SOOS

SOUTHERN OCEAN
OBSERVING SYSTEM

The Southern Ocean Observing System
2021-2025 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)

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Executive Summary

The Southern Ocean plays a central role in the Earth System by connecting the Earth's ocean basins, and it is a crucial link between the deep ocean, surface ocean and atmosphere. Hence, the ongoing changes in the Southern Ocean impact global climate, rates of sea level rise, biogeochemical cycles and ecological systems. Yet, understanding of the causes and consequences of these changes is limited by the short and incomplete nature of observations.

To address this issue, sustained, integrated and multidisciplinary observations are needed. Due to the size of the Southern Ocean, this requires international agreement on the priority observations to be collected, and also internationally coordinated data management and delivery. The Southern Ocean Observing System (SOOS) was initiated in 2011 to support these efforts. In the last decade, SOOS has enhanced regional coordination and observing system capabilities through network development, data curation and publication, development of data discovery and coordination tools, and providing strong advocacy mechanisms for the Southern Ocean community.

Significant data gaps remain in observations of the ice-affected ocean, sea ice habitats, the ocean at depths >2000 m, the air-ocean-ice interface, biogeochemical and biological variables, and for seasons other than summer. This Science and Implementation Plan articulates the scientific priorities for SOOS through the identification of these key gaps in the observational network and by identifying the priorities in addressing these gaps. This Plan covers the five year period 2021-2025, with 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 Theme 5 is cross-cutting and highlights a number of linkages amongst Themes 1-4. 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

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.

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Introduction

The importance of the Southern Ocean in the operation of the Earth System has been clearly recognised (e.g., IPCC, 2019; Meredith et al., 2019). It occupies a central position in the ocean circulation system and is critical for the mixing, storage and distribution of ocean heat, salt and dissolved constituents throughout the Earth's ocean basins, influencing ocean processes globally. Air-sea fluxes of momentum, heat and freshwater, carbon dioxide (CO_2) and other dissolved gases across the Southern Ocean regulate global climate and oceanic processes on short to long timescales. The Antarctic cryosphere (comprising sea ice and its snow cover, the ice sheet, ice shelves and icebergs) exerts a strong control on Southern Ocean physics, chemistry and biology, as well as large-scale atmospheric processes and the Earth's radiative heat budget. Southern Ocean ecosystems are globally important for resident and migratory organisms, its biogeochemical cycles and productivity, and contribute to ocean health, biodiversity and ecosystem services.

The Southern Ocean is changing in response to climate change and variability, and is also modulating this climate change and variability through a series of complex ice-ocean-atmosphere-ecosystem feedbacks. Warming atmospheric and oceanic temperatures, melting ice, and subsequent ocean freshening are modifying ocean circulation and structure; these changes, coupled with changes in nutrient distributions and light availability, are impacting the primary production and the functioning of high-latitude marine ecosystems. Short-term variability and longer-term changes in air-sea CO_2 fluxes are altering ocean chemistry and driving ocean acidification, with profound implications for marine ecosystems within and beyond the Southern Ocean.

The critical role of the Southern Ocean in the Earth System highlights the need for a coordinated approach to designing and implementing sustained, integrated observing systems for the delivery of data and data products to all stakeholders, through a data management system that follows FAIR data principles (e.g., Findable, Accessible, Interoperable, Reusable; Wilkinson et al., 2016). These data and observational needs provided the basis for establishing the Southern Ocean Observing System (SOOS) as a coordinating body to enhance and ensure the delivery of Southern Ocean data across nations, organisations, programs and stakeholders, and to provide the infrastructure for organisation of community networks to develop sustained observing systems and syntheses of existing Southern Ocean datasets.

SOOS is a joint initiative of the Scientific Committee on Oceanic Research (SCOR) and the Scientific Committee on Antarctic Research (SCAR). The myriad of programs that focus on particular aspects of the Southern Ocean is extensive, and covers both the Antarctic community (traditionally focused south of 60°S and coordinated predominantly by SCAR and the Antarctic Treaty System (ATS)), and the oceanographic community (traditionally focused north of 60°S and coordinated predominantly by SCOR and the Intergovernmental Oceanographic Commission (IOC)). SOOS bridges these two communities, and builds networks that integrate across the historical boundaries.

Developed over many years, SOOS was officially launched in August 2011 with the opening of the International Project Office (IPO), hosted by the Institute of Marine and Antarctic Studies at the University of Tasmania, Australia. Since then, SOOS has built a strong global network of community-driven initiatives and tools that combine to deliver a system of sustained observations for the Southern Ocean (Box 1 and Figure 1).

Box 1: SOOS Achievements

SOOS builds collaborative networks and products that align priorities, support shared resources and remove barriers, in order to enhance the delivery of Southern Ocean observational data. Towards this end, over the last decade SOOS has worked with the broader community to:

Align, advocate and support scientific and observational priorities through publications, research endorsement, alignment of observing system requirements and other advocacy actions:

Delivered 63 peer-reviewed scientific publications (1,257 citations); held 70 international SOOS workshops and meetings; and presented at over 150 international meetings; endorsed 32 successfully funded research programs; delivered workshops and publications on observing system design

Ensure the management and delivery of observational data by connecting data repositories, rescuing unpublished data, and encourage the use of FAIR data principles:

Provided direct access to over 49,200 individual datasets; increased single-point access to conductivity, temperature, depth (CTD) data by over 18,000 deployments; aggregated metadata for 800 Southern Ocean moorings; acted as a unique connector of polar and oceanographic data communities

Enhance collaboration and observational capabilities by building integrative networks, developing collaborative tools, supporting capacity development opportunities, and facilitating efficiencies in sensor, platform and data technologies:

Delivered 23 international networks (> 1,100 members from 33 nations) with strong early career researcher (ECR) engagement in SOOS (32% of members); delivered ECR leadership opportunities (14 since 2011); engaged with 85% of nations with SCAR defined Developing Antarctic Programs (DAPs); ensured DAP representation in leadership positions (17 positions); delivered products and networks for collaboration (e.g, DueSouth, 17 newsletters, and national networks); provided information on over 380 Southern Ocean voyages; connected SOOS with analogous communities (e.g., atmospheric, fishing, tourist, modelling, Arctic); supported the advancement of sensor-based networks (e.g., NECKLACE, AUV), publication of platform-based priorities (e.g., Pope et al., 2016) and development of best practice documentation (e.g., POLDER Task Team)

Share 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 and community coordination efforts:

Delivered into 6 policy documents; provided data and knowledge for the Intergovernmental Whaling Commission; collaborated with Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) on data and observational efforts; advocated oceanic flux variables for Global Climate Variables in the Global Climate Observing System; contributed to UN Sustainable Development Goals 13 and 14; coordinated development of the Southern Ocean contribution to the UN Decade for Ocean Sciences; and supported the Marine Ecosystem Assessment of the Southern Ocean

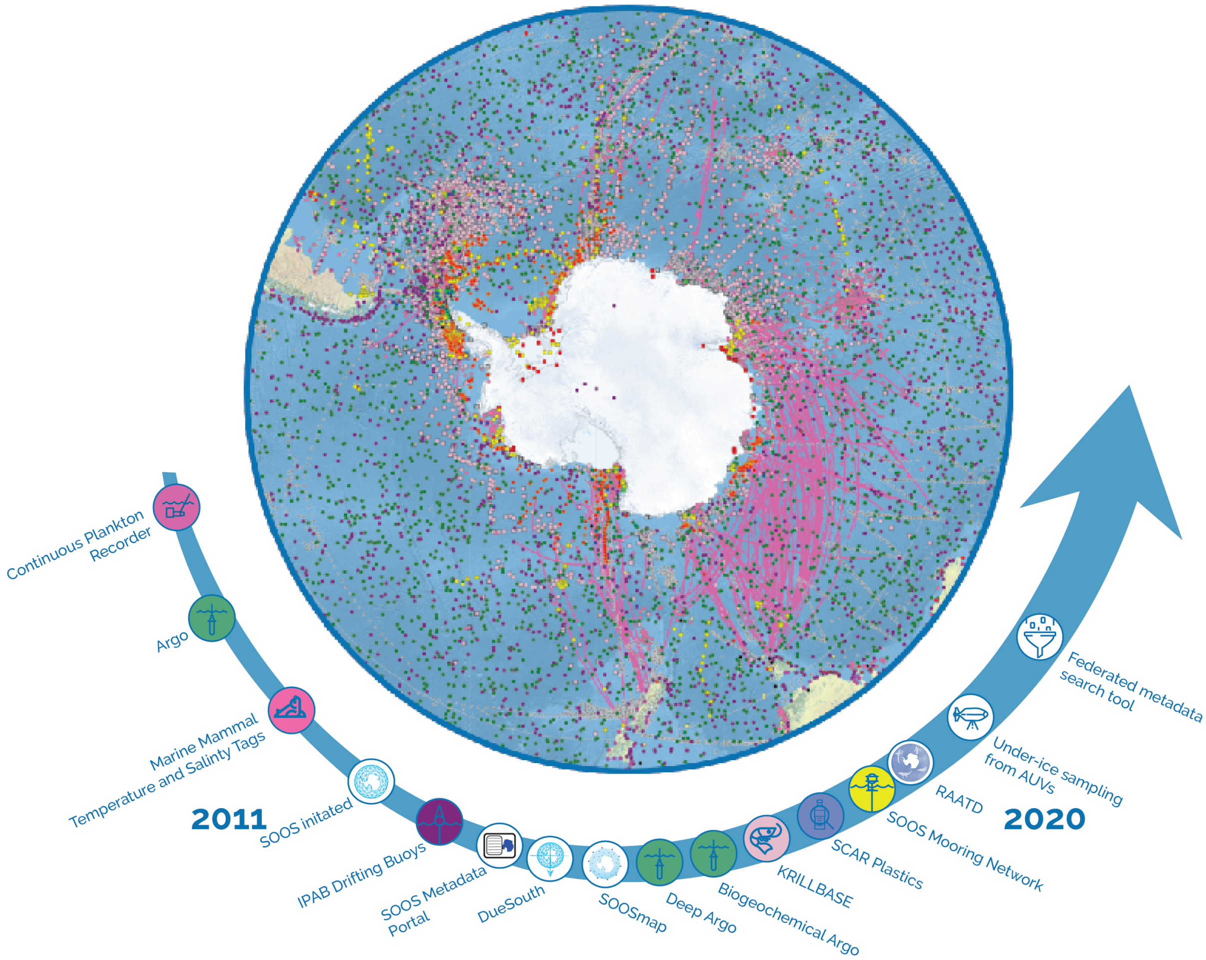


Figure 1: The growth of the observing system in the Southern Ocean showing all data available through SOOSmap (taken December 2021) and a timeline highlighting key example observational platforms, programs and tools that contribute to SOOS and its evolution, including expected new developments over the life of this plan.

