies, S.M., Hurlin, W.J., Rodgers, K.B., Sergienko, O.V., Stouffer, R.J., & Russell, J.L. (2018). Change in future climate due to Antarctic meltwater. *Nature*, 564, pp 53–58. DOI: 10.1038/s41586-018-0712-z.
- Bushinsky, S.M., Landschützer, P., Rödenbeck, C., Gray, A.R., Baker, D., Mazloff, MR., Resplandy, L., Johnson, K.S., & Sarmiento, J.L. (2019). Reassessing Southern Ocean Air-Sea CO₂ Flux Estimates With the Addition of Biogeochemical Float Observations. *Global Biogeochemical Cycles*, 33 (11), pp 1370–88. DOI: 10.1029/2019GB006176.
- Butterworth, B.J., & Miller, S.D. (2016). Automated underway eddy covariance system for air-sea momentum, heat, and CO₂ fluxes in the Southern Ocean. *Journal of Atmospheric and Oceanic Technology*, 33, 4, pp 635–652. DOI: 10.1175/JTECH-D-15-0156.1.
- Cabré, A., Marinov, I., & Leung, S. (2015). Consistent global responses of marine ecosystems to future climate change across the IPCC AR5 earth system models. *Climate Dynamics*, 45, 1253–1280. DOI: 10.1007/s00382-014-2374-3.
- Carranza, M.M., Long, M.C., Di Luca, A., Fassbender, A.J., Johnson, K.S., Takeshita, Y., Mongwe, P., & Turner, K.E. (2024). Extratropical storms induce carbon outgassing over the Southern Ocean. *npj Climate and Atmospheric Science*, 7, 57. DOI: 10.1038/s41612-024-00657-7.
- Cavan, E.L., Belcher, A., Atkinson, A., Hill, S.L., Kawaguchi, S., McCormack, S., Meyer, B., Nicol, S., Ratnarajah, L., Schmidt, K., Steinberg, D.K., Tarling, G.A., & Boyd, P.W. (2019). The importance of Antarctic krill in biogeochemical cycles. *Nature Communications*, 10, 4742. DOI: 10.1038/s41467-019-12668-7.
- Cavan, E.L., Mackay, N., Hill, S.L., Atkinson, A., Belcher, A., & Visser, A. (2024). Antarctic krill sequester similar amounts of carbon to key coastal blue carbon habitats. *Nature Communications*, 15, 7842. DOI: 10.1038/s41467-024-52135-6.

- Chamberlain, P.M., Talley, L.D., Mazloff, M.R., Riser, S.C., Speer, K., Gray, A.R., & Schwartzman, A. (2018). Observing the Ice-Covered Weddell Gyre with Profiling Floats: Position Uncertainties and Correlation Statistics. *JGR Oceans*, 123 (11), pp 8383–8410. DOI: 10.1029/2027JC012990.
- Chang, N., Nicholson, S.-A., du Plessis, M., Lebehot, A.D., Mashifane, T.B., Moalusi, T.C., Mongwe, P., & Monteiro, P.M.S. (2026). BIOPERIANT12: a mesoscale-resolving coupled physics-biogeochemical model for the Southern Ocean. *Geoscientific Model Development*, 18, pp 6415–6438. DOI: 10.5194/gmd-18-6415-2025.
- Clucas, G.V., Dunn, M.J., Dyke, G., Emslie, S.D., Levy, H., Navven, R., Polito, M.J., Pybus, O.G., Rogers, A.D., & Hart, T. (2014). A reversal of fortunes: climate change 'winners' and 'losers' in Antarctic Peninsula penguins. *Scientific Reports*, 4 (1), pp 5024. DOI: 10.1038/srep05024.
- Colominas-Ciuró, R., Bertellotti, M., D'amico, V.L., Carabajal, E., Benzel, J., Vidal, V., Molas, M., Santos, M., Coria, N., & Barbosa, A. (2021). Diet, antioxidants and oxidative status in pygoscelid penguins. *Marine Ecology Progress Series*, 665, pp 201–216. DOI: 10.3354/meps13651.
- Constable, A.J., Melbourne-Thomas, J., Corney, S., Arrigo, K.R., Barbraud, C., Barnes, D.K.A., Bindoff, N.L., Boyd, P.W., Brandt, A., Costa, D.P., Davidson, A.T., Ducklow, H.W., Emmerson, L., Fukuchi, M., Gutt, J., Hindell, M.A., Hofmann, E.E., Hosie, G.W., Iida, T., Jacob, S., Johnston, N.M., Kawaguchi, S., Kokubun, N., Koubbi, P., Lea, M.-A., Makhado, A., Massom, R.A., Meiners, K., Meredith, M.P., Murphy, E.J., Nicol, S., Reid, K., Richerson, K., Riddle, M.J., Rintoul, S.R., Smith, W.O.J., Southwell, C., Stark, J.S., Sumner, M., Swadling, K.M., Takahashi, K.T., Trathan, P.N., Welsford, D.C., Weimerskirch, H., Westwood, K.J., Wienecke, B.C., Wolf-Gladrow, D., Wright, S.W., Xavier, J.C., & Ziegler, P. (2014). Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. *Global Change Biology*, 20 (10), pp 3004–3025. DOI: 10.1111/gcb.12623.
- Constable, A.J., Costa, D.P., Schofield, O., Newman, L., Urban, E.R., Fulton, E.A., Melbourne-Thomas, J., Ballerini, T., Boyd, P.W., Brandt, A., de la Mare, W.K., Edwards, M., Eléaume, M., Emmerson, L., Fennel, K., Fielding, S., Griffiths, H., Gutt, J., Hindell, M.A., Hofmann, E.E., & Willis, Z. (2016). Developing priority variables ("ecosystem Essential Ocean Variables" — eEOVs) for observing dynamics and change in Southern Ocean ecosystems. *Journal of Marine Systems*, 161, pp 26–41. DOI: 10.1016/j.jmarsys.2016.05.003.
- Curran, M.A.J., & Jones, G.B., (2000). Dimethyl Sulfide in the Southern Ocean: Seasonality and Flux. *Journal of Geophysical Research: Atmospheres*, 105 (D16), pp 20, 451–20, 459. DOI: 10.1029/2000JD900176.
- Deppeler, S.L., & Davidson A.T., (2017). Southern Ocean Phytoplankton in a Changing Climate. *Frontiers in Marine Science*, 4 (40). DOI: 10.3389/fmars.2017.00040.
- DeVries, T., Yamamoto, K., Wanninkhof, R., Fruber, N., Hauck, J., Müller, J.D., Bopp, L., Carroll, D., Carter, B., Chau, T.-T., Doney, S.C., Gehlen, M., Gloege, L., Gregor, L., Henson, S., Kim, J.H., Iida, Y., Ilyina, T., Landschützer, P., Le Quéré, C., Munro, D., Nissen, C., Patara, L., Pérez, F.F., Resplandy, L., Rodgers, K.B., Schwinger, J., Séférian, R., Sicardi, V., Terhaar, J., Triñanes, J., Tsujino, H., Watson, A., Yasunaka, S., & Zeng, J. (2023). Magnitude, trends, and variability of the global ocean carbon sink from 1985 to 2018. *Global Biogeochemical Cycles*, 37 (10), e2023GB007780. DOI: 10.1029/2023GB007780.
- Dinniman, M.S., Klinck, J.M., Hofmann, E.E. & Smith Jr, W.O. (2018). Effects of projected changes in wind, atmospheric temperature, and freshwater inflow on the Ross Sea. *Journal of Climate*, 31 (4), pp 1619–1635. DOI: 10.1175/JCLI-D-17-03511.
- Dinniman, M.S., St-Laurent, P., Arrigo, K.R., Hofmann, E.E., & van Dijken, G.L. (2020). Analysis of Iron Sources in Antarctic Continental Shelf Waters. *Journal of Geophysical Research: Oceans*, 125 (5), e2019JC015736. DOI: 10.1029/2019JC015736.
- Doddridge, E. W., Hobbs, W. R., Auger, M., Boyd, P. W., Chua, S. M. T., Cook, S., Corney, S., Emmerson, L., Fraser, A. D., Heil, P., Kelly, N., Lannuzel, D., Li, X., Liniger, G., Massom, R. A., Meyer, A., Reid, P., Southwell, C., Spence, P., Stekete, A., Swadling, K.M., Teder, N., Wienecke, B., Wongpan, P., & Yamazaki, K. (2025). Impacts of Antarctic summer sea-ice extremes. *PNAS Nexus*, 4 (7), pgaf164. DOI: 10.1093/pnasnexus/pgaf164.
- Dotto, T. S., Naveira Garabato, A. C., Bacon, S., Holland, P. R., Kimura, S., Firing, Y.L., Tsamados, M., Wåhlin, A.K., & Jenkins, A. (2019). Wind-driven processes controlling oceanic heat delivery to the

- Amundsen Sea, Antarctica. *Journal of Physical Oceanography*, 49 (11), pp 2829-2849. DOI: 10.1175/JPO-D-19-00641.
- Ducklow, H.W., Fraser, W., Karl, D.M., Quetin, L.B., Ross, R.M., Smith, R.C., Stammerjohn, S.E., Vernet, M., & Daniels, R.M. (2006). Water-column processes in the West Antarctic Peninsula and the Ross Sea: Interannual variations and foodweb structure. *Deep Sea Research Part II: Topical Studies in Oceanography*, 53 (8), pp 834-852. DOI: 10.1016/j.dsr2.2006.02.009.
- Ducklow, H.W., Baker, K., Martinson, D.G., Quetin, L.B., Ross, R.M., Smith, R.C., Stammerjohn, S.E., Vernet, M., & Fraser, W. (2007). Marine pelagic ecosystems: the west Antarctic Peninsula. *Philosophical Transactions in the Royal Society B*, 362 (1477), pp 67-94. DOI: 10.1098/rstb.2006.1955.
- Ducklow, H.W., Fraser, W.R., Meredith, M.P., Stammerjohn, S.E., Doney, S.C., Martinson, D.G., Sailley, S.F., Schofield, O.M., Steinberg, D.K., Venables, H.J., & Amsler, C.D. (2013). West Antarctic Peninsula: an ice-dependent coastal marine ecosystem in transition. *Oceanography*, 26 (3), pp 190-203. DOI: 10.5670/oceanog.2013.62.
- Dufour, C. O., Morrison, A.K., Griffies, S.M., Frenger, I., Zanowski, H., & Winton, M. (2017). Preconditioning of the Weddell Sea Polynya by the Ocean Mesoscale and Dense Water Overflows. *Journal of Climate*, 30, 7719-7737. DOI: 10.1175/JCLI-D-16-05861.
- Eayrs, C., Holland, D., Francis, D., Wagner, T., Kumar, R., & Li, X. (2019). Understanding the seasonal cycle of Antarctic sea ice extent in the context of longer-term variability. *Reviews of Geophysics*, 57 (3), pp 1037-1064. DOI: 10.1029/2018RG000631.
- Edholm, J.M., du Plessis, M.D., Biddle, L.C., Gille, S.T., Mazloff, M.R., Rosenthal, H.S., & Swart, S. (2025). From synoptic to submesoscale: understanding sensible heat flux variability in the Southern Ocean. *JGR Oceans*, 130, 10, e2024JC022292. DOI: 10.1029/2024JC022292.
- EuroGO-SHIP Consortium (2025). EuroGO-SHIP Deliverable 2.2: Climate-quality hydrographic reference sections for autonomous sensor calibration. EU Horizon Europe Project Report, 78 pp.
- Espinosa, Z.I., Blanchard-Wrigglesworth, E., & Bitz, C.M. (2024). Understanding the drivers and predictability of record low Antarctic sea ice in austral winter 2023. *Communications Earth & Environment*, 5 (1), 723. DOI: 10.1038/s43247-024-01772-2.
- Evans, C., Brandsma, J., Meredith, M.P., Thomas, D.N., Venables, H.J., Pond, D.W., & Brussaard, C.P.D. (2021). Shift from carbon flow through the microbial loop to the viral shunt in coastal Antarctic waters during austral summer. *Microorganisms*, 9 (2), 460. DOI: 10.3390/microorganisms9020460.
- Fairall, C.W., Bradley, E.G., Hare, J.E., Grachev, A.A., & Edson, J.B. (2003). Bulk parameterization of air-sea fluxes: updates and verification for the COARE algorithm. *Journal of Climate*, 16 (4), pp 571-591. DOI: 10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2.
- Falco, P., Aulicino, G., Castagno, P., Capozzi, V., de Ruggiero, P., Garzia, A., Ian Ferola, A., Cotroneo, Y., Colella, A., Fusco, G., Pierini, S., Budillon, G., Zamianchi, E., & Spezie, G. (2024). Ocean-atmosphere-ice processes in the Ross Sea: a review. *Deep Sea Research Part II: Topical Studies in Oceanography*, 2178, 105429. DOI: 10.1016/j.dsr2.2024.105429.
- Fay, A.R., Heimdal, T.H., Acquaviva, V., Shaum, A.P., & McKinley, G.A. (2025). Sensitivity of ocean carbon sink estimates to rare observations. *Geophysical Research Letters*, 52 (19), e2025CL117961. DOI: 10.1029/2025GL117961.
- Ferreira, A., Costa R.R., Dotto T.S., Kerr R., Tavano V.M., Brito, A.C., Brotas, V., Secchi, E.R., & Mendes, C.R.B. (2020). Changes in Phytoplankton Communities Along the Northern Antarctic Peninsula: Causes, Impacts and Research Priorities. *Frontiers in Marine Science*, 7, 576254. DOI: 10.3389/fmars.2020.576254.
- Figuerola B., Hancock A.M., Bax N., Cummings V.J., Downey R., Griffiths H.J., Smith J., & Stark J.S., (2021). A Review and Meta-Analysis of Potential Impacts of Ocean Acidification on Marine Calcifiers From the Southern Ocean. *Frontiers in Marine Science*, 8 (584445). DOI: 10.3389/fmars.2021.584445.
- Fourquez, M., Bressac M., Deppeler S.L., Ellwood M., Obernosterer I., Trull, T.W., & Boyd, P.W. (2020). Microbial Competition in the Subpolar Southern Ocean: An Fe-C Co-limitation Experiment. *Frontiers in Marine Science*, 6 (776). DOI: 10.3389/fmars.2019.00776.

