Summary for Policymakers

Marine Ecosystem Assessment for the Southern Ocean

Summary for Policymakers

Marine Ecosystem Assessment for the Southern Ocean

Recommended Citation

Constable, A.J., J. Melbourne-Thomas, M.M.C. Muelbert, S. McCormack, M. Brasier, J.A. Caccavo, R.D. Cavanagh, S.M. Grant, H.J. Griffiths, J. Gutt, S.F. Henley, J. Höfer, A.B. Hollowed, N.M. Johnston, S.A. Morley, E.J. Murphy, M.H. Pinkerton, I.R. Schloss, K.M. Swadling, A.P. Van de Putte (2023) Marine Ecosystem Assessment for the Southern Ocean: Summary for Policymakers. Integrated Climate and Ecosystem Dynamics in the Southern Ocean, Scientific Committee on Antarctic Research, Scientific Committee on Oceanic Research, Integrated Marine Biosphere Research, doi: 10.5281/zenodo.8359585

Author affiliations can be found in MEASO Authors Section.

Publication details

Publishers

Scientific Committee on Antarctic Research, Scott Polar Research Institute, Lensfield Road, Cambridge, CB2 1ER, United Kingdom (www.scar.org)
Scientific Committee on Oceanic Research (www.scor-int.org)
Integrated Marine Biosphere Research (www.imber.info)

ISBN:

978-0-948277-31-3 (electronic)

978-0-948277-33-7 (paperback)

DOI: 10.5281/zenodo.8359585

Acknowledgements

MEASO is a core activity of the Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) program, which is a regional program of the Integrated Marine Biosphere Research (IMBeR, which is a joint program of Future Earth and the Scientific Committee for Oceanic Research) and co-sponsored by the Scientific Committee for Antarctic Research.

On behalf of ICED, the MEASO Scientific Steering Committee (MEASO SSC) is thanked for its pivotal role in maintaining the principles that MEASO would be open to participation by any scientists involved in Southern Ocean marine ecosystem research, would strive to ensure that authorship of the review and synthesis papers be representative of the community, including cultural and gender diversity, would ensure that early career scientists had opportunities to lead review papers, and would accept all contributions to the MEASO Frontiers Research Topic pending satisfactory completion of the review process. The MEASO SSC liaised with ICED, IMBeR, SCAR and SOOS, and provided reports to CCAMLR and the ATCM (CEP) via SCAR. Members of the MEASO SSC are identified in the MEASO Authors section.

Lead authors of the core review and synthesis papers are thanked for their commitment to engaging with the scientific community to complete their comprehensive reviews. They are also thanked for their ongoing participation in developing this Summary for Policymakers as well as assisting with outreach work on behalf of MEASO. Lead authors are identified in the MEASO Authors section as well as in the reference section.

All authors, including those submitting additional papers to the work of MEASO, are thanked for their contributions and are included in the MEASO Authors section.

Expert peer-reviewers are thanked for their work to check and provide comments on this report to help the team improve clarity, fill gaps and maintain accuracy of information.

MEASO activities and primary publication costs supported by:

Pew Bertarelli Ocean Legacy

Integrating Climate and Ecosystem Dynamics in the Southern Ocean
Southern Ocean Observing System

Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania, Australia
Australian Antarctic Division, Kingston, Tasmania, Australia
Australian Antarctic Program Partnership, Hobart, Tasmania, Australia
British Antarctic Survey, Cambridge, UK
University of Edinburgh, Edinburgh, UK
Belgian Science Policy (LifeWatch, contractn°FR/36/AN1/AntaBIS)
New Zealand MBIE Ross-RAMP (C01X1710) and ASP (ANTA1801)
University of Tasmania (Institute for Marine and Antarctic Studies; Centre for Marine Socioecology), Hobart, Tasmania, Australia

MEASO International Conference 2018, Hobart, Australia supported as follows:

Hosted by: Antarctic Climate and Ecosystems Cooperative Research Centre; Australian Antarctic Division.

Major sponsors: Pew Bertarelli Ocean Legacy; World Wide Fund for Nature (WWF) and ICED.

Other sponsors: Coalition of Legal Toothfish Operators (COLTO); Japan National Institute for Polar Research (NIPR); Tasmanian Polar Network; University of Tasmania Institute for Marine and Antarctic Studies (IMAS); Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO); Austral Fisheries; Australian Longline.

MEASO planning workshop, Woking, UK supported by: World Wide Fund for Nature (WWF) and ICED

Production of the Summary for Policymakers supported by: Pew Bertarelli Ocean Legacy

Infographics and layout of Summary for Policymakers: Stacey McCormack, Visual Knowledge

Other graphics: Eav Brennan, Lisa Roberts

Assistance with Box 2: Ariaan Purich, Monash University; Will Hobbs, University of Tasmania; Matthew England, University of New South Wales

Peer-review of this Summary for Policymakers: This document was peer-reviewed by the following invited experts: Dr. Renuka Badhe (European Polar Board), Prof. Hugh Ducklow (Lamont-Doherty Earth Observatory, USA), Dr. Sherilee Harper (University of Alberta, Canada), Dr. Kevin A. Hughes (British Antarctic Survey, UK), Dr. Mike Sparrow (World Climate Research Division, World Meteorological Organisation).

Table of Contents

©Eav Brennan

At-a-glance: Key findings of MEASO

i. The Antarctic Treaty System (beginning in 1959 with the Antarctic Treaty) and its emphasis on conservation and protection, exemplified in the Convention on the Conservation of Antarctic Marine Living Resources (1980) and its Protocol on Environmental Protection to the Antarctic Treaty (1991), provide the most recent articulation of the global interest in Antarctica and the Southern Ocean and the need for their protection.

ii. The Southern Ocean and its ecosystems play critical roles in the climate system. Ecosystem functions are at risk because of anthropogenic climate change.

iii. Global policies and actions are urgently required to safeguard Southern Ocean ecosystems from the effects of climate change, ocean warming and acidification caused by greenhouse gas emissions.

iv. Regional human pressures on Southern Ocean species and ecosystems have been dominated by fisheries, with human presence (science and tourism) and pollution having localised, but increasing, impacts.

v. The Marine Ecosystem Assessment for the Southern Ocean (MEASO) has demonstrated the array of existing knowledge, data, tools and approaches available for informing decisions on conserving and sustaining the marine ecosystems in the region and the services they provide, and how implementation of those processes could be improved.

Policy-relevant findings and recommended research priorities

Managing for change

vi. Effective regional and local protection is critical to safeguard ecosystems against the effects of climate change that are already underway. However, maintenance of Southern Ocean ecosystems, particularly polar-adapted Antarctic species and coastal systems, can only be achieved, with high confidence, in the long-term by significant and urgent global action to curb climate change and ocean acidification.

vii. Strategies for conserving Southern Ocean marine biodiversity, including management of fisheries, need to be further developed, based on current knowledge of the implications of climate change, to ensure resilience of Southern Ocean ecosystems into the future, accounting for not only long-term change but the potential for increased near-term variability and extreme events.

viii. Managing human activities in the Southern Ocean will benefit from assessing risks associated with different scenarios of climate change and future socio-economic demands; improved socio-ecological modelling and stakeholder engagement will enable better consideration of risks to environments, societies and economies.

Measuring Change

ix. Directly measuring the state of Southern Ocean ecosystems is central to ecosystem assessments; new approaches, and greater and more sustained investment than at present is required for covering the complexity of food webs, diverse communities, and the large extent and remoteness of the region.

x. A greater geographic spread of ongoing, comprehensive, long-term ecosystem studies is needed to assess spatial and seasonal variability, and for identifying trends in the structure and function of Southern Ocean ecosystems and the relative importance of different ecological processes in different areas.

xi. Systematic and sustained long-term measurements of habitats and biota are needed to underpin assessments of ecosystem change in the Southern Ocean, and for projecting future changes.

xii. Assessments of change will be facilitated by archiving, curating and openly sharing data, algorithms, and tools, based on FAIR principles (Findable, Accessible, Interoperable, and Reusable).

Projecting change to support risk assessments

xiii. Projecting future changes in the survival and/or dynamics of species and communities needs improved models of the impacts from change in habitats, food webs, and human activity.

xiv. Projecting change in ecosystems at appropriate spatial scales needs dynamic ecological models driven by outputs of global ice-ocean-atmosphere (physio-chemical) models down-scaled to spatial scales relevant to ecological processes.

State, variability and change in Southern Ocean ecosystems

Value and importance of Southern Ocean ecosystems in the Earth System

xv. Southern Ocean ecosystems are an integral part of the Earth System; changes in Southern Ocean ecosystems will have impacts throughout the world's oceans and climate system, and vice versa.

xvi. The Southern Ocean exchanges water with all oceans to the north through surface eddies driven by wind, as well as through deep water convection driven by temperature and salinity. Such connectivity enables movement of pelagic organisms (plankton and fish) and biological material into and out of the Southern Ocean.

xvii. The Southern Ocean provides important feeding and breeding grounds for migratory birds and marine mammals; migratory species transport important nutrients to and from the Southern Ocean each year and can contribute to the transport of invasive species.

xviii. In many parts of the world, people have a deep, often unacknowledged, connection with the Southern Ocean and value it greatly, despite not living there.

xix. Human activities in the region (science operations, fisheries, tourism) involve a large-scale transfer of people and material north and south each year, linking communities and social systems elsewhere to the Southern Ocean, and also potentially contributing to unexpected impacts in the region through transport of non-native species/diseases, direct disturbance, and pollution.

xx. The demand for, and global importance of, ecosystem services from the Southern Ocean are expected to increase during the 21st century, and climate change is expected to impact on these services.

Changing habitats in the Southern Ocean

xxi. The Southern Ocean is warming, with some areas warming faster than others.

xxii. Sea ice, a key habitat and defining feature of the Southern Ocean, has been declining in some areas but increasing in others; prognoses for sea ice are amongst the greatest uncertainties about the future of marine ecosystems in the region.

xxiii. The Southern Ocean is freshening, becoming windier, and has a changing light environment, all of which are affecting blooms of phytoplankton.

xxiv. Nutrients (iron, silicon, phosphorus, nitrogen) that are required for primary production are changing regionally but supply is dependent on local conditions.

xxv. Absorption of large amounts of atmospheric CO_2 by the Southern Ocean is causing ocean acidification.

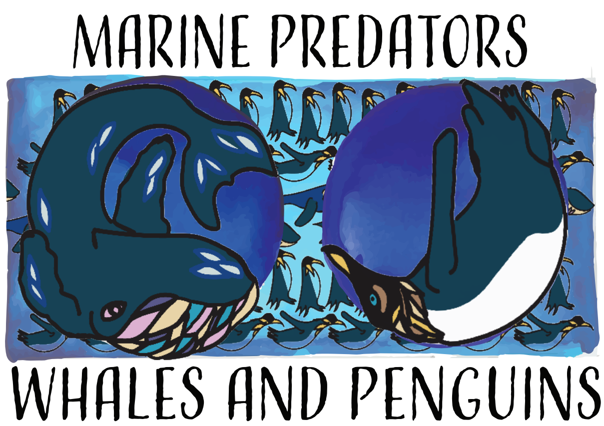
xxvi. The melting and retreat of glaciers and the collapse of ice shelves from increased oceanic and atmospheric temperatures are affecting coastal ecosystems.

xxvii. Globally-generated pollutants, including micro-plastics, are increasingly detected in the environment and in biota of the Southern Ocean, and local effects of pollution are altering environments adjacent to stations.

Biological changes and vulnerabilities

xxviii. Sea ice supports year-round productivity, and habitat for feeding, breeding and refuge for many species.

xxix. Coastal and shelf systems of the Southern Ocean in waters shallower than 2000 m are among the most productive ecosystems in the global ocean and drive production locally and downstream.



xxx. Primary production by phytoplankton and carbon export to deeper water around Antarctica are changing, but the drivers are complex and trajectories of change are uncertain.

xxxi. Warming will alter seasonal patterns (phenology) in production and the relative abundances of different types of phytoplankton (particularly diatom vs. non-diatom) with consequent effects to food webs and to climate.

xxxii. Individual sensitivities of benthic and pelagic species to individual drivers of change in habitat conditions are determined by their shape and size, ability to regulate their physiology, and ability to move away from inhospitable conditions.

xxxiii. Reduced dominance of Antarctic krill may arise in the Atlantic sector of the Southern Ocean due to sea ice and diatom loss, and warming, thereby impacting higher trophic levels and the energetic efficiency of the ecosystem.

xxxiv. Regional reductions in sea ice and increasing ocean temperatures are causing the Antarctic (polar) ecosystem to contract towards Antarctica, increasing the potential for more northern species to move southward; the interacting effects on polar species of changes in multiple environmental drivers make the consequences for lower trophic levels difficult to predict.

xxxv. Birds and marine mammals dependent on sea ice for breeding and resting will be negatively impacted by declining sea ice cover. Conversely, those that do not depend on sea ice may benefit from reduced sea ice, although this will depend on whether or not their prey are also affected by sea ice loss.

xxxvi. Species in shore-based colonies will be impacted by shifting prey distributions, particularly for subantarctic predators, and by changing on-shore environmental conditions at their colonies.

xxxvii. Foraging success of migratory birds and marine mammals may be disrupted should there be a change in timing of productivity in the ocean-ice systems.

xxxviii. Pollution and pathogens are emerging as factors impacting species in the Southern Ocean, including zooplankton, fish, marine mammals and birds.

xxxix. Benthic systems will be negatively impacted by warming, freshening and acidification of their habitats, and additionally by increased iceberg scour on the Antarctic continental shelf.

xl. Changes in Southern Ocean food webs are dependent on the energy pathways prevalent in any given area and the sensitivity of species (either as predators or as prey) to changes in other species impacted by environmental change.

THE ANTARCTIC AND SOUTHERN OCEAN

IS AN ECOSYSTEM OF GLOBAL SIGNFICANCE AS A HEAT AND CARBON SINK.

IT'S A PLACE THAT CAPTURES THE IMAGINATION OF
PEOPLE AROUND THE WORLD AS A MARINE ECOSYSTEM OF WONDER

... AND AS FERTILE GROUNDS FOR FISHERIES AND TOURISM

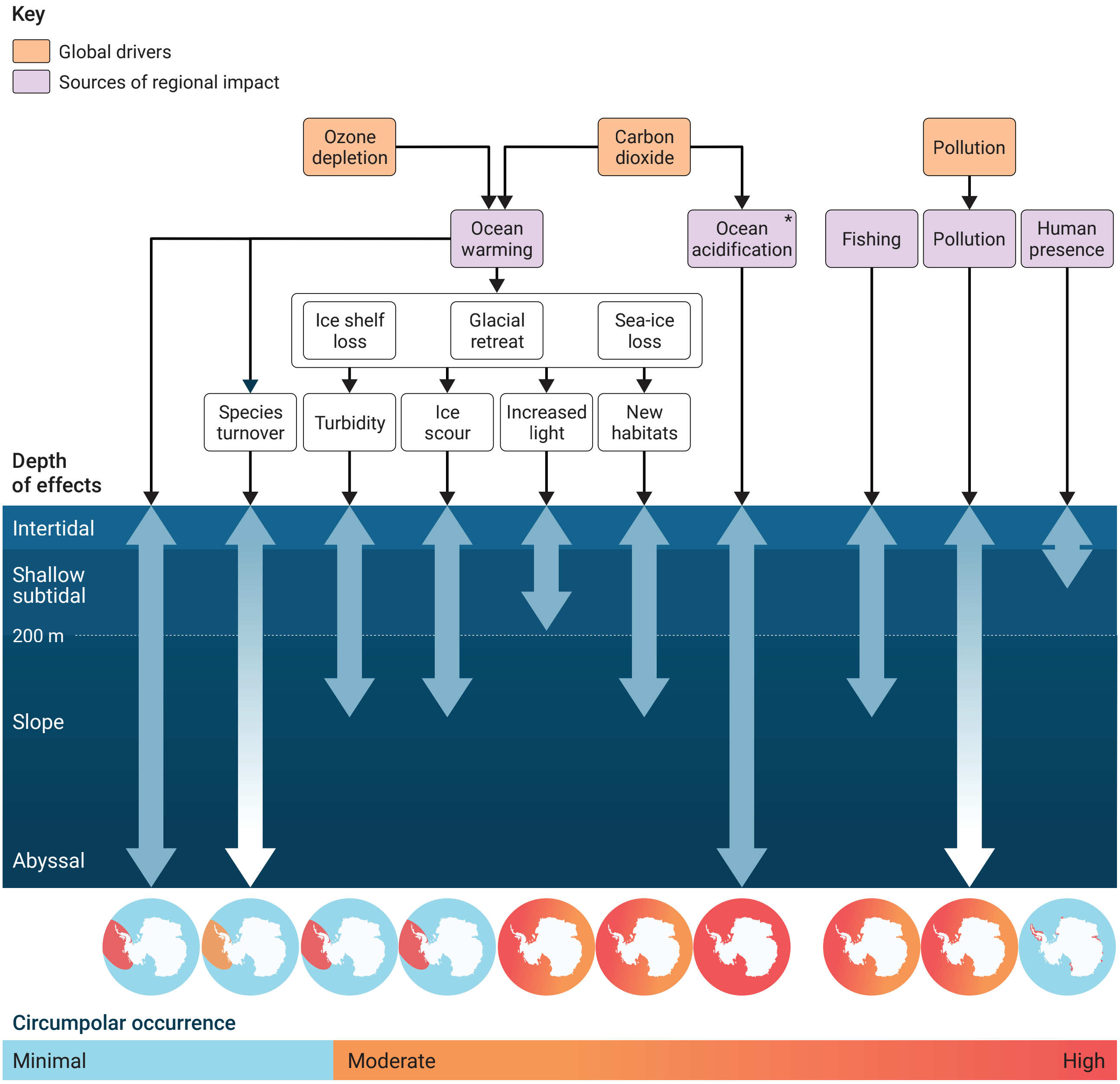


Figure 1: Where Southern Ocean ecosystems are experiencing underlying changes that may impact the system overall. Lighter shading of arrows indicates effects/drivers for which there is an expectation that these have occurred at deeper depths of the Southern Ocean, but there are no direct observations currently available.

*The Southern Ocean is particularly vulnerable to ocean acidification because of the effect of temperature on carbonate chemistry. Ocean acidification is affecting ecosystems at all depths, but organisms at deeper depths are particularly vulnerable because of the effects of both temperature and pressure on the dissolution of calcium carbonate.

Figure credit: Huw Griffiths, British Antarctic Survey

Glossary of specialised terms

The following explanations of terms are to help the reader understand the intended meaning in this document. Fuller technical definitions can be obtained in the MEASO papers.

ACC

Antarctic Circumpolar Current is the part of the Southern Ocean that flows uninterrupted from west to east around Antarctica and is mostly captured in the Subantarctic and Northern MEASO Zones (Box 1).

Antarctic Polar Front

This ocean front (a boundary between two distinct water masses) has been used as the northern boundary of the Convention for the Conservation of Antarctic Marine Living Resources. Formerly named the 'Antarctic Convergence', it was thought to be a biological boundary for Antarctic ecosystems.

ATCM

Antarctic Treaty Consultative Meeting

ATS

Antarctic Treaty System

Benthic

Relating to the lowest levels of the sea, including living on, in or in the vicinity of the seafloor.

Benthos

Species living on, in, or associated with the seafloor.

Biodiversity

The variety of genotypes, species and ecosystems within an area.

Biogeochemistry

The cycling of chemical elements through living systems and their environments by physical, chemical, biological and geological processes; a fundamental component of the functioning of Planet Earth.

Biota

All living organisms

Birds

When used alone, this term refers to flying birds and penguins.

CBD

Convention on Biological Diversity

CCAMLR

Commission for the Conservation of Antarctic Marine Living Resources

CEP

Committee on Environmental Protection

Cetaceans

This group of marine mammals is divided into two main groups – baleen whales (Mysticetes) and toothed whales (Odontocetes). The latter includes sperm whales, orca, dolphins and porpoises, all of which occur in the Southern Ocean.

CMIP

Coupled Model Intercomparison Project

CMIP (WCRP) models

Coupled Model Intercomparison Project of the World Climate Research Program - models that encompass physical and chemical processes aiming to resemble the global system over time.

Confidence

The robustness of a finding, which comes from a combination of the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgement) and on the degree of agreement across multiple lines of evidence.

Coupled ecosystem models

Biological models coupled to Earth System models. True coupling is when the dynamics within each model influence the dynamics of the other models at appropriate temporal and spatial scales of interaction and feedbacks.

Cryosphere

That part of the Earth system dominated by ice. For the Southern Ocean, this includes continental ice extending into the ocean, such as glacier tongues and ice shelves, and sea ice, which comprises fast ice attached to the coast and the marginal ice zone subject to the influence of wind and currents.

Driver

A factor potentially causing positive or negative change in the physiology, distribution and/or abundance of a species, which could be specific to a life-stage.

Earth System

All the interacting physical, chemical, biological and geological processes on the planet. It encompasses all the land, oceans, atmosphere and ice in polar and high mountain regions. The term Earth System also now includes human society.

Earth System model

Earth System models seek to simulate all relevant aspects of the Earth System and include physical, chemical and lower trophic level (phytoplankton and some zooplankton) biological processes. Global climate models, the predecessors to Earth System models, only included physical processes.

Ecosystem

The living and non-living components of a natural system and the combination of physical, chemical and biological interactions.

End-to-end models

Typically whole-of-ecosystem models including physical, chemical and biological components and processes.

EOVs

Essential Ocean Variables as defined by the Global Ocean Observing System are a set of ocean variables that describe and define the physics of the ocean system, the biogeochemistry, the biology and ecosystems.

EVs

Essential Variables critical for observing and monitoring a given facet of the Earth System (many professional groups have supported the identification and standardisation of essential variables for physics, chemistry, biology and geology).

FAIR data principles

Principles by which data should be Findable, Accessible, Interoperable and Reusable.

Food web

The combinations of interacting species through which energy flows from primary producers to top predators.

GOOS

Global Ocean Observing System

Habitat

Biological or physical environment in which organisms live.

Impact

Positive or negative change arising from a driver.

ICED

Integrating Climate and Ecosystem Dynamics in the Southern Ocean, an IMBeR regional program

IPBES

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC

Intergovernmental Panel on Climate Change

Macronutrients

Nutrients that are generally present in relatively high concentrations and can be taken up by primary producers, including nitrogen, phosphorous and silicon.

Marine mammals

When used alone, this term refers to all cetaceans, true seals, sea lions and fur seals.

MEASO Areas

Areas derived from the combination of Sectors and Zones, within which the dynamics of sea ice, ocean and benthic habitats together remain similar from east to west.

Micronutrients

Nutrients that are generally present in relatively low concentrations, but are important for biological processes, such as iron.

Mixed layer

The surface stratum of the ocean, which is well-mixed and separated from deeper water because of higher temperature and/or decreased salinity.

Nekton

Organisms freely living in the water column that can actively move against currents; they are larger than most plankton, ranging in size from small fish and krill to whales.

Ocean acidification / saturation horizon

Acidity is related to the concentration of carbon dioxide in the water; higher carbon dioxide can result in more acidic waters and under-saturation of calcium carbonate. Calcium carbonate is generally in excess (saturated concentration) in surface ocean waters; the depth at which calcium carbonate becomes undersaturated is the saturation horizon.

Phenology

Timing of biological processes, often related to the seasonal cycle of changes in physical and chemical environments.

Phytoplankton

Species living in the surface of the ocean that use photosynthesis to fix carbon, making energy available to zooplankton and, therefore, food webs.

Pinniped

Fin-footed marine mammals; in the Antarctic these include fur seals and earless (true) seals.

POPs

Persistent organic pollutants: organic pollutants travelling to the Antarctic and remaining in the environment for prolonged periods.

Primary Production

The process in species by which the energy in light is converted to usable energy, based on carbon, by living organisms.

Region

Often used in reference to the Southern Ocean as a whole. It may also be used to reference areas at the scale of seas, or large parts of the Antarctic coast, which equates to spatial areas at the scale of MEASO Sectors (Figure 4). The term 'subregion' may be used in reference to areas equivalent in size to MEASO Areas.

Risk

The degree to which a species or other ecosystem component is exposed and vulnerable to a driver or drivers.

SC-CAMLR

Scientific Committee for the Conservation of Antarctic Marine Living Resources

SCAR

Scientific Committee on Antarctic Research

SCOR

Scientific Committee on Oceanic Research

Sectors

MEASO Sectors are differentiated by a combination of the nature of the Antarctic coast and shelf, extent of sea ice from the coast, and large bathymetric features such as island chains, plateaus and ridges. The five sectors are Atlantic, Central Indian, East Indian, West Pacific, and East Pacific (see Figure 4).

Sedentary

Species or life stages of species that are unable to move far.

Sessile

Species or life stages of species that are fixed to the seafloor.

SOOS

Southern Ocean Observing System

Trophic

Referring to the relationships in a food web. Trophic structure is the overall feeding relationships between all species or functional groups in a food web. Trophic level refers to levels in a food chain. Primary producers (algae/phytoplankton) are at Trophic level 1, phytoplankton consumers (grazers) are at Trophic level 2, and so on.

Uncertainty

A state of incomplete knowledge represented by quantitative measures (e.g., statistical functions reflecting imprecision, accuracy or range of alternative values) or by qualitative statements (e.g., judgment of a team of experts on the importance of different theories). It does not reflect that the phenomenon in question is not important.