The scientific focus of SOOS was defined in the Initial Science and Implementation Strategy (Rintoul et al., 2012) published nearly a decade ago, and our most recent implementation plan concluded in 2020. It is also timely to update our plan with recent community efforts (e.g., Newman et al., 2019; Tanhua et al., 2019a) updating and refining SOOS priorities. Three new SCAR Science Research Programs starting also influence the direction of SOOS.

Rather than continue with separate science and implementation plans, a single Science and Implementation Plan (SIP) is presented here to guide SOOS over the next five years (2021-2025). This SIP articulates the scientific priorities of the Southern Ocean community, including scientific data and network requirements, and articulates the role of SOOS in coordinating and delivering these to address scientific priorities. The important collaborations with external communities and the implementation pathways required to facilitate activities are outlined. The Strategic Plan included in the SIP defines the trajectory of actions required to achieve the overall SOOS vision:

“Sustained observations of dynamics and change of the physics, chemistry, biology and geology of 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”

This SIP has been developed by the SOOS Scientific Steering Committee (SSC), working groups and broader Southern Ocean community members, and includes inputs from SCAR and SCOR projects, as well as a community of international reviewers.

Mission and Values of SOOS

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.

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, Scientific Committee on Oceanic Research, and the Scientific Committee on Antarctic Research.

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 that 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.

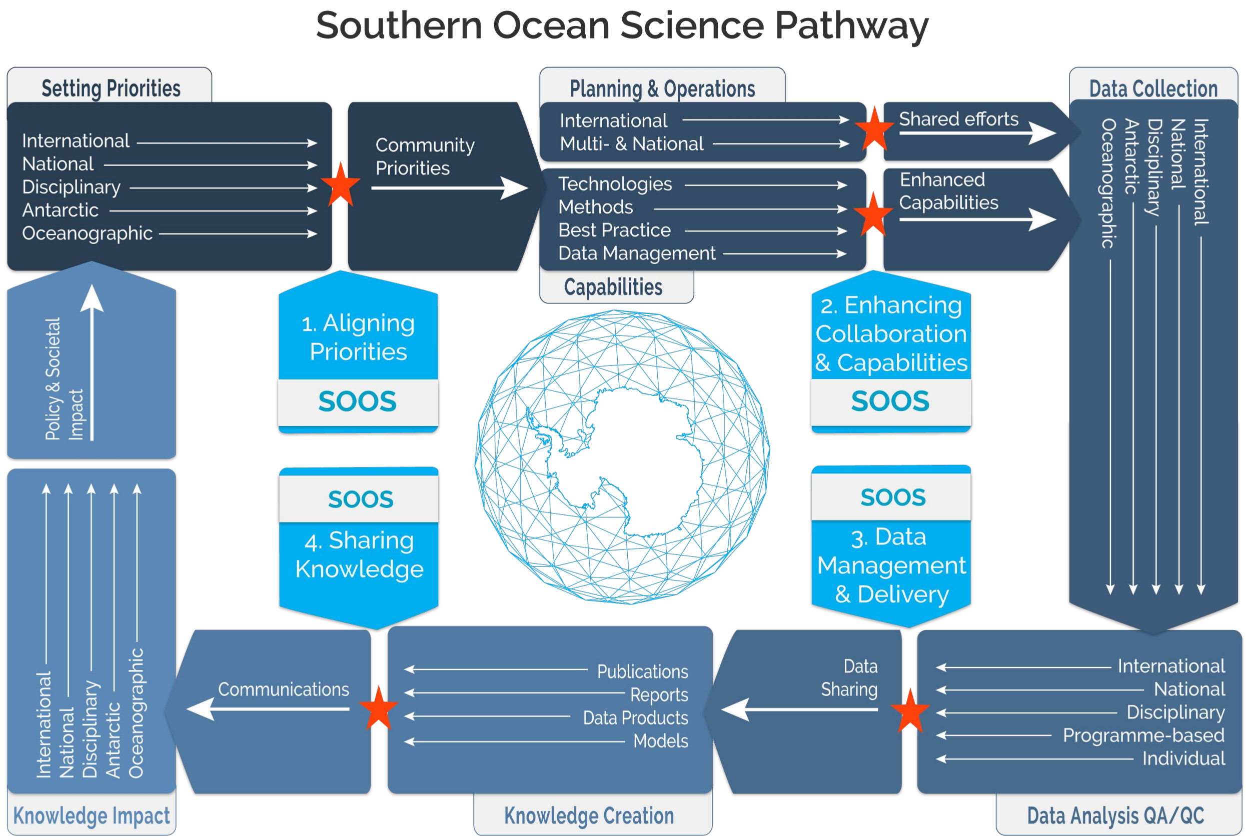
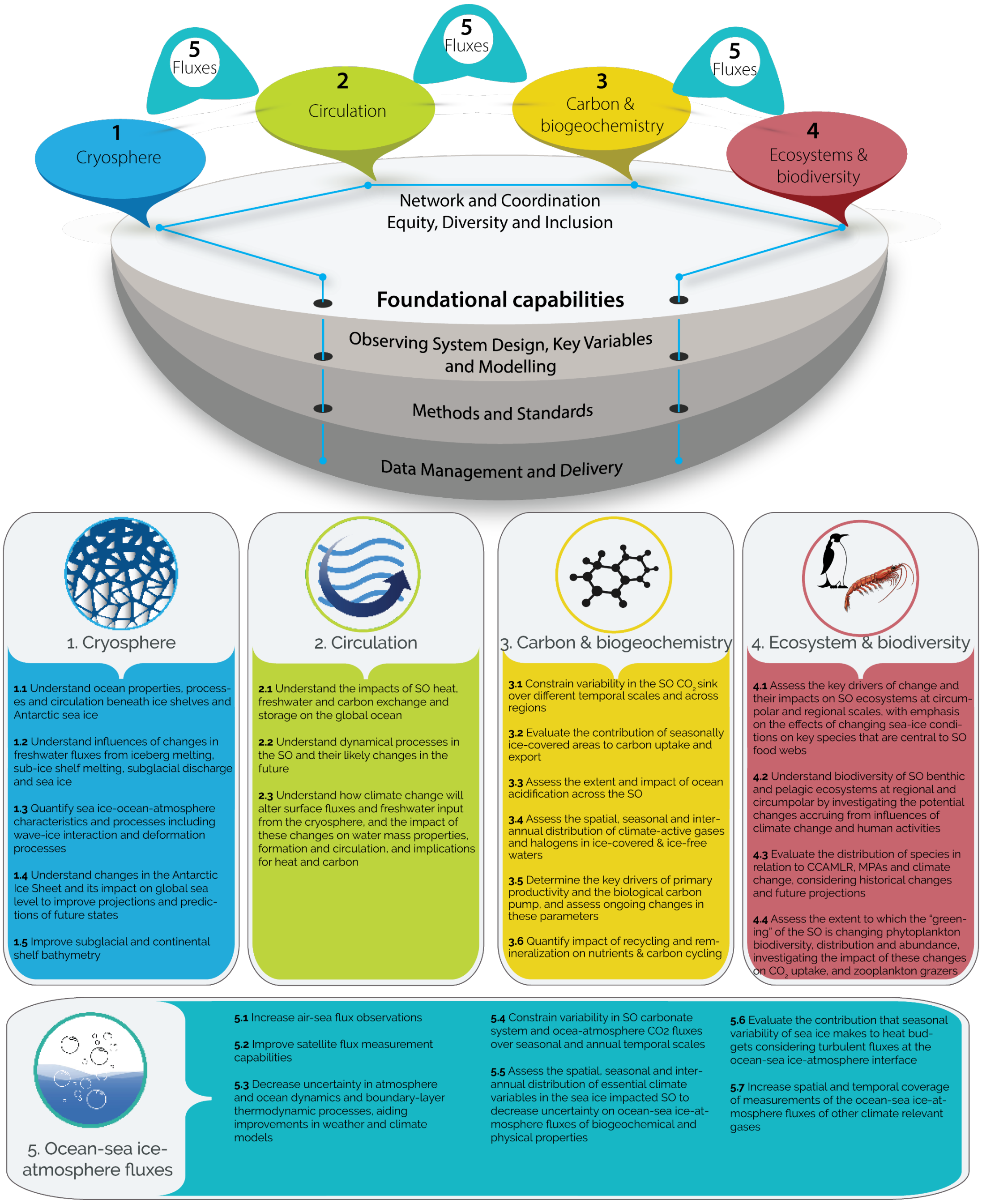


Figure 2: The role of SOOS in the Southern Ocean science pathway, indicating the value that SOOS delivers to the community (red stars).

The SOOS Science Plan

Overview

To focus SOOS activities over the next five years, the updated SOOS science structure (Figure 3) includes five community-agreed Science Themes (one of which is cross-cutting), which encompass both the previous SOOS science priorities and the eight key issues of focus for the coming decade identified in Newman et al. (2019). More detail on the scientific background for these themes is provided in Newman et al. (2019). These five Science Themes provide a balanced and integrated framework for coordination, collection and delivery of Southern Ocean data. For each SOOS Science Theme, Key Science Challenges are identified that articulate specific priorities of the SOOS community. 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 which are cross-disciplinary across multiple Science Themes. Delivery of the knowledge and scientific outputs that will address these challenges is carried out not only by SOOS working groups, 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.



1. Cryosphere

1.1 Understand ocean properties, processes and circulation beneath ice shelves and Antarctic sea ice

1.2 Understand influences of changes in freshwater fluxes from iceberg melting, sub-ice shelf melting, subglacial discharge and sea ice

1.3 Quantify sea ice-ocean-atmosphere characteristics and processes including wave-ice interaction and deformation processes

1.4 Understand changes in the Antarctic Ice Sheet and its impact on global sea level to improve projections and predictions of future states

1.5 Improve subglacial and continental shelf bathymetry

2. Circulation

2.1 Understand the impacts of SO heat, freshwater and carbon exchange and storage on the global ocean

2.2 Understand dynamical processes in the SO and their likely changes in the future

2.3 Understand how climate change will alter surface fluxes and freshwater input from the cryosphere, and the impact of these changes on water mass properties, formation and circulation, and implications for heat and carbon

3. Carbon & biogeochemistry

3.1 Constrain variability in the SO CO_2 sink over different temporal scales and across regions

3.2 Evaluate the contribution of seasonally ice-covered areas to carbon uptake and export

3.3 Assess the extent and impact of ocean acidification across the SO

3.4 Assess the spatial, seasonal and inter-annual distribution of climate-active gases and halogens in ice-covered & ice-free waters

3.5 Determine the key drivers of primary productivity and the biological carbon pump, and assess ongoing changes in these parameters

3.6 Quantify impact of recycling and remineralization on nutrients & carbon cycling

4. Ecosystem & biodiversity

4.1 Assess the key drivers of change and their impacts on SO ecosystems at circumpolar and regional scales, with emphasis on the effects of changing sea-ice conditions on key species that are central to SO food webs

4.2 Understand biodiversity of SO benthic and pelagic ecosystems at regional and circumpolar by investigating the potential changes accruing from influences of climate change and human activities

4.3 Evaluate the distribution of species in relation to CCAMLR, MPAs and climate change, considering historical changes and future projections

4.4 Assess the extent to which the "greening" of the SO is changing phytoplankton biodiversity, distribution and abundance, investigating the impact of these changes on CO_2 uptake, and zooplankton grazers

5. Ocean-sea ice-atmosphere fluxes

5.1 Increase air-sea flux observations

5.2 Improve satellite flux measurement capabilities

5.3 Decrease uncertainty in atmosphere and ocean dynamics and boundary-layer thermodynamic processes, aiding improvements in weather and climate models

5.4 Constrain variability in SO carbonate system and ocea-atmosphere CO2 fluxes over seasonal and annual temporal scales

5.5 Assess the spatial, seasonal and inter-annual distribution of essential climate variables in the sea ice impacted SO to decrease uncertainty on ocean-sea ice-atmosphere fluxes of biogeochemical and physical properties

5.6 Evaluate the contribution that seasonal variability of sea ice makes to heat budgets considering turbulent fluxes at the ocean-sea ice-atmosphere interface

5.7 Increase spatial and temporal coverage of measurements of the ocean-sea ice-atmosphere fluxes of other climate relevant gases

Figure 3: The SOOS Science Plan with five Science Themes (coloured circles) and Key Foundational Capabilities (grey base layers). Equitable and diverse networks are required to collect and deliver the data needed by the scientific community to deliver the Science Plan (blue line). For each Science Theme, a number of Key Challenges (coloured boxes) have been identified. More detail on each Key Challenge is available in Tables 1-5.