- Frölicher, T. L., Sarmiento, J. L., Paynter, D. J., Dunne, J. P., Krasting, J. P., & Winton, M. (2015). Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *Journal of Climate*, 28 (2), pp 862-886. DOI: 10.1175/JCLI-D-14-00117.1.
- Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Landschützer, Le Quéré, C., Li, H., Luijkx, I.T., Olsen, A., Peters, G.P., Peters, W., Pongratz, J., Schwingshackle, C., Sitch, S., Canadell, J.G., Ciais, P., Jackson, R.B., Alin, S.R., Arneeth, A., Arora, V., Bates, N.R., Becker, M., Bellouin, N., Berghoff, C.F., Bittig, H.C., Bopp, L., Cadule, P., Campbell, K., Chamberlain, M.A., Chandra, N., Chevallier, F., Chini, L.P., Colligan, T., Decayeux, J., Djeutchoung, L.M., Dou, X., Duran Rojas, C., Enjoy, K., Evans, W., Fay, A.R., Felly, R.A., Ford, D.J., Foster, A., Gasser, T., Gehlen, M., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Hurtt, G.C., Iida, Y., Ilyina, T., Jacobson, A.R., Jain, A.K., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Kato, E., Keeling, R.F., Klein Goldeqijk, K., Knauer, J., Ivar Korsbakken, J., Lan, X., Lauveset, S.K., Lefèvre, N., Liu, Z., Liu, J., Ma, M., Maksyutov, S., Marlkan, G., Mayot, N., McGuire, P.C., Metzl, N., Monacchi, N.M., Morgan, E.J., Nakaoka, S-I., Neill, C., Niwa, Y., Nützel, T., Oliver, L., Ono, T., Palmer, P.I., Pierrot, D., Qin, Z., Resplandy, L., Roobaert, A., Rosan, T.M., Rödenbeck, C., Schwinger, J., Smallman, T.L., Smith, S.M., Sospedra-Alfonso, R., Steinhoff, T., Sun, Q., Sutton, A.J., Séférian, R., Takao, S., Tatebe, H., Tian, H., Tilbrook, B., Torres, O., Tourigny, E., Tsujino, H., Tubiello, F., van der Werf, G., Wanninkhof, R., Wang, X., Yang, D., Yang, X., Yu, Z., Yuan, W., Yue, X., Zaehle, S., Zeng, N., & Zeng, J. (2025). Global carbon budget 2024. *Earth System Science Data*, 17 (3), pp 965-1039. DOI: 10.5194/essd-17-965-2025.
- Fretwell, P.T., Boutet, A., & Ratcliffe, N. (2023). Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins. *Communications Earth & Environment*, 4, 273. DOI: 10.1038/s43247-023-00927-x.
- Fretwell, P.T. (2024). A 6 year assessment of low sea-ice impacts on emperor penguins. *Antarctic Science*, 31 (1): 3-5. DOI: 10.1017/S0954102024000130
- Fretwell, P.T., Bamford, C., Skachkova, A., Trathan, P.N., & Forcada, J. (2025). Regional emperor penguin population declines exceed modelled projections. *Communications Earth & Environment*, 6 (436). DOI: 10.1038/s43247-025-02345-7.
- GCOS. (2022). The 2022 GCOS Implementation Plan (GCOS-244). Geneva: World Meteorological Organization: 1-98. Available at <https://library.wmo.int/records/item/58104-the-2022-gcos-implementation-plan-gcos-244>
- Golledge, N.R., Keller, E.D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L.D., & Edwards, T.L. (2019). Global environmental consequences of twenty-first-century ice-sheet melt. *Nature*, 566 (7742), pp 65-72. DOI: 10.1038/s41586-019-0889-9.
- Graham, J.A., Dinniman, M.S., & Klinck, J.M. (2016). Impact of model resolution for on-shelf heat transport along the West Antarctic Peninsula. *Journal of Geophysical Research: Oceans*, 121, pp 7880-7897. DOI: 10.1002/2016JC011875
- Gray, A.R., Johnson, K.S., Bushinsky, S.M., Riser, S.C., Russell, J.L., Talley, L.D., Wanninkhof, R., Williams, N.L., & Sarmiento, J.L. (2018). Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean. *Geophysical Research Letters*, 45 (17), pp 9049-9057. DOI: 10.1029/2018GL078013.
- Gray, A.R. (2024). The four-dimensional carbon cycle of the Southern Ocean. *Annual Review of Marine Science*, 16, pp 163-190. DOI: 10.1146/annurev-marine-041923-104057.
- Gregor, L., Shutler, J., & Gruber, N. (2024). High-resolution variability of the ocean carbon sink. *Global Biogeochemical Cycles*, 38 (8), e20204B008127. DOI: 10.1029/2024GB008127.
- Griffiths, H.J., Meijers, A.J., & Bracegirdle, T.J. (2017). More losers than winners in a century of future Southern Ocean seafloor warming. *Nature Climate Change*, 7, pp 749-754. DOI: 10.1038/nclimate3377.
- Gutt, J., Bertler, N., Bracegirdle, T.J., Buschmann, A., Comiso, J., Hosie, G., Isla, E., Schloss, I.R., Smith, C.R., Tournadre, J., & Xavier, J.C. (2015). The Southern Ocean ecosystem under multiple climate change stresses - an integrated circumpolar assessment. *Global Change Biology*, 21 (4), pp 1434-1453. DOI: 10.1111/gcb.12794.

- Gwyther, D.E., Galton-Fenzi, B.K., Hunter, J.R., & Roberts, J.L. (2014). Simulated melt rates for the Totten and Dalton ice shelves. *Ocean Science*, 10 (3), pp 267-279. DOI: 10.5194/os-10-267-2014
- Hackerott, J.A., Pezzi, L.P., Paskyabi, M.B., Oliveira, A.P., Reuder, J., de Souza, R.B., & de Camargo, R. (2018). The role of roughness and stability on the momentum flux in the marine atmospheric surface layer: a study on the southwestern Atlantic Ocean. *Journal of Geophysical Research: Atmospheres*, 123, pp 3914–3932. DOI: 10.1002/2017JD027994.
- Hancock, A.M., Schloss, I.R., Meijers, A., Tripathy, S.C., Henley, S.F., and Rack, W. in review. The Southern Ocean Observing System (SOOS): Connecting observations to understanding in a changing Southern Ocean. *Elementa: Science of the Anthropocene*.
- Halfter, S., Cavan, E.L., Swadling, K.M., Eriksen, R.S., & Boyd, P.W. (2020). The role of zooplankton in establishing carbon export regimes in the Southern Ocean - a comparison of two representative case studies in the Subantarctic region. *Frontiers in Marine Science*, 7. DOI: 10.3389/fmars.2020.567917.
- Halfter, S., Brokensha, L., Cotté, C., Eriksen, R., Friscourt, N., Green, D.B., Heil, P., Hellessey, N., Herraiz Borreguero, L., Hirawake, T., Hobbs, W., Jansen, J., Mahajan, A.S., Makhado, A.B., McMahon, C., von der Meden, C.E.O., Raes, E., Stirnimann, L., Subramaniam, R., Sundaram, S., Tagliabue, A., Wynn-Edwards, C., Verhaegen, G., Tripathy, S.C., & Shadwick, S. (2025). Status of ocean observations in the Indian Sector of the Southern Ocean. *Elementa: Science of the Anthropocene*, 13 (1), 00098. DOI: 10.1525/elementa.2024.00098.
- Hassler, C.S., Alasonati, E., Mancuso Nichols, C.A., & Slaveykova, V.I. (2011). Exopolysaccharides produced by bacteria isolated from the pelagic Southern Ocean - Role in Fe binding, chemical reactivity, and bioavailability. *Marine Chemistry*, 123 (1-4), pp 88-98. DOI: 10.1016/j.marchem.2010.10.003.
- Hauck, J., Zeising, M., Le Quéré, C., Gruber, N., Bakker, D.C.E., Bopp, L., Chau, T-T-T., Gürses, Ö., Ilyina, T., Landschützer, P., Lenton, A., Resplandy, L., Rödenbeck, C., Schwinger, J., & Séférian, R. (2020). Consistency and challenges in the ocean carbon sink estimate for the global carbon budget. *Frontiers in Marine Science*, 7. DOI: 10.3389/fmars.2020.5717209.
- Hauck, J., Nissen, C., Landschützer, P., Rödenbeck, C., Bushinsky, S., & Olsen, A. (2023a). Sparse observations induce large biases in estimates of the global ocean CO₂ sink: an ocean model subsampling experiment. *Philosophical Transactions A*, 381, 20220063. DOI: 10.1098/rsta.2022.0063.
- Hauck, J., Gregor, L., Nissen, C., Patara, L., Mongwe, P., Bushinsky, S., Doney, S.C., Gruber, N., LeQuéré, C., Manizza, M., Mazloff, M., Monteiro, P.M.S., & Terhaar, J. (2023b). The Southern Ocean carbon cycle 1985-2018: mean, seasonal cycle, trends, and storage. *Global Biogeochemical Cycles*, 37 (11), e2023GB007848. DOI: 10.1029/2023GB007848.
- Haumann, F.A., Gruber, N., Münnich, M., Frenger, I., & Kern, S. (2016). Sea-ice transport driving Southern Ocean salinity and its recent trends. *Nature*, 537 (7618), pp 89-92. DOI: 10.1038/nature19101.
- Hayward, A., Wright, S.W., Carroll, D., Law, C.S., Wongpan, P., Gutiérrez-Rodríguez, A., & Pinkerton, M.H. (2025). Antarctic phytoplankton communities restructure under shifting sea-ice regimes. *Nature Climate Change*, 15, pp 889-896. DOI: 10.1038/s41558-025-02379-x.
- Heil, P., Stevens, C., Lee, W.S., Eayrs, C., Shin, H.C., Alexander, S.P. & Rack, W. (2023). Bridging the gap for ice–ocean–ecosystem processes: integrated observing system for the Ross Sea-far East Antarctic Region. *Frontiers in Marine Science*, 10, p.1206119. DOI: 10.3389/fmars.2023.1206119.
- Henson, S.A., Laufkötter, C., Leung, S., Giering, S.L.C., Palevsky, H.I., & Cavan, E.L. (2022). Uncertain response of ocean biological carbon export in a changing world. *Nature Geoscience*, 15, 248-254. DOI: 10.1038/s41561-022-00927-0.
- Hernando, M., Schloss, I.R., Malanga, G., Almandoz, G.O., Ferreyra, G.A., Aguiar, M.B., & Puntarulo, S. (2015). Effects of salinity changes on coastal Antarctic phytoplankton physiology and assemblage composition. *Journal of Experimental Marine Biology and Ecology*, 466, pp 110-119. DOI: 10.1016/j.jembe.2015.02.012.
- Herraiz-Borreguero, L., Lannuzel, D., van der Merwe, P., Treverrow, A., & Pedro, P.B. (2016). Large flux of iron from the Amery Ice Shelf marine ice to Prydz Bay, East Antarctica. *Journal of Geophysical Research: Oceans*, 121 (8), pp 6009-6020. DOI: 10.1002/2016JC011687.