Vulnerability

The degree to which a species is vulnerable to a driver, such as ocean warming.

Water column / pelagic

All parts of the ocean from just above the seafloor (the benthic environment) to the surface.

WCRP

World Climate Research Programme

Zones

MEASO Zones are bounded by fronts and the Antarctic coast. The zones are Antarctic (south of the Southern ACC Front), Subantarctic (from the Subantarctic Front in the north to the Southern ACC Front in the south) and Northern (north of the Subantarctic Front to the Subtropical Front but no further north than 40°S)(see Figure 4).

Snapshot of MEASO organisation and activities

MEASO is the first circumpolar interdisciplinary assessment of Southern Ocean ecosystem status and trends, beginning its activities in 2018. It is a core activity of Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED), which is a regional program of Integrated Marine Biosphere Research (IMBeR, which is a joint program of the Scientific Committee on Oceanic Research [SCOR] and Future Earth), and co-sponsored by the Scientific Committee on Antarctic Research (SCAR). MEASO is also supported by the Southern Ocean Observing System (SOOS), a joint program of SCAR and SCOR.

Key Features

- A spatially-structured circumpolar ecosystem assessment.
- A five-year inclusive international program, modelled on a working group of the Intergovernmental Panel on Climate Change, providing a forward-looking assessment of status and trends in Southern Ocean ecosystems. It involved 203 scientists from across the Antarctic and Southern Ocean scientific community (19 countries, 51% female, 30% early career), contributing to 24 research articles published in a special research topic in Frontiers journals (at time of this publication, greater than 214,000 views, 37,000 downloads).

Outputs and events

2018 International Conference on the Marine Ecosystem Assessment for the Southern Ocean, including a one-day Policy Forum, Hobart, Australia.

2019 Workshop on progressing the first MEASO, Woking, UK.

2019-23 Delivery of the Marine Ecosystem Assessment research topic published in Frontiers; Contributions to Intergovernmental Panel on Climate Change: Special Report on Oceans and Cryosphere in a Changing Climate (Ch 3: Polar Regions), Working Group II (Ch 3: Oceans and Coastal Ecosystems and their Services; Cross-Chapter Paper 6: Polar Regions).

2021 UN Framework Convention on Climate Change, Conference of Parties 26 (UK) - Cryosphere Pavilion Polar Oceans Day: "Antarctic marine ecosystems under pressure: protection needs action locally and globally".

2022 UN Framework Convention on Climate Change, Conference of Parties 27 (Egypt) - Cryosphere Pavilion Polar Oceans Day: "Southern Ocean ecosystems: need for augmented understanding, research efforts and protection"; Presentations to SCAR Open Science Conference and to the Challenger 150 Symposium, among others.

2023 Presentations to the SCAR Biology Symposium, SOOS Symposium and the CCAMLR Workshop on Climate Change. Contributions to SOOS Workshop on essential variables and SOOS plenary on future needs in Southern Ocean science.

Publications

Research Topic in Frontiers with participating journals: Frontiers in Ecology and Evolution (Conservation & Restoration Ecology), Frontiers in Environmental Science (Conservation & Restoration Ecology), and Frontiers in Marine Science (Global Change and the Future Ocean). The research topic can be accessed at:

https://www.frontiersin.org/research-topics/10606/marine-ecosystem-assessment-for-the-southern-ocean-meeting-the-challenge-for-conserving-earth-ecosys#overview

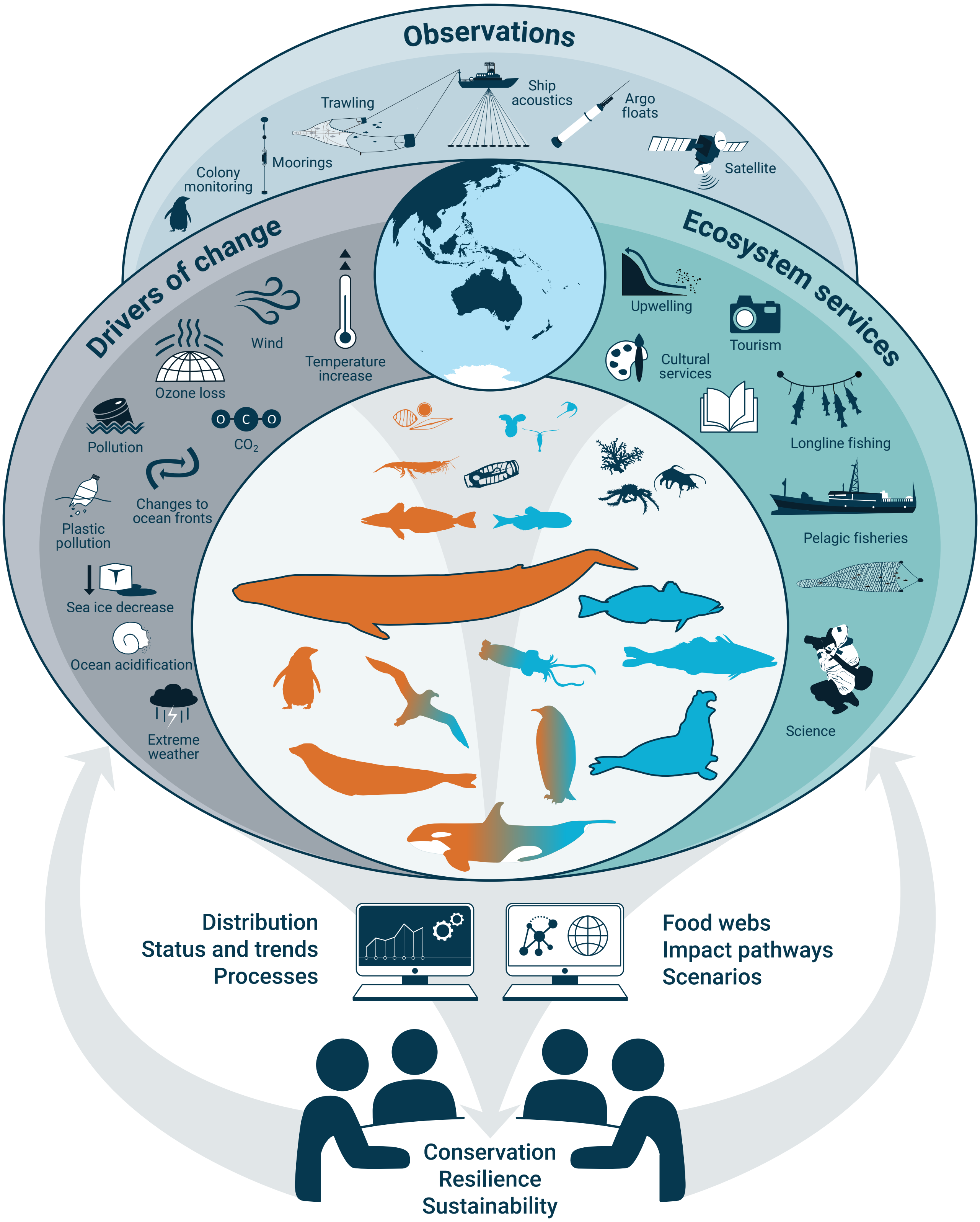


Figure 2: Scope of the MEASO assessment. MEASO provides a first assessment of status and trends for habitats (drivers of habitat change shown as icons on the left), species and food webs (central icons with colours denoting the two main pathways of energy flow through krill in orange and through fish in blue; species icons with both colours are part of both pathways; icons with solid outlines show species recovering from past exploitation, including blue whales, groundfish and elephant seals), and ecosystem services (icons on the right). Example observation platforms delivering data to underpin assessments are shown at the top. The assessment and modelling process is shown at the bottom, which in turn informs decision-making for conservation, resilience and sustainability. The decisions impact on the trajectories of drivers and the ecosystem (arrows looping back up to the central ellipse).

MEASO Authors

A.J. Constable[c,s,e,l,a (7,9,10,25)], J. Melbourne-Thomas[c,s,e (13,25)], M.M.C. Muelbert[c,s,l,p (33,34)], A.B. Hollowed[s,e (108)], J.A. Caccavo[s,l,p (48,51,52)], S.F. Henley[s,l,p (83)], J. Höfer[s,l,p (41,38,39)], N.M. Johnston[s,l,p (80)], E.J. Murphy[s,l,p (80)], A.P. van de Putte[s,l,p (29,30,28)], H.J. Griffiths[s,p (80)], J. Gutt[s,p (51)], Y. Ropert-Coudert[s,p (45)], I.R. Schloss[s,p (4,1,6)], D.P. Costa[s (100)], E.E. Hofmann[s (93)], L. Newman[s (20)], A. Piñones[s (38)], M.J. Brasier[s′,l,a,p (13,25)], S. McCormack[s′,l,p (25)], C.K. Weldrick[s′ (10,25)], S.A. Morley[l,p (80)], M.H. Pinkerton[l,p (63)], S. Bestley[l (13,25)], R.D. Cavanagh[l (80)], S.M. Grant[l (80)], K.M. Swadling[l (10,25)], K. Baldry[a (25)], A.-S. Bonnet-Lebrun[a (45,47)], B. Figuerola[a (78)], H.M. Kauko[a (69)], A.J. Press[a (10,25)], L. Roberts[a (18,26)], S. Sergi[a (48)], J. Solomonsz[a (19)], V. Warwick-Evans[a (80)], D.K.A. Barnes[p (80)], H. Christiansen[p (28)], A.B. Christianson[p (97)], S. Davie[p] (87), R. Downie[p (87)], S. Fielding[p (80)], L. Ghigliotti[p (57)], G. Griffith[p (69,94)], S.L. Hill[p (80)], P.N. Trathan[p (80,82)], R. Trebilco[p (13,25)], C.L. Waller[p (86)], D. Abele[(51)], M. Ardyna[(50,96)], A.A. Atkinson[(83)], A. Baudena[(48,50)], N. Bax[(25)], S. Bengtson-Nash[(17)], T. Benson[(66,23)], T. Berge[(68)], S. Blain[(50,96)], M.D. Borup[(25)], A.R. Bowie[(25)], P.W. Boyd[(25)], A. Brandt[(55)], G. Bratbak[(70)], P. Bricher[(20)], C.M. Brooks[(101)], C.A. Cárdenas[(40)], E.L. Cavan[(81)], M. Chierici[(67)], S.P. Corney[(25)], C.S. Cotté[(48)], M. Cox[(9)], V.J. Cummings[(63)], F. d'Ovidio[(48)], L. Dalla Rosa[(34)], K.L. Daly[(106)], C.S. de Oliveira[(44)], L. de Steur[(69)], S. Deppeler[(63)], T. Desvignes[(104)], M. Dewar[(14,15)], T. Dornan[(80)], M.C. Double[(9)], R. Downey[(8)], R. Driscoll[(51)], J.A. Ericson[(62)], T. Falkenhaug[(68)], S.E. Fawcett[(76)], V.V. Filgueira[(2)], D. Fiore[(3)], P. Fletcher[(24)], H. Flores[(51)], R. Flynn[(76)], A. Fransson[(69)], A.D. Fraser[(10)], C.I. Fraser[(65)], A.S. Friedlander[(100)], L. Goldsworthy[(25)], A. Granata[(59)], L. Guglielmo[(58)], S. Halfter[(25)], E.H. Hallfredsson[(67)], A.M. Hancock[(25,20)], T. Hatterman[(69)], A. Hayward[(63,65)], N. Hellessey[(25)], N. Henschke[(37)], N.A. Hill[(25)], C. Hoover[(35)], K.A. Hughes[(80)], B.P.V. Hunt[(37,36)], J.A. Jackson[(80)], E. Johnson[(26)], C.D. Jones[(95,88)], S. Kawaguchi[(9)], F. Kennedy[(25)], R. Kerr[(34)], R. Kiko[(53)], P. Koubbi[(49,50)], C. Kutay[(12)], S. Labrousse[(110)], D.J. Lindsay[(60)], C. Liszka[(80)], S. Lockhart[(89)], V. Loeb[(91)], A.D. Lowther[(69)], R. Makabe[(61)], C. Manno[(80)], T.I. Marina[(1)], T. Marshall[(76)], A. Martin[(66)], S.M. Martin[(79,80)], R.A. Massom[(9,10)], C.R. McMahon[(25,21)], A. McMinn[(25)], M. Meredith[(80)], B. Meyer[(51,56,54)], C. Moffat[(102)], T. Monteiro [(34)], S. Moreau[(69)], M. Moteki[(61)], E.A. Pakhomov[(37,36)], I. Peeken[(51)], K. Petrou[(26)], R.A. Phillips[(80)], P. Pistorius[(5)], E. Plagányi[(13,25)], A.L. Post[(16)], P. Provost[(27)], P.S. Puskic[(25)], M. Rapheal[(99)], B. Raymond[(9,25)], P. Reid[(10)], J. Reimer[(107)], A.O.d.A. Reis[(31)], R.R. Reisinger[(100)], C.S. Reiss[(95,88)], K. Richerson[(92)], K. Ryan[(66)], T. Ryan-Keogh[(74)], H. Saeedi[(55)], C.J. Sands[(80)], M. Santos[(4)], L.A. Saravia[(1,5)], R.A. Saunders[(80)], E. Secchi[(34)], E. Seyboth[(34,76)], R.M. Sherrell[(98)], M. Silk[(26)], A. Singh[(74,75)], J. Smith[(16)], S. Smith[(76)], W.O. Smith Jr[(109,43)], S.E. Stammerjohn[(101)], J.S. Stark[(9)], D.K. Steinberg[(109)], A. Strobel[(51)], P. Strutton[(25,11)], R.C. Subramaniam[(13,25,21)], C.C. Suckling[(105)], M. Sumner[(9)], M. Sweetlove[(29)], S. Taberner[(18,22)], G.A. Tarling[(80)], E. Tarszisz[(21)], S.E. Thorpe[(80)], P. Tixier[(14)], T. Tsagaraki[(70)], V.J.D. Tulloch[(17)], M. Vacchi[(57)], I. van Putten[(13)], D. Veytia[(25)], P. Virtue[(9,13,25)], J. Wallis[(25)], A. Walters[(25)], C.M. Waluda[(80)], P. Ward[(80)], M. Wege[(64)], B. Wienecke[(9)], P. Wongpan[(10,25)], B.L. Woods[(25)], S.J. Wotherspoon[(9)], J.C. Xavier[(71,80)], G. Yang[(42)], Q. Zhou[(67)]

[c] Co-convenor, [s] Steering Committee, [s′] Research support, [e] Research topic editor, [l] Lead author of core assessment, [a] Lead author on contributed paper, [p] Planning at Woking Workshop, UK

[(x)] Numbers in parentheses are affiliations as on the following pages

Affiliations

Institutions are organised by country. Numbers are used to assign affiliations to MEASO authors.

Argentina

[1] Centro Austral de Investigaciones Científicas

[2] Comunidad Indigena Yagan Paiakoala de Tierra del Fuego

[3] Conicet & Asociacion de Investigaciones Antropologicas & UBA

[4] Instituto Antártico Argentino

[5] Universidad Nacional de General Sarmiento

[6] Universidad Nacional de Tierra del Fuego

Australia

[7] Antarctic Climate and Ecosystems Cooperative Research Centre

[8] Australia National University

[9] Australian Antarctic Division

[10] Australian Antarctic Program Partnership

[11] Australian Research Council Centre of Excellence for Climate Extremes

[12] Charles Darwin University

[13] CSIRO Environment

[14] Deakin University

[15] Federation University

[16] Geoscience Australia

[17] Griffith University

[18] Living Data

[19] Monash University

[20] Southern Ocean Observing System

[21] Sydney Institute of Marine Science

[22] The Spooky Men's Chorale

[23] University of Canberra

[24] University of Melbourne

[25] University of Tasmania

[26] University of Technology Sydney

Belgium

[27] Intergovernmental Oceanographic Commission of UNESCO

[28] KU Leuven

[29] Royal Belgian Institute of Natural Sciences

[30] Université Libre de Bruxelles

Brazil

[31] Universidade do Estado do Rio de Janeiro

[32] Universidade Estadual do Rio Grande do Sul

[33] Universidade Federal de São Paulo

[34] Universidade Federal do Rio Grande

Canada

[35] Dalhousie University

[36] Hakai Institute

[37] University of British Columbia

Chile

[38] Centro FONDAP de Investigación Dinámica de Ecosistemas Marinos de Altas Latitudes

[39] Fundación San Ignacio del Huinay

[40] Instituto Antártico Chileno

[41] Pontificia Universidad Católica de Valparaíso

China

[42] Chinese Academy of Sciences Qindao

[43] Shanghai Jiao Tong University

Finland

[44] University of Eastern Finland

France

[45] Centre d'Etudes Biologiques de Chizé

[46] Institute Pierre-Simon Laplace

[47] La Rochelle Université

[48] Laboratoire d'océanographie et du climat expérimentations et approches numériques

[49] Muséum national d'Histoire naturelle

[50] Sorbonne Université

Germany

[51] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research

[52] Berlin Center for Genomics in Biodiversity

[53] GEOMAR Helmholtz Centre for Ocean Research

[54] Helmholtz Institute for Functional Marine Biodiversity

[55] Senckenberg Research Instutite and Natural History Museum

[56] University of Oldenburg

Italy

[57] Italian National Research Council

[58] Stazione Zoologica Anton Dohrn

[59] University of Messina

Japan

[60] Japan Agency for Marine-Earth Science and Technology

[61] National Institute of Polar Research

New Zealand

[62] Cawthron Institute

[63] National Institute of Water and Atmospheric Research

[64] University of Canterbury

[65] University of Otago

[66] Victoria University of Wellington

Norway

[67] Fram Centre

[68] Institute of Marine Research, Flødevigen

[69] Norwegian Polar Institute

[70] University of Bergen

Portugal

[71] Universidade de Coimbra

South Africa

[72] Nelson Mandela University

[73] South African Government

[74] Southern Ocean Carbon and Climate Observatory

[75] Stellenbosch University

[76] University of Cape Town

[77] University of Pretoria

Spain

[78] Institut de Ciències del Mar

Tristan da Cunha

[79] Tristan da Cunha, Edinburgh of the Seven Seas

United Kingdom

[80] British Antarctic Survey

[81] Imperial College London

[82] National Oceanography Centre Southampton

[83] Plymouth Marine Laboratory

[84] University of Bristol

[85] University of Edinburgh

[86] University of Hull

[87] World Wildlife Fund

United States of America

[88] Antarctic Ecosystem Research Division, NOAA

[89] California Academy of Sciences

[90] Columbia University

[91] Moss Landing Marine Laboratories

[92] Northwest Fisheries Science Center, NOAA

[93] Old Dominion University

[94] Princeton University

[95] Southwest Fisheries Science Center, NOAA

[96] Stanford University

[97] The Pew Charitable Trusts

[98] The State University of New Jersey

[99] University of California Los Angeles

[100] University of California Santa Cruz

[101] University of Colorado Boulder

[102] University of Delaware

[103] University of Georgia

[104] University of Oregon

[105] University of Rhode Island

[106] University of South Florida

[107] University of Utah

[108] University of Washington

[109] William and Mary's Virginia Institute of Marine Science

[110] Woods Hole Oceanographic Institution

Purpose of this MEASO Summary for Policymakers

This Summary for Policymakers uses information and infographics from the research articles, updated with other more recent research articles, to provide the following information:

1. How Southern Ocean species and ecosystems are already being affected by climate change and what the future looks like;
2. Where to find fuller explanations in MEASO articles for statements made in this summary;
3. Policy-relevant advice on protecting and conserving these ecosystems and enhancing their resilience; and
4. Priorities and processes for scientific research to support the provision of policy-relevant advice into the future.

Figure 3: How to use this Summary for Policymakers.

The summary is divided into 6 main sections. Each section comprises a number of headline statements or conclusions that provide the narrative of the section. Where needed, each headline statement has supporting statements to provide further background. In cases where the statements have uncertainty, a confidence level is assigned – ranging from low to medium to high to very high. The source of a statement and background to the confidence level can be found in the citation indicated by the number, which relates to the reference in the References section. Infographics are provided in each section to promote a better understanding of the conclusions in the text.

Confidence level

•○○○ Low confidence
••○○ Medium confidence
•••○ High confidence
•••• Very high confidence

01

Importance and background of MEASO

1.1

Southern Ocean ecosystems are important in the Earth System••••[74]

1.1.1

The Southern Ocean (south of 30°S) has a disproportionately large role in global excess heat uptake (75% in CMIP5 models)•••○[33, 65], and total oceanic uptake of CO_2 emissions (40%) produced over the industrial era•••○[42].

1.1.2

The biodiversity in the Southern Ocean is inextricably linked to the extreme seasonal cycle, and the unique polar environment, which has existed for millennia•••○[21, 23, 56].

1.1.3

Life in the Southern Ocean contributes significantly to global biodiversity•••○[50]; it is integral to the lives of many plants and animals in temperate and tropical waters because many birds and marine mammals move between the Southern Ocean and more northern areas, including the Arctic, and because there is exchange of life-rich water from south to north•••○[4, 42, 56, 74].

1.1.4

Life in the Southern Ocean affects us all [12,74], providing food•••○[35], having cultural significance•••○[94] and contributing to global nutrient and carbon cycles and Earth's climate•••○[42].

1.1.5

In many parts of the world, people have strong connections with Antarctica and the Southern Ocean and are concerned for the future of the region•••○[12, 74, 94].

1.2

The future of Southern Ocean ecosystems will be impacted by choices from peoples distant from the Southern Ocean••••[74].

1.2.1

The future of the Earth System depends on people [104], who are influenced by their material needs, their relationships between each other (in communities and societies, and within and between nations) and with their environment, their cultural needs and aspirations, and their dependencies on our living planet••••[1].

1.3

Advice on the state of, and change in, Southern Ocean ecosystems is needed to support the conservation of these systems[22], but such assessments can be challenging to undertake●●●●[8, 107].

1.3.1

States bordering the Southern Ocean, regional management bodies and global decision-making bodies need ecosystem assessments●●●○, including the Antarctic Treaty System (ATS, in which management bodies include the Antarctic Treaty Consultative Meeting [ATCM] and its Committee on Environmental Protection [CEP] and the Commission for the Conservation of Antarctic Marine Living Resources [CCAMLR])[48], the International Whaling Commission[34], the UN Convention on Biological Diversity (CBD)[14] and the UN Framework Convention on Climate Change[25].

1.3.2

Regional scientific assessments, such as from the Southern Ocean, inform global scientific assessments●●●○, such as the World Ocean Assessment[111], the Intergovernmental Panel on Climate Change[53], the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services[49] and the CBD Kunming-Montreal Global Biodiversity Framework[14].

1.3.3

Scientific challenges arise because of the difficulty in taking measurements across such a large region, which has extreme seasonality, variation in the environmental attributes among different sectors, with subregional differences in interannual variability and long-term change●●●●[5, 42, 68].

1.3.4

Responses to change by organisms living in the Southern Ocean are variable and uncertain[2, 4, 7, 11, 28, 56, 82, 105], with many ecological processes operating at different spatial scales●●●●[21, 23].

1.3.5

The ongoing recovery of Southern Ocean ecosystems from past impacts, particularly the exploitation of living marine resources[35], makes the provision of advice about future risks more difficult, notably on food webs[64], ecosystem services[12] and feedbacks to the Earth system●●●●[74].

1.3.6

An important challenge for all ecosystem assessments is to incorporate and portray findings from alternate sources of information, in original languages, and to facilitate use of the results of the assessments more broadly, which could include identifying local actors in different communities and countries who can amplify and incorporate the findings into local reality and culture●●●●[1, 53, 70].

1.4

Despite these challenges, sufficient evidence is available to establish that Southern Ocean ecosystems are at risk from climate change and ocean acidification●●●○[17, 65].

1.4.1

Significant changes in habitats in the Southern Ocean are occurring because of atmospheric and oceanic change driven primarily by greenhouse gas emissions, resulting in increased temperature, sea ice change, acidification, heatwaves, glacier retreat and ice shelf collapse●●●○[42, 68, 89, 101].

1.4.2

The unique regional biodiversity and functioning of the ecosystem are being undermined by changes in habitats●●●○[4, 7, 11, 56, 82].

1.4.3

Recovery of whales, seals, and fish from historical over-exploitation and seabirds from incidental mortality in fisheries[35] may be hindered by the effects of climate change on the environments and populations of these species●●○○[4, 11, 80].

1.4.4

Loss of biodiversity and ecosystem function because of the effects of climate change may result in irrevocable change in parts of the Southern Ocean, where species are unable to recover or return to their usual areas●●●○[7, 11, 105].

1.4.5

Global action is needed to mitigate climate change and ocean acidification impacting Antarctica and the Southern Ocean●●●●[17].

1.4.6

Climate change remains to be addressed in the development of measures to manage activities potentially impacting marine ecosystems in the region●●●○[13, 15, 17, 22].

1.5

The *Marine Ecosystem Assessment for the Southern Ocean* (MEASO) was an open participatory, interdisciplinary and up-to-date assessment (2018 to 2023) of status and trends in Southern Ocean ecosystems and drivers of change, for use by policymakers, scientists and the wider public.

1.5.1

203 researchers from 19 countries united in this international and inclusive collaboration facilitated by involvement and leadership of early career researchers (30%)[(9)] and female researchers (51%).