Science Themes and Challenges

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. Current climate projections of future sea-level rise to 2100 range from 0.45 m (Edwards et al., 2019) to 1.7 m (DeConto and Pollard, 2016), and more accurate future projections require better understanding of ice shelf-ocean interactions. These interactions also drive the ocean through fluxes of heat and freshwater at the surface, and uniquely in the oceans these fluxes can occur over depth ranges of 100s of metres. Observations indicate an increase in ocean-driven ice shelf basal melt during the last decade (e.g., Paolo et al., 2015; Rignot et al., 2013; 2019). The five largest ice shelves in the Amundsen Sea have already lost around 15% of their volume (IMBIE Team., 2018). This is modulated by the Amundsen Sea Low (Dotto et al., 2019) which in turn is connected to and influenced by the tropical Pacific atmospheric variability (Paolo et al., 2018; Dotto et al., 2019). Contributions of the East Antarctic Ice Sheet to global sea level appear to have accelerated from 40 Gt/y (1979-90) to over 250 Gt/y (2009-17), yet the processes responsible are not clear (Rignot et al., 2019). The 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).

Sea ice, which covers an area of the Southern Ocean ranging seasonally from about 3 million km^2 to 19 million km^2 (Parkinson, 2019), is key to modulating ocean-atmosphere fluxes; impacts glacial ice discharge and ice shelf stability (Massom et al., 2018); mediates biogeochemical processes; contributes to the formation of water masses that are key for ocean uptake of anthropogenic heat and carbon (Pellichero et al., 2018); and provides an essential habitat for many important marine species (Kennicutt et al., 2019; Newman et al., 2019). The increase then decrease of Antarctic sea ice extent in 2012 and 2016, respectively, followed by recovery to above approximately historic mean values in 2020, 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). Several studies identified the atmosphere as the main driver (Holland et al., 2018; Schemm, 2018; Schlosser et al., 2018; Wang et al., 2019; Silvano et al., 2020), while others suggest substantial oceanic influence (Kusahara et al., 2018; Meehl et al., 2019).

Observing the cryosphere where it interacts with the ocean is key to understanding change in the ocean. Under ice shelves the lack of bathymetric data, knowledge of ice shelf draft, observations of ice-ocean interactions, and water mass modification and ocean current measurements, limit the characterisation of the ocean dynamics, long-term trends (e.g., ocean warming) and variability. This places a higher dependency on models than where observations can be more easily taken to understand change and project the future state of the Antarctic Ice Sheet. Knowledge gaps in sea ice thickness, motion, deformation, floe-size distribution, snow depth, and feedback between sea ice variability and glacial ablation, inhibit reliable quantification and modelling of the relevant interaction processes impacting the Southern Ocean and the Antarctic Ice Sheet. This in turn reduces confidence in current model projections of Antarctic sea ice distribution and thickness in coming decades (NAS, 2017). Large-scale estimates of Antarctic sea ice thickness and snow cover depth are emerging from satellite altimeter data (e.g., Fons and Kurtz, 2019; Kacimi and Kwok, 2020), but these require validation using observations from multiple regions and seasons (Webster et al., 2018; Boisvert et al., 2020). Relevant feedback processes between ice shelves, icebergs and sea ice, both via the ocean and atmosphere are also needed to improve description and quantification (Nihashi and Ohshima, 2015; Merino et al., 2016; Fraser et al., 2019).

Advances in understanding drivers of ice shelf melt (Kennicutt et al., 2014) require direct observations of basal melt rates, ocean stratification, high resolution bathymetry on continental shelves and within ice shelf cavities, ice shelf draft, and basal topography/roughness. In addition, continuous and multi-decadal time-series that resolve seasonal and intra-annual water mass and ocean current variability near ice shelves and under sea ice are needed. Increased use of autonomous technologies and satellite transmission of the data is required to decrease the effort and cost involved in monitoring the transport of ocean heat toward ice shelf bases. Regular repeat observations of parameters required for deriving accurate sea ice thickness and hence volume by autonomous under-ice vehicles, *in situ* sensors within the sea ice and snow, and airborne sensors underneath satellite altimeter or microwave radiometry overflights are needed to enable routine evaluation of satellite-derived products using targeted measurements of physical ice and snow properties.

Table 1: Theme 1 Southern Ocean cryosphere Key Science Challenges and key international initiatives contributing to addressing each challenge. Acronyms are defined in Appendix 1.

Challenges	**International Initiatives Addressing Challenges**
1.1: Understand ocean properties, processes and circulation beneath ice shelves and Antarctic sea ice with emphasis on: ● Variability in space and time modulation by sea ice and the role of polynyas ● Sea ice loss and change in ice sheet mass balance ● Heat transfer and freshwater flux between sea ice/ice shelf and ocean	NECKLACE, FRISP, Argo, ASPeCt, INSTANT, AniBOS, SORP, SOFLUX, SOLAS, CMEMS, AntClimNOW, OASIIS, CLIVAR
1.2: Understand influences of changes in freshwater fluxes from iceberg melting, sub-ice shelf melting, subglacial discharge and sea ice	INSTANT, Argo, ASPeCt, BEPSII, CMEMS, AntClimNOW, SORP
1.3: Quantify sea ice-ocean-atmosphere characteristics and processes including wave-ice interaction and deformation processes to understand: ● The driver of change and variability in the volume, properties, floe-size and distribution of Antarctic sea ice and consequent impacts	ASPeCt, AFIN, Argo, AntClimNOW, CliC, CLIVAR, CMEMS, SORP

on atmospheric and oceanic properties and circulations - Changes in sea ice extent, thickness and volume over seasonal, annual, decadal, and millennial timescales - Change and variability in the Antarctic fast ice belt and its role in protecting glacier/ice shelf fronts, polynya formation/maintenance and water mass modification	
1.4: Understand changes in the Antarctic Ice Sheet and its impact on global sea level to improve projections and predictions of future states	IODP and ice sheet drilling projects; IMBIE; ice sheet mass balance estimates; grounding line retreat rates; modelling community; INSTANT
1.5: Improve subglacial and continental shelf bathymetry	Bedmap3; BedMachine, SOOS AUV Task Team, Seabed2030, IBCSO, AniBOS, Argo (grounded shelf floats)

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, 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 lack of understanding of the rate at which oceanic water masses can exchange heat and carbon with the atmosphere (Marshall and Speer, 2012). 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). 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.

The Argo array has significantly advanced observations of the upper 2000 m of the Southern Ocean, which has led to important progress in quantification of temperature and salinity changes and circulation dynamics, as well as in understanding and attributing those changes (Meredith et al., 2019). 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 and the role of mesoscale/submesoscale eddies. In particular, many important processes between the ocean and the cryosphere have been identified and highlighted as central in controlling Southern Ocean water mass properties and circulation, but these remain poorly observed and understood (Abernathey et al., 2016; Haumann et al., 2016).

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.

Table 2: Theme 2 Southern Ocean circulation Key Science Challenges and key international initiatives contributing to addressing each challenge. Acronyms are defined in Appendix 1.

Challenges	**International Initiatives Addressing Challenges**
2.1: Understand Southern Ocean heat, freshwater and carbon exchange and storage and effects on the global ocean. This includes: ● Production and export of Antarctic Bottom Water ● Upwelling of deep water ● Formation and subduction of Subantarctic Mode Water and Antarctic Intermediate Water	Argo, BGC-Argo, Deep Argo, GO-SHIP, AniBOS, DBCP, SOOP, OceanSITES, CLIVAR, SORP, SOFLUX, SOLAS, IBCSO, CMEMS, Seabed2030, AntClimNOW, AniBOS, SOCONet, OASIIS, SOCCOM, SOCAT
2.2: Understand dynamical processes in the Southern Ocean and their likely changes in the future. This includes: ● Interior water mass transformation due to iso/diapycnal mixing ● Processes and forcing mediating upwelling/subduction from the mixed layer ● Role of mesoscale and submesoscale eddies in setting water mass properties and mediating the overturning circulation ● Stability of the upper ocean overturning circulation in response to changes in winds, increased ice melt and surface warming ● Response of the ocean circulation to atmospheric variability (wind, air-sea heat momentum and freshwater fluxes) ● Stability, variability and future trends in frontal positions	Argo, BGC-Argo, Deep Argo, GO-SHIP, AniBOS, DBCP, SOOP, OceanSITES, CLIVAR, SORP, CMEMS, AntClimNOW, OASIIS

2.3: Understand how climate change will alter surface fluxes and freshwater input from the cryosphere, and the impact of these changes on water mass properties, formation and circulation, and implications for heat and carbon	Argo, BGC-Argo, Deep Argo, GO-SHIP, AniBOS, DBCP, SOOP, OceanSITES, CLIVAR, SORP, SOLAS, SOFLUX, IBCSO, Seabed2030, CMEMS, AntClimNOW, AniBOS, OASIIS

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 CO_2 (Khatiwala et al, 2009) and exerts a strong control on global climate and ocean fertility through solubility and biological carbon pump mechanisms (e.g., Sarmiento and Toggweiler, 1984; Sarmiento et al., 2004). It additionally regulates the uptake and emission of other climate-active gases such as methane (CH_4), nitrous oxide (N_2O) and dimethyl-sulphide (DMS) (e.g., Curran and Jones, 2000; Nevison et al., 2005; Römer et al., 2014).