- Herraiz-Borreguero, L., & Naveira Garabato, A. C. (2022). Poleward shift of Circumpolar Deep Water threatens the East Antarctic Ice Sheet. *Nature Climate Change*, 12 (8), 728–734. DOI: 10.1038/s41558-022-01424-3.
- Hinke, J.T., Trivelpiece, S.G., & Trivelpiece, W.Z. (2017). Variable vital rates and the risk of population declines in Adélie penguins from the Antarctic Peninsula region. *Ecosphere*, 8 (1), e01666. DOI: 10.1002/ecs2.1666.
- Hirose, K. (2007). Metal-organic matter interaction: Ecological roles of ligands in oceanic DOM. *Applied Geochemistry*, 22 (8), pp 1636–1645. DOI: 10.1016/j.apgeochem.2007.03042.
- Hobbs, W.R., Massom, R., Stammerjohn, S., Reid, P., Williams, G. & Meier, W. (2016). A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change*, 143, pp 228–250. DOI: 10.1016/j.gloplacha.2016.06.008.
- Hobbs, W.R., Spence, P., Meyer, A., Schroeter, S., Fraser, A.D., Reid, P., Tian, T.R., Wang, Z., Liniger, G., Doddridge, E.W., & Boyd, P.W. (2024). Observational evidence for a regime shift in summer Antarctic sea ice. *Journal of Climate*, 37 (7), pp 2263–2275. DOI: 10.1175/JCLI-D-23-0479.1.
- Holmes, C.R., Holland, P. R., & Bracegirdle, T.J. (2019). Compensating biases and a noteworthy success in theCMIP5 representation of Antarctic sea ice processes. *Geophysical Research Letters*, 46, pp 4299–4307. DOI: 10.1029/2018GL081796.
- Holthusen, L.A., Bange, H.W., Arévalo-Martínez, Badewien, T.H., Höfer, J., Löscher, C.R., Marin-Arias, C., Meyerjürgens, J., Schlangen, I., & Wurl, O. (2025). Glacial meltwater driver high CH₄ supersaturation in Maxwell Bay, King George Island (Southern Ocean). *Limnology and Oceanography*, 10 (6), pp 867–876. DOI: 10.1594/PANGAEA.974403.
- Huezé, C. (2021). Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models. *Ocean Science*, 17, pp 59–90. DOI: 10.5194/os-17-59-2021.
- Hunter, A., Thorpe, S.E., McCarthy, A.H., & Manno, C. (2024). Microplastic hotspots mapped across the Southern Ocean reveal areas of potential ecological impact. *Scientific Reports*, 14, 31599. DOI: 10.1038/s41598-024-79816-y.
- Hyder, P., Edwards, J.M., Allan, R.P., Hewitt, H.T., Bracegirdle, T.J., Gregory, J.M., Wood, R.A., Meijers, A.J.S., Mulcahy, J., Field, P., Furtado, K., Bodas-Salcedo, A., Williams, K.D., Copsey, D., Josey, S.A., Liu, C., Roberts, C.D., Sanchez, C., Ridley, J., Thorpe, L., Hardiman, S.C., Mayer, M., Berry, D.I., & Belcher, S.E. (2018). Critical Southern Ocean climate model biases traced to atmospheric model cloud errors. *Nature Communications*, 9, 3625. DOI: 10.1038/s41467-018-05634-2.
- Ionita, M. (2024). Large-scale drivers of the exceptionally low winter Antarctic sea ice extent in 2023. *Frontier in Earth Science Cryospheric Sciences*, 12. DOI: 10.3389/feart.2024.1333706.
- IPCC. (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].
- IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. DOI: 10.1017/9781009157896.
- IPCC. (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löscher, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., DOI:10.1017/9781009325844.
- Jiao, N., Herndl, G.J., Hansell, D.A., Benner, R., Kattner, G., Wilhelm, S.W., Kirchman, D.L., Weinbauer, M.G., Luo, T., Chen, F., & Azam, F. (2010). Microbial Production of Recalcitrant Dissolved Organic Matter: Long-Term Carbon Storage in the Global Ocean. *Nature Reviews Microbiology*, 8 (8), pp 593–99. DOI: 10.1038/nrmicro2386.

- Jiao, N., Luo, T., Chen, Q., Zhao, Z., Xiao, X., Liu, J., Jian, Z., Xie, S., Thomas, H., Hernd, G.J., Benner, R., Gonsio, M., Chen, F., Cai, W.-J., & Robinson, S. (2024). The microbial carbon pump and climate change. *Nature Reviews Microbiology*, 22 (7), pp 408–419. DOI: 10.1038/s41579-024-01018-0.
- Johnson, K. S., Plant, J.N., Coletti, L.J., Jannasch H.W., Sakamoto, C.M., Riser, S.C., Swift, D.D., Williams, N.L., Boss, E., Haëntjens, N., Talley, L.D., & Sarmiento, J.L. (2017a), Biogeochemical sensor performance in the SOCCOM profiling float array, *Journal of Geophysical Research: Oceans*, 122, pp 6416– 6436, DOI:10.1002/2017JC012838.
- Johnson, K.S., Plant, J.N., Dunne, J.P., Talley, L.D., & Sarmiento, J.L. (2017b). Annual nitrate drawdown observed by SOCCOM profiling floats and the relationship to annual net community production. *Journal of Geophysical Research: Oceans*, 122, pp 6668–6683. DOI: 10.1002/2017jc012839.
- Jones, R.L., Hawkings, J.R., Meredith, M.P., Lohan, M.C., Moore, O.W., Sherrell, R.M., Fitzsimmons, J.N., Kazemian, M., Araki, R., Kaulich, B., & Annett, A.L. (2025). Antarctic glaciers export carbon-stabilised iron (II)-rich particles to the surface Southern Ocean. *Nature Communications*, 16, 5015. DOI: 10.1038/s41467-025-59981-y.
- Josey, S.A., Meijers, A.J.S., Blaker, A.T., Grist, J.P. Mecking, J., & Ayres, H.C. (2024). Record-low Antarctic sea ice in 2023 increased ocean heat loss and storms. *Nature*, 636. DOI: 10.1038/s41586-024-08368-y.
- Kaartvedt, S., Røstad, A., Christiansen, S., & Klevjer, T.A. (2020). Diel vertical migration and individual behavior of nekton beyond the ocean's twilight zone. *Deep-Sea Research Part I*, 160 (103280). DOI: 10.1016/j.dsr.2020.103280.
- Kennicutt, M. C. II, Chown, S. L., Cassano, J. J., Liggett, D., Massom, R., Peck, L.S., Rintoul, S.R., Storey, J.W.V., Vaughan, D.G., Wilson, T.J., & Sutherland, W.J. (2014). Polar Research: Six priorities for Antarctic science. *Nature*, 512, pp 23–25. DOI: 10.1038/512023a.
- Khaliwala, S., Primeau, F., & Hall, T. (2009). Reconstruction of the history of anthropogenic CO₂ concentrations in the ocean. *Nature*, 462, pp 346–349. DOI: 10.1038/nature08526.
- Kubiszewski, I., Adams, VM, Baird, R, Boothroyd, A, Costanza, R, Hatton MacDonald, D, Finau, G, Fulton, EA, King, CK, King, MA, Lannuzel, D, Leane, E, Melbourne-Thomas, J, Ooi, C-S, Raghavan, M, Senigaglia, V, Stoeckl, N, Tian, J, & Yamazaki, S. (2024). Cascading tipping points of Antarctica and the Southern Ocean. *AMBIO: A Journal of the Human Environment* 54, pp 642–659. DOI: 10.1007/s13280-024-02101-9.
- Krumhardt, K.M., Landrum, L., Şen, B., DuVivier, A.K., Levy, M.N., Nissen, C., Holland, M.M., & Jenouvrier, S. (2026). Emergent climate change signals within Antarctic sea ice and associated ecosystems. *Nature Climate Change*, 16, pp 364–371. DOI: 10.1038/s41558-026-02561-9.
- Landschützer, P., Gruber, N., Haumann, F.A., Rödenbeck, C., Bakker, D.C.E., van Heuven, S., Hoppema, M., Metzl, N., Sweeney, C., Takahashi, T., Tilbrook, B., & Wanninkhof, R. (2015). The Reinvigoration of the Southern Ocean Carbon Sink. *Science*, 349 (6253), pp 1221–1224. DOI: 10.1126/science.aab2620.
- Latorre, M., Lachetti, C., Schloss, IR, Antoni, J, Malits, A, De la Rosa, F, De Troch, M, Garcia, M, Flores-Melo, X, Romero, S, Gil, M, & Hernando, M. (2023). Summer heatwaves affect coastal Antarctic plankton metabolism and community structure. *Journal of Experimental Marine Biology and Ecology*, 567, 151926. DOI: 10.1016/j.jembe.2023.151926.
- Lavergne, T., Kern, S., Aaboe, S., Derby, L., Dybkjaer, G., Garric, G., Heil, P., Hendricks, S., Holfort, J., Howell, S., Key, J., Lieser, J.L., Maksym, T., Maslowski, W., Meier, W., Muñoz-Sabater, J., Nicolas, J., Özsoy, B., Rabe, B., Rack, W., Raphael, M., de Rosnay, P., Smolyanitsky, V., Tietsche, S., Ukita, J., Vichi, M., Wagner, P., Willmes, S., & Zhao, X. (2022). A new structure for the sea ice essential climate variables for the global climate observing system. *Bulletin of the American Meteorological Society*, 103 (6), E1502–E1521. DOI: 10.1175/BAMS-D-21-02271.
- Legendre, L., Rivkin, R.B., Weinbauer, M.G., Guidi, L. & Uitz, J. (2015). The Microbial Carbon Pump Concept: Potential Biogeochemical Significance in the Globally Changing Ocean. *Progress in Oceanography*, 134, pp 432–50. DOI:10.1016/j.pocean.2015.01.008.
- Lenton, A., Matear, R.J., & Tilbrook, B. (2006). Design of an observational strategy for quantifying the Southern Ocean uptake of CO₂. *Global Biogeochemical Cycles*, 20, GB4010. DOI: 10.1029/2005GB002620.

- Lenton, A.B., Tilbrook, R.M., Law, D., Bakker, S.C., Doney, N., Gruber, N., Ishii, M., Hoppema, M., Lovenduski, N.S., Matear, R.J., McNeil, B.I., Metzl, N., Mikaloff Fletcher, S.E., Monteiro, P.M.S., Rödenbeck, C., Sweeney, C., & Takahashi, T. (2013). Sea-Air CO₂ Fluxes in the Southern Ocean for the Period 1990-2009. *Biogeosciences*, 10 (6), pp 4037–54. DOI: 10.5194/bg-10-4037-2013.
- Le Quéré, C., Rödenbeck, C., Buitenhuis, E.T., Conway, T.J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., & Heimann, M. (2007). Saturation of the Southern Ocean CO₂ sink due to recent climate change. *Science*, 316 (5832), pp 1735-1738. DOI: 10.1126/science.1136188.
- Leung, S., Cabre, A., & Marinov, I. (2015). A latitudinally banded phytoplankton response to 21st century climate change in the southern ocean across the CMIP5 model suite. *Biogeosciences*, 12, pp 5715–5734. DOI: 10.5194/bg-12-5715-2015
- Li, Q., England, M.H., Hogg, A.M., Rintoul, S.R., & Morrison, A.K. (2023). Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature*, 615 (7954), 7954. DOI: 10.1038/s41586-023-05762-w.
- Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., Glover, L.K., & Task Team for the Integrated Framework for Sustained Ocean Observing (2012). A Framework for Ocean Observing. UNESCO 2012, IOC Information Document 1284, Rev. 2. DOI: 10.5270/OceanObs09-FOO
- Liu, J., Zhu, Z., & Chen, D. (2023). Lowest Antarctic sea ice record broken for the second year in a row. *Ocean-Land-Atmosphere Research*, 2, 0007. DOI: 10.34133/olar.0007.
- Liu, Y., Nikurashin, M., & Peña-Molino, B. (2024). Seafloor roughness reduces melting of East Antarctic ice shelves. *Communications Earth & Environment*, 5, 322. DOI: 10.1038/s43247-024-01480-x.
- Loose B., & Schlosser, P. (2011). Sea ice and its effect on CO₂ flux between the atmosphere and the Southern Ocean interior. *JGR Oceans*, 116, C11. DOI: 10.1029/2010JV006509.
- López-García, P., Rodríguez-Valera, F., Pedrós-Alió, C., & Moreira, D. (2001). Unexpected diversity of small eukaryotes in deep-sea Antarctic plankton. *Nature*, 409 (6820), pp 603-7. DOI:10.1038/35054537.
- Lovenduski, N.S., Fay, A.R., & McKinley, G.A. (2015). Observing multidecadal trends in Southern Ocean CO₂ uptake: What can we learn from an ocean model?. *Global Biogeochemical Cycles*, 29 (4), pp 416-426. DOI: 10.1002/2014GB004933.
- Luo, F., Ying, J., Liu, T., & Chen, D. (2023). Origins of Southern Ocean warm sea surface temperature bias in CMIP6 models. *NPJ Climate and Atmospheric Science*, 6, 127. DOI: 10.1038/s41612-023-00456-6.
- Malyarenko, A., Wells, A.J., Langhorne, P.J., Robinson, N.J., Williams, M.J.M., & Nicholls, K.W. (2020). A synthesis of thermodynamic ablation at ice-ocean interfaces from theory, observations and models. *Ocean Modelling*, 154, 101692. DOI:10.1016/j.ocemod.2020.101692
- Manno, C., Fielding, S., Stowasser, G., Murphy, E.J., Thorpe, S.E., & Tarling, G.A. (2020). Continuous moulting by Antarctic krill drives major pulses of carbon export in the north Scotia Sea, Southern Ocean. *Nature communications*, 11 (1), 6051. DOI: 10.1038/s41467-020-19956-7.
- Manno, C., Carlig, E., Falco, P.P., Castagno, P., & Budillon, G. (2024). Life strategy of Antarctic silverfish promote large carbon export in Terra Nova Bay, Ross Sea. *Communications Biology*, 7, 450. DOI: 10.1038/s42003-024-06122-8.
- Marshall, J., & Speer, K. (2012). Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nature Geoscience*, 5 (3), pp 171-180. DOI: 10.1038/NGEO1391.
- Martin, T., Dufour, C.O., Meijers, A.J.S., & Hancock, A.M. 2026. Opinion: status, plans and needs of Southern Ocean modelling. *Ocean Science*, 22, pp 1429-1437. DOI: 10.5194/os-22-1429-2026..
- Massom, R.A., & Stammerjohn, S.E. (2010). Antarctic sea ice change and variability – Physical and ecological implications. *Polar Science*, 4 (2), pp 149-186. DOI: 10.1016/j.polar.2010.05.001.
- Massom, R.A., Scambos, T.A., Bennetts, L.G., Reid, P., Squire, V.A. & Stammerjohn, S.E. (2018). Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. *Nature*, 558, pp 383-389. DOI: 10.1038/s41586-018-0212-1.
- Mazloff, M.R., Heimbach, P. & Wunsch, C. (2010). An eddy-permitting Southern Ocean state estimate. *Journal of Physical Oceanography*, 40 (5), pp 880-899. DOI: 10.1175/2009JPO4236.1.