1.5.2

How and why Southern Ocean ecosystems are changing or may change in the future are synthesised, extending previous initiatives in the IMBeR program Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) and the SCAR[(20, 21, 23, 37, 38, 73, 109)].

1.5.3

Since the initiating conference in 2018, 24 articles have been published as a Frontiers research topic[1] with participating journals: Frontiers in Ecology and Evolution (Conservation & Restoration Ecology), Frontiers in Environmental Science (Conservation & Restoration Ecology), and Frontiers in Marine Science (Global Change and the Future Ocean).

1.5.4

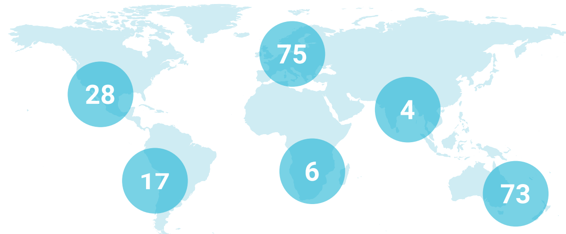
Each paper provides summaries to help guide decisions to protect and conserve this region.

[1] Marine Ecosystem Assessment for the Southern Ocean: Meeting the Challenge for Conserving Earth Ecosystems in the Long Term (https://www.frontiersin.org/research-topics/10606/marine-ecosystem-assessment-for-the-southern-ocean-meeting-the-challenge-for-conserving-earth-ecosys#overview)

Marine Ecosystem Assessment for the Southern Ocean

- Spatially structured ecosystem assessment
- 5-year international program of ~203 scientists providing a forward-looking assessment of trends in Southern Ocean ecosystems
- Key output of the IMBeR Program Integrating Climate and Ecosystem Dynamics of the Southern Ocean (ICED) and endorsed by SCAR
- 24 papers submitted with more than 200,000 views across all papers

Diversity in MEASO



Number of authors by continent

High level of Early Career Researcher involvement and leadership (30%)
51% of authors are female

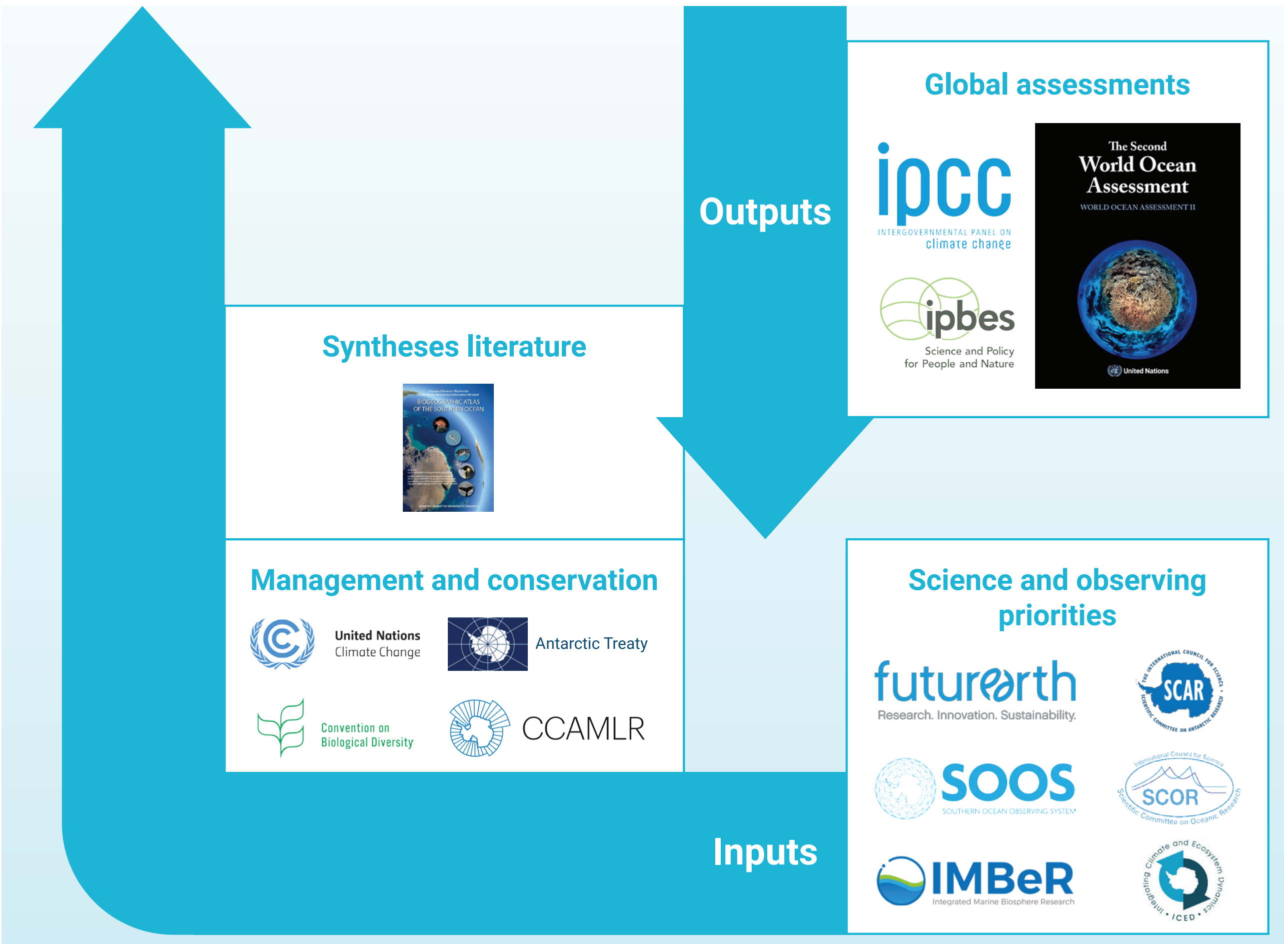


Figure 4: The context for MEASO: Data, Syntheses and scientific literature are used to assess status and trends in Southern Ocean ecosystems and to use these assessments to advise management and conservation agencies on their scientific needs, contribute to global assessments and to help identify priorities for science and observing systems.

Box 1

Dividing the Southern Ocean into meaningful Assessment Areas

B1.1

Terminology for classifying areas in the Southern Ocean is not consistently used in the literature and across disciplines. The term 'region' has been used to refer to the whole of the Southern Ocean in global assessments. However, within the Southern Ocean scientific community, the term usually applies to large areas within the Southern Ocean, either as a sea, e.g. Bellingshausen, Amundsen, Ross, Weddell, or with reference to the Antarctic coast, e.g. West Antarctic Peninsula, East Antarctica and so on. The term 'region' could equally apply to the spatial extent of the MEASO assessment areas, as these are of a similar scale.

B1.2

At its Woking workshop in 2019, MEASO participants agreed to establish areas for assessing how ecosystem attributes vary around Antarctica and the Southern Ocean and for assessing dynamics and change within those areas. MEASO areas were intended to reflect regions within which the dynamics of sea ice, ocean and benthic habitats combined remained similar across the region, from east to west. Connectivity arising from the large scale currents and gyres makes it difficult to define more-or-less isolated marine regions. While the MEASO areas are similar to areas designed for particular disciplines and for management of fisheries in CCAMLR, they do not match because of the intention in MEASO to reflect ecological and ecosystem properties (i.e., across many disciplines) within an area. For this reason, they are often larger than areas designed to coordinate field research activities across nations operating in a given area, such as those adopted by the Southern Ocean Observing System (https://www.soos.aq/activities/rwg).

B1.3

MEASO Areas are determined by a combination of 5 sectors and 3 zones (Figure 5).

B1.4

Sectors are differentiated by a combination of the nature of the Antarctic coast and shelf, extent of sea ice from the coast, and large bathymetric features such as island chains, plateaus and ridges. The five sectors are:

Atlantic **(code: AO):**
Covers the Scotia Arc and Weddell Sea, including the influence of the latter at the northern end of the Antarctic Peninsula (hence the boundary across Drake Passage) and most of the eastern margins of the Weddell Gyre, including Maud Rise. Winter sea ice extends far to the north in this region.

Central Indian **(CI):**
Covers the Kerguelen Plateau, Prydz Bay and its small gyre, the islands and banks to the west and the downstream area influenced by the plateau. Winter sea ice extends much further north in this region compared to parts of East Antarctica further to the east.

East Indian **(EI):**
Covers the eastern margins of East Antarctica through to the boundary of the Ross Sea (Cape Adare), including the Balleny Islands and the Macquarie Ridge. The continental shelf is narrow and the sea extent is closer to the continent than further west.

West Pacific **(WP):**
Covers the Ross Sea, gyre and the sea mounts to the north. Sea ice is more expansive in this area compared to further east and further west.

East Pacific **(EP):**
Covers the area noted for its much-reduced sea ice, including the Amundsen and Bellingshausen Seas and the west Antarctic Peninsula.

B1.5

Zones are bounded by fronts and the Antarctic coast. The zones are:

Antarctic **(A):**
Comprises the marine areas south of the Southern ACC Front, typically consisting of high latitude/polar biota and broadly encompassing the winter sea ice area.

Subantarctic **(S):**
Comprises the marine areas typically regarded as subantarctic due to the islands present in the regions and being north of the winter sea ice area, extending from the Subantarctic Front in the north to the Southern ACC Front in the south.

Northern **(N):**

Comprises the northern part of the Southern Ocean that has strong eddy fields and borders with the main ocean basins to the north. In these assessments it extends to the north of the Subantarctic Front to the Subtropical Front but no further north than 40°S.

A Temperate zone could be added in future to help assess differences between the Southern Ocean and adjacent areas to the north. It could be delineated between the Subtropical Front and a northern boundary, say, at 30ºS.

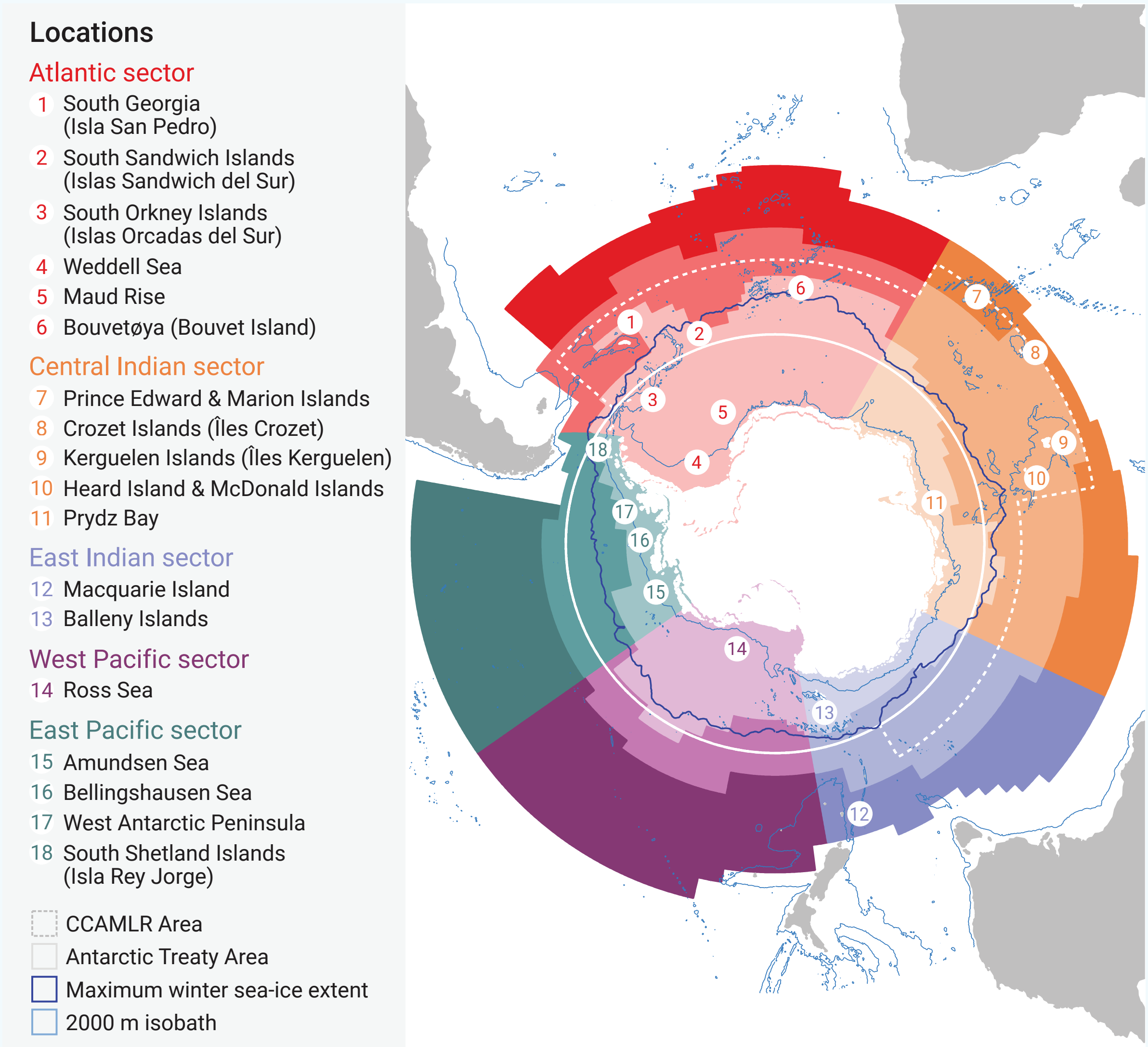


Figure 5: MEASO assessment areas.

Boundaries for the Marine Ecosystem Assessment for the Southern Ocean (MEASO) areas including five ocean sectors (Atlantic, Central Indian, East Indian, West Pacific, and East Pacific) each with three zone divisions. Sectors are divided meridionally. Zones extend from the coast to the Southern Antarctic Circumpolar Current Front (Antarctic Zone), to the Subantarctic Front (Subantarctic Zone) and to the Subtropical Front (Northern Zone). Islands are marked in white. Antarctica includes ice shelves, with the underlying coastline marked in brown. The Antarctic Treaty area is denoted by the solid white line and the extended area of the Convention on the Conservation of Antarctic Marine Living Resources is added with a dashed line, which approximately follows the Antarctic Polar Front. The 2,000 m isobath is shown in light blue. The approximate position of the average maximum winter sea ice extent is shown in dark blue. Numbers refer to locations often discussed in policy and science forums.

Adapted from McCormack et al., 2021

02

Changing habitats in the Southern Ocean

2.1

The Southern Ocean is warming, but to varying extents around Antarctica●●●○[68]

2.1.1

Warming sea water increases metabolic rates of organisms and rates of chemical processes●●●○[56, 69, 88].

2.1.2

Much of the Southern Ocean has seen stable temperatures or small increases during the last century●●○○[68], yet the West Antarctic Peninsula (WAP) has experienced warming of 2°C in the upper 150 m over the past 81 years●●●○[68].

2.1.3

Temperatures increase through the import of heat from outside the Southern Ocean and the movement and shallowing of these water masses from deep water onto the continental shelf●●●○[68].

2.2

Sea ice, a key habitat and defining feature of the Southern Ocean, is changing but in different ways around Antarctica●●●●[68, 105]; prognoses for sea ice change are amongst the greatest uncertainties on the future of marine ecosystems in the region●●●●[Box 2].

2.2.1

Sea ice is a major structuring feature of Antarctic ecosystems, regulating light, water column structure and nutrient availability, as well as providing physical refuge; changes to sea ice will affect everything from Antarctic microbes to whales●●●●[105].

2.2.2

Sea-ice extent has reduced in the East Pacific sector (West Antarctic Peninsula, Bellingshausen and Amundsen Seas, and the eastern margin of the Ross Sea) and increased in the West Pacific Sector (western Ross Sea) since the 1970s, driven by atmospheric ozone depletion and continued atmospheric and oceanic warming●●●○[68, 105].

2.2.3

Over the last eight years the extent of Antarctic sea ice each austral winter has varied greatly with some extreme low winter extents, and the lowest extent on record to date being winter in 2023●●●●[Box 2][30, 89].

2.2.4

The sea-ice system is threatened by warming and increased winds, combining to reduce the duration and extent of sea ice●●○○; the timing, magnitude and location of these impacts remain uncertain[105].

2.2.5

Broken sea ice in the marginal ice zone (the area with moving sea ice) will increase as a proportion of the sea ice system in warming and windy areas●●○○, forming complex habitats of a mixture of rafted (piled) sea ice and many smaller ice floes[105].

2.3

Surface mixing of the Southern Ocean is changing, which will change the dynamics of organisms in the sunlit surface layer●●●○[68].

2.3.1

Storminess and winds have increased in spring and summer●●●○[68].

2.3.2

Mixing of the water column brings nutrients to the surface, whilst increased stratification holds phytoplankton in the favourable well-lit surface environment for longer[see also 2.4]. Mixing is being altered in different parts of the Southern Ocean●●●○[2, 42, 68, 82] because: (a) warmer, fresher waters form a layer on the surface of the ocean inhibiting mixing, while (b) increased winds and storminess break this layer down and increase mixing.

2.4

The light environment in the Southern Ocean is changing due to changing sea ice and cloud cover●●●○[42, 82].

2.4.1

Ice regulates the amount of light that can penetrate the ocean and drive productivity and light-associated activities, including daily migrations of organisms[105].

2.4.1.1

Changing seasonal dynamics of sea ice will change the light environment in the surface of the ocean and in coastal habitats●●●○[68].

2.4.1.2

Loss of ice shelves and marine-terminating glaciers exposes new areas of ocean to the seasonal cycle of light and sea ice●●●○[68].

2.4.2

Cloud cover is expected to increase, thereby reducing total light available to the ocean●●○○[68, 105].

2.5

Availability of nutrients (iron, silicic acid, nitrate and phosphate) important to primary production is changing●●●○[42, 68].

2.5.1

Nutrient supply is dependent on local conditions bringing deep, nutrient-rich waters to the surface, and/or being near to, or downstream of, sources of iron, including resuspension from shallow sediments, release from sea ice, or indirect release from reservoirs associated with continental ice, and from dust blown from land masses around the Southern Ocean●●●●[42, 68].

2.5.2

Availability of nutrients can also be influenced by the degree to which organisms contribute to recycling nutrients through decomposition and waste●●●●[42].

2.5.3

Iron supply will increase in polar waters proximal to the Antarctic continent and in the lower latitudes of the Southern Ocean●●●○[42, 68].

2.5.4

Trace metal concentrations may be enhanced in coastal water from meltwater influx, but their wider distribution will be dependent on local shelf processes, rates of overturning, topography and the presence of ice shelves●●○○[42, 58].

2.5.5

The supply of the major nutrients nitrate, phosphate and silicic acid will be modified across the Southern Ocean by changes in mixing and stratification as well as biological activity●●●○[42].

2.5.6

Changes in nutrient concentrations in the subantarctic will influence the transport of Southern Ocean nutrients to the oceans north of 30°S, and may lead to declines in low-latitude productivity•••○[42].

2.6

Absorption of large amounts of atmospheric CO_2 by the Southern Ocean is causing ocean acidification[42, 68].

2.6.1

Changing carbon chemistry in the ocean is expected to have widespread impacts on primary production, biogeochemistry and ecosystem functioning in the coming decades••○○[42].

2.6.2

The Southern Ocean is particularly susceptible to ocean acidification because deep waters with high CO_2 concentrations upwell in this region, and absorption of CO_2 is greater in cooler waters••••[42].

2.6.3

Ocean acidification increases the solubility of carbonate minerals calcite and aragonite, which are important foundations of calcified skeletons and shells•••○[28, 56]; the ‘saturation horizons’ of these carbonate minerals, which are the depths below which calcite and aragonite dissolve readily (i.e., undersaturated water), are becoming shallower in the Southern Ocean•••○[42].

2.6.4

Aragonite undersaturation in surface waters has already been observed in a number of Southern Ocean regions and is expected to become more widespread and impact Southern Ocean ecosystem components and processes increasingly over the coming decades••○○[42].

2.7

The melting and retreat of glaciers and the collapse of ice shelves from increased oceanic and atmospheric temperatures are affecting coastal ecosystems••••[7, 68, 101].

2.7.1

Increased melting of glaciers adds freshwater and nutrients to nearby surface waters, which can facilitate increased local primary production••○○[101].

2.7.2

Particles released from melting glaciers and from erosion caused by meltwater streams on land can increase turbidity and reduce light in coastal waters, thereby reducing primary production•••○[59, 67]; the total impact of turbidity on primary production will be determined by the respective increase in nutrients due to melting. Particles can also potentially increase mortality of filter feeding zooplankton by clogging their feeding apparatus•••○[7].

2.7.3

New ice-free marine areas become open to colonisation by benthic and pelagic organisms••○○[7].

2.7.4

Iceberg scouring happens across the shelf, especially in shallow depths (less than 200 m). Its intensity is governed by calving rates from local glaciers and ice shelves in combination with factors influencing movement such as the duration of seasonal sea ice, local current patterns, and seafloor topography•••○[7].

2.8

Globally-generated pollutants, including micro-plastics, are increasingly detected in the environment and biota of the Southern Ocean, and local effects of pollution are altering environments adjacent to stations•••○[4, 11, 56, 68].

Drivers of change in Southern Ocean habitats and ecosystems

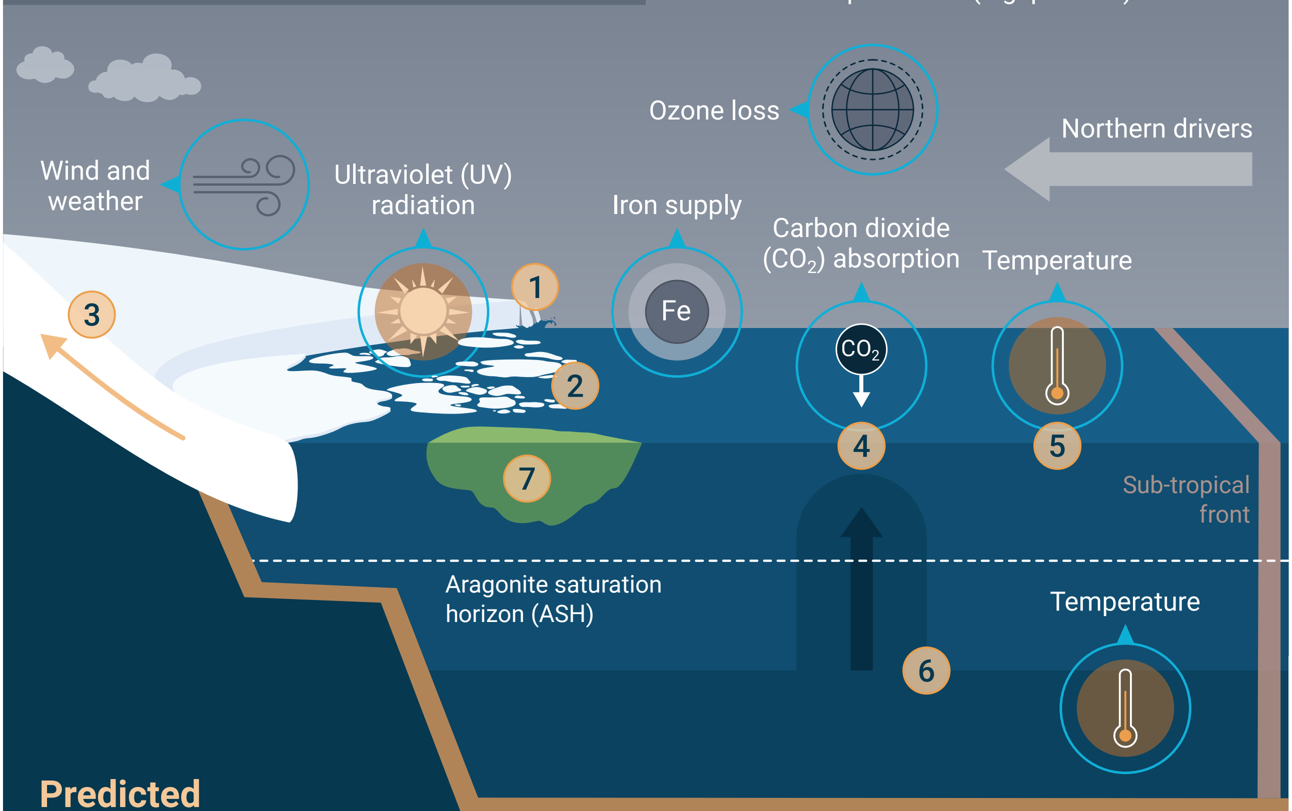
Global changes in the atmosphere and ocean are driving changes in Southern Ocean habitats and ecosystems.

Key drivers and their expected influences on the Southern Ocean are represented in the image below. The majority of these global drivers have an anthropogenic component, reflecting the reach of human activity.

Northern Drivers

There are further key drivers north of the sub-tropical front. These include:

- Variability in the Southern Annular Mode (wind strength)
- Species range shifts (e.g. invasive species)
- Persistent pollutants (e.g. plastics)



Predicted consequences

	Driver	Example impacts
1 Ice-shelf collapse	Temperature	Altered stability of the water column and mixed layer depth.
2 Sea-ice loss	Temperature	Increased vertical mixing and lower micronutrient supply.
3 Glacial retreat	Temperature	Changes to primary productivity, pelagic and benthic food webs.
4 Ocean acidification	CO_2	Altered ecosystem structure/function, carbon export, biogeochemical cycling and shallowing of the ASH.
5 Ocean warming	Temperature	Species migrations, altered ecosystem structure/function.
6 Shoaling of deep-water	Temperature	Altered stability of ice shelf/sheets and benthic habitats.
7 Changes to primary productivity	Fe, UV	Altered ecosystem structure/function and carbon uptake.