Despite the importance of the Southern Ocean in global biogeochemical cycles and climate, major uncertainties persist in our understanding of its carbon budget (e.g., Bushinsky et al., 2019). Several studies suggest that Southern Ocean CO_2 uptake declined in recent decades (e.g., Yoshikawa-Inoue and 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). How the Southern Ocean CO_2 sink will evolve in the future remains an open question, especially considering the importance of Antarctic coastal zones as summer carbon sinks (Monteiro et al., 2020) and winter outgassing south of the Polar Front (Gray et al., 2018). The full impact of decreased ocean pH (ocean acidification) resulting from enhanced CO_2 uptake is also unclear. Carbonate undersaturation events and their deleterious effects on shelled organisms have already been observed in the Southern Ocean (Bednaršek et al., 2012) and are predicted to become more frequent (McNeal and Matear, 2009). Models indicate the shoaling of the aragonite saturation depth to the surface in some areas of the Southern Ocean by the end of the century (Negrete-García et al., 2019). Beyond CO_2, a benchmark assessment of how biogenic gases, such as CH_4, N_2O and DMS, will respond to environmental and biological changes is currently lacking.

Sea ice and glacial meltwater rates will impact biogeochemical processes differently depending on the region of the Southern Ocean considered (Arrigo et al., 2015; Hernando et al., 2015). Sea ice restricts light but enhances iron availability. As a consequence, light rather than iron generally limits primary productivity at the coast, in contrast to offshore waters. That said, increased ice melt will enhance surface stratification, at least in the short-term, possibly increasing the exposure of phytoplankton to light. While earlier studies suggested that iron-rich glacial meltwaters supply substantial amounts of iron to coastal areas (Arrigo et al., 2015; Herraiz-Borreguero et al., 2016), recent studies highlight sediment resuspension and Circumpolar Deep Water as primary sources of iron to some regions (St-Laurent et al., 2017; Dinniman et al., 2020). Away from the coast, large-scale ongoing changes driven by changes in iron and light availability (among other drivers) are already evident, such as in the Subantarctic Zone and Permanently Open Ocean Zone where productivity appears to be increasing (e.g., "greening") (Del Castillo et al., 2019; Henley et al., 2020; Pinkerton et al., 2021). How the mode, magnitude and bio-availability of the iron supply to Antarctic waters may change in the future is unknown and needs quantification.

The biological carbon pump is a key mechanism driving the carbon and nutrient cycles at higher latitudes. How primary productivity (e.g., Leung et al., 2015) and carbon export (Cabré 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 within the seasonally varying mixed layer (e.g., Fourquez et al., 2020; Mdutyana et al., 2020) and potential shifts in phytoplankton dynamics (Deppeler and Davidson, 2017). The microbial carbon pump also contributes to carbon sequestration and food-web fluxes (Jiao et al., 2010), yet the response of nutrient recycling and the Microbial Carbon Pump to Southern Ocean warming and acidification is uncertain, as is how interactions between the biological carbon pump and microbial carbon pumps are likely to change (Jiao et al., 2010; Legendre et al., 2015).

Autonomous platforms have greatly enhanced the availability and quality of the carbon and biogeochemical data available for the Southern Ocean, including for the winter when observations are particularly scarce. Combined with shipboard observations, data from autonomous instruments have been used to better constrain the air-sea flux of CO_2 and remove potential biases (e.g., Bushinsky et al., 2019; Sutton et al., 2021). 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 west of the Antarctic Peninsula.

Marine biogeochemistry still relies heavily on vessel-based observations that, while critical, yield only snapshots of system functioning. 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), and uncrewed surface vehicles (e.g., Saildrone; Sutton et al., 2021), have vastly increased the number and timing of the available observations; their continued and expanded deployment is critical for observing short- and long-term changes in Southern Ocean carbon cycling and biogeochemistry. The development and improvement of new satellite sensors (e.g., Sentinel-3A OLCI sensor) and *in situ* sensors (e.g., for nutrients) are necessary to enhance the quantity and quality of Southern Ocean data. Ship-based programmes like Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) and GEOTRACES also remain essential, both for calibrating autonomous platforms and sensors, making measurements not currently feasible by satellite, and for monitoring the Southern Ocean response to climate change.

Table 3: Theme 3 Southern Ocean carbon and biogeochemical cycles Key Science Challenges and key international initiatives contributing to addressing each challenge. Acronyms are defined in Appendix 1.

Challenges	**International Initiatives Addressing Challenges**
3.1: Constrain variability in the Southern Ocean CO_2 sink over different temporal scales and across regions	Global Carbon Project, GO-SHIP, IMOS-SOTS, SOFLUX, SOCAT, SORP, SOLAS, IOCCP
3.2: Evaluate the contribution of seasonally ice-covered areas to carbon uptake and export	IOCCG, BEPSII, BGC-Argo, SOCCOM, SOLAS, IOCCP
3.3: Assess the extent and impact of ocean acidification across the Southern Ocean	GOA-ON, IOCCP
3.4: Assess the spatial, seasonal and interannual distribution of climate-active gases and halogens in ice-covered and ice-free waters	BEPSII, SOLAS, CATCH
3.5: Determine the key drivers of primary productivity and the Biological Carbon Pump (light, stratification, circulation, and supply of micro- and macronutrients) and assess ongoing changes in these parameters	GO-SHIP, GEOTRACES, BGC-Argo, SOCCOM, SOCLIM, IOCCG, AniBOS
3.6: Quantify the impact of recycling and remineralisation, including via the Microbial Carbon Pump, on nutrients and carbon cycling	GEOTRACES, BGC-Argo, SOCLIM, SOCCOM

Theme 4: Understanding and Quantifying the State and Variability of the 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; 2013; Massom and Stammerjohn, 2010). During the past few decades, the oceanographic and cryospheric characteristics of the Southern Ocean have changed with consequences for ecosystems, such as decreased Antarctic krill abundance in the Atlantic sector (Atkinson et al., 2004; 2019; Meredith et al., 2019), and changes in primary production and phytoplankton size structure and composition along the Antarctic Peninsula (Montes-Hugo et al., 2008; 2009; Mendes et al., 2013; 2018; Schloss et al., 2014; Moreau et al., 2015; Schofield et al., 2017; Ferreira et al., 2020). These in turn have affected top predator populations, 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). Such changes have contributed to regional increases in oceanic CO_2 uptake (Brown et al., 2019). Variability in the physical environment can lead to changes in productivity through biogeochemical linkages (e.g., see Theme 3).

Accurate estimates of biomass in all trophic levels are essential to assess the impacts of climate change (Murphy et al., 2012; Rogers et al., 2020). Models have shown changes in biomass estimates can have cascading impacts on dependent predators (Xavier et al., 2013), for example reduced growth rates in Antarctic krill (*Euphausia superba*) due to warming (Klein et al., 2018). 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). Observations of top predators as sentinels of change (Bestley et al., 2020) remain critical to assess 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 creates a complex field of “winners and losers” with respect to faunal abundance and distributions (Clucas et al., 2014).

The challenges posed under this Theme focus on understanding responses of Southern Ocean ecosystems to climate change and human activities. 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). Addressing these challenges requires sustained observations that capture population changes of key species, main components of food webs, their spatio-temporal changes and/or the overall structure and function of food webs. Increased observing efforts of mid-trophic level groups, for which major data gaps persist, will require better standardisation of net sampling (Kaartvedt et al., 2020), as well as improved models to convert acoustic backscatter data into biomass (Proud et al., 2019). 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 sampling, acoustics, profiles, predator observations), and measures of diversity and relative biomass of key taxa, links and flux rates. 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. Observation systems must work towards being integrated end-to-end, from virus, bacteria, archaea and primary producers to top predators, 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.

Table 4: Theme 4 Southern Ocean ecosystems and biodiversity Key Science Challenges and key international initiatives contributing to addressing each challenge. Acronyms are defined in Appendix 1.

Challenges	**International Initiatives Addressing Challenges**
4.1: Assess the key drivers of change and their impacts on Southern Ocean ecosystems (food webs and biogeochemical cycling) at circumpolar and regional scales, with emphasis on the effects of changing sea ice conditions on key species that are central to Southern Ocean food webs (e.g., Antarctic krill, upper trophic level species)	CCAMLR, BGC Argo (SOCCOM, SOCLIM), Ant-ICON, ICED, SO-CPR, KRILLBASE, MAPPPD, MEASO, AniBOS, AntOBIS/SCAR Antarctic Biodiversity Portal, SKAG, EG-BAMM
4.2: Understand biodiversity of Southern Ocean benthic and pelagic ecosystems at regional and circumpolar by investigating the potential changes accruing from influences of climate change and human activities	Ant-ICON, SO-CPR, MAPPPD, CMEMS, AniBOS, AntOBIS/SCAR Antarctic Biodiversity Portal, EG-BAMM, ICED
4.3: Evaluate the distribution of species in relation to Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Marine Protected Area (MPAs) and climate change, considering historical changes and future projections	SOOS, CCAMLR, ICED, Ant-ICON, SO-CPR, AniBOS, AntOBIS/SCAR Antarctic Biodiversity Portal, EG-BAMM, ICED
4.4: Assess the extent to which the "greening" of the Southern Ocean is changing phytoplankton biodiversity, distribution and abundance, investigating the impact of these changes on CO_2 uptake, and zooplankton grazers	SO-CPR, AntOBIS/SCAR Antarctic Biodiversity Portal, ICED

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, carbon and other climatic gases) across the ocean-sea ice-atmosphere 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, freshwater, carbon and other important climate-relevant gases (such as CO_2) are key components of the global ocean and climate system. The Southern Ocean heat uptake now accounts for 75±22% of the total oceanic heat uptake and ~40% of the global oceanic uptake of anthropogenic CO_2 (Frölicher et al., 2015).

Attribution of the processes leading to increased Southern Ocean heat uptake is currently lacking (Meredith et al., 2019), mainly because *in situ* measurements of the ocean-atmosphere turbulent fluxes are sparse and often non-existent (Garzoli et al., 2013; Swart et al., 2019). As a consequence, accurate estimates of turbulent heat fluxes are difficult to obtain (Villas Bôas et al., 2015; Santini et al., 2020), which leads to large differences among existing satellite-reanalysis heat flux products (Bourassa et al., 2013; Pinker et al., 2014; Swart et al., 2019). This has led to a knowledge gap that increases uncertainty in atmosphere and ocean dynamics and boundary-layer thermodynamic processes, limiting improvements in weather and climate models (Swart et al., 2019). No less important is understanding how the fluxes of CO_2 and other climate-relevant trace gases and aerosol precursors (e.g., N_2O, CH_4, DMS) behave at the ocean-sea ice-atmosphere interface of the Southern Ocean (Thomas et al., 2019). Considerable uncertainty remains, due to the lack of measurements spatially and temporally and the variety of methodologies used to obtain the fluxes. Accurate flux measurements also contribute to the reduction of uncertainties in the global balances of heat and climate relevant gases such as CO_2 and in present climate models . 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. Many of the transfer coefficients used in these flux parameterisations are from studies based on *in situ* measurements (Hackerott et al., 2018; Bharti et al., 2019; Santini et al., 2020). 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), and the sea ice zone (Mazloff et al., 2018; Swart et al., 2020).