- Mazloff, M.R., Cornuelle, B.D., Gille, S.T., & Verdy, A. (2018). Correlation lengths for estimating the large-scale carbon and heat content of the Southern Ocean. *Journal of Geophysical Research: Oceans*, 123, pp 883–901. DOI: 10.1002/2017jc013408.
- McCarthy, A.H., Peck, L.S., Hughes, & Aldridge, D.C. (2019). Antarctica: the final frontier for marine biological invasions. *Global Change Biology*, 25 (7), pp 2221–2241. DOI: 10.1111/gcb.14600.
- McCarthy, A.H., Peck, L.S., & Aldridge, D.C. (2021). Ship traffic connects Antarctica's fragile coasts to worldwide ecosystems. *PNAS*, 119 (3), e2110303118. DOI: 10.1073/pnas.2110303118.
- McCormack, S.A., Melbourne-Thomas, J., Trebilco, R., Griffith, G., Hill, S.L., Hoover, C., Johnston, N.M., Marina, T.I., Murphy, E.J., Pakhomov, E.A., Pinkerton, M., Plagányi, É., Saravia, L.A., Subramaniam, R.C., van de Putt, A.P., & Constable, A.J. (2021). Southern Ocean food web modelling: progress, prognoses, and future priorities for research and policy makers. *Frontiers in Ecology and Evolution*, 9, 624763. DOI: 10.3389/fevo.2021.624763.
- McCormack, F. S., Cook, S., Goldberg, D. N., Nakayama, Y., Seroussi, H., Nias, I., An, L., Slater, D., & Hattermann, T. (2024). The case for a Framework for UnderStanding Ice-Ocean iNteractions (FUSION) in the Antarctic-Southern Ocean system. *Elementa: Science of the Anthropocene*, 12 (1), 00036. DOI: 10.1525/elementa.2024.00036.
- McQuaid, C.D. (2018). 'Implications of Long-Term Climate Change for Biogeography and Ecological Processes in the Southern Ocean' in *Oceanography and Marine Biology An Annual Review Volume 56*, Hawkins, S.J., Evans, A.J., Dale, A.C., Firth, L.B., Smith, I.P. (eds). Boca Raton, USA: CRC Press: 1-71. DOI: 10.1201/9780429454455-1.
- Mdutyana, M., Thomalla, S.J., Philibert, R., Ward, B.B., & Fawcett, S. E. (2020). The seasonal cycle of nitrogen uptake and nitrification in the Atlantic sector of the Southern Ocean. *Global Biogeochemical Cycles*, 34, e2019BG0D6363. DOI: 10.1029/2019GB006363.
- Mendes, C.R.B., Tavano V.M., Leal M.C., de Souza M.S., Brotas V., & Garcia C.A.E. (2013). Shifts in the dominance between diatoms and cryptophytes during three late summers in the Bransfield Strait (Antarctic Peninsula). *Polar Biology*, 36, pp 537–547. DOI:10.1007/s00300-012-1282-4.
- Mendes, C.R.B., Tavano V.M., Dotto T.S., Kerr R., de Souza M.S., Eiras Garcia, C.A., & Resende Secchi, E. (2018). New insights on the dominance of cryptophytes in Antarctic coastal waters: A case study in Gerlache Strait. *Deep-Sea Research Part II Topical Studies in Oceanography*, 149, pp 161–170. DOI: 10.1016/j.dsr2.2017.02.010.
- Meredith, M.M. Sommerkorn, S., Cassotta, C., Derksen, A., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M.M.C., Ottersen, G., Pritchard, H., & Schuur, E.A.G. (2019). Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].
- Meredith, M.P., Melbourne-Thomas, J., Naveira Garabato, A.C., & Raphael, M. (2025). *Antarctica and the Earth System* (1st ed.). Routledge. DOI: 10.4324/9781003406471.
- Mestre, M., Prior, A., Marín-Arias, C., Rodríguez-Solís, D.R., Laso-Pérez, R., Alarcón, E., Vásquez-Lepio, González, H.E., Logares, R., McNichol, J., Fuhrman, J., Fernandez, C., Hopwood, M.J., & Höfer, J. (2026). Microbial fingerprinting of marine water masses in an Antarctic and hydrographically complex area. *BMC Biology*, 24, 144. DOI: 10.1186/s12915-026-02621-8.
- Mignot, A., Claustre, H., Cossarini, G., D'Ortenzio, F., Gutknecht, E., Lamouroux, J., Lazzari, P., Perruche, C., Salon, S., Sauzède, R., Taillandier, V., & Teruzzi, A. (2023). Using machine learning and Biogeochemical-Argo (BGC-Argo) floats to assess biogeochemical models and optimize observing system design. *Biogeosciences*, 20, pp 1405–1422. DOI: 10.5194/bg-20-1405-2023.
- Miloslavich, P., Bax, N.J., Simmons, S.E., Klein, E., Appeltans, W., Aburto-Oropeza, O., Andersen Garcia, M., Batten, S.D., Benedetti-Cecchi, L., Checkley, D.M.J., Chiba, S., Duff, J.E., Dunne, D.C., Fischer, A., Gunn, J., Kudela, R., Marsac, F., Muller-Karger, F.E., Obura, D., & Shin, Y-J. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Global Change Biology*, 24 (6), pp 2416–2433. DOI: 10.1111/gcb.14108.

- Monteiro, P.M.S., Gregor, L., Lévy, M., Maenner, S., Sabine, C.L., & Swart, S. (2015). Intraseasonal variability linked to sampling alias in air-sea CO₂ fluxes in the Southern Ocean. *Geophysical Research Letters*, 42, pp 8507–8514. DOI: 10.1002/2015GL066009.
- Monteiro, T., Kerr, R., Orselli, I.B., & Lencina-Avila, J.M. (2020). Towards an intensified summer CO₂ sink behaviour in the Southern Ocean coastal regions. *Progress in Oceanography*, 183, 102267. DOI: 10.1016/j.pocean.2020.102267.
- Montes-Hugo, M.A., Vernet, M., Martinson, D., Smith, R., & Lannuzzi, R. (2008). Variability on phytoplankton size structure in the western Antarctic Peninsula (1997–2006). *Deep Sea Research Part II: Topical Studies in Oceanography*, 55 (18), pp 2106–2117. DOI: 10.1016/j.dsr2.2008.04.036.
- Montes-Hugo, M., Doney, S.C., Ducklow, H.W., Fraser, W., Martinson, D., Stammerjohn, S.E., & Schofield, O. (2009). Recent changes in phytoplankton communities associated with rapid regional climate change along the western Antarctic Peninsula. *Science*, 323 (5920), pp 1470–1473. DOI: 10.1126/science.1164533.
- Moore, J.K., Fu, W.W., Primeau, F., Britten, G.L., Lindsay, K., Long, M., Doney, S.C., Mahowald, N., Hoffman, F., & Randerson, J.T. (2018). Sustained climate warming drives declining marine biological productivity. *Science*, 359, pp 1139–1142. DOI: 10.1126/science.aao6379.
- Moreau, S., Mostajir, B., Bélanger, S., Schloss, I.R., Vancoppenolle, M., Demers, S., & Ferreyra, G.A. (2015). Climate change enhances primary production in the western Antarctic Peninsula. *Global Change Biology*, 21 (6), pp 2191–2205. DOI: 10.1111/gcb.12878.
- Morley, S.A., Hirse, T., Pörtner, H.O., & Peck, L.S., (2009). Geographical variation in thermal tolerance within Southern Ocean marine ectotherms. *Comparative Biochemistry and Physiology Part A*, 153, pp 154–161. DOI: 10.1016/j.cbpa.2009.02.001.
- Morrison, A.K., Hogg, A.M., England, M.H., & Spence, P. (2020). Warm Circumpolar Deep Water transport toward Antarctica driven by local dense water export in canyons. *Science advances*, 6 (18), p.eaav2516. DOI: 10.1126/sciadv.aav2516.
- Müller, S., Vähätalo, A.V., Stedmon, C.A., Granskog, M.A., Norman, L., Asla, S.N., Underwood, G.J.C., Dieckmann, G.S., & Thomas, D.N. (2013). Selective incorporation of dissolved organic matter (DOM) during sea ice formation. *Marine Chemistry*, 155, pp 148–157. DOI: 10.1016/j.marchem.2013.06.008.
- Murphy, E.J. (1995). Spatial Structure of the Southern Ocean Ecosystem: Predator-Prey Linkages in Southern Ocean Food Webs. *Journal of Animal Ecology*, 64 (3), pp 333–347. DOI: 10.2307/5895.
- Murphy, E.J., Cavanagh, R.D., Hofmann, E.E., Hill, S.L., Constable, A.J., Costa, D.P., Pinkerton, M.H., Johnston, N.M., Trathan, P.N., Klinck, J.M., Wolf-Gladrow, D.A., Daly, K.L., Maury, O., & Doney, S.C. (2012). Developing integrated models of Southern Ocean food webs: including ecological complexity, accounting for uncertainty and the importance of scale. *Progress in Oceanography*, 102, pp 74–92. DOI: 10.1016/j.pocean.2012.03.006.
- Murphy, E.J., Cavanagh, R.D., Drinkwater, K.F., Grant, S.M., Heymans, J.J., Hofmann, E.E., Hunt, G.L.J., & Johnston, N.M. (2016). Understanding the structure and functioning of polar pelagic ecosystems to predict the impacts of change. *Proceedings of the Royal Society B: Biological Sciences*, 283, 10. DOI: 10.1098/rspb.2016.1646.
- Murphy, K., Fierro-Arcos, D., Rohr, T., Green, D., Novaglio, C., Baker, K., Ortega-Cisneros, K., Eddy, T.D., Harrison, C.S., Hill, S.L., Eskuche-Keith, P., Cataldo-Mendez, C., Petrik, C.M., Pinkerton, M., Spence, P., Stollberg, I., Subramaniam, R.C., Trebilco, R., Tulloch, V., Palacios-Abrantes, J., Bestley, S., Bianchi, D., Boyd, P., Buchanan, P.J., Bryndum-Buchholtz, A., Coll, M., Corney, S., Datta, S., Everett, J.D., Forestier, R., Fulton, E.A., Guibourd de Luzinai, V., Heneghan, R., Mason, J.G., Maury, O., McMahon, C.R., Murphy, E., Richardson, A.J., Tittensor, D.P., Spillias, S., Steenbeek, J., Veytia, D., & Blanchard, J. (2025). Developing a Southern Ocean marine ecosystem model ensemble to assess climate risks and uncertainties. *Earth's Future*, 13 (3), e2024EF004849. DOI: 10.1029/2024EF004849.
- NAS (National Academies of Sciences, Engineering, and Medicine) (2017). *Antarctic Sea Ice Variability in the Southern Ocean–Climate System: Proceedings of a Workshop*. Washington, DC: The National Academies Press. DOI: 10.17226/24696.