Figure 6: Global drivers of change in Southern Ocean habitats and ecosystems. Adapted from Morley et al., 2020

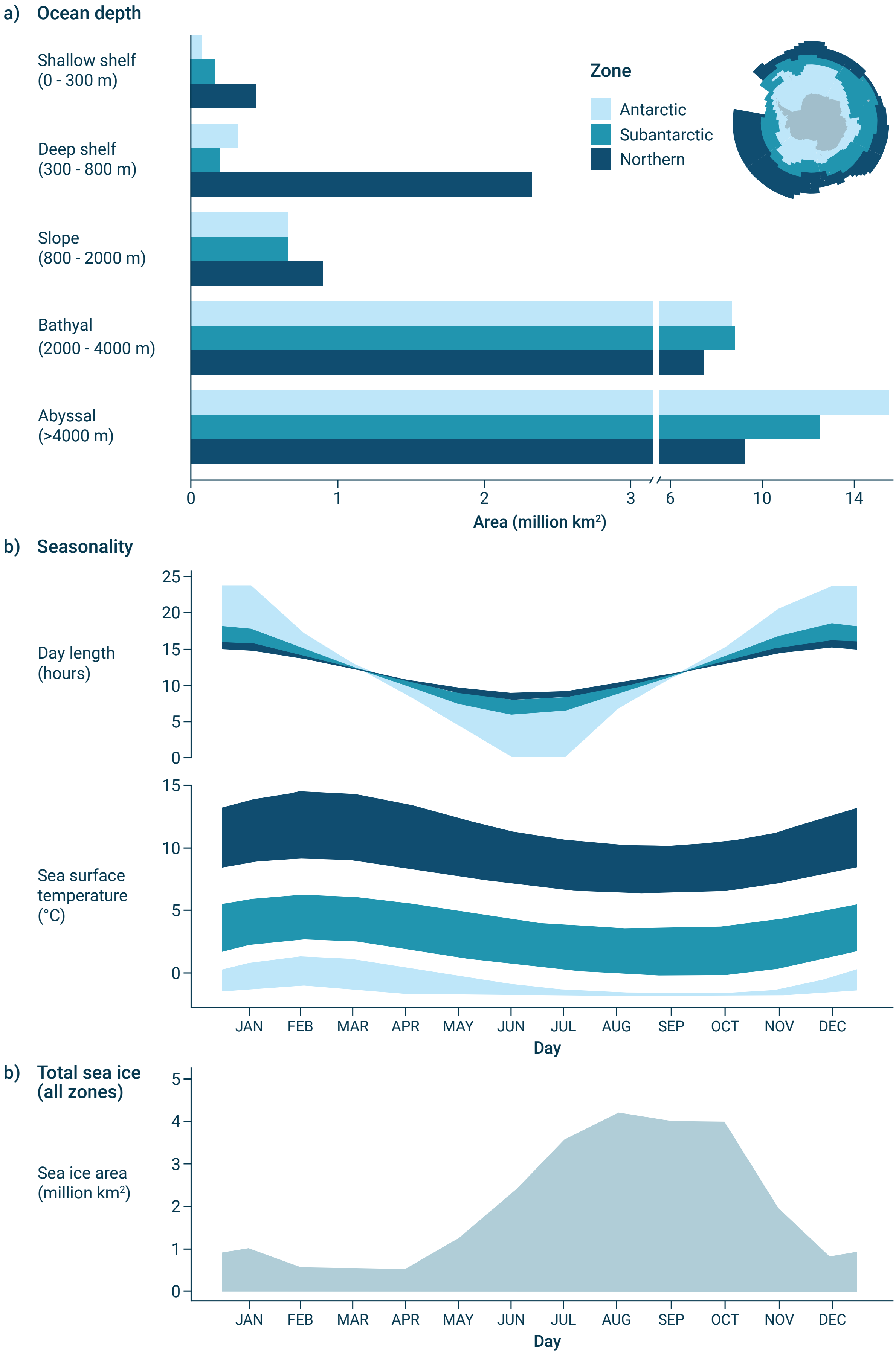


Figure 7: General attributes of MEASO zones. **(a)** Ocean depth: area (million km²) in different bathomes (depth range shown). **(b)** Seasonality: day length (hours) and sea surface temperature (°C)[method as footnote]. **(c)** sea-ice area (million km² of more than 90% concentration of sea ice)*.

*the region was divided into 25 km² grid. Average values over 2013-2022 were calculated for each month. For day length and sea surface temperature, the range shown was determined as the 20th and 80th percentiles from the zone cell means. Sea-ice area was the sum of the cell areas where percent cover was greater than or equal to 90%.

Box 2

Update from IPCC Working Group I and recent literature on sea ice change and scenarios for the future

B2.1

Morley et al (2020) and Henley et al (2020) reviewed the evidence of current and expected changes of habitats in the Southern Ocean as part of MEASO. Since that time, the Intergovernmental Panel on Climate Change (IPCC) has released its reports for the 6th Assessment Report (AR6)(51, 52, 54), providing more background to the conclusions in MEASO papers, along with more recent papers on some aspects of habitat change; for example, ocean warming, sea ice, ocean stratification, continental ice melt, iceberg calving and ice shelf collapse(29).

B2.2

A great uncertainty in the IPCC AR6 has been the current and future trajectories for sea ice in the Southern Ocean(29). Since the MEASO papers and the IPCC reports, recent events of extreme low sea-ice cover have led to suggestions that the observed increase in sea-ice extent since the late 1970s has suddenly transitioned to a decline(27, 89, 92). As yet there is no robust evidence that this is the case, but recent work indicates that the variability of summer sea ice has increased significantly (Hobbs et al., in review). There is still debate over drivers and change of sea ice over the last century(29, 76) but further modelling and analyses are showing that the inclusion of eddy systems in Southern Ocean dynamics(91) and ice sheet meltwater, primarily from under ice shelves and glacier tongues, enables Earth System models to better replicate the observed sea-ice coverage(90). This is improving confidence in understanding where, when and by how much sea ice will decline in the future. Given long-term trends in drivers of sea-ice, sea ice extent is expected to begin generally trending downward over the next 20 years(27).

B2.3

With respect to scenarios of future change, this summary for policymakers is written according to scenarios consistent with current commitments to reduce greenhouse gas emissions. While the IPCC reports were mostly based on commitments prior to 2021, "policies currently in place with no additional action are projected to result in global warming of 2.8 °C over the twenty-first century. Implementation of unconditional and conditional Nationally Determined Contribution scenarios reduce this to 2.6 °C and 2.4 °C respectively" (110)[p XVI, Figure ES.3]. These conclusions were based on projection scenarios used by IPCC Working Group III(60).

03

Biological changes and vulnerabilities

3.1

Sea ice supports year-round productivity and habitat for feeding, breeding, and refuge for many species●●●●[56, 82, 83, 105].

3.1.1

Shorter duration of the sea-ice season will result in less sea-ice algal production and can negatively affect the initiation of the spring bloom in the marginal ice zone●●○○[82, 83], although other drivers may make this more complicated in coastal areas.

3.1.2

Change in the structural complexity of sea-ice habitat may be more important than change in sea-ice extent for some species, such as krill; increased complexity of habitat may be a positive local benefit to these species as refuge or because of heightened production●●●○[105].

3.2

Coastal and shelf systems of the Southern Ocean in waters shallower than 2000 m are among the most productive ecosystems in the global ocean and drive production locally and downstream●●●○[42, 82, 99].

3.2.1

The Antarctic continental shelf, subantarctic islands, and plateaus, ridges, seamounts and banks, can be major sources of iron●●●●[42, 99].

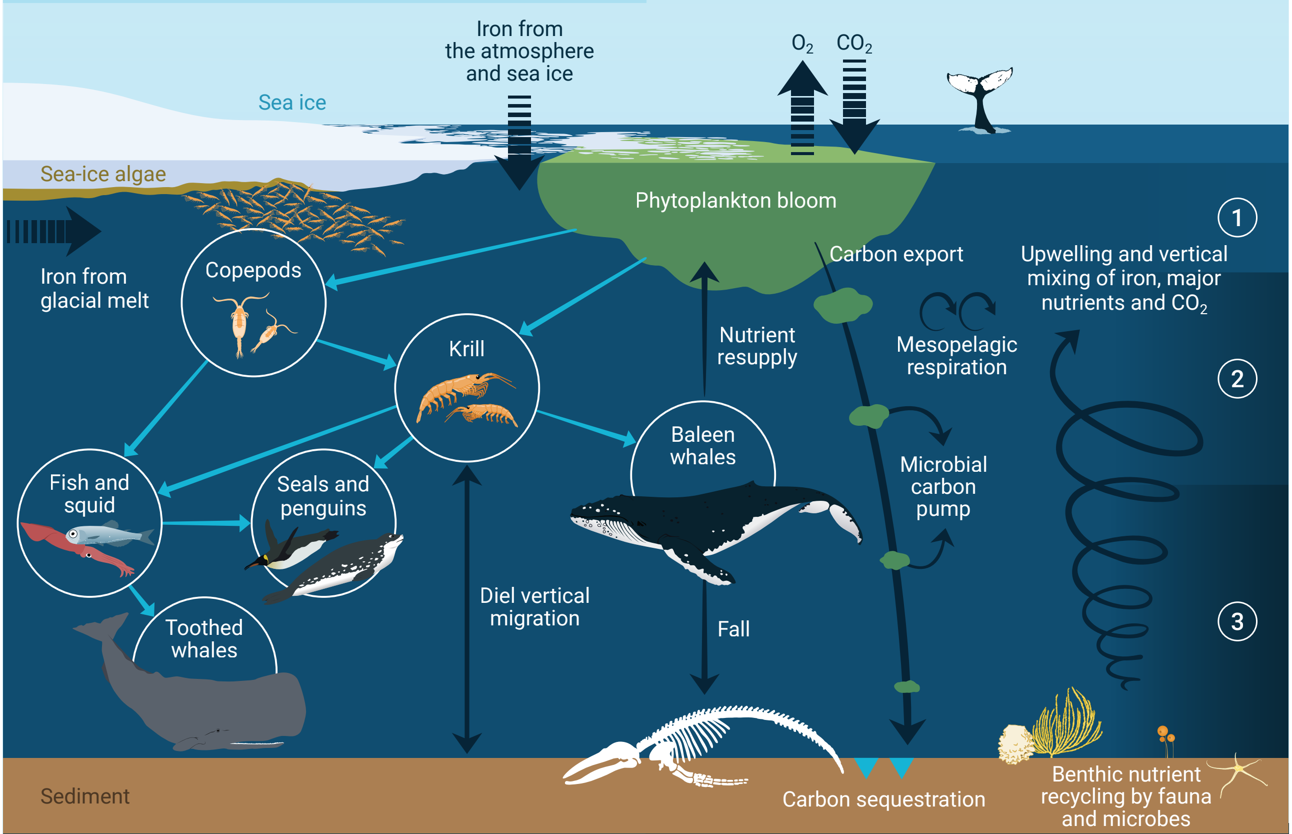
Biogeochemical cycling and the role of organisms

Marine organisms play a number of important roles in biogeochemical cycling of carbon and major and minor nutrients:

- Storage of carbon in their tissues and skeletons
- Recycling of nutrients through decay and remineralisation
- Transport of carbon to deeper waters where it can be stored and sequestered
- Carbon and nutrient cycling, storage and burial by Antarctic benthos

Key

- Energy flow
- Nutrient transport
- 1 Euphotic zone
- 2 Intermediate / mesopelagic
- 3 Deep waters



Benthic-pelagic coupling

Benthic-pelagic coupling describes the links and interactions between processes occurring in the water column and seafloor systems. This can include vertical transfer of carbon and nutrients via sinking material, animal movements and physical processes, as well as carbon and nutrient recycling by seafloor organisms, resupply to surface waters by upwelling and vertical mixing, and/or burial in sediments. Benthic-pelagic coupling is important because it maintains biogeochemical cycles on which marine organisms and food webs rely, and which are globally important for their role in nutrient supply to the global ocean, oceanic carbon uptake and climate regulation.

Future change

Carbon uptake and storage in food webs is important for regulating atmospheric CO_2 and could be altered substantially by potential ecosystem shifts related to warming, freshening, ice losses and acidification.

Observed and expected changes in primary production and ecosystem structure and functioning in response to ongoing and future changes in climate, sea ice and ocean chemistry (acidification) are likely to have a strong impact on benthic-pelagic coupling and biogeochemical cycling over timescales of years to decades.

Figure 8: How Southern Ocean organisms and productivity are linked to biogeochemical processes. Adapted from Henley et al., 2020

Drivers of change in Antarctic Sea-ice Systems

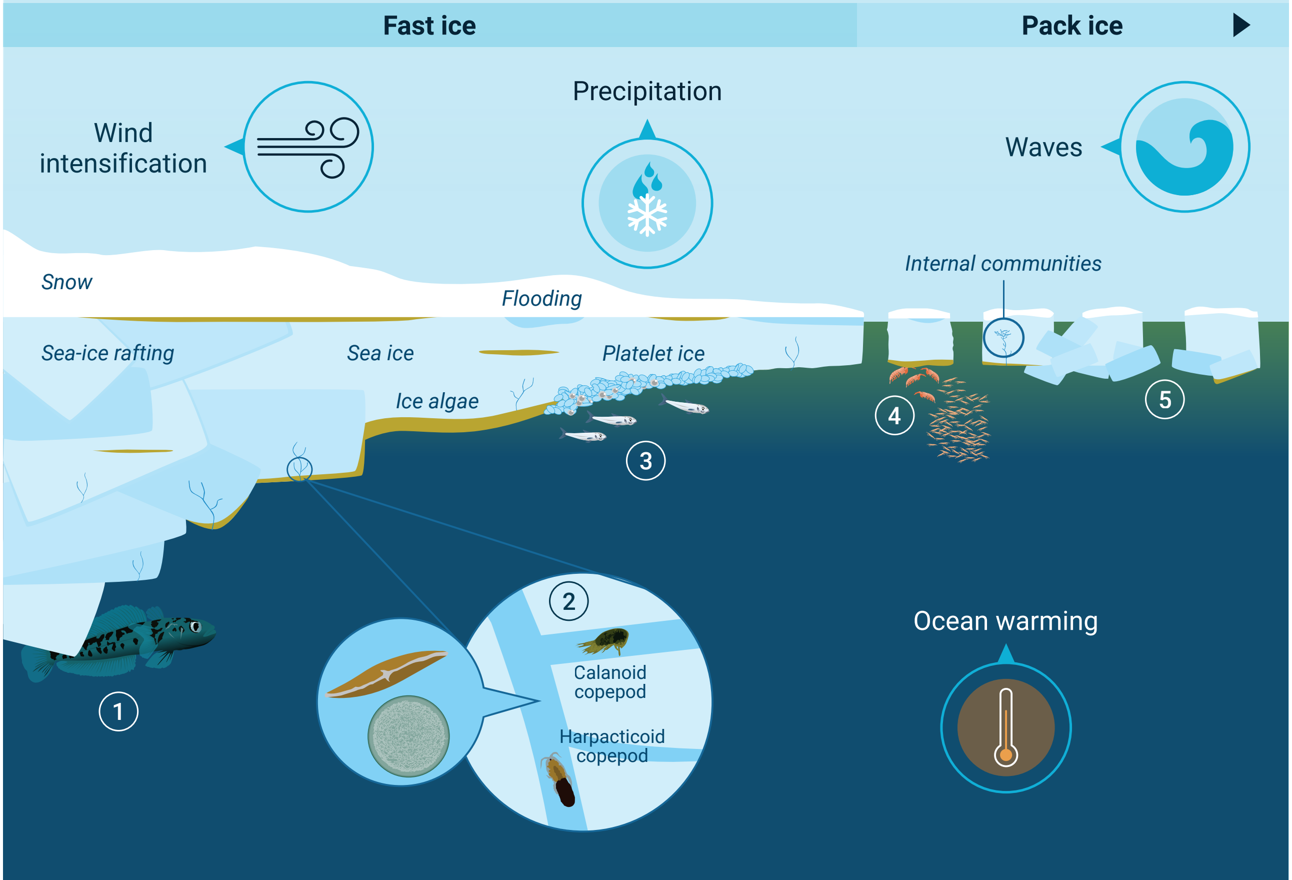
Sea ice is a key habitat in the Southern Ocean and is predicted to change in its extent, thickness and duration in coming decades.

The sea-ice cover is instrumental in mediating ocean-atmosphere exchanges and provides an important substrate for organisms from algae and microbes to predators.

Sea-ice habitat, transitioning from inshore (stationary) landfast ice to offshore (mobile) pack ice is illustrated below. Shown are key **ice-associated biota** and **drivers of change**.

Key

▶ Drivers of change



Ice-associated biota

1. **Bald rockcod**

2. **Antarctic brine-channel system**
   Small brine channels, characterised by sub-zero temperatures with varying salinities spread throughout the sea-ice column. Within these systems, a diverse array of fauna and flora thrive including various copepod and algal species.

3. **Antarctic silverfish**
   Lay their eggs in platelet ice.

4. **Antarctic krill**
   The early stages of the Antarctic krill life-cycle rely on sea-ice systems, feeding on ice algae and using sea ice as a refuge from predation.

5. **Phytoplankton**
   Blooms under sea ice and near the ice edge.

Figure 9: How sea-ice systems influence the biology of the Southern Ocean. Adapted from Swadling et al., 2023

3.3

Primary production by phytoplankton and carbon export to deeper water around Antarctica are changing but drivers are complex and trajectories of change are uncertain●●●○[82].

3.3.1

Satellite observations show mainly increases in phytoplankton biomass in the Southern Ocean over the last 20 years (1997–2019) except in the Ross Sea region, but the satellite record is not long enough yet to separate long-term trends of phytoplankton biomass and production from variability associated with decadal climate cycles●●○○[82].

3.3.2

Primary production at the base of the mixed-layer may have decreased over the same period, especially in the Atlantic sector●○○○[82].

3.3.3

Earth system models project increasing primary production in the Northern and Antarctic MEASO zones but decreases in the Subantarctic Zone, with changes in phytoplankton species composition●○○○[42, 82].

3.4

Ocean warming will alter seasonal patterns in production (phenology) and the relative abundances of different types of phytoplankton (particularly diatom vs. non-diatom)●●●○[16, 82].

3.4.1

Diatoms, which are a large component of the diet of Antarctic krill●●●○[56] and important for biogeochemical cycling●●●○[42], become dominant when iron and silicic acid are abundant●●●○[82].

3.4.2

Projections of future productivity are more certain than how the species composition will change●●●○[82].

Primary production in the Southern Ocean

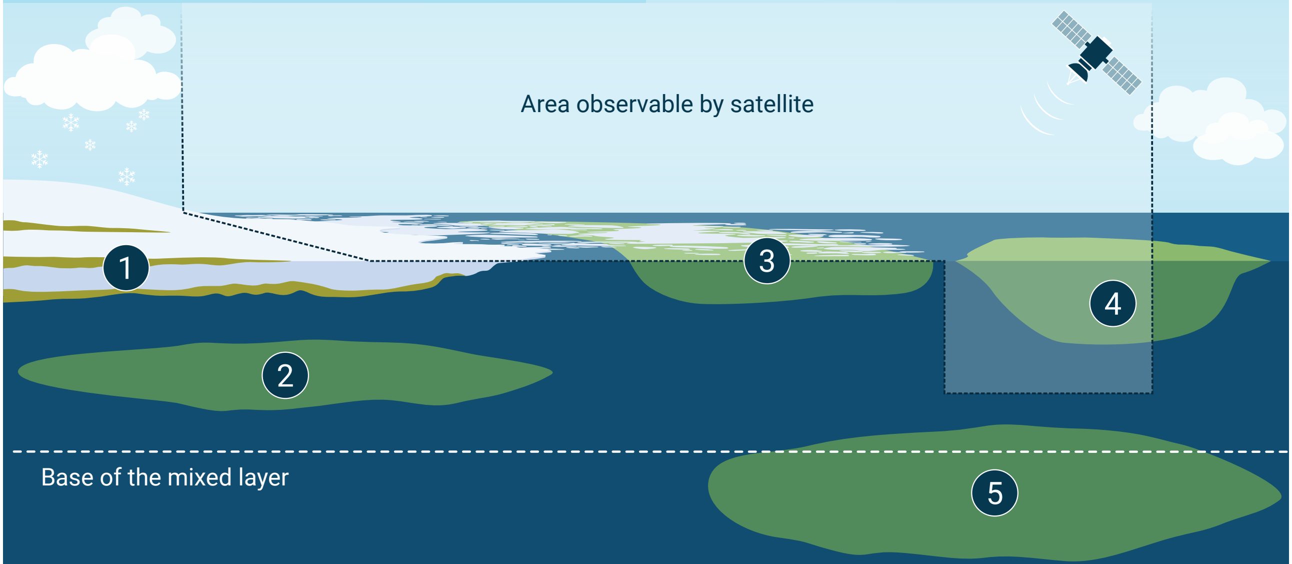
There are different types of microalgal primary production in the Southern Ocean, each play an important role in providing the energy and organic matter to support various marine organisms and the marine food web.
Types (locations pictured below) include:

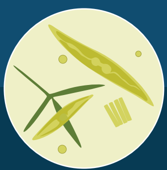
1. Sea-ice algae
2. Phytoplankton beneath sea ice
3. Ice-edge phytoplankton bloom
4. Mixed-layer phytoplankton
5. Deep chlorophyll maximum (DCM)

Observing and predicting change

Recent past changes (last 20 - 30 years) in primary production have been observed by satellites. However, these observations are limited by various factors such as cloud coverage, snow and water depth.

To project future changes (50 - 100+ years) in primary production, Earth System models are used.





Sea-ice algae

Sea-ice algae communities are mostly found in the upper metres or at the bottom of sea ice with the abundance and community compoisition dependent on the time of year.

Composition:
Motile diatoms, small flagellates

*	Past	Future
Subantarctic	↑	↓
Antarctic	↑	↓

Phytoplankton

Most (>80%) primary production in the Southern Ocean occurs in the mixed layer.

Composition:
~350 species, including diatoms, dinoflagellates, and haptophytes (coccolithophores, Phaeocystis)

*	Past	Future
North	↑	↑
Subantarctic	↑	↓
Antarctic	↑	↑

Deep chlorophyll maximum

Deep chlorophyll maxima support blooms of large diatoms that can grow to high abundance and contribute significantly to carbon and silica flux.

Composition:
Mostly large diatoms

*	Past	Future
North	↓	?
Subantarctic	↓	?
Antarctic	?	?

*Arrows indicate changes (increase ↑, decrease ↓ or unknown ?) in primary production
Note: changes to biomass are expected to follow the same trend

Figure 10: How primary production in the Southern Ocean is changing. Adapted from Pinkerton et al., 2021

3.5

Sensitivities of benthic and pelagic species to individual drivers of change in habitat conditions are determined by their shape and size, ability to regulate their physiology, and ability to move away from inhospitable conditions●●●●[7, 56].

3.5.1

Many zooplankton species live in waters with specific temperature ranges, forming unique community assemblages between frontal systems in the Southern Ocean●●●○[56].

3.5.2

Many Antarctic species of zooplankton (such as Antarctic krill and crystal krill) are adapted to the cool temperatures, sea ice, and the intense seasonality of the Southern Ocean, exhibited through their life history strategies, distributions and abundances●●●○[56].

3.5.3

Antarctic krill are predominantly found in the MEASO Antarctic zone●●●○; warmer temperatures and increased dissolved CO_2 concentrations may reduce reproductive success of krill●●○○, and larval krill depend on sea-ice habitat for food and refuge over winter●●○○[56].

3.5.4

Sessile benthic species, particularly reef builders that provide habitat for a diversity of bottom invertebrates and fish, cannot escape unfavourable environmental conditions because they are fixed to the bottom●●●●. As temperature tolerance is species-specific, different impacts (winners and losers) are expected as a result of ocean warming; consequences for biotic interactions, food webs and dominance of species will be dependent on the current species composition of an area●●●○[7].

3.5.5

Species with aragonitic shells, including shelled pteropods and bivalves, or high-magnesium calcite skeletons, including sea stars and a number of attached reef-building animals such as corals will be particularly vulnerable to shell dissolution from increased acidification by 2100●●○○[28, 56].

3.5.6

Antarctic benthic fish species are at risk from increased temperatures in the subantarctic●●○○[11] and changing patterns of ocean circulation combined with increased temperature have the potential to impact the recruitment of larval fish in areas downstream from spawning grounds●●●○[11].

3.5.7

Antarctic fish species dependent on the sea-ice system will be impacted by declining sea ice and warmer temperatures●●●○[11]. Antarctic silverfish face a decline in population in regions where incursions of circumpolar deep water onto the continental shelf are melting ice shelves and reducing the production of platelet ice, an important nursery habitat●●○○[105].

3.6

Relationships with sea ice vary between species of birds and marine mammals; species dependent on sea ice for breeding (e.g. emperor penguins) and haul-out resting (e.g. crabeater seals) will be negatively impacted by declining sea-ice cover, while ice-independent species are expected to be less impacted●●●○[4, 16, 65].