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). It is essential to have a robust observing system operating year round as many observation points are currently made only during spring and summer. The absence of a year-round observing system greatly reduces the chances of sampling the seasonal behaviour of fluxes and essential climate variables, along with the extreme short-term events which are often missed by bulk formulas for the Southern Ocean. These will ultimately lead to reduced bias between direct observations and bulk formulas (Santini et al., 2020; Pezzi et al., 2021). 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) as well as taking advantage of ships, coastal research stations, surface moorings, and the growing capabilities of autonomous platforms such as Saildrones and Wave Gliders (Monteiro et al., 2015; Sutton et al., 2021). 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.

Table 5: Theme 5 Southern Ocean-sea ice-atmosphere fluxes Key Science Challenges and key international initiatives contributing to addressing each challenge. Acronyms are defined in Appendix 1.

Challenges	**International Initiatives Addressing Challenges**
5.1: Increase air-sea flux observations with emphasis on: ● Varying conditions imposed by wind patterns, storms and sea state ● Regions and times (winter) of high uncertainty in reanalysis products ● Areas covered by sea ice and influenced by polynyas/leads	SOFLUX, OASIS, CMEMS, SORP, CATCH, SOLAS, OceanSITES, SOOP
5.2: Improve satellite-derived air-sea flux measurement capabilities: ● Develop reliable retrievals of ocean-sea ice-atmosphere turbulent heat fluxes, especially in high winds and sea state ● Improve freshwater flux retrievals for regions with variable ice-induced freshwater inputs	SOFLUX, Satellite Programmes, CMEMS, SOLAS
5.3: Decrease uncertainty in atmosphere and ocean dynamics and boundary-layer thermodynamic processes, aiding improvements in weather and climate models, including ocean waves, ocean mixed-layer turbulence, atmospheric boundary layer physics, cloud condensation nuclei and ice nucleating particles	WCRP, OASIS, CMEMS, AntClimNOW, AniBOS, SOLAS
5.4: Constrain variability in Southern Ocean carbonate system and ocean-atmosphere CO_2 fluxes over seasonal and annual temporal scales	SOCCOM, BGC-Argo, SOLAS, SOOS Task Team on Acidification, OASIS, CMEMS, SORP
5.5: Assess the spatial, seasonal and interannual distribution of essential climate variables in the sea ice impacted Southern Ocean (e.g., the marginal sea ice zone) to decrease uncertainty of ocean-sea ice-atmosphere fluxes of biogeochemical and physical properties	BEPSII, OASIS, SOLAS, SOFLUX, CMEMS, ASPeCt, AntClimNOW, AniBOS, SORP, CATCH
5.6: Evaluate the contribution that seasonal variability of sea ice makes to heat budgets, considering turbulent fluxes at the ocean-sea ice-atmosphere interface	WCRP, AntClimNow, OASIS, SOFLUX, CMEMS, ASPeCt, AniBOS, SOLAS
5.7: Increase spatial and temporal coverage of measurements of the ocean-sea ice-atmosphere fluxes of climate relevant gases other than CO_2 (e.g., N_2O, CH_4, DMS, halogens, isoprene)	SOLAS, AntClimNow, WCRP, OASIS, SOFLUX, CMEMS, BEPSII, ASPeCt, CATCH

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. In the past decade, SOOS publications have been used in over 10 policy documents including the IPCC AR6 Synthesis Report. SOOS will also be delivering into the UN Decade of Ocean Science for Sustainable Development through being a key partner of the Southern Ocean UN Decade effort. 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 SW western Australia), and the impacts of Southern Ocean ecosystems on food security.

Implementation Framework

Foundational Capabilities

In addition to defining science priorities, SOOS recognises the importance of enhancing our ability to collect, manage and use observational data. The SOOS Foundational Capabilities (shown in Figure 3) provide the framework to enable these efforts.

Observing System Design, Key Variables and Modelling

Observing System Design

Methods exist to design, prioritise and assess observing systems, including determining the minimum number of observations required to constrain a quantity of interest (e.g., Observing System Simulation Experiment, OSSE). Different quantities have different optimal strategies and observing system design can contribute to understanding how a quantity is observed, and if observation strategies exist to support observations of multiple quantities. These tools provide a quantitative estimate of the value of ocean observations with respect to how well they deliver the goals of the observing system. This information is important to prioritise allocation of data collection resources, justify required funding, and ensure delivery of the knowledge required from the observations collected. In the five years covered by this Science and Implementation Plan (SIP), the SOOS Observing System Design Capability Working Group (OSD CWG) will coordinate and deliver SOOS contributions to advance this Foundational Capability.

The OSD CWG aims to advance the knowledge and tools used in designing optimal observing systems, and to consult with stakeholders to assess current inadequacies in the observing system and prioritise instrumentation. Activities include assessment of correlation scales, mapping methods, and times of emergence. Activities also consist of planning and carrying out OSSEs, including assessments of the “nature” model run used in these experiments as the quality of these nature runs limits the value of the OSSE results. This working group also plays an advisory role within SOOS and the broader Southern Ocean community, providing guidance on OSD methodologies and capabilities e.g., the role of OSD CWG in the Animal-Borne Ocean Sensor (AniBOS - previously MEOP) network (GOOS-252) or engaging in research efforts that further the use, impact or uptake of OSD methods (e.g., Wei et al., 2020). The aim of the working group is to gather data through the methods described above to be combined with human intuition and experience to make maximum use of our human and material resources.

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. Over the last decade, 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., 2019b). 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-led initiative to identify a process for determining ecosystem EOVs for the Southern Ocean (e.g., Constable et al., 2016).

Looking forward, 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. The current key variables are shown in Appendix 2.

Modelling

Over the past decades, the ocean modelling community has made significant advances in simulating Southern Ocean processes and systems. High-resolution 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 circulation models, have been implemented at regional (Salmon et al., 2020; Twelves et al., 2021) and circumpolar scales (Lovenduski et al., 2015; Verdy and Mazloff, 2017). These models have been used to 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). 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, and oceanic circulation and basal melting within ice shelf cavities (Utolia et al., 2017; Beadling et al., 2020). Increased spatial resolution in circulation models permits resolution of eddy fluxes (e.g., Stewart et al. 2018, 1/48° resolution) and improved simulation of Antarctic Bottom Water formation (e.g., Morrison et al. 2020, 0.1° resolution) but observations are still required for simulation verification and process parameterisation.

The regional and circumpolar circulation models have also provided the basis for simulating population connectivity (Pinones et al., 2013; Pinones et al., 2016; Thorpe et al., 2019) and for assessing projected changes (Pinones and Federov, 2016). Coupling food webs, especially upper trophic levels, with circulation and biogeochemical models remains to be done (Murphy et al., 2012). 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.

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, 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), and other networks to facilitate integration between the Southern Ocean observational and modelling communities.

Methods and Standards

Observational Technologies

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. 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 Argo, and international programmes dedicated to advancing the maturity and use of these autonomous platforms. These, in addition to satellite-sensor technology and advances in fixed assets such as moorings, have caused a step-change in Southern Ocean observational capabilities (Schofield and Kohut, 2018). A detailed consideration of the current status of observational technologies is provided in Newman et al. (2019).

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 (e.g., the SOOS Under Ice Strategy (Rintoul et al., 2014); and the Satellite Data Task Team (Pope et al., 2016));
- Support platform/sensor-specific networking (e.g., SOOS Autonomous Underwater Vehicles Task Team (AUV Task Team); the Network for the Collection of Knowledge on meLt of Antarctic iCe shElves (NECKLACE) programme);
- Transition platforms through the Framework for Ocean Observing (Lindstrom et al., 2012) readiness levels towards sustained, operational implementation (e.g., SOOS involvement in the AniBOS network development as a sustained programme of GOOS, and the NECKLACE programme development);
- Support data technology development (e.g., the Polar Data Discovery Enhancement Research Task Team (POLDER Task Team) developing data discovery technologies), including AI/Machine Learning efforts.

SOOS will continue to support activities that contribute to enhanced technological capabilities, through continuation of the aforementioned activities (see Appendix 2 for details), 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.

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 greatest impact for society. This requires that observations be collected using standardised sampling, analytical protocols and reference materials, and the resulting data be interoperable and comparable 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 (Censusing Animal Populations from Space Capability Working Group (CAPS CWG)); advocating the development of standards for the collection and management of emerging data types, including acoustic moorings (Acoustic Trends CWG) and ice shelf melt data (NECKLACE programme); the development of standardised data policies for polar regions (Tronstad et al., in prep); 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. Some SOOS working groups will continue to deliver into this capability (see Appendix 2), 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 easily "Findable, Accessible, Interoperable, and Reusable" (the FAIR Principles, Wilkinson et al., 2016; Tanhua et al., 2019a). The variety of data types, barriers to the widespread adoption of data- and metadata-exchange 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 DMSC has contributed to a set of aligned data principles for the polar regions (Tronstad et al. 2021) 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). 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 populate 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 as and when they become available and technical resources allow. Additionally, SOOS will continue to encourage best practices in data management, inform the community of external data sources (e.g., model outputs, remote sensing, and gridded products), and broker data management relationships between scientists and data centres. In all of 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 IPO 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 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' 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.

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 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 and Acoustic Trends Capability Working Group), or directly by SOOS to address a gap in our capabilities (e.g., SOFLUX and OSD CWGs), define priorities in order to align strategies (e.g., OASIIS CWG), 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 (Tanhua et al., 2019a)(e.g., POLDER Task Team, SOOS Data Management Sub-Committee). Since 2016, SOOS has developed 10 international working groups and 8 task teams.

Looking forward, SOOS will continue to support these existing networks, whilst also identifying gaps that require new collaborative partnerships or networks to be built. Future priorities, for example, include working with Global Ocean Acidification Observing Network (GOA-ON), SCAR's expert group on ocean acidification and other ocean acidification and carbon communities, to identify community requirements and initiate an integrated effort to collect and deliver ocean acidification-relevant data from the Southern Ocean. Coordination of a Ships of Opportunity (SOOP) initiative, to better utilise all potential vessels operating in the Southern Ocean, is another priority for the coming years, ensuring connection to existing global SOOP programmes where appropriate. In recognising these new priorities, however, SOOS also recognises the need to grow the resources used to support these networks. As it currently stands, the SOOS IPO is oversubscribed in supporting the existing 10 working groups and 3 task teams, and this will be taken into consideration in the development of any future groups.