- Naughten, K. A., Holland, P. R., & De Rydt, J. (2023). Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century. *Nature Climate Change*, 13 (11), pp 1222–1228. DOI: 10.1038/s41558-023-01818-x.
- Naughten, K.A., Meissner, K.J., Galton-Fenzi, B.K., England, M.H., Timmermann, R., Hellmer, H.H., Hattermann, T., & Debernard, J.B. (2018). Intercomparison of Antarctic ice-shelf, ocean, and sea-ice interactions simulated by MetROMS-ice shelf and FESOM 1.4. *Geoscientific Model Development*, 11 (4), pp 1257–1292. DOI: 10.5194/gmd-11-1257-2018.
- Negrete-Garcia, G., Lovenduski, N.S., Hauri, C., Krumhardt, K.M., & Lauvset, S.K. (2019). Sudden emergence of a shallow aragonite saturation horizon in the Southern Ocean. *Nature Climate Change*, 9, pp 313–317. DOI: 10.1038/s41558-019-0418-8.
- Nevison, C.D., Keeling, R.F., Weiss, R.F., Bopp, B.N.A., Jin, X., Fraser, P.J., Porter, L.W., & Hess, P.G. (2005). Southern Ocean Ventilation Inferred from Seasonal Cycles of Atmospheric N₂O and O₂/N₂ at Cape Grim, Tasmania. *Tellus B*, 57 (3), pp 218–29. DOI: 10.1111/j.1600-0889.2005.00143.
- Newman, L., Heil, P., Trebilco, R., Katsumata, K., Constable, A., van Wijk, E., Assmann, K., Beja, J., Bricher, P., Coleman, R., Costa, D., Diggs, S., Farneti, R., Fawcett, S., Gille, S.T., Hendry, K.R., Henley, S., Hofmann, E., Maksym, T., Mazloff, M., Meijers, A., Meredith, M.M., Moreau, S., Ozsoy, B., Robertson, R., Schloss, I., Schofield, O., Shi, J., Sikes, E., Smith, I.J., Swart, S., Wahlin, A., Williams, G., Williams, M.J.M., Herraiz-Borreguero, L., Kern, S., Lieser, J., Massom, R.A., Melbourne-Thomas, J., Miloslavich, P., & Spreen, G. (2019). Delivering Sustained, Coordinated, and Integrated Observations of the Southern Ocean for Global Impact. *Frontiers in Marine Science*, 6, 433. DOI: 10.3389/fmars.2019.00433.
- Newman, L., Hancock, A.M., Hofmann, E., Williams, M.J.M., Henley, S.F., Moreau, S., Bricher, P., Ackley, S., Beja, J., Caccavo, J.A., Diggs, S., Fawcett, S., Fretwell, P., Gille, S., Heil, P., Herraiz Borreguero, L., Höfer, J., ten Hoopen, P., Kern, S., Kool, J., Lannuzel, D., Massom, R., Mazloff, M., Meijers, A., Ozsoy, B., Ponzi Pezzi, L., Pfeil, B., du Plessis, M., Raphael, M.N., Sallée, J-B., Schofield, O., Schloss, I., Shadwick, E.H., Swart, S., van Wijk, E., Altieri, K., Barbosa, A., Barreira, S., Budillon, G., Casciotti, K., Colleoni, F., Currie, K., Frey, M., Halfter, S., Hendry, K., Hobbs, W., Janout, M., Kerr, R., Kukliński, P., LaRue, M., Martin, T., McMahon, C.R., Mendes, C.R.B., Miller, L., Miloslavich, P., Murphy, E., Nishioka, J., Novellino, A., Queste, B.Y., Rack, W., Rivaro, P., Schiller, A., Smith, W., Stevens, C., Tripathy, S., & Wang, Z. (2022). The Southern Ocean Observing System 2021–2025 Science and Implementation Plan. DOI: 10.5281/zenodo.6324359.
- Newsom, E., Zanna, L., & Gregory, J. (2023). Background pycnocline depth constrains future ocean heat uptake efficiency. *Geophysical Research Letters*, 50, 22, e2024GL105673. DOI: 10.1029/2023GL105673.
- Nicholson, S-A., Whitt, D.B., Fer, I., du Plessis, M.D., Lebéhot, A.D., Swart, S., Sutton, A.J., & Monteiro, P.M.S. (2022). Storms drive outgassing of CO₂ in the subpolar Southern Ocean. *Nature Communications*, 13, 158. DOI: 10.1038/s41467-021-27780-w.
- Nickford, S., Palter, P.B., & Mu, L. (2024). The importance of contemporaneous wind and pCO₂ measurements for regional air-sea CO₂ flux estimates. *JGR Oceans*, 129 (6), e2023JC020744. DOI: 10.1029/2023JC020744.
- Nissen, C., Timmermann, R., Hoppema, M., Gürses, Ö., & Hauck, J. (2022). Abruptly attenuated carbon sequestration with Weddell Sea dense waters by 2100. *Nature Communications*, 13, 3402. DOI: 10.1038/s41467-022-30671-3.
- Nissen, C., Lovenduski, N.S., Brooks, C.M., Hoppema, M., Timmermann, R., & Hauck, J. (2024). Severe 21st-century ocean acidification in Antarctic Marine Protected Areas. *Nature Communications*, 15, 259. DOI: 10.1038/s41467-023-44438-x.
- Norman, L., Thomas, D. N., Stedmon, C. A., Granskog, M. A., Papadimitriou, S., Krapp, R. H., Meiners, K.M., Lannuzel, D., van der Merwe, P., & Dieckmann, G. S. (2011). The characteristics of dissolved organic matter (DOM) and chromophoric dissolved organic matter (CDOM) in Antarctic sea ice. *Deep Sea Research Part II: Topical Studies in Oceanography*, 58 (9–10), pp 1075–1091. DOI: 10.1016/j.dsr2.2010.10.030.

- Oke, P.R., & O'Kane, T.J. (2011). Observing System Design and Assessment. In: Schiller, A., Brassington, G. (eds) *Operational Oceanography in the 21st Century*. Springer, Dordrecht. DOI: 10.1007/978-94-007-0332-2_5
- Oke, P.R., Rykova, R., Pilo, G.S., & Lovell, J.L. (2022). Estimating Argo Float Trajectories Under Ice. *Earth and Space Science*, 9 (7), e2022EA002312. DOI: 10.1029/2022EA002312.
- Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., Van Den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., Geruo, A., Agosta, C., Ahlstrøm, A.P., Blazquez, A., Colgan, W., Engdahl, M.E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B.C., Harig, C., Helm, V., Abbas Khan, S., Kittel, C., Konrad, H., Lange, P.L., Lecavalier, B.S., Liang, C-C., Loomis, B.D., McMillan, M., Melini, D., Mernild, S.H., Mottram, R., Mouginot, J., Nilsson, J., Noël, B., Pattle, M.E., Peltier, W.R., Pie, N., Roca, M., Sasgen, I., Save, H.V., Seo, K-W., Scheuchl, B., Schrama, E.J.O., Schröder, L., Simonsen, S.B., Slater, T., Spada, G., Sutterley, T.C., Dutt Vishwakarma, B., Melchior van Wessem, J., Wiese, D., van der Wal, W., & Wouters, B. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth System Science Data*, 15 (4), pp 1597–1616. DOI: 10.5194/essd-15-1597-2023.
- Paolo, F.S., Padman, L., Fricker, H.A., Adusumilli, S., Howard, S., & Siegfried, M.R. (2018). Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. *Nature Geoscience*, 11, pp 121–126. DOI: 10.1038/s41561-017-0033-0.
- Parkinson, C.L. (2019). A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. *PNAS*, 116, pp 14414–14423. DOI: 10.1073/pnas.1906556116.
- Patterson, R.G., Cronin, M.F., Swart, S., Beja, J., Edholm, J.M., McKenna, J., Palter, J.B., Parker, A., Addey, C.I., Boone, W., Bhuyan, P., Buck, J.J.H., Burger, E.F., Burris, J., Camus, L., de Young, B., du Plessis, M., Flanagan, M., Foltz, G.R., Gille, S.T., Grare, L., Hansen, J.E., Hole, L.R., Honda, M.C., Hormann, V., Kohlmann, C., Kosaka, N., Kuhn, C., Lenain, L., Looney, L., Marouchos, A., McGeorge, E.K., McMahon, C.R., Mitarai, S., Mordy, C., Nagano, A., Nicholson, S-A., Nickford, S., O'Brien, K.M., Peddie, D., Ponsoni, L., Ramasco, V., Rozenauers, N., Siddle, E., Stienbarger, C., Sutton, A.J., Tada, N., Thomson, J., Ueki, I., Yu, L., Zhang, C., & Zhang, D. (2025). Uncrewed surface vehicles in the Global Ocean Observing System: a new frontier for observing and monitoring at the air-sea interface. *Frontiers in Marine Science*, 12. DOI: 10.3389/fmars.2025.1523585.
- Pearlman, J., Bushnell, M., Coppola, L., Karstensen, J., Buttigieg, P.L., Pearlman, F., Simpson, P., Barbier, M., Muller-Karger, F.E., Munoz-Mas, C., Pissierssensm P., Chandler, C., Hermes, J., Heslop, E., Jenkyns, R., Achterberg, E.P., Bensi, M., Bittig, H.C., Blandin, J., Bosch, J., Bourles, B., Bozzano, R., Buck, J.J.H., Burger, E.F., Cano, D., Cardin, V., Llorens, M.C., Cianca, A., Chen, H., Cusack, C., Delory, E., Garello, R., Giovanetti, G., Harscoat, V., Hartman, S., Heitsenrether, R., Jirka, S., Lara-Lopez, A., Lantéri, N., Leadbetter, A., Manzella, G., Maso, J., McCurdy, A., Moussat, E., Ntoumas, M., Pensieri, S., Petihakis, G., Pinardi, N., Pouliquen, S., Przeslawski, R., Roden, N.P., Silke, J., Tamburri, M.N., Tang, H., Tanhua, T., Telszewski, M., Testor, P., Thomas, J., & Waldmann, C. (2019). Evolving and sustaining ocean best practices and standards for the next decade. *Frontiers of Marine Science*, 6 (277). DOI: 10.3389/fmars.2019.00277.
- Pellichero, V., Sallée, J.-B., Chapman, C.C. & Downes, S.M. (2018) The southern ocean meridional overturning in the sea-ice sector is driven by freshwater fluxes. *Nature Communications*, 9 (1789). DOI: 10.1038/s41467-018-04101-2.
- Pezzi, L.P., de Souza, R.B., Santini, M.F., Miller, A.J., Carvalho, J.T., Parise, C.K., Quadro, M.F., Rosa, E.B., Justino, F., Sutil, U.A., Cabrera, M.J., Babanin, A.V., Voermans, J., Mascimento, E.L., Alves, R.C.M., Munchow, G.B., & Rubert, J. (2021). Oceanic eddy-induced modifications to air-sea heat and CO₂ fluxes in the Brazil-Malvinas Confluence. *Scientific Reports*, 11 (10648). DOI: 10.1038/s41598-021-89985-9.
- Pinker, R.T., Bentamy, A., Katsaros, K.B., Ma, Y., & Li, C. (2014). Estimates of net heat fluxes over the Atlantic Ocean. *Journal of Geophysical Research: Oceans*, 119 (1), pp 410–427. DOI: 10.1002/2013JC009386.

- Piñones, A., Hofmann, E.E., Daly, K.L., Dinniman, M.S. & Klinck, J.M. (2013). Modeling the remote and local connectivity of Antarctic krill populations along the western Antarctic Peninsula. *Marine Ecology Progress Series*, 481, pp 69–92. DOI: 10.3354/meps10256.
- Piñones, A., Hofmann, E.E., Dinniman, M.S. & Davis, L.B. (2016). Modeling the transport and fate of euphausiids in the Ross Sea. *Polar Biology*, 39 (1), pp 177–187. DOI: 10.1007/s00300-015-1798-5.
- Piñones, A. & Fedorov, A.V. (2016). Projected changes of Antarctic krill habitat by the end of the 21st century. *Geophysical Research Letters*, 43 (16), pp 8580–8589. DOI: 10.1002/2016GL069656.
- Piñones, A., Aziares-Aguayo, N., Amador-Véliz, P., Mercado-Peña, O., González-Reyes, A., Valdivia, N., Garcés-Vargas, J., Garrido, I., Pardo, L.M., & Höfer, J. (2024). Local and remote atmosphere-ocean coupling during extreme warming events impacting subsurface ocean temperature in an Antarctic embayment. *JGR Oceans*, 129 (9), e2023JC020735. DOI: 10.1029/2023JC020735.
- Plasman, C., Hancock, A.M., Raymond, B., Bax, N., Fierro-Arcos, D., Henley, S.F., Benson, A., Corney, S., Evans, K., Friscourt, N., Eriksen, R.S., Henderson, A.F., Halfter, S., Jansen, J., McMahon, C.R., Meijers, A., Miloslavich, P., ten Hoopen, P., Corney, I., Walters, A., Swadling, K., Gan, Y-M., & Van de Putte, A. (2026). Developing Essential Biodiversity Variables for the Southern Ocean: From data gaps to valuable insights. *Elementa: Science of the Anthropocene*, 14 (1), 00038. DOI: 10.1525/elementa.2025.00038.
- Prend, C.J., du Plessis, M.D., Mazloff, M.R., Sunnercrantz, L., Swart, S., & Gille, S.T. (2025). Observing system requirements for measuring high-frequency air-sea fluxes in the Southern Ocean. *Elementa: Science of the Anthropocene*, 13 (1), 00061. DOI: 10.1525/elementa.2024.00061.
- Proud, R., Handegard, N.O., Kloser, R.J., Cox, M.J., & Brierley, A.S. (2019). From siphonophores to deep scattering layers: uncertainty ranges for the estimation of global mesopelagic fish biomass. *ICES Journal of Marine Science*, 76 (3), pp 718–733. DOI:10.1093/icesjms/fsy037.
- Purich, A., & Doddridge, E.W. (2023). Record low Antarctic sea ice coverage indicates a new sea ice state. *Communications Earth & Environment*, 4, 314. DOI: 10.1038/s43247-023-00961-9.
- Raphael, M.N., Maierhofer, T.J., Fogt, R.L., Hobbs, W.R., & Hancock, M.S. (2025). A twenty-first century structural change in Antarctica's sea ice system. *Communications Earth & Environment*, 6, 131. DOI: 10.1038/s43247-025-02107-5.
- Reid, P.A., & Masson, R.A. (2015). Successive Antarctic sea ice extreme records during 2012, 2013 and 2014. In: *State of the Climate in 2014*, Special Supplementary to Bulletin of American Meteorological Society, 96 (7), pp S163–S164. DOI: 10.1175/2015BAMSStateoftheClimate.1.
- Reid, P.A., & Masson, R.A. (2022). Change and variability in Antarctic coastal exposure, 1979–2020. *Nature Communications*, 13, 1164. DOI: 10.1038/s41467-022-28676-z.
- Rignot, E. (2023). Observations of grounding zones are the missing key to understand ice melt in Antarctica. *Nature Climate Change*, 13, pp 1010 – 1013. DOI: 10.1038/s41558-023-01819
- Rintoul, S. R. (2018). The global influence of localized dynamics in the Southern Ocean. *Nature*, 558 (7709), pp 209–218. DOI: 10.1038/s41586-018-0182-3.
- Rintoul, S.R., Stewart, A.L., Johnson, G.C., Zhou, S., Foppert, A., Li, Q., Morrison, A.K., Silvano, A., Gunn, K.L., England, M.H., Nishihashi, S., & Aoki, S. (2026). Antarctic Bottom Water in a changing climate. *Nature Reviews Earth & Environment*, 7, pp 86–102. DOI: 10.1038/s43017-025-00750-2.
- Roach, L.A., & Polvani, L.M. (2026). Persistent Antarctic sea ice biases in CMIP6 models in spite of recent decadelong sharp decline. *Journal of Climate*, 39 (7), pp 1669–1679. DOI: 10.1175/JCLI-D-25-04771.
- Rogers, A.D., Frinault, B.A.V., Barnes, D.K.A., Bindoff, N.L., Downie, R., et al., (2020) Antarctic Futures: An Assessment of Climate-Driven Changes in Ecosystem Structure, Function, and Service Provisioning in the Southern Ocean. *Annual Review of Marine Science*, 12, pp 87–120. DOI: 10.1146/annurev-marine-010419-011028
- Römer, M., Torres, M.E., Kasten, S., Kuhn, G., Graham, A.G.C., Mau, S., Little, C.T.S., Linse, K., Pape, T., Geprags, P., Fischer, D., Wintersteller, P., Marcon, Y., Rethemeyer, J., Bohrmann, G., & shipboard scientific party ANT-XXIX/4. (2014). First evidence of widespread active methane seepage in the Southern Ocean, off the Sub-Antarctic Island of South Georgia. *Earth and Planetary Science Letters*, 403, pp 166–177. DOI: 10.1016/j.epsl.2014.06.036.