3.6.1

Diverse changes in the characteristics of the sea-ice zone (sea-ice duration, concentration, thickness, floe size and structure, early fast-ice breakup, increased iceberg mobility, changed polynya activity) have more complex and mixed biological impacts depending on the species, such as for Adélie penguins●●○○[4, 16].

3.6.2

Species that do not depend on sea ice, such as gentoo penguins, may benefit from reduced sea ice but this will depend on whether their prey, like krill, are also affected by sea-ice loss●●○○[4, 64, 65].

3.7

Species in shore-based colonies will be impacted by shifting prey distributions, particularly for subantarctic predators, and by changing conditions at their colonies[4].

3.7.1

Penguins and flying birds are expected to experience increased numbers of large-scale mortalities of chicks with increased extreme weather events and storminess (precipitation/snowfall) (e.g. Adélie penguins)●●●○[4, 16, 31].

How will Southern Ocean zooplankton taxa respond to change?

In the Southern Ocean, several zooplankton taxonomic groups notable for their biomass, abundance and their roles in maintaining food webs and ecosystem structure and function, including the provision of globally important ecosystem services.

The table below shows the potential impacts of key physical and chemical drivers of change on the distribution and abundance of key Southern Ocean zooplankton taxa.

Key

- U — Unknown/influence varies greatly according to species
- L — Low influence
- M — Medium influence
- H — High influence

This assessment represents expert consensus as explained in Johnston et al., 2022

Key physical and chemical drivers of change	Antarctic krill	Other euphausiids	Copepods	Salps	Pteropods
Wind	U	U	U	M	U
Sea ice	H	H	U	M	M
Sea surface temperature	H	H	U	H	H
Ocean circulation	M	M	U	H	U
Ocean stratification	U	U	U	M	M
Mixed layer depth	L	M	U	M	M
Ocean acidification	L	L	U	L	H
Extreme climate-related events	U	U	U	H	U
Climate indices	H	H	U	H	H

Figure 11: Sensitivities of krill and zooplankton to change in physical and chemical drivers. Adapted from Johnston et al., 2022

How will Southern Ocean fish and squid respond to change?

Fish and squid make up a significant portion of the biomass within the Southern Ocean, filling key roles in food webs from forage to mid-trophic species and top predators. Fisheries currently are the major local driver of change in Southern Ocean fish productivity, but global climate change presents an even greater challenge to assess future changes.

The table below shows the impacts of key historical and future drivers on Southern Ocean fish and squid taxa.

Key

- No data
- Negative impact
- Mixed impact
- Positive impact
- Driver
- Climate change
- Pollution
- Sea-ice loss
- Fisheries

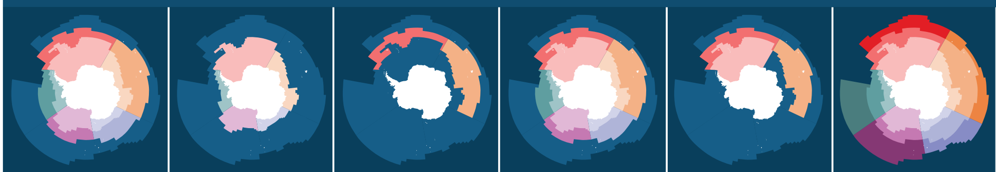
	Lanternfish	Silverfish	Marbled rockcod	Toothfish	Icefish	Antarctic squid
Distribution by MEASO area						
Historical impact	No data	No data	Negative	Negative	Negative	No data
Drivers of historical impact	No data	No data	Fisheries	Fisheries	Fisheries	No data
Future impacts	*Subantarctic* Positive *Antarctic* Negative	Negative	Mixed	Mixed	Negative	Positive
Drivers of future impacts	Climate change, Pollution, Sea-ice loss	Climate change, Pollution, Sea-ice loss	Climate change, Pollution	Climate change, Pollution, Fisheries	Climate change, Pollution	Climate change

Figure 12: Drivers of change in fish and squid. Adapted from Caccavo et al., 2021

3.8

Foraging success of migratory birds and marine mammals may be disrupted should there be a change in timing of productivity in the ocean-ice systems••◦◦[4].

3.8.1

Many marine mammals and birds time their long-distance migrations into the Southern Ocean to the seasonal resource peaks associated with sea-ice retreat and oceanic productivity•••◦[4].

3.8.2

Species that have preferred foraging locations may also be impacted if those locations were to shift because of these changes[4].

3.9

Pollution and pathogens are emerging as factors impacting species in the Southern Ocean, including zooplankton, fish, marine mammals and birds•◦◦◦[4, 11, 35, 56].

3.10

Benthic systems will be negatively impacted by warming, freshening, and acidification of their habitats and additionally by increased iceberg scour on the Antarctic continental shelf•••◦[7].

3.10.1

More light will reach the sea floor in Antarctic coastal areas due to less sea ice and could result in shifts from invertebrate- to algal-dominated assemblages, reducing coastal biodiversity in some locations, and leading to alterations in ecosystem function••◦◦[7].

3.10.2

The northern tip of the Antarctic Peninsula and around subantarctic islands in the Scotia Arc are high risk areas for the establishment of non-indigenous species••◦◦[7].

3.10.3

More frequent scouring of the seafloor in shallow areas of the continental shelf by icebergs will result in assemblages being dominated by fast-colonising, short-lived species, e.g., bryozoans (sea mosses) and spirorbid worms, rather than allowing the development of long-lived and diverse sponge grounds, dense coral aggregations and other rare and vulnerable reef-like three-dimensional assemblages•••◦[7].

3.10.4

After the immediate effects of a collapsed ice shelf have passed, reduced iceberg scour may be expected and result in less patchy colonisation patterns with a lower large-scale biodiversity••◦◦[7].

3.10.5

Any changes in benthic biodiversity are expected to impact biological processes with consequences for long-term carbon sequestration and benthic nutrient recycling•••◦[39].

3.11

Regional reductions in sea ice and increasing ocean temperatures are causing parts of the Antarctic (polar) ecosystem to contract towards Antarctica, increasing the potential for more northern species to move southward; the interacting effects on polar species of changes in multiple environmental drivers make the consequences for lower trophic levels difficult to predict••◦◦[56, 68, 82].

3.11.1

Changes in Southern Ocean food webs are dependent on the energy pathways prevalent in any given area and the sensitivity of species (either as predators or as prey) to changes in other species impacted by environmental change•••◦[64].

How will Southern Ocean birds and marine mammals respond to change?

The below table shows the effects of high-level drivers on Southern Ocean birds and marine mammals with associated confidence indicated as:

- ●●● High confidence
- ●● Medium confidence
- ● Low confidence

Key

- Need data
- Negative impact
- Mixed impact
- Positive impact
- No change

Key physical and chemical drivers of change	Flying seabirds	Penguins	Seals	Cetaceans
Oceanic processes	●● (Negative impact) Warmer ocean temperatures	●● (Negative impact) Warmer ocean temperatures	●●● (Negative impact) Warmer ocean temperatures	● (Negative impact) Climate-driven reduction in prey
	●● (Positive impact) Increased wind	●●● (Negative impact) Local frontal shifts	(Need data) Local frontal shifts	
	●●● (Negative impact) Extreme weather events	●●● (Negative impact) Extreme weather events	● (Negative impact) Extreme weather events	
		●● (Negative impact) Deeper mixed layers	(Need data) Deeper mixed layers	
Sea-ice processes	●●● (Mixed impact) Decreased ice extent/duration	●●● (Mixed impact) Decreased ice extent/duration	●● (Mixed impact) Decreased ice extent/duration	(Need data) Decreased ice extent/duration
		●●● (Mixed impact) Reduced fast ice	● (Negative impact) Reduced fast ice	● (Negative impact) Ice changes shifting forage ranges
		●●● (Negative impact) Increased snowfall	● (Negative impact) Altered flow size/structure	
		●●● (Mixed impact) Polynya changes		
		●●● (Negative impact) Increased iceberg mobility		
Fisheries interactions	●●● (Negative impact) Bycatch		● (Negative impact) Bycatch	● (Negative impact) Bycatch
	● (No change) Resource extraction (krill)	● (Negative impact) Resource extraction (krill)	(Need data) Resource extraction	(Need data) Resource extraction (krill)
				●● (Negative impact) Resource extract-ion (toothfish)
	●● (Negative impact) Debris	(Need data) Debris	● (Negative impact) Debris	(Need data) Debris
	●● (Positive impact) Discards			●● (Mixed impact) Depredation
Global pollution	●● (Negative impact) POPs	● (Negative impact) POPs	●● (Negative impact) POPs	●● (Negative impact) POPs
	●● (Negative impact) Mercury	● (Negative impact) Mercury	●● (Negative impact) Mercury	● (Negative impact) Mercury
	●●● (Negative impact) Plastic ingestion	● (Negative impact) Plastic ingestion	● (Negative impact) Plastic ingestion	●● (Negative impact) Plastic ingestion
Health and disease	●●● (Negative impact) Bacterial disease	●●● (Negative impact) Bacterial disease	●●● (Negative impact) Bacterial disease	●●● (Negative impact) Bacterial disease
	●● (Negative impact) Macroparasites	●● (Negative impact) Macroparasites	● (Negative impact) Macroparasites	● (Negative impact) Macroparasites
	(Need data) Viruses	●● (Negative impact) Viruses	●●● (Negative impact) Viruses	(Need data) Viruses
Land-based disturbance	●●● (Negative impact) Non-indigenous species	●● (Negative impact) Increased visitation	●● (No change) Handling intensity	●● (Negative impact) Noise disturbance
	(Need data) Drone usage	(Need data) Drone usage	(Need data) Drone usage	(Need data) Drone usage

Figure 13: Factors impacting Southern Ocean birds and marine mammals. Adapted from Bestley et al., 2020

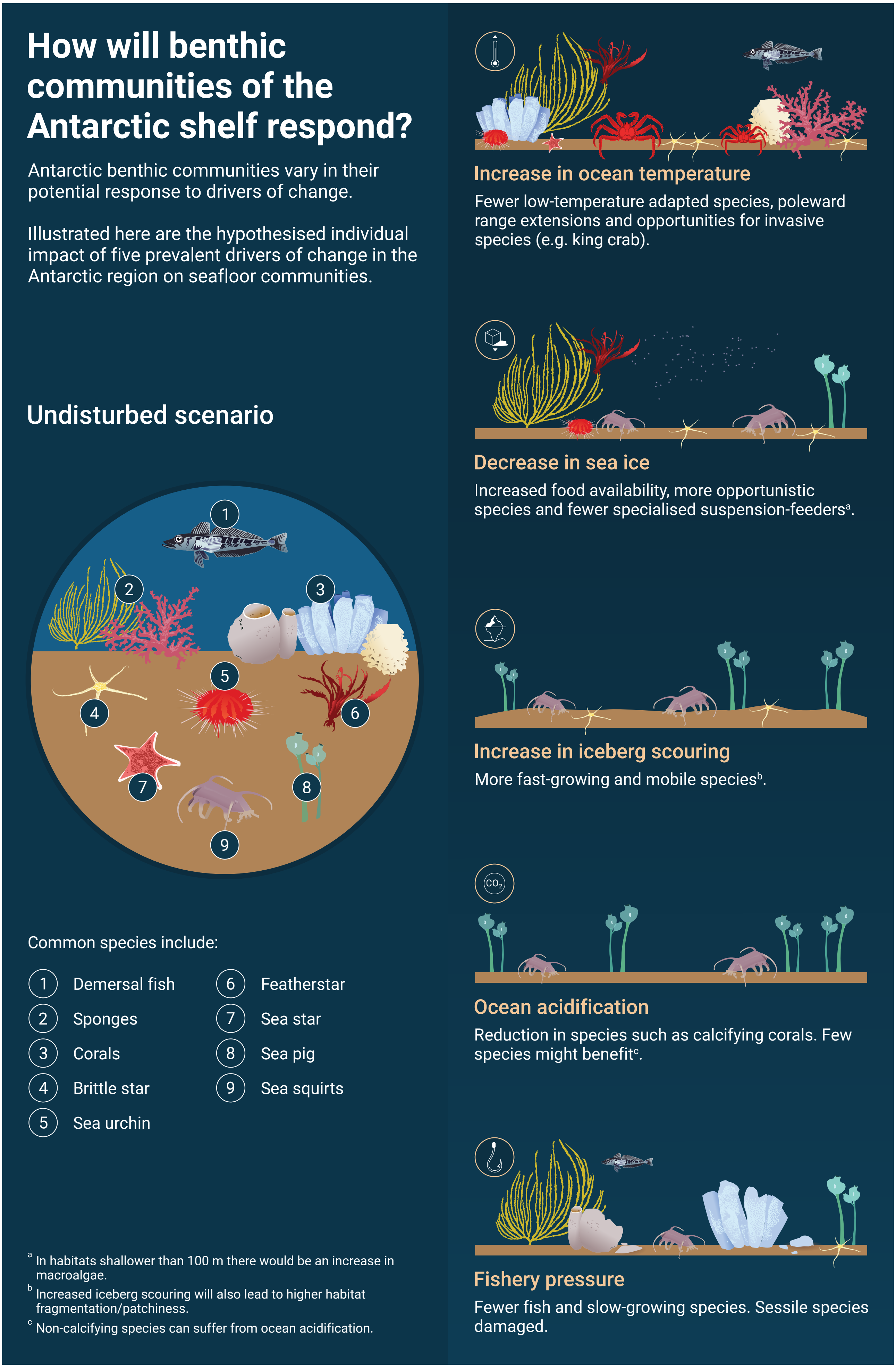


Figure 14: How will benthic communities of the Antarctic shelf respond to change? Adapted from Brasier et al., 2021

3.11.1.1

Three main pathways from phytoplankton to higher trophic levels can occur in Southern Ocean food webs; these are all dependent on sea ice and thus affected by climate change●●●○: (i) via krill, (ii) via copepods and other zooplankton, followed by mesopelagic fish, and (iii) via salps [56, 64]. Diatoms are the primary food of krill, while smaller phytoplankton and microbes provide food for copepods and salps[56, 64].

3.11.1.2

The structures of food webs vary around Antarctica; the krill pathway dominates in the East Pacific and Atlantic sectors while being confined to the Antarctic Zone and of mixed importance in the Indian and East Indian sectors●●●○[64].

3.11.1.3

The West Pacific sector hosts a mixed food web with greater dominance of mesopelagic fish●●●○[64].

3.11.1.4

Subantarctic islands in the Indian and East Indian sectors are dominated by a copepod-mesopelagic fish pathway●●●○[56, 64].

3.11.2

Whilst warming, ocean acidification, and sea-ice loss may restrict the areas of suitable habitat for some species (Antarctic and crystal krill) to more southerly locations, the complexity of interactions may expand suitable habitat for others such as *Thysanoessa macrura* (a type of krill) and salps●●○○[56].

3.11.3

Salps are expected to benefit from climate change impacts on the Southern Ocean with increased abundance of smaller phytoplankton species, thereby displacing krill and copepods and having negative impacts on higher trophic levels, but potentially increasing carbon export●●●○[56, 64].

3.11.4

Change in the relative importance of these pathways in different areas will arise from the sensitivities of lower trophic level species to habitat change, including whether diatoms or smaller phytoplankton are dominant●●○○[42, 56, 82].

3.11.5

Changes in pelagic food webs resulting in changes in the size of biological material (phytoplankton, detritus or dead animals) sinking from the surface waters will affect the structure of benthic assemblages; those assemblages tend to be dominated by animals that can capitalise on the types of material reaching the seafloor●●○○[7].

3.12

Reduced dominance of Antarctic krill may arise in the Atlantic sector of the Southern Ocean due to sea ice and diatom loss and warming, thereby impacting higher trophic levels and the energetic efficiency of the ecosystem●●○○[4, 42, 56, 68].

3.12.1

The phytoplankton-Antarctic krill-baleen whales energy pathway contributes to iron recycling in surface waters, potentially enabling greater carbon export to deeper waters●○○○[42, 56].

3.12.2

The status and trends in the distribution and abundance of Antarctic krill are still highly uncertain, despite monitoring in some locations of the Atlantic and East Pacific sectors for over 20 years[56].

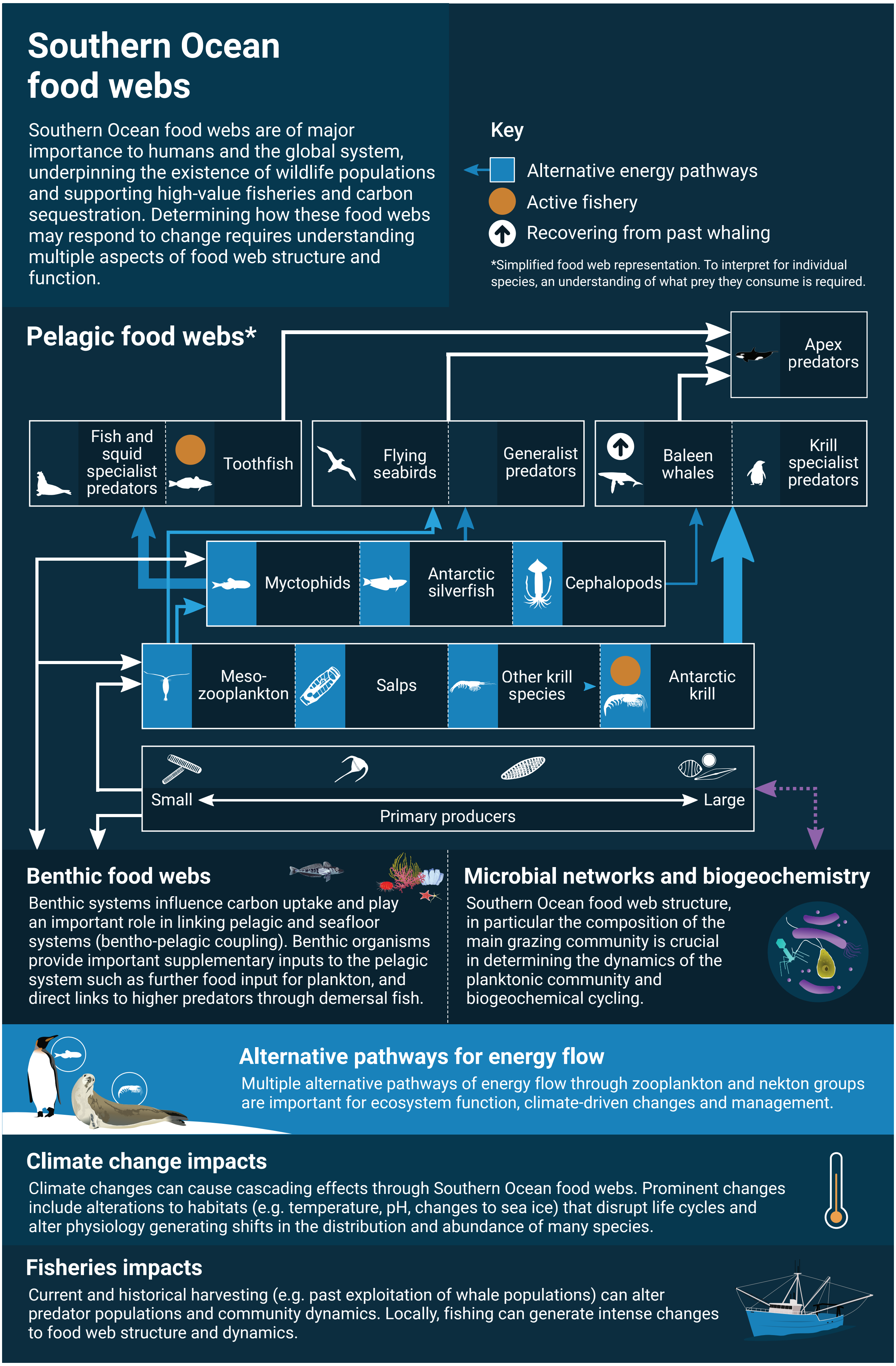


Figure 15: Different energy pathways in Southern Ocean food webs and the effects of exploitation. Adapted from McCormack et al., 2021

Confidence level

●○○○ Low confidence

●●○○ Medium confidence

●●●○ High confidence

●●●● Very high confidence

©Jess Melbourne-Thomas

04

Value and importance of Southern Ocean ecosystems in the Earth System

4.1

Southern Ocean ecosystems are an integral part of the Earth System●●●○; changes in Southern Ocean ecosystems will have impacts throughout the world's oceans and climate system, and vice versa●●○○[74].

4.1.1

The Southern Ocean regulates global ocean biogeochemistry and productivity[42] by supplying at least 60% of the nutrient pool in low-latitude regions north of 30ºS●●●○[see e.g. 32, 96].

4.1.2

The Southern Ocean plays a critical role in regulating global climate by absorbing large amounts of atmospheric CO_2●●○○, although the increased capacity for drawdown may be limited[42].

4.1.3

A negative feedback to climate change may arise with increased primary production due to more iron and light in some regions[42] coupled with the collapse of ice shelves opening areas to primary production and enhanced carbon uptake●○○○[12].

4.2

The Southern Ocean is closely interconnected with the Earth System●●●●[61, 74].

4.2.1

Water is exchanged with all oceans to the north through surface eddies driven by wind in some locations as well as through deeper water convection driven by temperature and salinity●●●●[74].

4.2.2

Large-scale ocean connectivity enables movement of pelagic organisms (plankton and fish) and biological material into and out of the Southern Ocean●●●○[74].

4.2.3

Human activities in the Southern Ocean region (government operations, science, fisheries, tourism) involve the large-scale transfer of people and material north and south each year, linking communities and social systems elsewhere to the Southern Ocean but also potentially contributing to unexpected impacts in the region through transport of non-indigenous species and pathogens, direct disturbance, and pollution●●●○[35, 74].

Global Connectivity of Southern Ocean Ecosystems

Southern Ocean ecosystems are globally important. Processes in the Antarctic cryosphere, atmosphere and the Southern Ocean directly influence global atmospheric and oceanic systems.

Physical connectivity

- The Southern Ocean is the central hub of the global ocean.
- Waters leaving the Southern Ocean flow into the 3 major ocean basins.
- It may take decades or even centuries before waters from the Southern Ocean rise towards the surface.
- The exported waters transport nutrients northwards helping to fuel productivity in distant ocean ecosystems.
- Waters flowing south into the Southern Ocean also carry lots of nutrients. These help support the rapid growth of plankton in the southern summer.

Ecological connectivity

Below we broadly assess seasonal shifts in demand for prey of key groups of marine predators, including seabirds and cetaceans. The seasonal shift in and out of the Southern Ocean of these communities and their demand for prey in the Southern Ocean compared with waters north of the Antarctic Polar Front were estimated:

Seabirds

68.5 million birds move seasonally

South		North
9.42×10^6 tonnes	Summer prey demand	0.08×10^6 tonnes
1.99×10^6 tonnes	Winter prey demand	1.79×10^6 tonnes

Cetaceans

6 million cetaceans move seasonally

South		North
16.98×10^6 tonnes	Summer prey demand	?
0.35×10^6 tonnes	Winter prey demand	3.13×10^6 tonnes

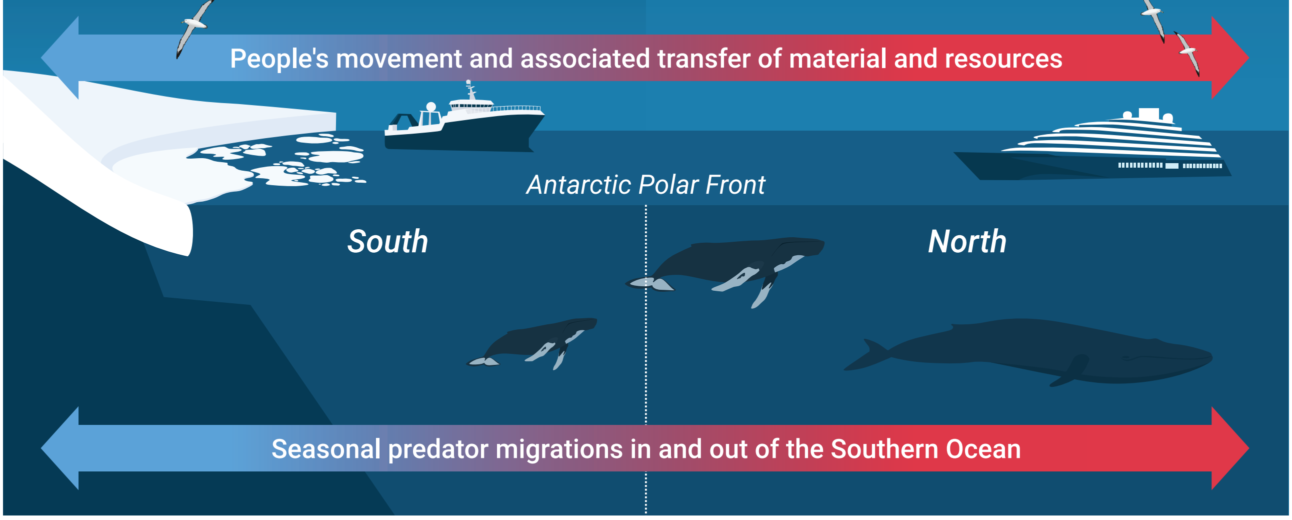


Figure 16: Global connections and feedbacks with Southern Ocean ecosystems. Adapted from Murphy et al., 2021

4.3

The Southern Ocean provides important feeding and breeding grounds for migratory birds and marine mammals•••○; migratory species transport important nutrients and carbon to and from the Southern Ocean each year••○○[74], and can contribute to the transport of invasive species•○○○[4, 68].