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. Developed for SOOS by the Australian Antarctic Data Centre and hosted by the European Polar Board, DueSouth provides information on upcoming research vessel expeditions, flights, fishing vessel plans and incorporating tourist expeditions. DueSouth is delivered in collaboration with the Council of Managers of National Antarctic Programs (COMNAP), the CCAMLR, the Joint Centre for Oceanography and Marine Meteorology in situ Observations Programmes Support (OceanOPS), 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, Data Buoy Cooperation Panel (DBCP), OceanSITES, Integrated Marine Observing System Southern Ocean Time Series (IMOS-SOTS), Global Sea Level Observing System (GLOSS), OceanGliders, Animal Borne Ocean Sensors Network (AniBOS), as part of GOOS, and others outside of GOOS, such as GEOTRACES. 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). As an example, Table 6 provides examples of the SOOS-endorsed national/multi-national efforts. 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.

Table 6: Examples of national and multinational initiatives that contribute to SOOS through the collection of observational data from the Southern Ocean. The examples listed are those that have been officially endorsed by SOOS. Endorsed projects undergo a review process by SOOS, and if successful are provided with a letter of support for their funding proposal, and are communicated through the website and news. Endorsement applications are open year-round to all, via the SOOS website https://soos.aq/activities/endorsed-projects/soos-endorsement

Programme Name	Nation	Type
Southern Ocean Continuous Plankton Recorder (SO-CPR)	International	Internationally coordinated observing programme
The Humpback Whale Sentinel Program	Australian	Long-term observational programme
IMOS Southern Ocean Time Series Observatory (IMOS-SOTS)	Australian	Long-term observational programme
Polar Citizen Science Collective	International	Internationally coordinated observing programme
Palmer LTER	USA with multinational involvement	Long-term observational programme

Southern Ocean Carbon and Heat Impact on Climate (SO-CHIC)	European with multinational involvement	Mid-length observational programme
Detecting, attributing, predicting and monitoring ecological change in the Southern Ocean	Australian	Short-term project
Saildrone Antarctic Circumnavigation	Multinational	Short-term project
Carbon Uptake and Seasonal Traits in Antarctic Remineralisation Depth (CUSTARD)	UK	Short-term project
Southern Ocean Nanoplankton Response to CO_2 (SONAR-CO_2)	Multinational	Short-term project
Role of the Southern Ocean Earth System (RoSES)	UK	Mid-length observational programme
Robotic Observations and Modelling of the Marginal Ice Zone (ROAM-MIZ)	Sweden	Mid-length observational programme
Research of Ocean-Ice Boundary Interaction and Change around Antarctica (ROBOTICA)	Japan	Mid-length observational programme
Ocean Regulation of Climate through Heat and Carbon Sequestration and Transports (ORCHESTRA)	UK	Mid-length observational programme
Dynamics of High Latitude Marine Ecosystems (IDEAL)	Chile	Long-term observational programme
Marine Ross Sea Observatory (MORSea)	Italy	Long-term observational programme
Resolving CO_2 system seasonality in the West Antarctic Peninsula with year-round autonomous observations	USA	Short-term project
Network for the collection of Knowledge on Melt of Antarctic Ice Shelves (NECKLACE)	International	Long-term observational programme (based on short-term project funding)
Southern Ocean Seasonal Cycle Experiment (SOSCEx)	South Africa	Short-term project
Mapping Application for Penguin Populations and Predicted Dynamics (MAPPPD)	USA	Mid-length observational programme
Nutrient dynamics and deep water behaviour in the West Antarctic Peninsula sea ice zone	UK	Short-term project
Towards an improved heat budget for the floating glaciers in Antarctica	Sweden	Short-term project
Polynyas, Ice Production and Seasonal Evolution in the Ross Sea	USA	Short-term project
Changes in Stratification at the Antarctic Peninsula	USA	Short-term project
Southern Ocean Network of Acoustics	UK with	Short-term project

	multinational involvement	
Dynamics of the Orkney Passage Outflow (DynOPO)	UK	Short-term project
Investigation of Bottom Water formation in Prydz Bay, Antarctica	China	Short-term project
Terra Nova Bay Research Experiment (T-REx)	Italy	Short-term project
High Latitude Oceanography Group (GOAL)	Brazil	Mid-length observing programme

Science, Policy and Management Programmes

In addition to the programmes and projects that collect, manage and deliver Southern Ocean observations, there are more still 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; EC-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 International 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 Acoustic Trends Capability Working Group, which was a joint initiative of SOOS and the International Whaling Commission. SOOS outputs also deliver into the UN Sustainable Development Goals 13 (Climate Action) and 14 (Life Below Water).

UN Decade of Ocean Science for Sustainable Development

The UN Decade of Ocean Science for Sustainable Development ("UN Ocean Decade"), is a global effort to reverse the cycle of decline in ocean health and provide a common framework to support actions to sustainably manage the Oceans and achieve the 2030 Agenda for Sustainable Development.

The SOOS mission aligns with the objectives of the UN Decade, therefore SOOS' ongoing activities will inherently deliver into the Decade, while the Decade provides impetus for SOOS stakeholders to invest in the SOOS mission. SOOS has been centrally involved in the initiation of a Southern Ocean UN Decade programme, and will work to ensure SOOS outputs and impacts are delivered through the Decade programme where appropriate.

SOOS Implementation

Regional Working Groups

SOOS implementation (e.g., integration of the national and international observing efforts) is regional and based on interconnected sectors of national infrastructure and activities. To support this regional implementation, SOOS has developed five Regional Working Groups (RWGs, Figure 4): The Southern Ocean Indian Sector, the Ross Sea, the Weddell Sea and Dronning Maud Land, the West Antarctic Peninsula and Scotia Arc, and the Amundsen/Bellingshausen Sea.

The RWGs coordinate and implement regional observing systems and enable integration of the internationally coordinated observing programmes with the shorter-term national/multi-national observing projects. The RWGs also identify overlap in national areas of focus and observational activities that could be translated into better logistic coordination, scientific collaboration, and sharing of operational resources. An important RWG activity is to support synthesis efforts for data served by SOOS and the creation of joint funding proposals to progress SOOS in the five regions, where such mechanisms exist. The RWGs are also important conduits for knowledge and information on data requirements between the scientific community addressing the Science Themes, SOOS, and SOOS data efforts, ensuring linkage between all components of the required system.

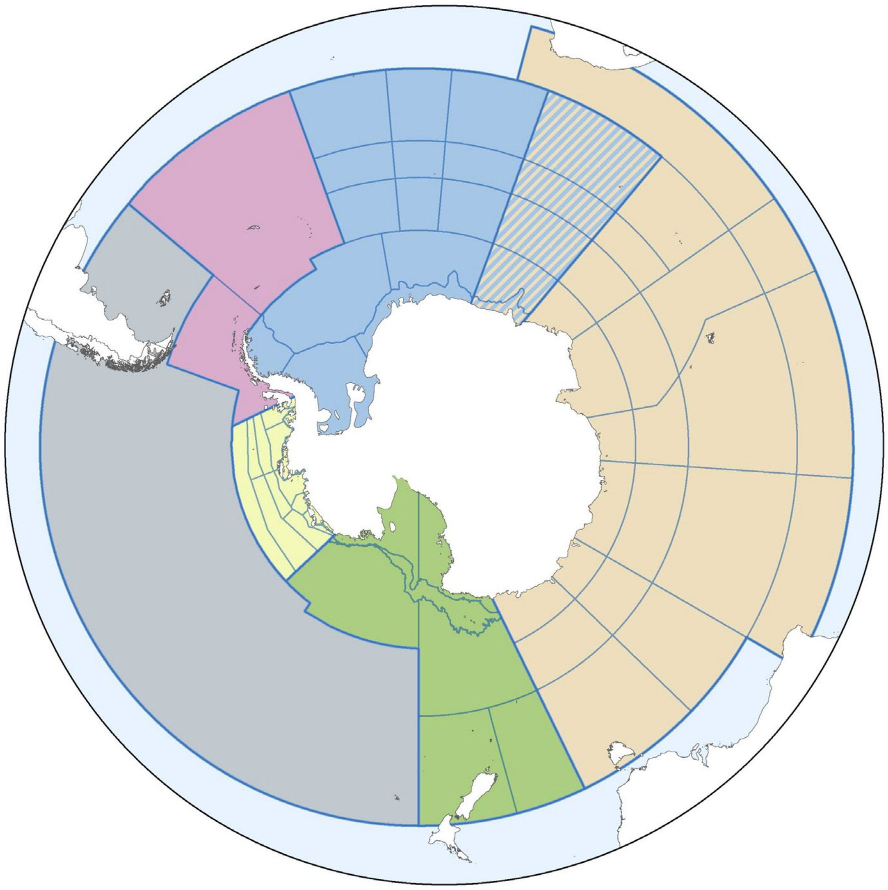


Figure 4: The five SOOS Regional Working Groups, which coordinate and integrate observing efforts in each region: Indian Sector (Brown), Ross Sea (Green), Amundsen-Bellingshausen Sea (Yellow), West Antarctic Peninsula-Scotia Arc (Pink), and the Weddell Sea-Dronning Maud Land (Blue). The smaller divisions of each regional group (thin blue lines) are "sub-regions" and will be used by each region to identify observational requirements and coverage (see Objective 3). Sub-regions were developed by each regional group, and are organised around oceanographic or bathymetric features, or take into account other community boundaries, such as CCAMLR fishing zones or Marine Protected areas. These sub-regions may change once discussions on observational requirements and coverage are progressed. The grey region denotes a "Partner Observing Area", which is a region of lower priority for the nations involved in the Amundsen-Bellingshausen Sea and Ross Sea RWGs, and thus facilitating sustained observational coverage in this region is beyond the capacity of these groups. SOOS will work with international programmes, such as GO-SHIP, Argo, and with remote sensing, to ensure continued coverage of this region. Regional Working Group boundaries are approximate only. We fully acknowledge all exclusive economic zones and shading is shown for indicative purposes only.

Data Management Sub-Committee

SOOS has built a strong and inclusive Southern Ocean data management community that acts as an efficient platform for sharing knowledge on data sources, management and delivery. This network of data experts from national and international data centres and programmes forms the SOOS Data Management Sub-Committee (DMSC), and advises the SOOS SSC on the most effective collaboration mechanisms for managing and publishing observational data from the Southern Ocean, implements SOOS' data management activities, and provides guidance for the SOOS Data Officer. The DMSC collaborates closely with the SCAR Standing Committee on Antarctic Data Management (SCADM), as well as with partners on a global scale and in other regions, such as the Arctic. It also promotes existing data standards and the FAIR data principles, as well as development of OBP, and the use of data exchange formats. Fostering close connections with many research institutions and scientists, whilst also forging strong ties with worldwide data repositories, enables the SOOS DMSC to work as a powerful and meaningful broker of data management relationships.

Capability Working Groups

Capability Working Groups (CWGs) are developed to enhance our ability to make observations in the Southern Ocean, either through developing knowledge and tools aligned with the Foundational Capabilities, or knowledge or tools that enhance our ability to address the Science Themes. CWGs can be either bottom-up community proposed initiatives, or SOOS-initiated efforts to address key gaps in our capabilities. Most CWGs operate for a 3-5 year period, with the option for renewal if required.