- Roquet, F., Williams, G., Hindell, M., Harcourt, R., McMahon, C., Guinet, C., Charrassin, J-B., Reverdin, G., Boehme, L., Lovell, P., & Fedak, M. (2014). A Southern Indian Ocean database of hydrographic profiles obtained with instrumented elephant seals. *Scientific Data*, 1, 140028. DOI: 10.1038/sdata.2014.28.
- Russell, J.L., Kamenkovich, I., Bitz, C., Ferrari, R., Gille, S.T., Goodman, P.J., Hallberg, R., Johnson, K., Khazmutdinova, K., Marinov, I., Mazloff, M., Riser, S., Sarmiento, J.L., Speer, K., Talley, L.D., & Wanninkhof, R. (2018). Metrics for the evaluation of the Southern Ocean in coupled climate models and earth system models. *Journal of Geophysical Research: Oceans*, 123 (5), pp 3120-3143. DOI: 10.1002/2017JC013461.
- Russell, J.L., Long, D.G., Chang, P., Cowell, M., Curchitser, E., Dinniman, M.S., Fellows, C., Goodman, P., Hofmann, E., Jelenak, Z., Klinck, J., Krasting, J.P., Lovenduski, N.S., Lofverstrom, M., Mazloff, M.R., Petroy, S., Polit, A., Rodriguez, E., Schofield, O., Stoffelen, A., Stouffer, R.J., Wanninkhof, R., Weimer, C., & Zeng, X. (2021). Measuring winds from space to reduce the uncertainty in the Southern Ocean carbon fluxes: science requirements and proposed mission. ESS Open Archive. DOI: 10.1002/essoar.10506276.1
- Rutgers van der Loeff, M.M., Cassar, N., Nicolaus, M., Rabe, B., & Stimac, I. (2014). The influence of sea ice cover on air-sea gas exchange estimates with radon-222 profiles. *JGR Oceans*, 119 (5), pp 2735-2751. DOI: 10.1002/2013JC009321.
- Ryan-Keogh, T.J., Thomalla, S., Monteiro, P.M.S., & Tagliabue, A. (2023). Multidecadal trend of increasing iron stress in Southern Ocean phytoplankton. *Science*, 379, 6634. DOI: 10.1126/science.abl5237.
- Saba, G.K., Burd, A.B., Dunner, J.P., Hernández-León, S., Martin, A.H., Rose, K.A., Salisbury, J., Steinberg, D.K., Trueman, C.N., Wilson, R.W., & Wilson, S.E. (2021). Toward a better understanding of fish-based contribution to ocean carbon flux. *Limnology and Oceanography*, 66 (5), pp 1639-1664. DOI: 10.1002/lno.11709.
- Sallée, J.B., Shuckburgh, E., Bruneau, N., Meijers, A.J.S., Bracegirdle, T.J., Wang, Z., & Roy, T. (2013). Assessment of Southern Ocean water mass circulation and characteristics in CMIP5 models: Historical bias and forcing response. *JGR Oceans*, 118 (4), pp 1830-1844. DOI: 10.1002/jgrc.20135.
- Salmon, E., Hofmann, E.E., Dinniman, M.S., & Smith Jr, W.O. (2020). Evaluation of iron sources in the Ross Sea. *Journal of Marine Systems*, 212, pp103429. DOI: 10.1016/j.jmarsys.2020.103429.
- Santini, M.F., Souza, R.B., Pezzi, L.P., & Swart, S. (2020). Observations of air-sea heat fluxes in the southwestern Atlantic under high-frequency ocean and atmospheric perturbations. *Quarterly Journal of the Royal Meteorological Society*, 146 (733), pp 4226-4251. DOI: 10.1002/qj.3905.
- Sarmiento, J.L., Gruber, N., Brzezinski, M.A., & Dunne, J.P. (2004). High-Latitude Controls of Thermocline Nutrients and Low Latitude Biological Productivity. *Nature*, 427, pp 56-60. DOI: 10.1038/nature02204.1.
- Sarmiento, J.L., Johnson, K.S., Arteaga, L.A., Bushinsky, S.M., Cullen, H.M., Gray, A.R., Hotinski, R.M., Maurer, T.L., Mazloff, M.R., Riser, S.C., Russell, J.L., Schofield, O.M., & Talley, L.D. (2023). The Southern Ocean carbon and climate observations and modelling (SOCCOM) project: A review. *Progress in Oceanography*, 219, 103130. DOI: 10.1016/j.pocean.2023.103130.
- Schloss, I.R., Wasilowska, A., Dumont, D., Almandoz, G.O., Hernando, M.P., Michaud-Tremblay, C.-A., Saravia, L., Rzepecki, M., Monien, P., Monien, D., Kopczyńska, E.E., Bers, A.V., & Ferreyra, G.A. (2014). On the phytoplankton bloom in coastal waters of southern King George Island (Antarctica) in January 2010: An exceptional feature? *Limnology and Oceanography*, 59 (1), pp 195-210. DOI: 10.4319/lo.2014.59.1.0195.
- Schroeter, S., O'Kane, T.J., & Sandery, P.A. (2023). Antarctic sea ice regime shift associated with decreasing zonal symmetry in the Southern Annular Mode. *The Cryosphere*, 17, pp 701-717. DOI: 10.5194/tc-17/701/2023.
- Schofield, O., Saba, G., Coleman, K., Carvalho, F., Couto, N., Ducklow, H., Finkel, Z., Irwin, A., Kahl, A., Miles, T., Montes-Hugo, M., Stammerjohn, S., & Waite, N. (2017). Decadal variability in coastal phytoplankton community composition in a changing West Antarctic Peninsula. *Deep Sea Research Part I: Oceanographic Research Papers*, 124, pp 42-54. DOI: 10.1016/j.dsr.2017.04.014.

- Schofield, O., & Kohut, J. (2018). Sampling the Southern Ocean: technology for observing the marine system. Antarctic Environmental Portal.
- Schmidt, G.A., Mankoff, K.D., Bamber, J.L., Burgard, C., Carroll, D., Chandler, D.M., Coulon, V., Davison, B.J., England, M.H., Holland, P.R., Jourdain, N.C., Li, Q., Marson, J.M., Mathiot, P., McMahon, C.R., Moon, T.A., Mottram, R., Nowicki, S., Abelló, A.O., Pauling, A.G., Rackow, T., & Ringesien, D. (2025). Datasets and protocols for including anomalous freshwater from melting ice sheets in climate simulations. *Geoscientific Model Development*, 18, pp 8333-8361. DOI: 10.5194/gmd-18-8333-2025.
- Seabrook, S., Law, C.S., Thurber, A.R., Lacroix, Y., Cummings, V., Tait, L., Maurice, A., & Hawes, I. (2025). Antarctic seep emergency and discovery in the shallow coastal environment. *Nature Communications*, 16, 8740. DOI: 10.1038/s41467-025-63404-3.
- Sedgwick, P.N., & DiTullio, G.R. (1997). Regulation of algal blooms in Antarctic shelf waters by the release of iron from melting sea ice. *Geophysical Research Letters*, 24 (20), pp 2515-2518. DOI: 10.1029/97GL02596.
- Senigaglia, V., Hatton MacDonald, D., Stoeckl, N., Tian, J., Leane, E., Adams, V., Baird, R., Boothroyd, A., Costanza, R., Fulton, E.A., Hartman, S., Kubiszewski, I., Nielsen, H., & Ooi, C.-S. (2026). Managing tourism in Antarctica: impacts, forecasts, and suitable economic instruments. *Journal of Sustainable Tourism*, 34 (2), pp 382-402. DOI: 10.1080/09669582.2025.2488958.
- Shadwick, E.H., Wynn-Edwards, C.A., Eriksen, R.S., Jansen, P., Yang, X., Woodward, G., & Davies, D. (2025). The Southern Ocean Time Series: a climatological view of hydrography, biogeochemistry, phytoplankton community composition, and carbon export in the Subantarctic Zone. *Ocean Science*, 21, pp 1549-1579. DOI: 10.5194/os-21-1549-2025.
- Shimada, K., Kitade, Y., Aoki, S., Mizobata, K., Cheng, L., Takahashi, K.T., Makabe, R., Kanda, J., & Odate, T. (2022). Shoaling of abyssal ventilation in the Eastern Indian Sector of the Southern Ocean. *Communications Earth & Environment*, 3, 120. DOI: 10.1038/s43247-022-00445-2.
- Siahaan, A., Smith, R.S., Holland, P.R., Jenkins, A., Gregory, J.M., Lee, V., Mathiot, P., Payne, A.J., Ridley, J.K., & Jones, C.G. (2022). The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth System Model with an interactive ice sheet. *The Cryosphere*, 16, pp 4053-4086. DOI: 10.5194/tc-16-4053-2022.
- Silvano, A., Purkey, S., Gordon, A.L., Castagno, P., Stewart, A.L., Rintoul, S.R., Foppert, A., Gunn, K.L., Herraiz-Borreguero, L., Aoki, S., Nakayama, Y., Naveira Garabato, A.C., Spingys, C., Hayatte Akhondas, C., Sallée, J.-B., de Lavergne, C., Abrahamesen, E.P., Meijers, A.J.S., Meredith, M.P., Zhou, S., Tamura, T., Yamazaki, K., Ohshima, K.I., Falco, P., Budillon, G., Hatterman, T., Janout, M.A., Llanillo, P., Bowen, M.M., Darelus, E., Østerjhus, S., Nicholls, K.W., Stevens, C., Fernandez, D., Cimoli, L., Jacobs, S.S., Morrison, A.K., Hogg, A.McC., Haumann, F.A., Mashayek, A., Wang, Z., Kerr, R., Williams, G.D., & Lee, W.S. (2023). Observing Antarctic bottom water in the Southern Ocean. *Frontiers in Marine Science*, 10, pp 1221701. DOI: 10.3389/fmars.2023.1221701.
- Sinha, A.K., Venkateswaran, B.P., Tripathy, S.C., Sarkar, A., & Prabhakaran, S. (2019). Effects of growth conditions on siderophore producing bacteria and siderophore production from Indian Ocean sector of Southern Ocean. *Journal of Basic Microbiology*, 59 (4), pp 412-424. DOI: 10.1002/jobm.201800537.
- Sloyan, B.M., Wanninkhof, R., Kramp, M., Johnson, G.C., Talley, L.D., Tanhua, T., McDonagh, E., Cusack, C., O'Rourke, E., McGovern, E., Katsumata, K., Diggs, S., Hummon, J., Ishii, M., Azetsu-Scott, K., Boss, E., Ansorge, I., Perez, F.F., Mercier, H., Williams, M.J.M., Anderson, L., Lee, J.H., Murata, A., Kouketsu, S., Jeansson, E., Hoppema, M., & Campos, E. (2019). The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP): a platform for integrated multidisciplinary ocean science. *Frontiers in Marine Science*, 6. DOI: 10.3389/fmars.2019.00445.
- Smith Jr, W.O., Dinniman, M.S., Hofmann, E.E., & Klinck, J.M. (2014). The effects of changing winds and temperatures on the oceanography of the Ross Sea in the 21st century. *Geophysical Research Letters*, 41 (5), pp 1624-1631. DOI: 10.1002/2014GL059311.
- Song, H., Marshall, J., Munro, D.R., Dutkiewicz, S., Sweeney, C., McGillicuddy, D.J.J., & Hausmann, U. (2016). Mesoscale modulation of air-sea CO₂ flux in Drake Passage. *JGR Oceans*, 121 (9), pp 6635-6649. DOI: 10.1002/2026JC011714.