4.3.1

Millions of seabirds, pinnipeds and whales migrate into and out of the Southern Ocean. This seasonal movement connects distant food webs and will transfer the impacts of regional changes between ecosystems and into different basins••○○[74].

4.4

People have a deep connection with the Southern Ocean and its ecosystems, and value these greatly, despite not living there•••○[12, 74, 94].

4.4.1

Cultural knowledge and narratives about Southern Ocean ecosystems, generated from within the region or from afar, and including Indigenous stories, are an important reflection of the non-utilitarian connection of people to Southern Ocean ecosystems[94].

4.4.2

The cultural significance of the Southern Ocean is an important factor in decision-making for Southern Ocean ecosystem management (Cavanagh et al. 2021, Murphy et al. 2021a, Roberts et al. 2021). The global importance of the Southern Ocean ecosystem to people – both in terms of its role in the earth system, and its cultural values – could be recognised more explicitly when formulating and assessing policies and making decisions[94, 102].

4.5

The demand for, and global importance of, ecosystem services from the Southern Ocean, is expected to increase during the 21st century, but climate change is expected to impact these services•••○[12].

4.5.1

Globally important ecosystem services from the Southern Ocean include climate regulation, fishery products, primary production, nutrient cycling, science, tourism, and the cultural value of the region, all underpinned by the preservation of biodiversity[12, 74].

4.5.2

Climate change will impact the overall capacity of the Southern Ocean to supply ecosystem services, and this is expected to be accompanied by increases in demand for most services••○○[12].

4.5.3

Southern Ocean ecosystem services, such as primary production (supporting service), and fishery products (provisioning service), are vulnerable to changes in connectivity between ecosystems in the Southern Ocean and ecosystems across the world's oceans•••○[12, 74].

4.5.4

Southern Ocean ecosystem provisioning services (fisheries) are under threat from climate impacts on species and habitats, including high risk for krill••○○, and medium risk for mackerel icefish•○○○ and toothfish•○○○[12].

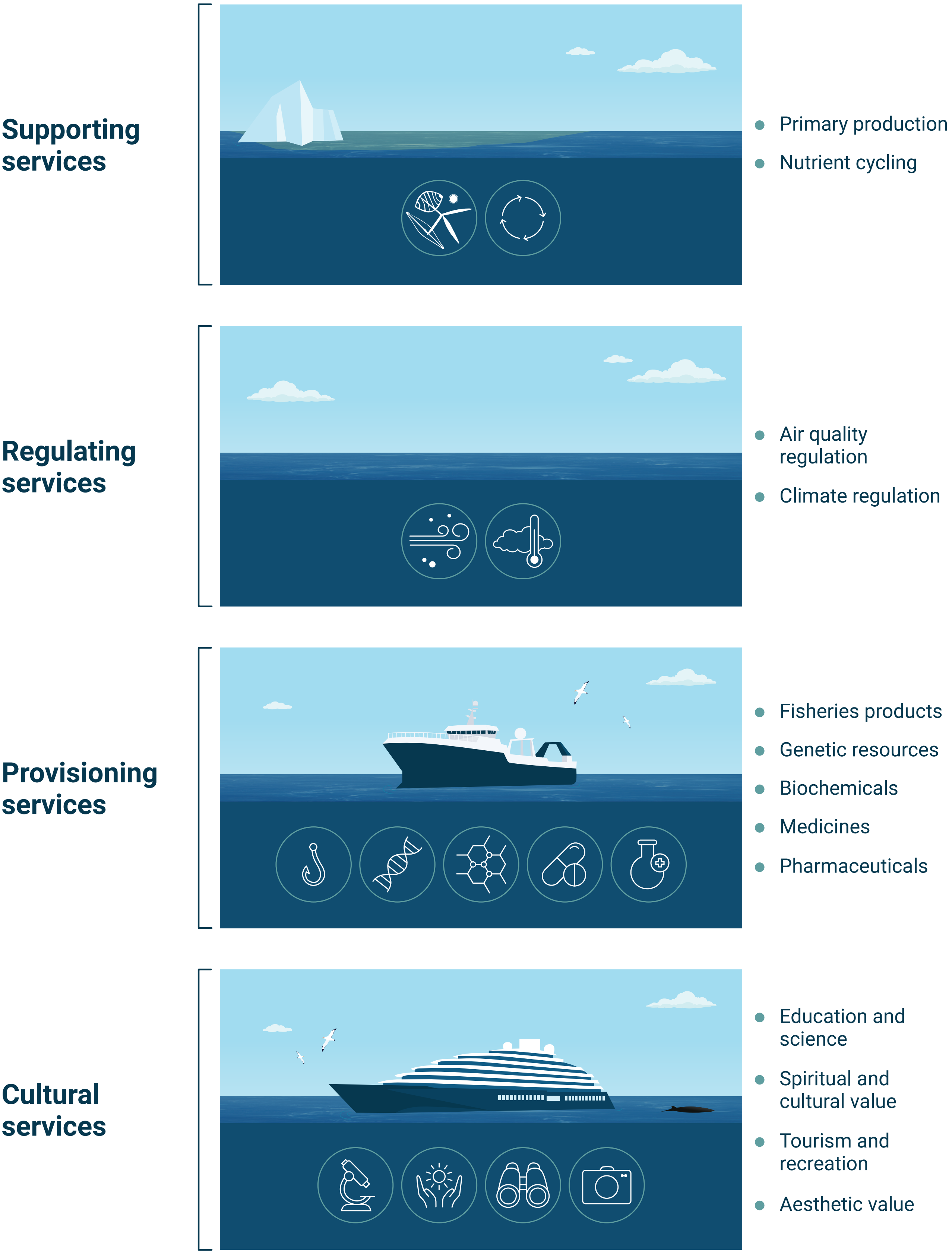


Figure 17: Summary of marine ecosystem services in the Southern Ocean. See Cavanagh et al., 2021 (Table S2) for more information.

05

Priorities for improving future assessments and policy-relevant advice

5.1

MEASO has demonstrated the array of existing knowledge, data, tools, and approaches available for informing decisions on conserving and sustaining the marine ecosystems in the region and the services they provide, and how implementation of those processes could be improved●●●○[4, 7, 11, 12, 35, 42, 56, 64, 68, 74, 82, 105, 112].

5.1.1

Assessments of change and the design of future field programs will be facilitated by archiving, curating, and openly sharing data, algorithms, and tools based on the FAIR principles for data, which are for them to be Findable, Accessible, Interoperable and Reusable●●●○[Box 3][81, 112].

5.1.2

Availability of existing data, including fisheries data through CCAMLR, could be improved using existing data networks●●●○, such as in SCAR[5, 112] and SOOS[78], which have connections to other global and regional networks[24, 71].

5.1.2.1

Existing platforms and standards need to be transparent and traceable●●●○[112].

5.2.1.2

International coordination is needed to facilitate the matching, aggregation and integration of datasets using common methodologies for comparative analyses of current and future ecosystem risks●●●○[41, 44, 112].

5.2.1.3

Data from fishing vessels provide the most comprehensive time series of data available on many fish and krill species in the main fishing grounds and could help inform assessments of ecosystem change●●●○[112]; mechanisms for appropriately making these data available to the scientific community would be a valuable contribution to future assessments●●●●.

5.1.3

Syntheses of information and analyses of existing data for different MEASO areas would enable planning and development of future assessments●●●○[8]. A system to support future assessments in the Southern Ocean will need to address the knowledge and data gaps caused by sampling bias, non-standardised sampling methods and data management processes, and by data being kept out of the public domain●●●●[112].

5.1.4

Modelling tools are available and can be readily developed further for assessing risks to the region and their implications for ecosystem services and for managing fisheries and onshore activities●●●○, including (i) assessing implications of change for food web interactions affected by fisheries and other activities●●●○[64] and (ii) how to spatially distribute fishery catches to lessen risks for food webs and biodiversity●●●●[18, 114] and ecosystem services more generally●●○○[12].

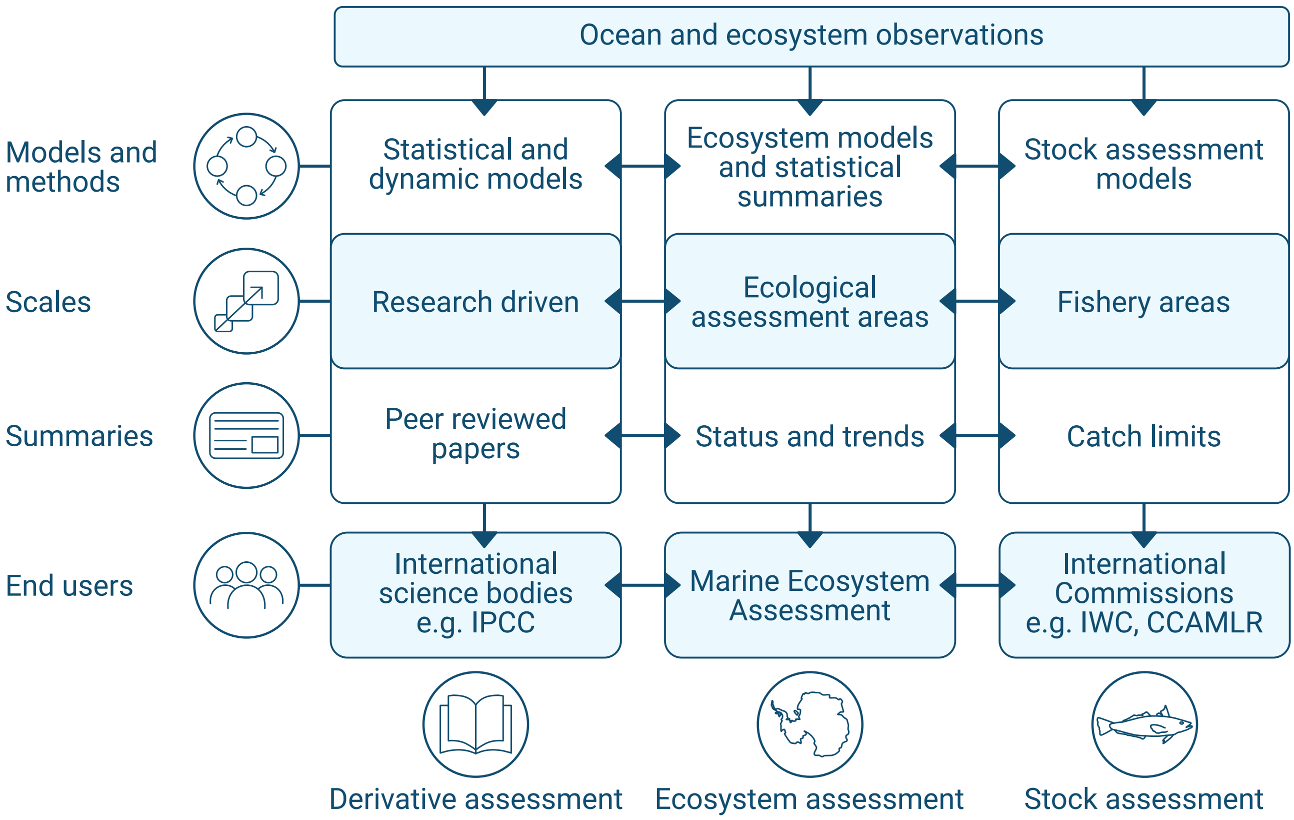


Figure 18: How research fits in to providing advice for future marine ecosystem assessments for the Southern Ocean. Adapted from Brasier et al., 2019

Box 3

Promoting FAIR data principles

B3.1

MEASO promotes the application of the FAIR data principles to data, algorithms and tools, helping ensure (meta)data are Findable, Accessible, Interoperable, and Reusable[112]. These principles emerged to help make (meta)data readily available to the research community and other stakeholders, including having data archived and not lost when a research program is finished[115].

B3.2

The FAIR data principles are designed to be implemented in the context of long-term data stewardship, where data centres have ongoing funding to maintain datasets and make them available to new generations of researchers, even as sharing technology advances. Contributing countries and programs must assure long-term data management.

B3.3

These principles are promoted in the Antarctic Treaty System, which has a policy of sharing data between nations, with policies and procedures to support their implementation developed in SCAR via its Standing Committee on Antarctic Data Management[97] and in the Southern Ocean Observing System (Data Management Subcommittee)[103]. Principles have also been developed to align polar data policies[108]. The objective for promoting FAIR data is to ensure research programs have ready access to data in planning and undertaking their research programs (field observations and monitoring, experiments) including having data made available for use by ecosystem modellers and statisticians, who may find those data useful for extending our systemic understanding of Southern Ocean ecosystems. FAIR data also create opportunities for scientists undertaking applied research to have all available data when supporting policymakers.

5.2

A greater geographic spread across MEASO sectors of comprehensive, long-term ecosystem studies is needed to assess spatial and seasonal variability in the structure and function of Southern Ocean ecosystems and the relative importance of different ecological processes in different areas●●●○[5, 8, 19, 20, 74].

5.2.1

Systematic whole-of-ecosystem studies will enable more robust projections of future change in Antarctic ecological communities and food webs●●●●[20, 36, 105] and help refine knowledge on the scale and location of areas needed for protecting and maintaining marine biodiversity into the future, including satisfying conservation outcomes for biodiversity in the Antarctic Treaty System●●●○[20] and in the United Nations●○○○[14, 50].

5.2.2

Replication of whole-of-ecosystem programs such as the US Palmer Antarctica Long-Term Ecological Research project in the West Antarctic Peninsula (East Pacific MEASO sector) and the South Georgia Western Core Box (Atlantic MEASO sector) is needed●●●●[8].

5.2.2.1

The dynamics of coastal and sea-ice systems vary around Antarctica and are known to result in different outcomes for food webs, and may have different outcomes from change in local and/or global drivers●●●○[30, 56, 63, 64, 105].

5.2.2.2

Representative whole-of-ecosystem studies, similar in scale to those that exist for the Atlantic MEASO sector, could be in the following areas: Dronning Maud Land/eastern Weddell Sea (Atlantic MEASO sector)[36], the area around Prydz Bay and the Kerguelen Plateau (Indian MEASO sector), and the Ross Sea (West Pacific MEASO sector)●●●○.

5.2.3

Time series of observations need to be made at seasonally appropriate times and places, and not just be concentrated in ice-free areas or in summer months●●●●[7, 8, 78, 95, 112].

5.3

Systematic and sustained measurements of habitats and biota in all relevant MEASO areas are needed to underpin assessments of ecosystem change in the Southern Ocean, and for projecting future changes●●●●[5, 20, 71].

5.3.1

Species of direct interest to management bodies, as well as species that are important indicators of ecosystem-level change, include diatoms, krill, mesopelagic fish, penguins, flying birds, seals and whales[20].

5.3.2

The Southern Ocean Observing System (SOOS) provides a useful integrated approach to long-term ecosystem observations, based on coordination through their regional working groups●●●●; standard field and analytical methods are needed for enabling metrics for assessments and for tuning models●●●○[20, 55, 77, 78, 81].

Box 4

Status and development of Southern Ocean ecosystem models

B4.1

A combination of different types of models are needed to understand changes occurring to date, to project future changes to Southern Ocean ecosystems and to explore appropriate management responses. Types of models that are needed include (a) Earth System Models (ESMs – coupled climate-ocean models); (b) ecosystem models (e.g. species-based, size-based, process-based, end-to-end models); and (c) single/multi-species models (such as fisheries assessment models, or species-distribution models). Models focussed on different aspects of Southern Ocean ecosystems have significantly advanced over the last decade[64], which has been a major priority of the program Integrating Climate and Ecosystem Dynamics of the Southern Ocean (ICED)[73].

B4.2

Recent modelling studies of the Southern Ocean using CMIP5 and CMIP6 Earth System projections[3] have been valuable but have also identified the limitations of current physical and biogeochemical projections for the Southern Ocean, e.g., projections of sea ice[100], biogeochemical cycles and primary productivity[98]. These limitations therefore limit ecological projections.

B4.3

Major gaps remain in connecting species/population and ecosystem models with Earth System models. In particular, there are few ecosystem models for ice covered regions or that consider seasonal dynamics (particularly winter). The generation of year-round and climate-ocean-ecosystem coupled models is an area where Southern Ocean modelling can draw on advances made in other ecosystems (see Box 5 on the Arctic experience). Models used for providing management advice (e.g. in fisheries) should take into account the effects of climate change and uncertainties in order to reduce risk of undesirable effects of human activities.

B4.4

A systematic effort is required to develop an ensemble of multi-scale models for the Southern Ocean ecosystems to assess the potential impacts of future change and to provide scientific advice for conservation and management. These models will need to include the global context and connections of Southern Ocean ecosystems, the services they provide and human dimensions (e.g. future drivers of change and societal connections and context). The models should explicitly consider the effects of parameter and model uncertainties on the projections. A systematic programme of model development for Southern Ocean species, food webs and regional and circumpolar ecosystems and the global connections and context is a major future priority for development in the ICED Programme. It will benefit from close coordination with, and investment in, a range of bodies and groups modelling aspects of Southern Ocean ecosystems and the future impacts of change, including ocean and ice modellers linked through

SCAR to the programme on future environmental change, AntClimNow, and the CMIP activity of the World Climate Research Programme (WCRP). An interaction between Southern Ocean ecosystem modellers and those involved with the global Fish-MIP (Fisheries and Marine Ecosystem Model Intercomparison Project)[106] is needed.

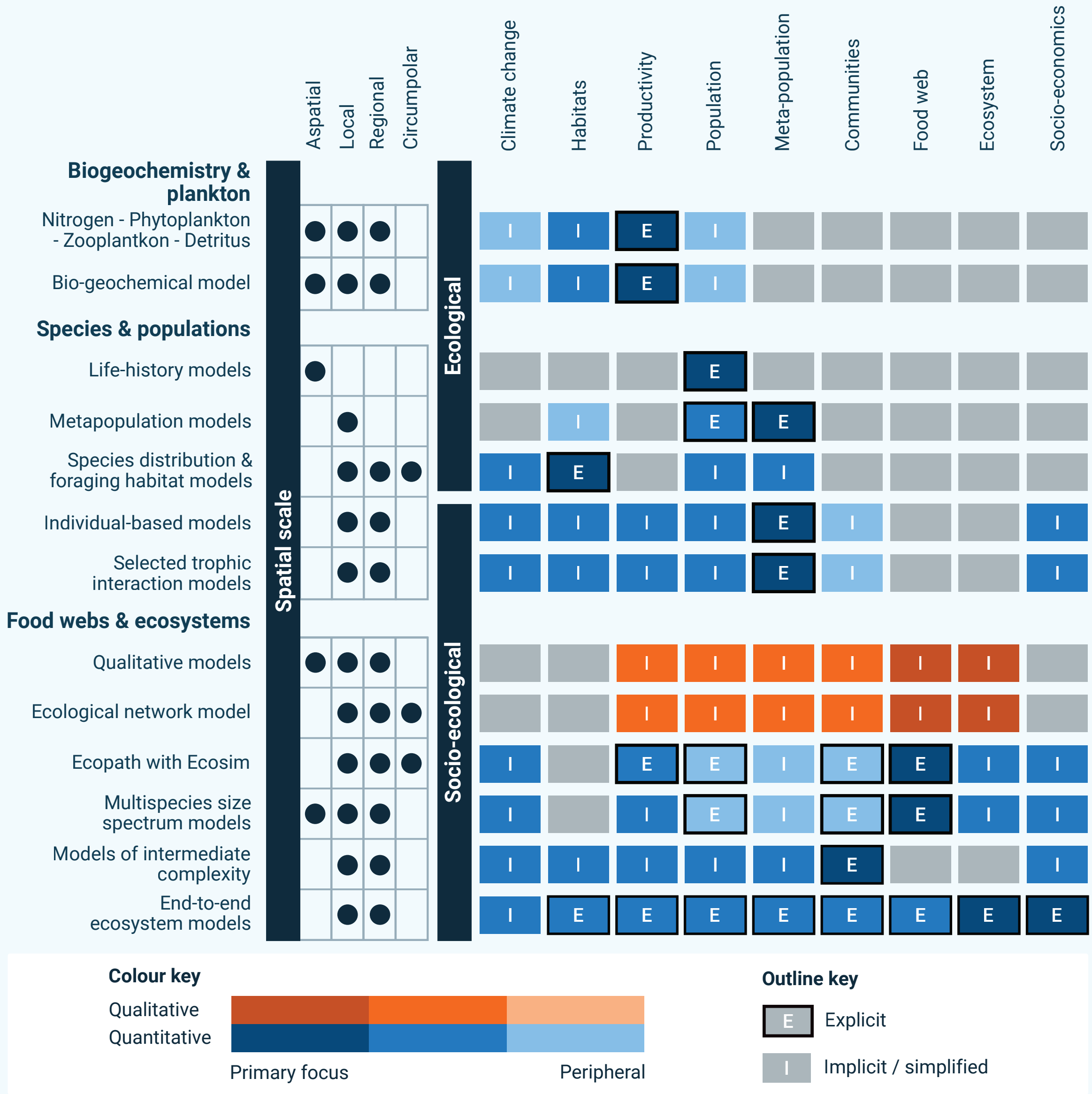


Figure 19: Summary of currently available modelling tools to support assessments of Southern Ocean ecosystems. Adapted from McCormack et al., 2021

5.4

Direct measurement of Southern Ocean ecosystems needs new approaches, and greater and more sustained investment than at present because of the complexity of food webs, diverse communities, the large extent and remoteness of the region, and the rapid pace of changes underway••••[5, 78, 79].

5.4.1

Pooled resources, platforms, infrastructure, and collaborative research across institutions and countries, such as in the coordinated tracking of birds and marine mammals in SCAR[44], are needed to achieve the field work necessary for the whole-of-ecosystem study areas and the observations of essential biological variables[20]; coordinated efforts can be achieved through the existing programs in SCAR and ICED, as well as greater coordination in field programs using SOOS and its relationship with Council of Managers of National Antarctic Programs (COMNAP)••••[77, 78].

5.4.2

Existing operations in the Southern Ocean, such as fisheries, tourism, and station resupply (ships of opportunity), could be used to undertake routine measurements and observations as well as for deploying and retrieving autonomous equipment, which may also require support from scientists and/or equipment at sea●●●○[77, 78].

5.4.3

Autonomous and/or remotely operated systems, such as multi-frequency acoustics, profiling drifters (floats), fixed long-term moorings, mobile remotely-operated stations (gliders, wave-riders, autonomous seacraft), and remote weather and observation stations provide opportunities to collect data from across the spectrum of pelagic organisms and conditions at large spatial scales, and year-round, for a fraction of the cost of research vessels●●●●[77, 78].

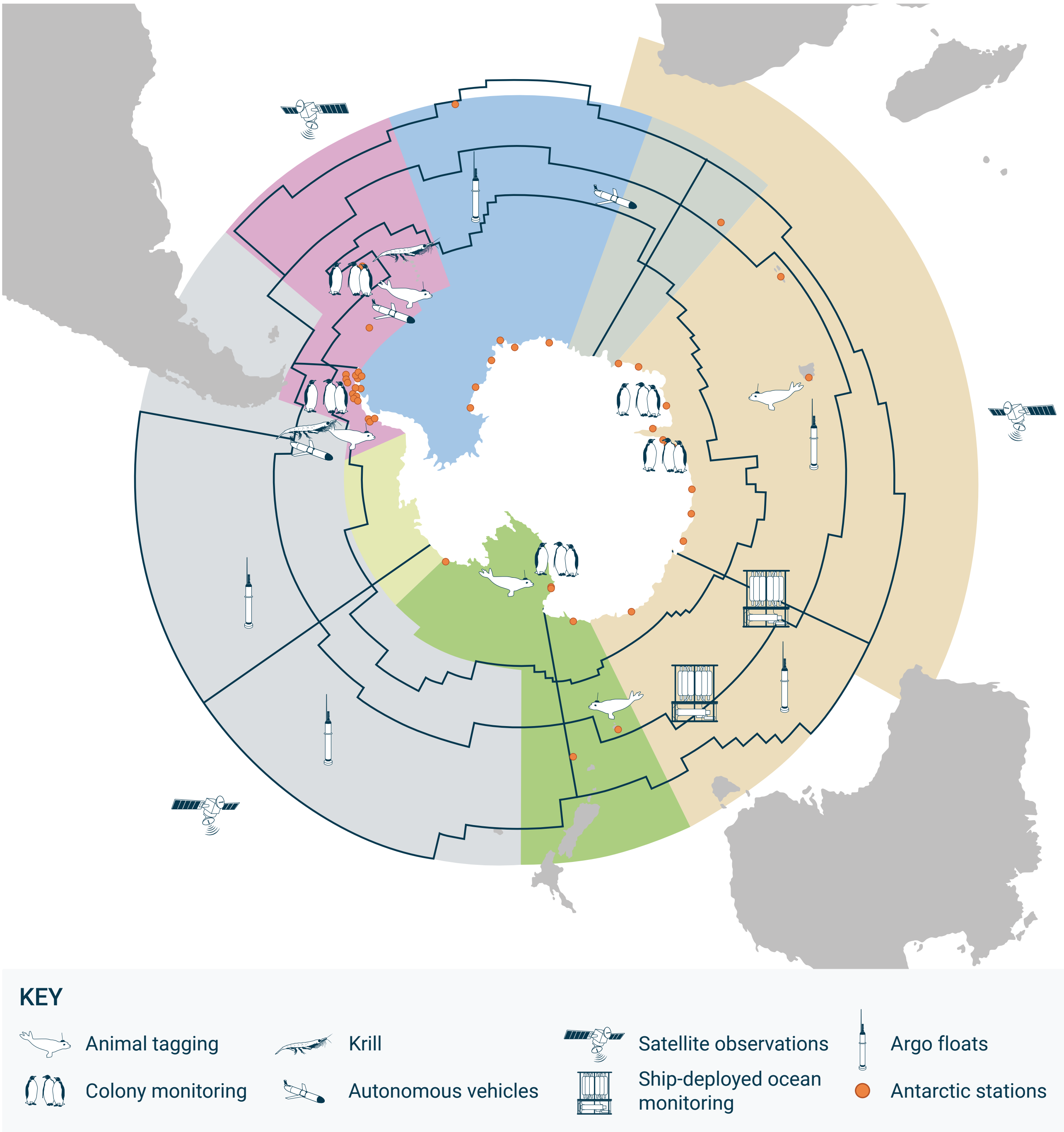


Figure 20: Current biological observing to support management and science, within the context of the Southern Ocean Observing System and the CCAMLR Ecosystem Monitoring Program. Colours indicate SOOS group zones, black lines show MEASO assessment areas.