Equity, Diversity and Inclusion Group

Equity, Diversity and Inclusion (EDI) are core tenets of SOOS values (page 7), and are actively considered in all SOOS activities, including the selection of SOOS leadership. The SOOS EDI group is an ongoing initiative within SOOS to ensure we continue to act in accordance with our values. The SOOS EDI group will play a strategic, implementation and advisory role and make recommendations to the SOOS Executive Committee and broader community where appropriate.

SOOS EDI actions will focus on developing and implementing approaches that make Southern Ocean science more welcoming to people of all races, nationalities, language backgrounds, career levels, genders, sexualities, and other axes of diversity. Identifying barriers to full participation in SOOS, and acting where possible to circumvent them, will be the focus of the SOOS EDI remit in 2021-2025, in addition to making explicit what was previously assumed - that SOOS activities and efforts are open to all those interested in being involved.

Task Teams

Task Teams are short-term groups developed to produce a specific SOOS product (e.g., publication or document), scope out community needs and readiness for actions on specific capabilities, or organise an activity. To date, SOOS has supported 10 Task Teams, resulting in 5 publications (with 3 more in preparation) and 2 international networks. Looking forward, task teams will continue to be supported by SOOS as the need arises.

SOOS Governance and Oversight

SOOS Governing Bodies

SOOS is an initiative of SCAR and SCOR. In addition to providing guidance and advice, SCAR and SCOR provide important access for SOOS to engage with intergovernmental agencies, such as the Antarctic Treaty Consultative Meeting, the CCAMLR and the IOC. Furthermore, both governing bodies also sponsor the annual SOOS SSC meeting.

Executive Committee and Scientific Steering Committee

The strategic vision and governance of SOOS is led by the Executive Committee (EXCOM) comprising two Co-Chairs and two Vice Chairs, and the Executive Officer. The EXCOM is in regular contact with sponsors and core stakeholders to ensure international input in the strategic governance of SOOS.

All SOOS activities are overseen by the international SOOS SSC. The SSC provides scientific direction for SOOS towards achieving its mission. The SSC comprises three organisational levels: EXCOM members, Scientific Members, and ex-officio representatives from key sponsors and SOOS Regional Working Groups.

National Representatives and National Networks

The mission of SOOS is an international venture, and SOOS ensures broad international representation across all its implementation groups. Engagement of all nations in the strategic direction and oversight of SOOS is important, however with limited positions available for the SOOS SSC, not all nations can be represented. National Representatives are therefore invited, from any nation wishing to develop or strengthen its national representation in SOOS.

National SOOS Networks are developed as partnerships between a National Antarctic Programme or institute and SOOS. Examples of network objectives include building a strong national Southern Ocean community, enhancing knowledge sharing and collaborative efforts, supporting national data management efforts, ensuring greater international uptake and use of national data and products, and sharing knowledge of funding opportunities, as well as providing enhanced opportunities for national member involvement in international Southern Ocean initiatives and efforts.

International Project Office

The SOOS International Project Office (IPO) is the central hub of the SOOS effort, coordinating international research efforts, facilitating communication, developing avenues for data management/sharing, and fostering programmatic, national and disciplinary relationships. The IPO acts as the communicating body between the SOOS SSC, researchers, observational platform operators, data centres and other stakeholders.

The IPO is hosted by the Institute for Marine and Antarctic Studies at the University of Tasmania, Australia (IMAS-UTAS). IMAS-UTAS have hosted the IPO since its inception in 2011, providing SOOS with the necessary core structure and funding to coordinate activities and deliver the mission, also enabling SOOS to leverage this support and build international partnerships and sponsorships to grow SOOS capacity and outputs.

From 2020-2022, the SOOS office will continue to be hosted at IMAS-UTAS through a partnership between IMAS-UTAS, the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Tasmanian State Government Department of State Growth. Hosting of the IPO beyond the 2022 end-of-contract will be determined in 2021/2022.

The 5-Year Strategic Plan

SOOS has identified five Objectives that combined will deliver the SOOS mission. Within each of these Objectives are a number of Implementation Actions that indicate more specifically how these objectives will be achieved.

A schematic illustrating how these objectives will be delivered is shown in Figure 5 below, and a full, detailed plan will be kept as a live document and is shown in Appendix 3.

Objective 1: Develop and coordinate inclusive and collaborative networks for shared knowledge, enhanced observational capability, and data collection, management and delivery

1.1 Coordination of regional networks

1.2 Coordination of networks to enhance observational capacity at any point in the value chain

1.3 Integrate and engage between and across relevant programmes, organisations, and institutes to leverage and enhance impact of the SOOS programme as a whole

1.4 Build an effective, networked community of Southern Ocean data managers

1.5 Actively review and reflect on networking processes, activities, and structures to ensure that they are equitable, diverse and inclusive

1.6 Build Southern Ocean community capacity, including early career development and support for new and emerging national programmes

Objective 2: Address gaps and inefficiencies in our ability to collect, deliver, and use sustained observations

2.1 Support and lead efforts to better integrate modelling and observational efforts, including OSD elements, such as OSSEs and EOV identification

2.2 Support and lead efforts to advance observing system and data sharing technologies (hardware, software) and methods

2.3 Support and lead efforts to agree, document, advocate for and implement best practice, in both science and data

2.4 Identify gaps and opportunities across the Foundational Capabilities and support efforts to address them

Objective 3: Identify the spatio-temporal and thematic requirements of observations needed to address the Science Themes; identify existing coverage and work to maintain it; and address identified gaps

3.1 Map the geographic distribution of Theme Challenges to understand their regional importance, existing data coverage and the national/international efforts to address them

3.2 Develop a regional understanding of stakeholder requirements and priorities for data pertaining to the Theme Challenges

3.3 Develop and utilise a system for identification of observational coverage and requirements

3.4 Enhance logistical collaborations to ensure sustained data coverage

3.5 Support and advocate for efforts to collect, deliver or use observational data

Objective 4: Deliver high-quality scientific data, synthesis activities/products and knowledge that are needed to deliver our mission

4.1 Delivery of publications (scientific, strategic, data) that provide scientific knowledge towards addressing the Science Themes, enhancing observational capabilities, or delivering directly to policy and management

4.2 Populate SOOSmap with high-priority standardised datasets that are required to address the Science Themes and encourage broader use of SOOSmap by Southern Ocean researchers

4.3 Enhance FAIR data management and delivery through use and linkage of existing tools and networks, and assist in connecting resources to needs

4.4 Ensure SOOS data activities align with a clear data policy that is itself, aligned with the FAIR data principles of being Findable, Accessible, Interoperable and Reusable and with data policy of other polar communities

Objective 5: Maintain SOOS as the world-leading hub to support the collection and delivery of Southern Ocean observations

5.1 Reporting metrics and information are collected, compiled and delivered to stakeholders as required

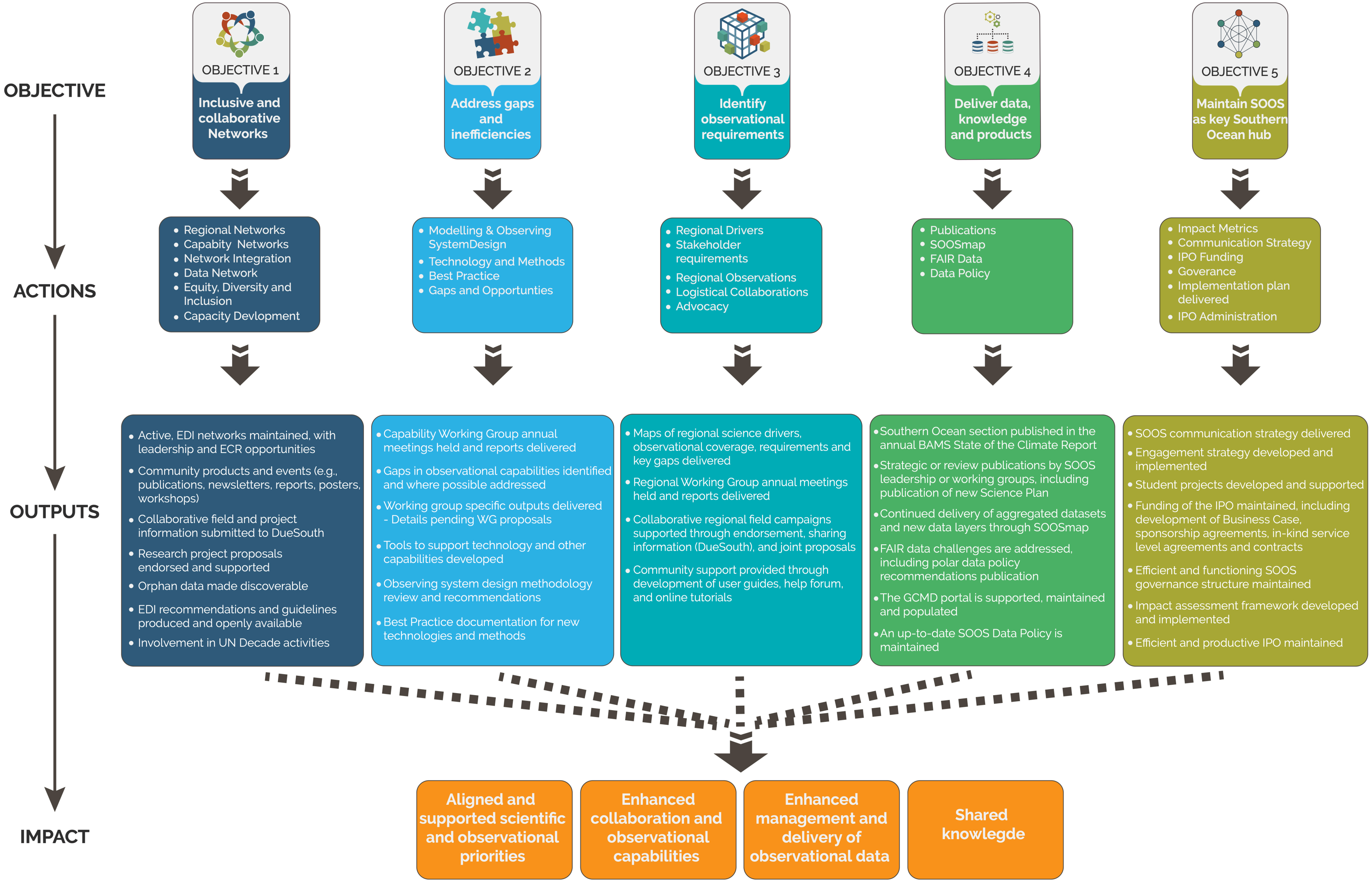
5.2 The SOOS communication and engagement strategy is kept up-to-date and implemented