- SOOS Data Management Sub-Committee (DMSC) (2022): SOOS Data Policy 02/2022. Zenodo. DOI: 10.5281/zenodo.6041433.
- Stark, J.S., Johnstone, G.J., King, C., Raymond, T., Rutter, A., Stark, S.C., & Townsend, A.T. (2023). Contamination of the marine environment by Antarctic research stations: Monitoring marine pollution at Casey station from 1997 to 2015. *PLoS ONE*, 18 (8), e0288485. DOI: 10.1371/journal.pone.0288485.
- Steig, E.J., Schneider, D.P., Rutherford, S.D., Mann, M.E., Comiso, J.C. & Shindell, D.T., (2009). Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature*. 457 (7228). DOI: 10.1038/nature07669.
- Stewart, A.L., Klocker, A. & Menemenlis, D. (2018). Circum-Antarctic shoreward heat transport derived from an eddy-and tide-resolving simulation. *Geophysical Research Letters*, 45 (2), pp 834-845. DOI: 10.1002/2017GL075677.
- St-Laurent, P., Yager, P.L., Sherrell, R.M., Stammerjohn, S.E., & Dinniman, M.S. (2017). Pathways and supply of dissolved iron in the Amundsen Sea (Antarctica). *Journal of Geophysical Research: Oceans*, 122, pp 7135-7162. DOI: 10.1002/2017JC013162.
- Sudmanns, M., Tiede, D., Augustin, H., & Lang, S. (2020). Assessing global Sentinel-2 coverage dynamics and data availability for operational Earth observation (EO) applications using the EO-Compass. *International Journal of Digital Earth*, 13 (7), pp 768-784. DOI: 10.1080/17538947.2019.1572799.
- Suryawanshi, K., Jena, B., Bajish, C. C., & Anilkumar, N. (2023). Recent Decline in Antarctic Sea Ice Cover From 2016 to 2022: Insights From Satellite Observations, Argo Floats, and Model Reanalysis. *Tellus A: Dynamic Meteorology and Oceanography*, 75 (1), pp 193-212. DOI: <https://doi.org/10.16993/tellusa.3222>
- Sutton, A.J., Williams, N.L., & Tilbrook, B. (2021). Constraining Southern Ocean CO₂ Flux Uncertainty Using Uncrewed Surface Vehicle Observations. *Geophysical Research Letters*, 48, e2020GL091748. DOI: 10.1029/2020GL091748.
- Szekely Tanguy, Gourrion Jerome, Pouliquen Sylvie, Reverdin Gilles (2024). CORA, Coriolis Ocean Dataset for Reanalysis. SEANOE. DOI: 10.17882/46219.
- Swart, S., Gille, S.T., Delille, B., Josey, S., Mazloff, M., Newman, L., Thompson, A.F., Thomson, J., Ward, B., du Plessis, M.D., Kent, E.C., Giron, J., Gregor, L., Heil, P., Hyder, P., Ponzi Pezzi, L., Budd de Souza, R., Tamsitt, V., Weller, R.A., & Zappa, C.J. (2019) Constraining Southern Ocean Air-Sea-Ice Fluxes Through Enhanced Observations. *Frontiers in Marine Science*, 6 (421). DOI: 10.3389/fmars.2019.00421.
- Swart, S., du Plessis, M.D., Thompson, A.F., Biddle, L.C., Giddy, I., Linders, T., Mohrmann, M., & Nicholson, S-A. (2020). Submesoscale fronts in the Antarctic marginal ice zone and their response to wind forcing. *Geophysical Research Letters*, 47, e2019GL086649. DOI: 10.1029/2019GL086649.
- Swart, S., du Plessis, M.D., Nicholson, S-A., Monteiro, P.M.S., Dove, L.A., Thomalla, S., Thompson, A.F., Biddle, L.C., Edhol, J.M., Giddy, I., Heywood, K.J., Lee, C., Mahadevan, A., Shilling, G., & Buss de Souza, R. (2023). The Southern Ocean mixed layer and its boundary fluxes: fine-scale observational progress and future research priorities. *Philosophical Transactions A*, 381, 2249. DOI: 10.1098/rsta.2022.0058. 2023.
- Takahashi, T., Sweeney, C., Hales, B., Chipman, D.W., Newberger, T., Goddard, J.G., Lannuzzi, R.A., & Sutherland, S.C. (2012). The changing carbon cycle in the Southern Ocean. *Oceanography*, 25 (3), pp 26-37. DOI: 10.5670/oceanog.2012.71.
- Tanhua, T., McCurdy, A., Fischer, A., Appeltans, W., Bax, N., Currie, K., DeYoung, B., Dunn, D., Heslop, E., Glover, L.K., Gunn, J., Hill, K., Ishii, M., Legler, D., Lindstrom, E., Miloslavich, P., Moltmann, T., Nolan, G., Palacz, A., Simmons, S., Sloyan, B., Smith, L.M., Smith, N., Telszewski, M., Visbeck, M., & Wilkin, J. (2019a). What we have learned from the Framework for Ocean Observing: Evolution of the Global Ocean Observing System. *Frontiers Marine Science*, 6 (471). DOI: 10.3389/fmars.2019.00471.
- Tanhua, T., Pouliquen S., Hausman J., O'Brien K., Bricher P., de Bruin, T., Buck, J.J.H., Burger, E.F., Carval, T., Casey, K.S., Diggs, S., Giorgetti, A., Graves, H., Harscoat, V., Kinkade, D., Muelbert, J.H., Novellino, A., Pfeil, B., Pulsifer, P.L., Van de Putte, A., Robinson, E., Schaap, D., Smirnov, A., Smith, N., Snowden,

- D., Spears, T., Stall, S., Tacoma, M., Thijssen, P., Tronstad, S., Vandenberghe, T., Wengren, M., Wyborn, L., & Zhao, Z. (2019b). Ocean FAIR data services. *Frontiers in Marine Science*, 6. DOI: 10.3389/fmars.2019.00440.
- Teder, N. J., Bennetts, L. G., Reid, P. A., Massom, R. A., Pitt, J. P. A., Scambos, T. A., & Fraser, A. D. (2025). Large-scale ice-shelf calving events follow prolonged amplifications in flexure. *Nature Geoscience*, 18 (7), 599–606. DOI: 10.1038/s41561-025-01713-4.
- ten Hoopen, P., Novellino, A., Hancock, A.M., Bricher, P., De Pooter, D., Felden, J., Henley, S.F., Kool, J., Kozyr, A., Miller, M.E., Treasure, A.M., Van de Putte, A.P., Verhey, C., & SOOS Data Management Sub-Committee. (2025). SOOSmap: Your gateway to Antarctica data discovery. *Elementa: Science of the Anthropocene*, 13 (1), 00099. DOI: 10.1525/elementa.2024.00099.
- Thomalla, S.J., Nicholson, S.-A., Ryan-Keogh, T.J., & Smith, M.E. (2023). Widespread changes in Southern Ocean phytoplankton blooms linked to climate drivers. *Nature Climate Change*, 13, pp 975–984. DOI: 10.1038/s41558-023-01768-4.
- Thomalla, S.J., Hancock, A.M., Beadling, R.L., Josey, A., Milward, J., Adjou, M., Pezzi, L.P., du Plessis, M., Ryan-Keogh, T.J., Schulz, E., Shi, J.-R., & Souza, E. (2025). Southern Ocean in State of the Climate in 2024, Blunden, J, Reagan, J eds. *Bulletin of American Meteorological Society*, 106 (8), pp S357–S400. DOI: 10.1175/BAMS-D-25-00871.
- The IMBIE Team. (2018). Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature*, 558, pp 219– 222. DOI: 10.1038/s41586-018-0179-y.
- Thomas, J.L., Stutz, J., Frey, M.M., Bartels-Rausch, T., Altieri, K., Baladima, F., Browse, J., Dall'osto, M., Marelle, L., Mouginot, J., Murphy, J.G., Nomura, D., Pratt, K.A., Willis, M., Zieger, P., Abbatt, J., Douglas, T.A., Facchini, M.C., France, J.L., Jones, A., Kim, K., Matrai, P., McNeill, V.F., Alfonso, S.-L., Shepson, P.B., Steiner, N., Law, K.S., Arnold, S.R., Delille, B., Schmale, J., Sonke, J.E., Dommergue, A., Voisin, D., Melamed, M.L., & Gier, J. (2019). Fostering multidisciplinary research on interactions between chemistry, biology, and physics within the coupled cryosphere-atmosphere system. *Elementa: Science of the Anthropocene*, 7 (58). DOI: 10.1525/elementa.396.
- Thorpe, S.E., Tarling, G.A., & Murphy, E.J., (2019). Circumpolar patterns in Antarctic krill larval recruitment: an environmentally driven model. *Marine Ecology Progress Series*, 613, pp 77–96. DOI: 10.3354/meps12887.
- Trivelpiece, W.Z., Hinke, J.T., Miller, A.K., Reiss, C.S., Trivelpiece, S.G., & Watters, G.M. (2011) Variability in krill biomass links harvesting and climate warming to penguin population changes in Antarctica. *PNAS*, 108, pp 7625–7628. DOI: 10.1073/pnas.1016560108.
- Tronstad, S., Bricher, P., Kool, J., Pulsifer, P., van de Putte, A., Larsen, J.R., Peat, H., Rayner, D., De Bruin, T., Tacoma, M., Thomas, J., Nitsche, F., Samy, V.S., Ignatiuk, D., Buch, E., Treasure, A., Persäter, F., Riopel, S., Pouplier, P., & Eicken, H. (2021) Alignment of Polar Data Policies - Recommended Principles. DOI: 10.5281/zenodo.5734900.
- Turner, J., & Comiso, J. (2017). Solve Antarctica's sea-ice puzzle. *Nature*, 547 (7663), pp 275–277. DOI: 10.1038/547275a.
- Twelves, A.G., Goldberg, D.N., Henley, S.F., Mazloff, M.R., & Jones, D.C. (2021). Self-shading and meltwater spreading control the transition from light to iron limitation in an Antarctic coastal polynya. *Journal of Geophysical Research: Oceans*, 126, e2020JC016636. DOI: 10.1029/2020JC016636
- Uotila, P., Goosse, H., Haines, K., Chevallier, M., Barthélemy, A., Bricaud, C., Carton, J., Fučkar, N., Garric, G., Iovino, D., Kauker, F., Korhonen, M., Lien, V.S., Marnela, M., Massonnet, F., Mignac, D., Peterson, K.A., Sadikni, R., Shi, L., Tietsche, S., Toyoda, T., Xie, J., & Zhang, Z. (2019). An assessment of ten ocean reanalyses in the polar regions. *Climate Dynamics*, 52 (3), pp 1613–1650. DOI: 10.1007/s00382-018-4242-z.
- van de Putte, A.P., Griffiths, H.J., Brooks, C., Bricher, P., Sweetlove, M., Halfter, S., & Raymond, B. (2021) From data to Marine Ecosystem Assessments of the Southern Ocean: achievements, challenges and lessons for the future. *Frontiers in Marine Science*, 8 (637063). DOI: 10.3389/fmars.2021.637063.
- Venables, H., Meredith, M. P., Hendry, K. R., Ten Hoopen, P., Peat, H., Chapman, A., Beaumont, J., Piper, R., Miller, A.J., Mann, P., Rossetti, H., Massey, A., Souster, T., Reeves, S., Fenton, M., Heiser, S.,