5.4.4

Efficient spatial and temporal sampling requirements can be designed through Observation System Simulation Experiments, which use coupled ecosystem-Earth system models to test the power of the field program to estimate change●●●○[20, 62, 79].

5.5

Projecting future changes in the survival and/or dynamics of species and communities needs improved models of the impacts from change in habitats, food webs, and human activity●●●●[8, 64, 79].

5.5.1

The degree of tolerance of benthic and pelagic species to change in temperature needs to be reviewed and strategies developed to refine approaches for assessing how species will respond to warming, including the potential for multiple drivers to have interacting effects●●●○[56, 69].

5.5.2

How sea ice influences populations of krill, zooplankton and pelagic fish remains a very important question for predicting how changes in sea ice will influence species in the Southern Ocean●●●●[56, 105].

5.5.3

Models of the spatial distribution of benthic habitats are needed for translating synoptic data (bathymetry, ocean surface features) into expectations for where sessile and sedentary biota may be concentrated and how they may be impacted by environmental change●●●○[7].

5.5.4

Dynamic population models of mobile pelagic (nektonic) species, including krill, fish and marine mammals, are needed for assessing how these species may respond to habitat and/or food web changes and exploitation, through altered reproductive success (recruitment), mortality, and/or migration●●●●[64].

5.5.5

Squid, zooplankton, such as salps, and mesopelagic fish are important in terms of biomass, but their roles in food webs are poorly understood and need elaborating●●●●[64].

5.5.6

Models of how species are influenced by processes outside the Southern Ocean are needed to better elaborate models of the dynamics of those populations within the region●●●○[74].

5.6

Projecting change in ecosystems at appropriate spatial scales will need dynamic ecological models driven by outputs of global ice-ocean-atmosphere (physico-chemical) models downscaled to spatial scales relevant to ecological processes●●●●[Box 4][64, 79].

5.6.1

Earth system physico-chemical models need to better replicate ice-ocean-atmosphere conditions in the Southern Ocean generally and relevant MEASO areas in particular●●●●[64, 79].

5.6.2

Coupled ecosystem models need to include the networks of interactions necessary to realistically replicate the dynamics of ecosystems, including linkages with other areas and processes within and external to the Southern Ocean, as well as include relevant feedbacks from local human drivers, such as pollution, disturbance and fisheries●●●●[35, 64, 74].

5.6.2.1

The behaviour of ecosystem models needs to be validated against known ecosystem behaviours in different parts of the Southern Ocean and under different ecological scenarios, which reinforces the need for sustained time series of essential biological variables from across the Southern Ocean●●●○[79].

5.6.2.2

Uncertainties in the dynamics of ecosystems can be usefully explored using an ensemble approach, where different models represent different plausible ecosystem structures●●●○[64, 79].

5.6.3

As part of assessing uncertainty, modelling studies are needed to consider the potential for rapid ecological changes resulting from (i) rate of environmental change, (ii) changing frequencies of environmental fluctuations (e.g. impacts associated with changes in the global scale weather phenomena like the El Niño and Southern Oscillation), and (iii) extreme events or reaching tipping points[46, 79].

Box 5

Approaches to advising on managing future risks to polar ecosystems: the Arctic experience

B5.1

Research challenges imposed by climate change have many parallels in Antarctic and Arctic marine ecosystems[17, 65], including important gaps in time series of ecosystem data, uncertainty in how polar marine ecosystems function, and, not least, the need for ecosystem models to reliably develop scenarios for the future based on Earth System models and for examining how well different management approaches will meet their objectives[79].

B5.2

Ensemble approaches to dynamic modelling to support management of climate risks have advanced greatly in recent years for Arctic marine ecosystems. This modelling capability could be readily applied to Antarctic and Southern Ocean requirements.

B5.3

In some regions (e.g., the eastern Bering Sea and the Barents Sea), interdisciplinary multi-scale modelling teams are working with coupled physical, chemical and biological models to evaluate (i) past, present and future implications of climate change on living marine resources and (ii) the effectiveness of current and alternative management and adaptation strategies for fisheries and other activities in the regions[40, 46]. These teams utilise downscaled Earth System model output to provide high resolution simulations of physical and biogeochemical ocean conditions[26]; key oceanographic processes are resolved at ecological scales satisfactory for representing the relationships between these drivers and fish and shellfish production[43]. The down-scaled oceanographic models are coupled to biological models of different levels of ecological complexity for fish and shellfish to allow users to explore implications of uncertainty in the representation of the ecosystem (structural uncertainty) on future projections and assessments[93].

B5.4

Modelling teams work with fishery-dependent communities and managers to select combinations of management and adaptation scenarios that could inform decision-makers of the social, economic and ecological trade-offs associated with current and alternative management strategies[47, 84]. Within the U.S., this transfer of knowledge to managers and the public is facilitated through the Bering Sea Fishery Ecosystem Plan, Climate Change Task Team (CCTF). The CCTF identified opportunities for the uptake of climate-change-informed outcomes within the existing management process for making decisions, which provided a trusted process for sustaining delivery of that information. Efforts are underway to provide reliable, downscaled outputs from ocean models for sustained support of this modelling system throughout the coastal waters of North America and the Arctic.

B5.5

Creation of similar climate change decision-support modelling systems in the Antarctic could be accelerated through the formation of a Polar Research Partnership involving scientists working in Arctic and Antarctic systems. This type of partnership could support rapid transfer of knowledge and best practices for the delivery of state-of-the-art science to decision makers to sustain high latitude ecosystems and their services under changing climate conditions.

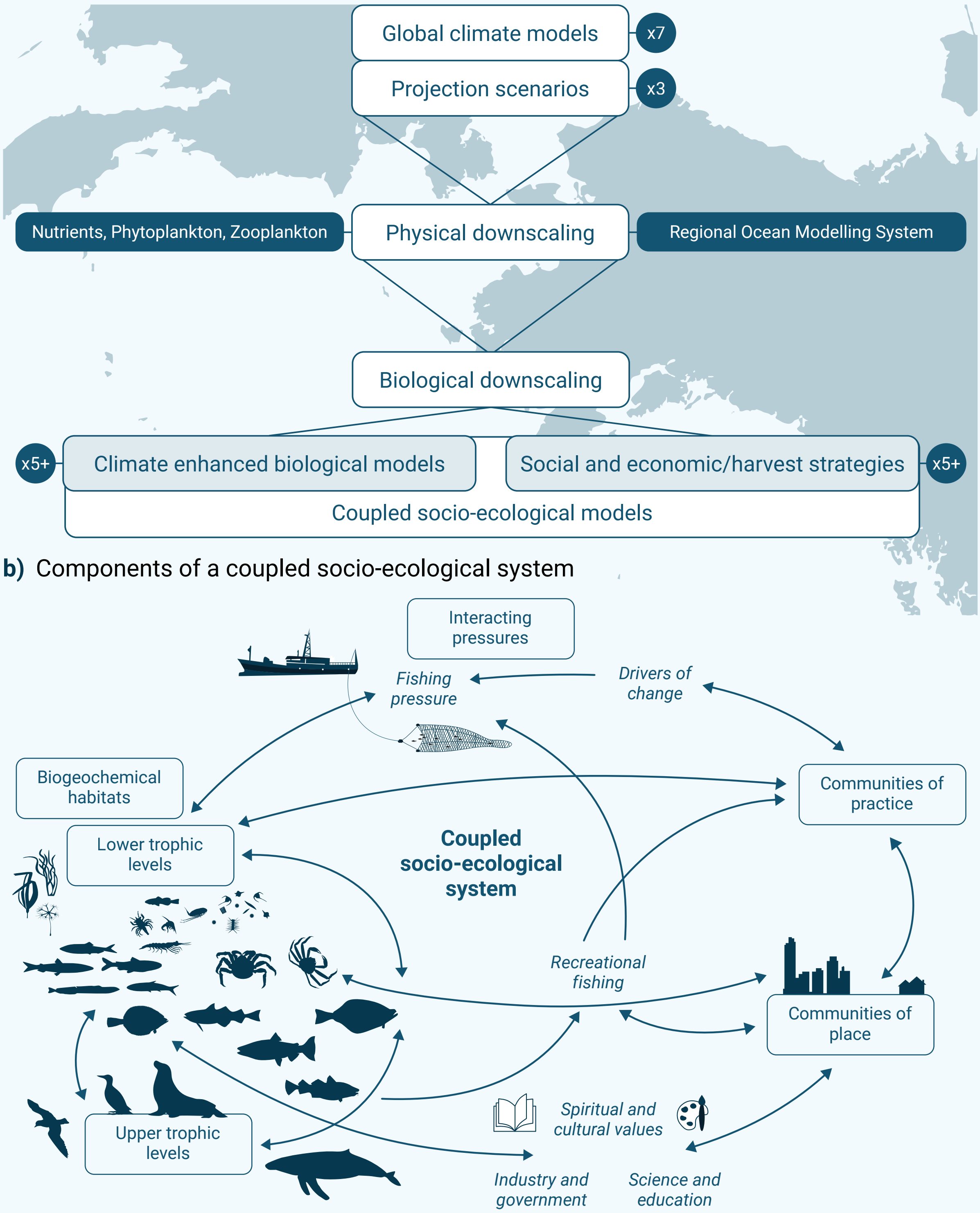


Figure 21: Ensemble modelling of Arctic marine socio-ecological systems to advise on adapting them to climate change. Adapted from Hollowed et al., 2020
a) Boxes show sub-models in the ensemble related to physical, biological and social systems, and the number of different representations of the sub-models. Coupling these models at relevant spatial and biological scales can produce outputs relevant to stakeholders to decide the best strategies for managing activities in regions and how to adapt these systems to environmental change.
b) Relationships between different components of the socio-ecological system at the scale of biological processes and stakeholder interactions.

Global climate models: ECHO-G, MIROC3.2 med res., CGCM3-t47, CCSM4-NCAR-PO, MIROCESM-C-PO, GFDL-ESM2M*-PO, GFDL-ESMRM*-PON; **Projection scenarios:** AR4 A1B, AR5 RCP 4.5, AR5 RCP 8.5; **Nutrients, Phytoplankton, Zooplankton (NPZ) model:** Bering Sea 10K Model; **Climate enhanced biological models:** CE-single-spp assessment models, CE-multi-spp model (CEATTLE), CE-Size spectrum model, CE-Ecopath with Ecosim, End-to-end model (FEAST), CE-spatial MICE model, CE-IBM (crab); **Social and economic/harvest strategies:** No fishing, Status quo, 2MT cap-gadid, 2MT cap-flatfish, CE-control rules

5.7

Managing human activities in the Southern Ocean will benefit from assessing risks associated with different scenarios of climate change and future socio-economic demands; improved socio-ecological modelling and stakeholder engagement will enable better consideration of risks to environments, societies, and economies●●●●[Boxes 4,5][64].

5.7.1

Modelling procedures, including accounting for uncertainty, need to be developed for assessing how the ecosystems may recover from past exploitation [64, 73] combined with the risks of (i) significant change in species, (ii) changing variability and extreme events, (iii) potential tipping points in ecosystems, such as shifting dominance of energy pathways, and (iv) loss of resilience, under different scenarios of habitat change and/or human activities, such as fishing●●●●[Box 5][46, 79].

5.7.2

Consultations across the broad range of stakeholders would improve decision-making on conserving and sustaining ecosystem services in the region●●●○[12, 102].

5.7.3

Consultations across the diversity of cultural and national interests in Antarctica and the Southern Ocean is needed to help frame the objectives and undertaking of scientific assessments and the methods for delivering results into the broader scientific community, civil society and policymakers●●●●[1, 53, 70].

5.8

Extensive collaboration and coordination of activities is needed for further developing observation and data access systems, ecosystem assessments, models, and projections of future change in Southern Ocean ecosystems●●●●[77-79, 102, 113].

5.8.1

Increased collaboration and coordination of international and national activities is required to generate integrated analyses at the scale needed, linking activities of SCAR, ICED, SOOS, CCAMLR, and associated groups including early career researchers●●●●[8, 102].

5.8.1.1

The developing Southern Ocean coordination activity being led by SCAR under the UN Decade of Ocean Science for Sustainable Development provides a mechanism for generating the integration required●●●○[55].

5.8.1.2

The early career APECS and IMBeR-IMECAN communities have a crucial role in leading the development of Southern Ocean and global marine science and are needed to ensure the diverse development and engagement of the Southern Ocean science community●●●●[9].

5.8.1.3

Increased collaboration and coordination is required with science, conservation and management groups in areas outside the Southern Ocean and across the global ocean. SCAR, SOOS, ICED, and the UN Decade activities can provide the mechanism for developing the coordination needed●●●●[55, 75].

5.8.2

The ICED program, a regional program of the global IMBeR program, provides a useful approach to ecosystem modelling, developing a Southern Ocean ecosystem modelling community●●●●[45, 72].

5.8.2.1

Development and comparison of alternative model approaches is needed for models of key species, food webs and ecosystems at regional and circumpolar scales●●●○[45, 46, 72, 79].

Confidence level

•○○○ Low confidence

••○○ Medium confidence

•••○ High confidence

•••• Very high confidence

06

Protecting and enhancing the resilience of Southern Ocean ecosystems

6.1

Evidence from MEASO and recent publications is showing that substantial ecosystem changes are occurring now•••• and could occur in the future over periods of only a few years or decades as a result of rapid environmental shifts, changing patterns of variability, extreme events, or the crossing of system thresholds to alternative states.

6.1.1

There have been rapid changes in species distributions and food webs west of the Antarctic Peninsula over the last few decades, with observed changes in environmental conditions[4, 56, 64, 68, 82, 105].

6.1.2

Assessments of the climate impact pathways on species indicate that recent rapid environmental changes are expected to have regional and circumpolar ecological impacts•••○[2, 4, 7, 11, 28, 56, 82, 105]. These include the observed record minima of circumpolar winter sea-ice extent[Box 2][89], changing frequencies of interannual variability of sea ice and ocean temperatures[68], and the occurrence of marine and atmospheric heatwaves[Box 2][30, 101].

6.1.3

These rapid changes may be unexpected and have diverse ecological impacts, such as the breeding failure in emperor penguin colonies in 2022•••○[31] and shifts in phytoplankton community structure••○○[59].

6.1.4

These ecosystem changes are expected to have consequences for marine ecosystems globally over the course of this century••○○[74].

6.2

The Antarctic Treaty System (beginning in 1959 with the Antarctic Treaty) and its emphasis on conservation and protection, exemplified in the Convention on the Conservation of Antarctic Marine Living Resources (1980) and the Protocol on Environmental Protection to the Antarctic Treaty (1991), provide the most recent articulation of the global interest in Antarctica and the Southern Ocean and the desire for their protection•••○[86, 87].

6.2.1

A primary objective in the Antarctic Treaty System is to conserve the biodiversity and ecosystems of the Southern Ocean●●●●[48, 86, 87].

6.2.2

Sound management of the region is dependent not only on scientific understanding but also on incorporating different perspectives, cultural sensitivities and global priorities●●○○[102].

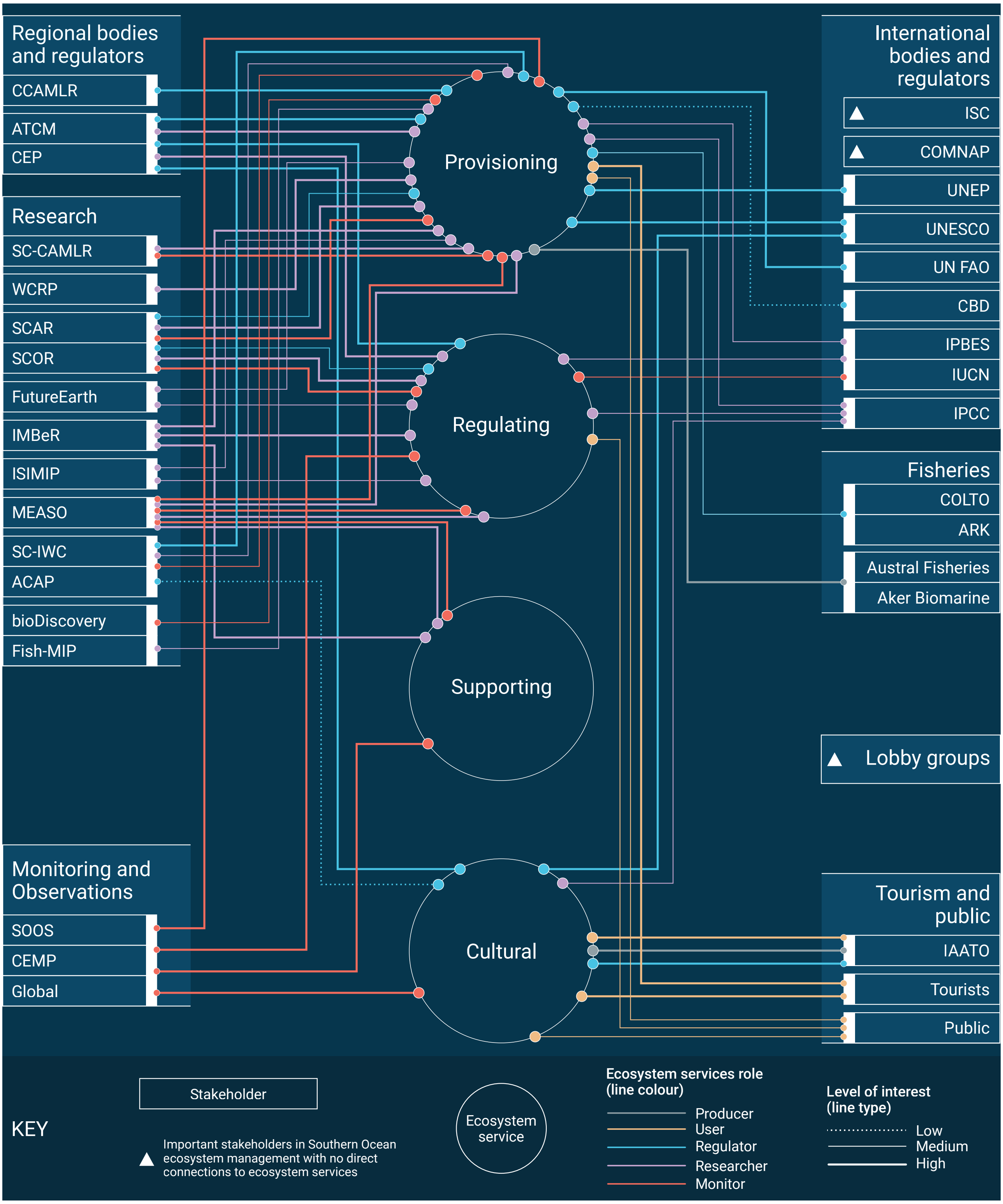


Figure 22: Stakeholder engagement, including the wider public, needed to manage and protect ecosystem services in the Southern Ocean (adapted from Solomonsz et al. 2021). Stakeholders have influencing links to an ecosystem service either through scientific advice/evidence, as users or as policymakers/managers. Stakeholders listed under 'Research' are examples - i.e. not comprehensive. Acronyms are detailed in the Glossary.

6.3

Regional pressures on Southern Ocean species and ecosystems have been dominated by fisheries, with human presence (stations and tourism) and associated sources of pollution having localised, but increasing, impacts•••○[35]. Pollution originating from outside the Southern Ocean has been detected for decades and is increasing•••○[68].

6.3.1

Seal and whale populations were substantially over-exploited from the late 18th to mid 20th centuries••••; no commercial sealing or whaling is occurring in the Southern Ocean at present [35].

6.3.1.1

Antarctic fur seals and humpback whales have had strong recoveries, but many whale species have not recovered from being critically endangered ••○○[4].

6.3.1.2

Southern elephant seals exhibit differing population trends among colonies as a result of variations in habitat quality, wintering ice conditions, food quality and availability at foraging grounds, and particularly long-term regional trends in sea-ice extent••○○[4, 30, 58].

6.3.2

Finfish stocks were over-exploited prior to the establishment of CCAMLR in 1982•••○; fishing is currently permitted for Antarctic krill, Antarctic and Patagonian toothfish and mackerel icefish under the management of CCAMLR[35].

6.3.2.1

A reconstruction of historical finfish fishing shows substantial removals by bottom trawling around most subantarctic islands and in some areas of the Antarctic continental shelf[35]; many species are yet to recover•••○[11].

6.3.2.2

Seabirds affected by fisheries in the CCAMLR area[35] are still declining despite a near cessation of their mortality in CCAMLR fisheries•••○[4].

6.3.3

Pollutants, such as persistent organic pollutants (POPs), are increasingly transported to the Southern Ocean via the atmosphere, oceans and migratory animals; pollution accumulated in glaciers could be released with increased ice melt••○○[4, 68].

6.4

Strategies for conserving Southern Ocean marine biodiversity, including management of fisheries, need to be further developed, based on current knowledge of the implications of climate change, to ensure resilience of Southern Ocean ecosystems into the future•••○[35].

6.4.1

CCAMLR has an ecosystem approach for achieving conservation embedded within its Convention[85, 86] and maintains a precautionary approach for the fisheries it manages•••○[35].

6.4.1.1

CCAMLR is yet to implement specific approaches for managing the needs of krill predators in an expanding fishery, although methods have been agreed for development in the Scientific Committee of CCAMLR (SC-CAMLR)•••○[18, 114].

6.4.1.2

The SC-CAMLR has not yet assessed whether the strategies for managing fisheries will be successful under scenarios of climate change and ocean acidification•••○[15].

6.4.2

CCAMLR agreed in 2011 to establish a representative system of marine protected areas (MPAs) in the Southern Ocean; to date, only two MPAs have been established••○○[6, 10].

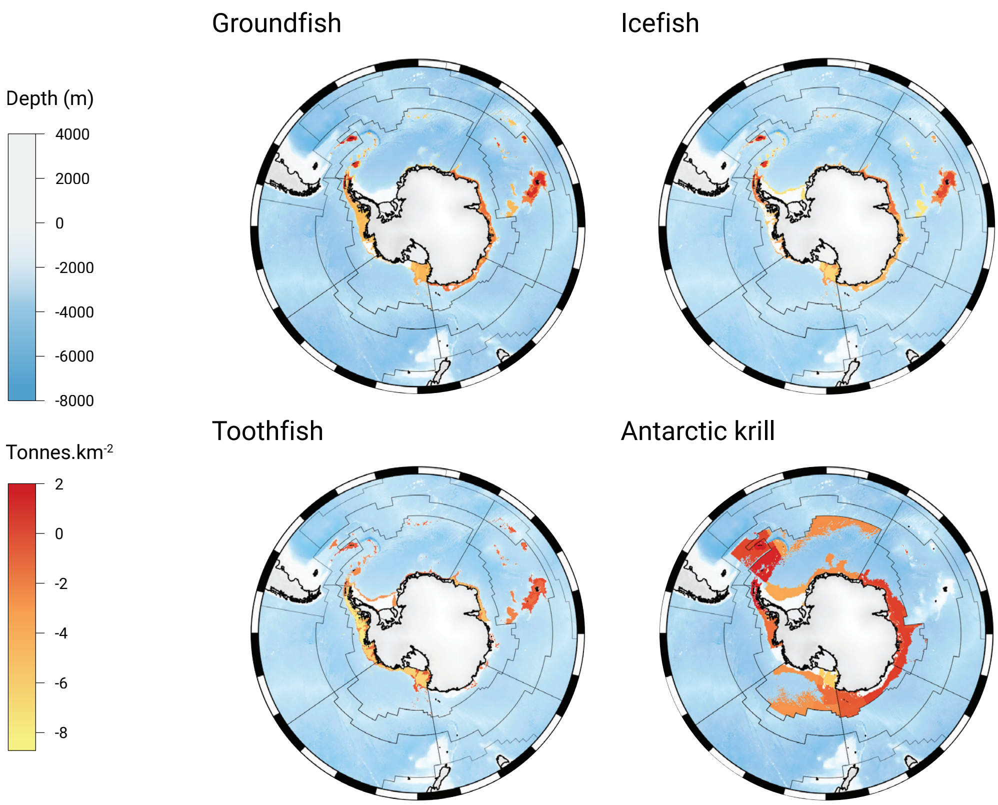
6.4.3

The current state of finfish species depleted prior to CCAMLR is not well documented•••○[15].