5.3 Funding for the SOOS IPO is maintained and enhanced

5.4 SOOS governance is managed and maintained

5.5 Implementation Plan objectives are coordinated and supported

5.6 SOOS IPO administration and management is carried out efficiently and effectively



OBJECTIVE

OBJECTIVE 1
Inclusive and collaborative Networks

OBJECTIVE 2
Address gaps and inefficiencies

OBJECTIVE 3
Identify observational requirements

OBJECTIVE 4
Deliver data, knowledge and products

OBJECTIVE 5
Maintain SOOS as key Southern Ocean hub

ACTIONS

- Regional Networks
- Capabity Networks
- Network Integration
- Data Network
- Equity, Diversity and Inclusion
- Capacity Devlopment

- Modelling & Observing SystemDesign
- Technology and Methods
- Best Practice
- Gaps and Opportunities

- Regional Drivers
- Stakeholder requirements
- Regional Observations
- Logistical Collaborations
- Advocacy

- Publications
- SOOSmap
- FAIR Data
- Data Policy

- Impact Metrics
- Communication Strategy
- IPO Funding
- Goverance
- Implementation plan delivered
- IPO Administration

OUTPUTS

- Active, EDI networks maintained, with leadership and ECR opportunities
- Community products and events (e.g., publications, newsletters, reports, posters, workshops)
- Collaborative field and project information submitted to DueSouth
- Research project proposals endorsed and supported
- Orphan data made discoverable
- EDI recommendations and guidelines produced and openly available
- Involvement in UN Decade activities

- Capability Working Group annual meetings held and reports delivered
- Gaps in observational capabilities identified and where possible addressed
- Working group specific outputs delivered - Details pending WG proposals
- Tools to support technology and other capabilities developed
- Observing system design methodology review and recommendations
- Best Practice documentation for new technologies and methods

- Maps of regional science drivers, observational coverage, requirements and key gaps delivered
- Regional Working Group annual meetings held and reports delivered
- Collaborative regional field campaigns supported through endorsement, sharing information (DueSouth), and joint proposals
- Community support provided through development of user guides, help forum, and online tutorials

- Southern Ocean section published in the annual BAMS State of the Climate Report
- Strategic or review publications by SOOS leadership or working groups, including publication of new Science Plan
- Continued delivery of aggregated datasets and new data layers through SOOSmap
- FAIR data challenges are addressed, including polar data policy recommendations publication
- The GCMD portal is supported, maintained and populated
- An up-to-date SOOS Data Policy is maintained

- SOOS communication strategy delivered
- Engagement strategy developed and implemented
- Student projects developed and supported
- Funding of the IPO maintained, including development of Business Case, sponsorship agreements, in-kind service level agreements and contracts
- Efficient and functioning SOOS governance structure maintained
- Impact assessment framework developed and implemented
- Efficient and productive IPO maintained

IMPACT

Aligned and supported scientific and observational priorities

Enhanced collaboration and observational capabilities

Enhanced management and delivery of observational data

Shared knowlegde

Figure 5: Summary of the SOOS 5-Year Strategic Plan including objectives, implementation actions, outputs and societal impact of those outputs. The link to the full Implementation Plan is available in Appendix 3.

Resources and Funding

Resourcing the collection and delivery of Southern Ocean data is expensive. SOOS provides a framework for the international community to efficiently and effectively align priorities and share resources towards common goals. This requires a central coordinating hub; the SOOS International Project Office (IPO). Further, the success of SOOS is dependent on voluntary and in-kind efforts and contributions. This is an important mechanism that supports broad community participation, maximises leveraged efforts and resource sharing, and enables delivery of products that would otherwise not be achievable. However, this approach has implications for management of risk associated with sustained delivery of products and services, control over the timing or quality of products being delivered, and the ability of an organisation to control, manage or adapt to disruptions in the value chain. A well-funded IPO is therefore essential to provide international coordination, oversee and manage voluntary efforts, and to provide the core support that enables stronger leverage capacity and co-investment opportunities.

SOOS IPO sponsors provide support and hosting of the IPO and funding for SOOS operations (e.g., SOOS workshops, data and communication products, travel support and maintenance of general SOOS operations). Currently, the core sponsors and hosts include IMAS-UTAS, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Department of State Growth in a partnership agreement spanning 2020-2022 (and building on previous IMAS-UTAS core sponsorship from 2011-2019). Sponsorship of operational activities varies, depending on level of contribution and requirements of sponsors. Antarctica New Zealand has been a SOOS operating sponsor since 2012, providing much-needed funding stability. The funding has predominantly supported SOOS data activities and products, and has been well-leveraged by Antarctica New Zealand in support of their national data needs. The Swedish Polar Research Secretariat is a new sponsor in 2020 through a collaborative agreement for delivery of the SOOS-Swedish National Network, and building on previous years of sponsorship by the University of Gothenburg, Sweden. New operating sponsors in 2021 include the University of Cape Town, South Africa (2021-2023) and the Scientific and Technological Research Council of Turkey Marmara Research Centre Polar Research Institute, Turkey (2021).

In addition to direct sponsorship, SOOS and the IPO are supported by in-kind sponsors, who provide important services for SOOS. These include the State Oceanic Administration of China, which provides personnel support for data curation efforts; EMODnet Physics, who deliver and maintain SOOSmap, with support from SO-CHIC; the European Polar Board who host and maintain DueSouth; and National Aeronautics and Space Administration (NASA) Global Change Master Directory (GCMD) who host and maintain the SOOS metadata portal. Other in-kind providers are indicated on the SOOS website and include programmes such as COMNAP (for DueSouth expedition information) and the Tasmanian Partnership for Advanced Computing who provide IT website support and have done since 2012.

Event- or product-based support also plays a crucial role in ensuring the maintenance of SOOS networks, broad international and diverse engagement, and timely delivery of publications and products. The SOOS IPO works with the SOOS working groups and the broader community, to source funding for events and products as required, leveraged where possible on support from the central operating funds.

In addition to the abovementioned support, the SOOS governing bodies, SCAR and SCOR, provide not only oversight and connections into intergovernmental bodies, but also financial support for the annual SSC meetings. This support enables participation by all members, and ensures international input into all SSC discussions and decisions.

Despite the acknowledged rationale and imperative, funding of the SOOS IPO is an ongoing challenge. The lack of funding opportunities for sustained international collaborative efforts means IPO funding is sourced from research budgets on a short-term basis, which makes long-term strategic planning difficult and adds a heavy burden on the IPO to continuously source funding.

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Appendix 1: Acronyms

Acronym	Full Name	Programme Governing Body
AFIN	Antarctic Fast Ice Network	
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	
AUV	Autonomous Underwater Vehicle	
BEPSII	Biogeochemical Exchange Processes at the Sea Ice Interfaces	SCAR
BGC-Argo	Biogeochemical-Argo	
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

COMNAP	Council of Managers of National Antarctic Programs	
CPR	Continuous Plankton Recorder	
CSIRO	The Commonwealth Scientific and Industrial Research Organisation	
CTD	Conductivity, Temperature, Depth	
CWGs	Capability Working Groups	SOOS
DAP	Developing Antarctic Programmes	SCAR
DBCP	Data Buoy Cooperation Panel	JCOMM
DMSC	Data Management Sub-Committees	SOOS
EDI	Equity, diversity and inclusion	
EG-BAMM	Expert Group on Birds and Marine Mammals	SCAR
EC-PHORS	Executive Council Panel of Experts on Polar and High Mountain Observations, Research and Services	WMO
ECVs	Essential Climate Variables	
EOVs	Essential Ocean Variables	
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
GCMD	Global Change Master Directory	NASA
GLOSS	Global Sea Level Observing System	IOC
GOA-ON	Global Ocean Acidification Observing Network	
GOOS	Global Ocean Observing System	
GO-SHIP	The Global Ocean Ship-Based Hydrographic Investigations Program	
IAATO	International Association of Antarctic Tour Operators	

IBCSO	International Bathymetric Chart of the Southern Ocean	IBSCO
ICED	Integrated Climate and Ecosystem Dynamics	
IMAS-UTAS	Institute for Marine and Antarctic Studies-University of Tasmania	
IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise	ESA and NASA
IMOS-SOTS	Integrated Marine Observing System-Southern Ocean Time Series	IMOS CSIRO
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
MAPPPD	Mapping Application for Penguin Populations and Projected Dynamics	
MEASO	Marine Ecosystem Assessment of the Southern Ocean	
MEOP	Marine Mammals Exploring the Oceans Pole to Pole	
NASA	National Aeronautics and Space Administration	
NECKLACE	Network for the Collection of Knowledge on meLt of Antarctic iCe shElves	
OASIS	Observing Air-Sea Interactions Strategy	SCOR

OASIIS	Observing and understanding the ocean below Antarctic Sea Ice and Ice Shelves	SOOS
OBPS	Ocean Best Practices System	IODE
OceanOPS	The Joint Centre for Oceanography and Marine Meteorology in situ Observations Programmes Support	WMO-IOC
ORCHESTRA	Ocean Regulation of Climate through Heat and Carbon Sequestration and Transports	National Oceanographic Centre, UK
OSD CWG	Observing System Design Capability Working Group	SOOS
OSSE	Observing System Simulation Experiments	
POLDER	Polar Data Discovery Enhancement Research	SOOS
RWGs	Regional Working Groups	SOOS
ROBOTICA	Research of ocean-ice boundary interaction and change around Antarctica	Japan
SCAR	Scientific Committee on Antarctic Research	
SCOR	Scientific Committee on Oceanic Research	
SIP	Science and Implementation Plan	SOOS
SKAG	SCAR Krill Action Group	SCAR
SOCAT	Surface Ocean CO_2 Atlas	
SOCCOM	The Southern Ocean Carbon and Climate Observations and Modelling	
SO-CHIC	Southern Ocean Carbon and Heat Impact on Climate	European Union
SOCLIM	Southern Ocean and Climate Field Studies with Innovative Tools	
SOCONet	Surface Ocean CO_2 Reference Observing Network	
SO-CPR	Southern Ocean Continuous Plankton Recorder	

SOFLUX	Southern Ocean Fluxes	SOOS
SOLAS	Surface Ocean-Lower Atmosphere Study	
SOOP	Ships-of-Opportunity Programme	GOOS and GCOS
SOOS	Southern Ocean Observing System	SCAR/SCOR
SOOS AUV Task Team	SOOS Autonomous Underwater Vehicles Task Team	SOOS
SORP	CliC/CLIVAR/SCAR Southern Ocean Regional Panel	
SSC	Scientific Steering Committee	SOOS
WCRP	World Climate Research Programme	
WMO	World Meteorological Organization	UN
YOPP	Year of Polar Prediction	WMO

Appendix 2: Key Variables

The Key Variables table is a live document that remains under discussion, development and review by the SOOS community to optimise its utility.

https://soos.aq/images/soos/about_us/Key_Variables_Table.pdf

Appendix 3: Detailed Implementation Plan

Although the objectives and implementation activities are finalised, some aspects of the detailed Implementation Plan will remain flexible, to include new opportunities and activities that may arise. This table is therefore a live document that will be updated and modified throughout the life of the plan.

https://soos.aq/images/soos/about_us/SOOS_2021_2025_Objectives_Deliverables_Table.pdf