- Pountney, S., Reed, S., Waring, Z., Clark, M., Bolton, E., Mathews, R., London, H., Clement, A., Stuart, E., Reichardt, A., Brandon, M., Leng, M., Arrowsmith, C., Annett, A., Henley, S.F., & Clarke, A. (2023). Sustained year-round oceanographic measurements from Rothera Research Station, Antarctica, 1997–2017. *Scientific Data*, 10(1), 265. DOI: 10.1038/s41597-023-02172-5.
- Verdy, A. & Mazloff, M.R. (2017). A data assimilating model for estimating Southern Ocean biogeochemistry. *Journal of Geophysical Research: Oceans*, 122 (9), pp 6968–6988. DOI: 10.1002/2016JC012650.
- Villas Bôas, A.B., Sato, O.T., Chaigneau, A., & Castelão, G.P. (2015). The signature of mesoscale eddies on the air-sea turbulent heat fluxes in the South Atlantic Ocean. *Geophysical Research Letters*, 42, pp 1856–1862. DOI: 10.1002/2015GL063105.
- Wallace, L.O., van Wijk, E.M., Rintoul, S.R., & Hally, B. (2020). Bathymetry-constrained navigation of Argo floats under sea ice on the Antarctic continental shelf. *Geophysical Research Letters*, 47 (11), e2020GL087019. DOI: 10.1029/2020CL087019.
- Wang, J., Luo, H., Yang, Q., Liu, J., Yu, L., Shi, Q., & Han, B. (2022). An unprecedented record low Antarctic sea-ice extent during austral summer 2022. *Advances in Atmospheric Sciences*, 38, pp 1591–1597. DOI: 10.1007/s00376-022-2087-1.
- Wei, Y., Gille, S.T., Mazloff, M.R., Tamsitt, V., Swart, S., Chen, D., & Newman, L. (2020). Optimizing mooring placement to constrain Southern Ocean air-sea fluxes. *Journal of Atmospheric and Oceanic Technology*, 37 (8), pp 1365–1385. DOI: 10.1175/JTECH-D-19-0203.1.
- Wanninkhof, R. (2014). Relationship between wind speed and gas exchange over the ocean revisited. *Limnology and Oceanography*, 12, 6, pp 351–362. DOI: 10.4319/lom.2014.12.351.
- Webster, H.N., Whitehead, T., & Thomson, D.J. (2018). Parameterizing unresolved mesoscale motions in atmospheric dispersion models. *Journal of Applied Meteorology and Climatology*, 57 (3), pp 645–657. DOI: 10.1175/JAMC-D-17-0075.1.
- Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Biotin, J.-W., Bonino da Silva Santos, L., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hohen, A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenberg, P., Wolstencroft, K., Zhao, J., & Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, 3, 160018. DOI: 10.1038/sdata.2016.18.
- Williams, R.G., Meijers, A.J.S., Rouseenov, V.M., Katavouta, A., Ceppi, P., Rosser, J.P., & Salvi, P. (2024). Asymmetries in the Southern Ocean contribution to global heat and carbon uptake. *Nature Climate Change*, 14, pp 823–831. DOI: 10.1038/s41558-024-02066-3.
- Workman, E., Fisher, R.E., France, J. L., Linse, K., Yang, M., Bell, T., Dong, Y., & Jones, A.E. (2024). Methane emissions from seabed to atmosphere in polar oceans revealed by direct methane flux measurements. *Journal of Geophysical Research: Atmospheres*, 129 (14), e2023JD040632. DOI: 10.1029/2023JD040632
- Workman, E., Jones, A.E., Fisher, R.E., France, J.L., Linse, K., Delille, B., & Squires, F.A. (2025). Methane emissions and dynamics in the Weddell and Scotia Seas. *Global Biogeochemical Cycles*, 39 (5), e2024GB008425. DOI: 10.1029/2024GB008425.
- Xavier, J.C., Barbosa A., Agustí, S., Alonso-Sáez, L., Alvito, P., Ameneiro, J., Ávila, C., Baeta, A., Canário, J., Carmona, R., Catry, P., Ceia, F., Clark, M.S., Cristobo, F.J., Cruz, B., Duarte, C.M., Figuerola, B., Gili, J.-M., Gonçalves, A.R., Gordillo, F.J.L., & Viñegla, B. (2013). Polar marine biology science in Portugal and Spain: Recent advances and future perspectives. *Journal of Sea Research*, 83, pp 9–29. DOI: 10.1016/j.seares.2013.05.013.
- Yang, G., Atkinson, A., Pakhomov, E.A., Katrin, Schmidt, & Wang, W. (2025). Seasonally migrating zooplankton strongly enhance Southern Ocean carbon sequestration. *Limnology and Oceanography*, 70, 8, pp 2208–2222. DOI: 10.1002/lno.70120.

- Yoshikawa-Inoue, H., & Ishii, M. (2005). Variations and Trends of CO₂ in the Surface Seawater in the Southern Ocean South of Australia between 1969 and 2002. *Tellus B: Chemical and Physical Meteorology*, 57 (1), pp 58–69. DOI: 10.3402/tellusb.v57i1.16773.
- Zhang, L., Delworth, T.L., Yang, X., Zeng, F., Lu, R., Morioka, Y., & Bushuk, M. (2022). The relative role of the subsurface Southern Ocean in driving negative Antarctic sea ice extent anomalies in 2016–2021. *Communications Earth & Environment*, 3, 302. DOI: 10.1038/s43247-022-00624-1.
- Zhang, G., Yang, Q., Han, B., Prytherch, J., Thornton, B.R., & Chen, D. (2024). Sea ice modulates air-sea methane flux in the Southern Ocean. *Geophysical Research Letters*, 52, 1, e2024GL112073. DOI: 10.1029/2024GL112073.
- Zhang, S., Chen, P., Bisson, K., Jamet, C., Di Girolamo, P., Dionisi, D., Hu, Y., Zhang, Z., Shi, K., & Pan, D. (2025). Substantially underestimated winter CO₂ sources of the Southern Ocean revealed by observation-based reconstructions. *Science Advances*, 11, eaea0024. DOI: 10.1126/sciadv.aea0024.
- Zhong, W., Ma, X., Shi, T., Han, G., Zhang, H., & Gong, W. (2025). Reconstruction of global ocean surface pCO₂ and air-sea CO₂ flux: based on multigrained cascade forest model. *JGR Oceans*, 130, 2, e2024JC021483. DOI: 10.1029/2024JC021483.
- Zhou, S., Meijers, A.J.S., Meredith, M.P., Abrahamsen, E.P., Holland, P.R., Silvano, A., Sallée, J-B., & Østerhus, S. (2023). Slowdown of Antarctic Bottom Water export driven by climatic wind and sea ice changes. *Nature Climate Change*, 13, pp 701–709. DOI: 10.1038/s41558-023-01695-4.
- Zilberman, N.V., Thierry, V., King, B., Alford, M., André, X., Balem, K., Briggs, N., Chen, Z., Cabanes, C., Coppola, L., Dall’Olmo, G., Desbruyères, D., Fernandez, D., Foppert, A., Gardner, W., Gasparin, F., Hally, B., Hosoda, S., Johnson, G.C., Kobayashi, T., Le Boyer, A., Llovel, W., Oke, P., Purkey, S., Remy, E., Roemmich, D., Scanderbeg, M., Sutton, P., Walicka, K., Wallace, L., & van Wijk, E.M. (2023). Observing the full ocean volume using Deep Argo floats. *Frontiers in Marine Science*, 10, 12847867. DOI: 10.3389/fmars.2023.1287867.

Acronyms

Acronym	Full Name	Programme Governing Body
AABW	Antarctic Bottom Water	
AAPP	Australian Antarctic Program Partnership	
AFIN	Antarctic Fast Ice Network	AWI
AniBOS	Animal Borne Ocean Sensor Network	GOOS
AntClimNOW	Near-term Variability and Prediction of the Antarctic Climate System	SCAR
Ant-ICON	Integrated Science to Inform Antarctic and Southern Ocean Conservation	SCAR
AntOBIS	Antarctic thematic node of the Ocean Biodiversity Information System (OBIS)	SCAR
Ant RCC	Antarctic Regional Climate Centre	WMO
ASPeCt	Antarctic Sea Ice Processes & Climate	SCAR
ATS	Antarctic Treaty System	
AWI	Alfred Wegener Institute	
BAMS	Bulletin of American Meteorological Society	
BCP	Biological Carbon Pump	
BEPSII	Biogeochemical Exchange Processes at the Sea Ice Interfaces	SCAR
BGC-Argo	Biogeochemical-Argo	Argo
BIPOLE	Biogeochemical processes and ecosystem function in changing polar systems and their global impacts	BAS
CAPS CWG	Censusing Animal Populations from Space Capability Working Group	SOOS
CATCH	Cryosphere and Atmospheric Chemistry	SOLAS; IGAC
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources	
CEP	Committee for Environmental Protection	ATS
CLiC	Climate and Cryosphere	WCRP
CLIVAR	Climate and Ocean-Variability, Predictability, and Change	WCRP

CMEMS	Copernicus Marine Environmental Monitoring Service	European Union
CMIP	Coupled Model Intercomparison Project	WCRP
COMNAP	Council of Managers of National Antarctic Programs	
COP	UN Climate Change Conference	UN
CPR	Continuous Plankton Recorder	
CSIRO	The Commonwealth Scientific and Industrial Research Organisation	
CWG	Capability Working Group	SOOS
DBCP	Data Buoy Cooperation Panel	JCOMM
DCC-SOR	Decade Collaborative Centre for the Southern Ocean region	SCAR
DMSC	Data Management Sub-Committees	SOOS
DOM	Dissolved Organic Matter	
EDI	Equity, diversity and inclusion	
EG-BAMM	Expert Group on Birds and Marine Mammals	SCAR
ECVs	Essential Climate Variables	
EBVs	Essential Biological Variables	
eEOVs	ecosystem Essential Ocean Variables	
EOVs	Essential Ocean Variables	
ENSO	El-Niño Southern Ocean Oscillation	
EMODnet Physics	European Marine Observation & Data Network Physics	EMODnet
EXCOM	Executive Committee	SOOS
FAIR	Findable, Accessible, Interoperable, Reusable	
FRISP	Forum for Research into Ice Shelf Processes	SCAR
GOA-ON	Global Ocean Acidification Observing Network	
GOOS	Global Ocean Observing System	IOC, WMO
GO-SHIP	The Global Ocean Ship-Based Hydrographic Investigations Program	
IAATO	International Association of Antarctica Tour Operators	

IBCSO	International Bathymetric Chart of the Southern Ocean	IBSCO
ICED	Integrated Climate and Ecosystem Dynamics	
IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise	ESA and NASA
IMOS	Integrated Marine Observing System	
INSTANT	Instabilities and Thresholds in Antarctica	SCAR
IOC	Intergovernmental Oceanographic Commission	UNESCO
IOCCG	International Ocean-Colour Coordinating Group	IOC
IOCCP	International Ocean Carbon Coordination Project	SCOR
IODP	International Ocean Discovery Program	
IPAB	The International Programme for Antarctic Buoys	WCRP/SCAR
IPCC	International Panel on Climate Change	UN
IPO	International Project Office	SOOS
IPY	International Polar Year	SCAR, IASC, WMO
JCIOI	Joint Commission on Ice-Ocean Interactions	UGG, IACS
JGOFS	Joint Global Ocean Flux Study	NSF
LTER	Long-Term Ecological Research	
MAPPPD	Mapping Application for Penguin Populations and Projected Dynamics	
MEOP	Marine Mammals Exploring the Oceans Pole to Pole	
NASA	National Aeronautics and Space Administration	
NCPOR	National Centre for Polar and Ocean Research	Ministry of Earth Sciences, India
NECKLACE	Network for the Collection of Knowledge on meLt of Antarctic iCe shElves	
OASIS	Observation system design with AI for Sea Ice Surveillance	Antarctica InSync
OBPS	Ocean Best Practices System	IOC (IODE and GOOS)
OLCI	Ocean and Land Colour Instrument	

ORCAS	Observational Requirements in the Context of AI prediction systems for Sea ice	SCOR and PCAPS
OSD CWG	Observing System Design Capability Working Group	SOOS
OSSE	Observing System Simulation Experiments	
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission	NASA
PCAPS	Polar Coupled Analysis and Prediction for Services	WMO/WWRP
PHOCIS	Pelagic High Seas Ocean Ecoregionalisation of the Indian Subantarctic	
PHORS	Panel of Experts on Polar and High Mountain Observations, Research and Services	WMO
POC	Particulate Organic Carbon	
POLDER	Polar Data Discovery Enhancement Research	SOOS/ARC/SCADM
RaTS	Rothera Oceanographic Time Series	BAS
RDOC	Recalcitrant Dissolved Organic Carbon	
RWG	Regional Working Group	SOOS
SAM	Southern Ocean Annular Mode	
SCAR	Scientific Committee on Antarctic Research	
SCOOBIES	Scotia Sea Open Biological laboratories	BAS
SCOR	Scientific Committee on Oceanic Research	
SIP	Science and Implementation Plan	SOOS
SKEG	SCAR Krill Expert Group	SCAR
SOCAT	Surface Ocean CO₂ Atlas	
SOCCOM	The Southern Ocean Carbon and Climate Observations and Modelling	
SOCONet	Surface Ocean CO₂ Reference Observing Network	IOC (GOOS, IOCCP)
SO-CPR	Southern Ocean Continuous Plankton Recorder	SCAR
SOFIA	Southern Ocean Freshwater research experiments Initiatives	CLIVAR
SOFLUX	Southern Ocean Fluxes	SOOS
SOLAS	Surface Ocean-Lower Atmosphere Study	SCOR, Future Earth,

		ICAGGP WCRP
SO-OA	Southern Ocean - Ocean Acidification Hub	SOOS/GOA-ON
SOOS	Southern Ocean Observing System	SCAR/SCOR
SORP	CliC/CLIVAR/SCAR Southern Ocean Regional Panel	CliC/CLIVAR/SCAR
SOTS	Southern Ocean Time Series	IMOS
SSC	Scientific Steering Committee	SOOS
SYNCHRONY	Synchronous Southern Ocean Observatory	EU Horizon
TRUST	Transparency Responsibility, User focus, Sustainability, and Technology	
UNESCO	United Nations Educational, Scientific and Cultural Organisation	UN
UNOC	UN Ocean Conference	UN
WCRP	World Climate Research Programme	WMO
WMO	World Meteorological Organization	UN
WWRP	https://wmo.int/activities/world-weather-research-programme-wwrp	WMO
YOPP	Year of Polar Prediction	WMO