6.4.4

Effective regional and local protection is critical to safeguard ecosystems against the effects of climate change which are already underway; strategies are needed for planning, preparing and responding to rapid and potentially unexpected or surprising changes in Southern Ocean ecosystems•••○[79, 101].

a) Accumulated catch (1970-2022)



b) Current spatial protection and management areas

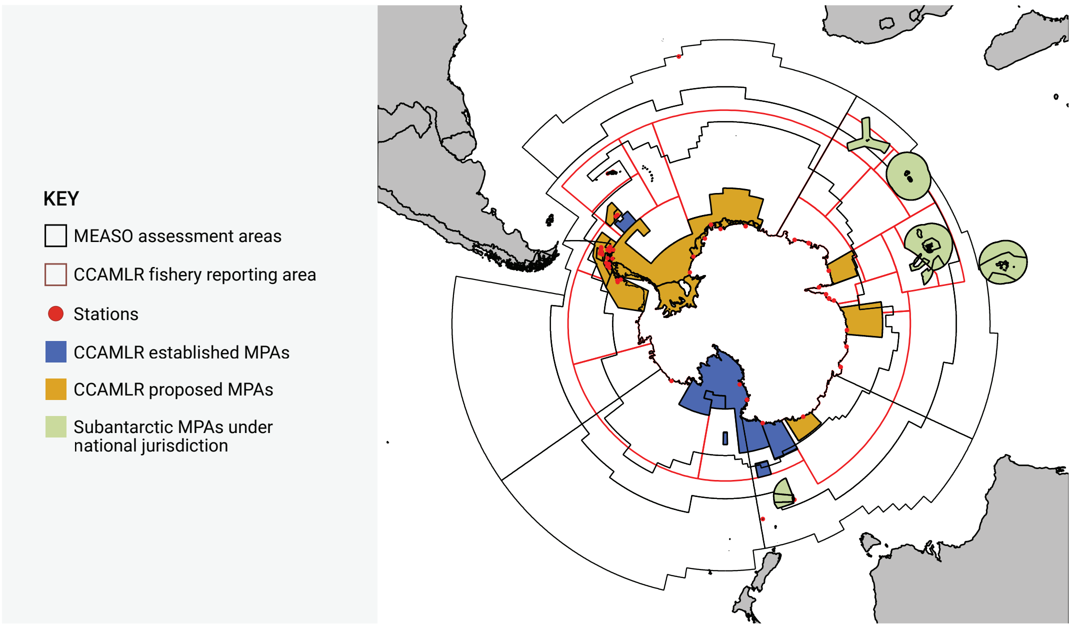


Figure 23: a) Accumulated catch for groundfish, icefish, toothfish and Antarctic krill from 1970 to 2022 plotted against ocean depth as catch density (tonnes per square kilometre). Source data: CCAMLR Statistical Bulletin 2022. Black lines show the boundaries of the 15 MEASO areas. Note: haul data are not available in the Bulletin, so catch records are distributed by rules relating to depth and general locations of fishing operations resulting in some catches being dispersed over large areas, such as for Antarctic krill[35].
b) Current management areas in the area of the Convention on the Conservation of Antarctic Marine Living Resources: fishery reporting areas (red lines), CCAMLR marine protected areas - established (blue) and proposed (brown). Nationally enforced subantarctic reserves (olive green), coastal Antarctic stations (red dots), and MEASO areas (black lines) are also shown. Small protected areas not visible on this map also include Antarctic Specially Protected Areas and Vulnerable Marine Ecosystems.

Risk assessment for Southern Ocean ecosystem services

The below table summarises the risk assessment for Southern Ocean ecosystem services with associated confidence indicated as:

●●● High confidence
●● Medium confidence
● Low confidence
○ No assessed level of confidence available

Key

- High-level risk
- Intermediate risk
- Low-level risk
- Insufficient evidence to assess level of risk

Ecosystem services	Sea ice	Ocean temperature	Ocean acidification	Stratification	Glaciers, ice shelves, & ice sheets	Ocean circulation	Overall risk rating
	Drivers						
Provisioning							
Antarctic krill	●●	●●	●			○	
Toothfish		●					
Other harvested species		●					
Regulating							
Blue carbon pathway	○	○	○	○	●●	○	
Supporting							
Primary production (open ocean)	●●		●	●●		○	
Primary production (coastal)	●●		●●	●	●●		
Nutrient cycling	○			○	○	○	
Cultural							
Tourism and recreation	●●*				○		

*there is medium confidence for the effects on wildlife, but no assessment on the level of confidence for the effect of sea-ice change on tourism and recreation overall.

Figure 24: Risk assessment for Southern Ocean ecosystem services. Adapted from Cavanagh et al., 2021

6.5

Long-term maintenance of Southern Ocean ecosystems, particularly polar-adapted Antarctic species and coastal systems, can only be achieved with high confidence by significant and urgent global action to curb climate change and ocean acidification••••[17].

6.5.1

Climate change is the most significant driver of species and ecosystem change in the Southern Ocean and coastal Antarctica••••[4, 7, 11, 42, 56, 68, 82, 105].

6.5.2

Direct human interventions at sufficient scale to reduce sensitivities and exposure of cold- and sea-ice-adapted species to the impacts of climate change and preserve Southern Ocean ecosystems are unavailable at present••••.

6.5.3

Actions are needed to ensure local and regional human activities do not impact resilience of these species and systems••••[12, 35], and to reduce the risk of Southern Ocean ecosystems transitioning into alternative states from which recovery cannot be achieved.

Figure 25: Developing cultural awareness by bridging diversity of experiences in conversation and the arts. Figure credit: Lisa Roberts

References

MEASO articles:

Context (35, 68, 74, 112)

Biota and food webs (4, 7, 11, 42, 56, 64, 82, 105)

Challenges for policymakers (12)

Extensions of MEASO (2, 28, 57, 99)

Giving effect to MEASO (5, 9, 18, 85, 94, 102, 114)

1.
Anon. 2022. Climate change and human behaviour. Nat Hum Behav 6(11):1441-2. doi: 10.1038/s41562-022-01490-9

2.
Baldry K, Strutton PG, Hill NA, Boyd PW. 2020. Subsurface chlorophyll-a maxima in the Southern Ocean. Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.00671

3.
Beadling RL, Russell JL, Stouffer RJ, Mazloff M, Talley LD, Goodman PJ, et al. 2020. Representation of Southern Ocean Properties across Coupled Model Intercomparison Project Generations: CMIP3 to CMIP6. Journal of Climate 33(15):6555-81. doi: 10.1175/jcli-d-19-0970.1

4.
Bestley S, Ropert-Coudert Y, Bengtson Nash S, Brooks CM, Cotté C, Dewar M, et al. 2020. Marine Ecosystem Assessment for the Southern Ocean: Birds and marine mammals in a changing climate. Frontiers in Ecology and Evolution 8 doi: 10.3389/fevo.2020.566936

5.
Bonnet-Lebrun A-S, Sweetlove M, Griffiths HJ, Sumner M, Provoost P, Raymond B, et al. 2023. Opportunities and limitations of large open biodiversity occurrence databases in the context of a Marine Ecosystem Assessment of the Southern Ocean. Frontiers in Marine Science 10 doi: 10.3389/fmars.2023.1150603

6.
Boothroyd A, Adams V, Alexander K, Hill N. 2023. Benefits and risks of incremental protected area planning in the Southern Ocean. Nature Sustainability:10. doi: 10.1038/s41893-023-01077-w

7.
Brasier MJ, Barnes D, Bax N, Brandt A, Christianson AB, Constable AJ, et al. 2021. Responses of Southern Ocean seafloor habitats and communities to global and local drivers of change. Frontiers in Marine Science 8:30. doi: 10.3389/fmars.2021.622721

8.
Brasier MJ, Constable A, Melbourne-Thomas J, Trebilco R, Griffiths H, Van de Putte A, et al. 2019. Observations and models to support the first Marine Ecosystem Assessment for the Southern Ocean (MEASO). Journal of Marine Systems 197:103182. doi: 10.1016/j.jmarsys.2019.05.008

9.
Brasier MJ, McCormack S, Bax N, Caccavo JA, Cavan E, Ericson JA, et al. 2020. Overcoming the obstacles faced by early career researchers in marine science: Lessons from the Marine Ecosystem Assessment for the Southern Ocean. Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.00692

10.
Brooks CM, Chown SL, Douglass LL, Raymond BP, Shaw JD, Sylvester ZT, et al. 2020. Progress towards a representative network of Southern Ocean protected areas. PLoS One 15(4):e0231361. doi: 10.1371/journal.pone.0231361

11.
Caccavo JA, Christiansen H, Constable AJ, Ghigliotti L, Trebilco R, Brooks CM, et al. 2021. Productivity and change in fish and squid in the Southern Ocean. Frontiers in Ecology and Evolution 9 doi: 10.3389/fevo.2021.624918

12.
Cavanagh RD, Melbourne-Thomas J, Grant SM, Barnes DKA, Hughes KA, Halfter S, et al. 2021. Future risk for Southern Ocean ecosystem services under climate change. Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.615214

13.
Cavanagh RD, Trathan PN, Hill SL, Melbourne-Thomas J, Meredith MP, Hollyman P, et al. 2021. Utilising IPCC assessments to support the ecosystem approach to fisheries management within a warming Southern Ocean. Marine policy 131 doi: 10.1016/j.marpol.2021.104589

14.
CBD. 2022. Decision 15/4: Kunming-Montreal Global Biodiversity Framework. Conference of Parties 15, Convention on Biological Diversity.

15.
CCAMLR Performance Review Panel. 2017. Second Performance Review of CCAMLR - Final Report of the Panel. Commission Paper CCAMLR-XXXV/01 presented to the Commission for the Conservation of Antarctic Marine Living Resources doi: https://www.ccamlr.org/en/system/files/e-cc-xxxvi-01-w-cp.pdf.

16.
Cimino MA, Conroy JA, Connors E, Bowman J, Corso A, Ducklow H, et al. 2023. Long-term patterns in ecosystem phenology near Palmer Station, Antarctica, from the perspective of the Adélie penguin. Ecosphere 14(2) doi: 10.1002/ecs2.4417

17.
Constable A, Harper S, Dawson J, Holsman K, Mustonen T, Piepenburg D, et al. 2022. Cross-Chapter Paper 6: Polar Regions. In: Pörtner H-O, Roberts D, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, et al., editors. Climate Change 2022: Impacts, Adaptation and Vulnerability Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press. p. 2319–68.

18.
Constable A, Kawaguchi S, Sumner M, Trathan P, Warwick-Evans V. 2023. A dynamic framework for assessing and managing risks to ecosystems from fisheries: demonstration for conserving the krill-based food web in Antarctica. Frontiers in Ecology and Evolution 11 doi: 10.3389/fevo.2023.1043800

19.
Constable AJ, Costa D, Murphy E, Hofmann E, Schofield O, Press A, et al. 2014. Chapter 9.3 Assessing status and change in Southern Ocean ecosytems. In: De Broyer C, Koubbi P, Griffiths H, Raymond B, d'Udekem d'Acoz C, Van de Putte A, et al., editors. Biogeographic Atlas of the Southern Ocean. Cambridge UK: Scientific Committee on Antarctic Research. p. 404-7.

20.
Constable AJ, Costa DP, Schofield O, Newman L, Urban Jr ER, Fulton EA, et al. 2016. Developing priority variables ("ecosystem Essential Ocean Variables" — eEOVs) for observing dynamics and change in Southern Ocean ecosystems. Journal of Marine Systems 161:26-41. doi: 10.1016/j.jmarsys.2016.05.00

21.
Constable AJ, Melbourne-Thomas J, Corney SP, Arrigo KR, Barbraud C, Barnes DKA, et al. 2014. Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. Global Change Biology 20(10):3004-25. doi: 10.1111/gcb.12623

22.
Constable AJ, Melbourne-Thomas J, Trebilco R, Press AJ, Haward M. 2017. ACE CRC Position Analysis: Managing change in Southern Ocean ecosystems. Hobart, Australia: Antarctic Climate and Ecosystems Cooperative Research Centre. doi.

23.
De Broyer C, Koubbi P, Griffiths H, Raymond B, d'Udekem d'Acoz C, Van de Putte A, et al. 2014. Biogeographic Atlas of the Southern Ocean. Cambridge UK: Scientific Committee on Antarctic Research. xii + 498 p.

24.
deYoung B, Visbeck M, de Araujo Filho MC, Baringer MON, Black C, Buch E, et al. 2019. An integrated all-Atlantic Ocean Observing System in 2030. Frontiers in Marine Science 6 doi: 10.3389/fmars.2019.00428

25.
Dobush B-J, Gallo ND, Guerra M, Guilloux B, Holland E, Seabrook S, et al. 2021. A new way forward for ocean-climate policy as reflected in the UNFCCC Ocean and Climate Change Dialogue submissions. Climate Policy:1-18. doi: 10.1080/14693062.2021.1990004

26.
Drenkard EJ, Stock C, Ross AC, Dixon KW, Adcroft A, Alexander M, et al. 2021. Next-generation regional ocean projections for living marine resource management in a changing climate. ICES Journal of Marine Science 78(6):1969-87. doi: 10.1093/icesjms/fsab100

27.
Eayrs C, Li X, Raphael MN, Holland DM. 2021. Rapid decline in Antarctic sea ice in recent years hints at future change. Nature Geoscience 14(7):460-4. doi: 10.1038/s41561-021-00768-3

28.
Figuerola B, Hancock AM, Bax N, Cummings VJ, Downey R, Griffiths HJ, et al. 2021. A review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the Southern Ocean. Frontiers in Marine Science 8 doi: 10.3389/fmars.2021.584445

29.
Fox-Kemper B, Hewitt HT, Xiao C, Aðalgeirsdóttir G, Drijfhout SS, Edwards TL, et al. 2021. Ocean, Cryosphere and Sea Level Change. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, et al., editors. Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. p. 1211–362.

30.
Fraser AD, Wongpan P, Langhorne PJ, Klekociuk AR, Kusahara K, Lannuzel D, et al. 2023. Antarctic landfast sea ice: a review of its physics, biogeochemistry and ecology. Reviews of Geophysics 61(2) doi: 10.1029/2022rg000770

31.
Fretwell PT, Boutet A, Ratcliffe N. 2023. Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins. Communications Earth & Environment 4(1) doi: 10.1038/s43247-023-00927-x

32.
Fripiat F, Martínez-García A, Marconi D, Fawcett SE, Kopf SH, Luu VH, et al. 2021. Nitrogen isotopic constraints on nutrient transport to the upper ocean. Nature Geoscience 14(11):855-61. doi: 10.1038/s41561-021-00836-8

33.
Frölicher TL, Sarmiento JL, Paynter DJ, Dunne JP, Krasting JP, Winton M. 2015. Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. Journal of Climate 28(2):862-86. doi: 10.1175/jcli-d-14-00117.1

34.
Gales N. 2022. At 75 years old, the IWC has never been more globally relevant. Marine policy 141 doi: 10.1016/j.marpol.2022.105089

35.
Grant SM, Waller CL, Morley SA, Barnes DKA, Brasier MJ, Double MC, et al. 2021. Local drivers of change in Southern Ocean ecosystems: human activities and policy implications. Frontiers in Ecology and Evolution 9 doi: 10.3389/fevo.2021.624518

36.
Gutt J, Arndt S, Barnes DKA, Bornemann H, Brey T, Eisen O, et al. 2022. Reviews and syntheses: A framework to observe, understand and project ecosystem response to environmental change in the East Antarctic Southern Ocean. Biogeosciences 19(22):5313-42. doi: 10.5194/bg-19-5313-2022

37.
Gutt J, Bertler N, Bracegirdle TJ, Buschmann A, Comiso J, Hosie G, et al. 2015. The Southern Ocean ecosystem under multiple climate change stresses - an integrated circumpolar assessment. Global Change Biology 21(4):1434-53. doi: 10.1111/gcb.12794

38.
Gutt J, Isla E, Bertler AN, Bodeker GE, Bracegirdle TJ, Cavanagh RD, et al. 2018. Cross-disciplinarity in the advance of Antarctic ecosystem research. Mar Genomics 37:1-17. doi: 10.1016/j.margen.2017.09.006

39.
Gutt J, Isla E, Xavier JC, Adams BJ, Ahn IY, Cheng CC, et al. 2021. Antarctic ecosystems in transition - life between stresses and opportunities. Biol Rev Camb Philos Soc 96(3):798-821. doi: 10.1111/brv.12679

40.
Hansen C, Nash RDM, Drinkwater KF, Hjøllo SS. 2019. Management Scenarios Under Climate Change – A Study of the Nordic and Barents Seas. Frontiers in Marine Science 6 doi: 10.3389/fmars.2019.00668

41.
Harcourt R, Sequeira AMM, Zhang X, Roquet F, Komatsu K, Heupel M, et al. 2019. Animal-borne telemetry: an integral component of the ocean observing toolkit. Frontiers in Marine Science 6 doi: 10.3389/fmars.2019.00326

42.
Henley SF, Cavan EL, Fawcett SE, Kerr R, Monteiro T, Sherrell RM, et al. 2020. Changing biogeochemistry of the Southern Ocean and its ecosystem implications. Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.00581

43.
Hermann AJ, Gibson GA, Cheng W, Ortiz I, Aydin K, Wang M, et al. 2019. Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. ICES Journal of Marine Science doi: 10.1093/icesjms/fsz043

44.
Hindell MA, Reisinger RR, Ropert-Coudert Y, Hückstädt LA, Trathan PN, Bornemann H, et al. 2020. Tracking of marine predators to protect Southern Ocean ecosystems. Nature 580(7801):87-92. doi: 10.1038/s41586-020-2126-y

45.
Hofmann E, Bundy A, Drinkwater K, Piola AR, Avril B, Robinson C, et al. 2015. IMBER – Research for marine sustainability: Synthesis and the way forward. Anthropocene 12:42-53. doi: 10.1016/j.ancene.2015.12.002

46.
Hollowed AB, Holsman KK, Haynie AC, Hermann AJ, Punt AE, Aydin K, et al. 2020. Integrated modeling to evaluate climate change impacts on coupled social-ecological systems in Alaska. Frontiers in Marine Science 6 doi: 10.3389/fmars.2019.00775

47.
Holsman KK, Haynie AC, Hollowed AB, Reum JCP, Aydin K, Hermann AJ, et al. 2020. Ecosystem-based fisheries management forestalls climate-driven collapse. Nat Commun 11(1):4579. doi: 10.1038/s41467-020-18300-3

48.
Hughes KA, Constable A, Frenot Y, López-Martínez J, McIvor E, Njåstad B, et al. 2018. Antarctic environmental protection: Strengthening the links between science and governance. Environmental Science & Policy 83:86-95. doi: 10.1016/j.envsci.2018.02.006

49.
IPBES. 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Version 1). doi: 10.5281/zenodo.6417333

50.
IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). Bonn, Germany: IPBES Secretariat.

51.
IPCC. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY: Cambridge University Press.

52.
IPCC. 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge, UK and New York: Cambridge University Press. 3-33 p.

53.
IPCC. 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge, UK and New York, NY, USA: Cambridge University Press.

54.
IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York: Cambridge University Press. doi: 10.1017/9781009157926

55.
Janssen AR, Badhe R, Bransome NC, Bricher P, Cavanagh R, de Bruin T, et al. 2022. Southern Ocean Action Plan (2021-2030) in support of the United Nations Decade of Ocean Science for Sustainable Development. doi: 10.5281/zenodo.6412191.

56.
Johnston NM, Murphy EJ, Atkinson AA, Constable AJ, Cotté CS, Cox M, et al. 2022. Status, change and futures of zooplankton in the Southern Ocean. Frontiers in Ecology and Evolution 9:41. doi: 10.3389/fevo.2021.624692

57.
Kauko HM, Hattermann T, Ryan-Keogh T, Singh A, de Steur L, Fransson A, et al. 2021. Phenology and Environmental Control of Phytoplankton Blooms in the Kong Håkon VII Hav in the Southern Ocean. Frontiers in Marine Science 8 doi: 10.3389/fmars.2021.623856

58.
Laborie J, Authier M, Chaigne A, Delord K, Weimerskirch H, Guinet C. 2023. Estimation of total population size of southern elephant seals (Mirounga leonina) on Kerguelen and Crozet Archipelagos using very high-resolution satellite imagery. Frontiers in Marine Science 10 doi: 10.3389/fmars.2023.1149100

59.
Latorre MP, Iachetti CM, Schloss IR, Antoni J, Malits A, de la Rosa F, et al. 2023. Summer heatwaves affect coastal Antarctic plankton metabolism and community structure. Journal of Experimental Marine Biology and Ecology 567 doi: 10.1016/j.jembe.2023.151926

60.
Lecocq F, Winkler H, Daka JP, Fu S, Gerber JS, Kartha S, et al. 2022. Mitigation and development pathways in the near- to mid-term. In: Shukla P, Skea J, Slade R, Al Khourdajie A, van Diemen R, McCollum D, et al., editors. Climate Change 2022: Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press. doi: 10.1017/9781009157926.006

61.
Li Q, England MH, Hogg AM, Rintoul SR, Morrison AK. 2023. Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. Nature 615(7954):841-7. doi: 10.1038/s41586-023-05762-w

62.
Mazloff M, Chai F, Constable A, Pei Y, Newman L. 2018. Southern Ocean Modelling: status and observational data requirements. Report of a SOOS Workshop, Second Institute of Oceanography, Hangzhou, China 7-8 May 2018. doi: 10.5281/zenodo.3951902

63.
McCormack SA, Melbourne-Thomas J, Trebilco R, Blanchard JL, Raymond B, Constable A. 2021. Decades of dietary data demonstrate regional food web structures in the Southern Ocean. Ecol Evol 11(1):227-41. doi: 10.1002/ece3.7017

64.
McCormack SA, Melbourne-Thomas J, Trebilco R, Griffith G, Hill SL, Hoover C, et al. 2021. Southern Ocean food web modelling: progress, prognoses, and future priorities for research and policy makers. Frontiers in Ecology and Evolution 9 doi: 10.3389/fevo.2021.624763

65.
Meredith M, Sommerkorn M, Cassotta S, Derksen C, Ekaykin A, Hollowed A, et al. 2019. Polar Regions. In: Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, et al., editors. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge, UK and New York, NY, USA: Cambridge University Press. p. 203–320.

66.
Meredith M, Sommerkorn M, Cassotta S, Derksen C, Ekaykin A, Hollowed A, et al. 2019. Polar Regions. In: Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, et al., editors. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. p. 203-320.

67.
Meredith MP, Falk U, Bers AV, Mackensen A, Schloss IR, Ruiz Barlett E, et al. 2018. Anatomy of a glacial meltwater discharge event in an Antarctic cove. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 376(2122):20170163. doi: doi:10.1098/rsta.2017.0163

68.
Morley SA, Abele D, Barnes DKA, Cárdenas CA, Cotté C, Gutt J, et al. 2020. Global drivers on Southern Ocean ecosystems: changing physical environments and anthropogenic pressures in an Earth System. Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.547188

69.
Morley SA, Barnes DKA, Dunn MJ. 2019. Predicting which species succeed in climate-forced polar seas. Frontiers in Marine Science 5 doi: 10.3389/fmars.2018.00507

70.
Muelbert MMC, Copertino M, Cotrim da Cunha L, Lewis MN, Polejack A, Peña-Puch AdC, et al. 2021. The ocean and cryosphere in a changing climate in Latin America: knowledge gaps and the urgency to translate science into action. Frontiers in Climate 3 doi: 10.3389/fclim.2021.748344

71.
Muller-Karger FE, Miloslavich P, Bax NJ, Simmons S, Costello MJ, Sousa Pinto I, et al. 2018. Advancing marine biological observations and data requirements of the complementary Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) frameworks. Frontiers in Marine Science 5 doi: 10.3389/fmars.2018.00211

72.
Murphy E, Corney S, Hoffman E, Meyer B, Johnston N, Thorpe S, et al. 2022. Using models to improve our understanding of Antarctic krill and their ecological role in the Southern Ocean. Zenodo. doi: 10.5281/zenodo.6780069

73.
Murphy EJ, Cavanagh RD, Hofmann EE, Hill SL, Constable AJ, Costa DP, et al. 2012. Developing integrated models of Southern Ocean food webs: Including ecological complexity, accounting for uncertainty and the importance of scale. Progress in Oceanography 102:74-92. doi: 10.1016/j.pocean.2012.03.006

74.
Murphy EJ, Johnston NM, Hofmann EE, Phillips RA, Jackson JA, Constable AJ, et al. 2021. Global connectivity of Southern Ocean ecosystems. Frontiers in Ecology and Evolution 9 doi: 10.3389/fevo.2021.624451

75.
Murphy EJ, Robinson C, Hobday AJ, Newton A, Glaser M, Evans K, et al. 2021. The global pandemic has shown we need an action plan for the ocean. Frontiers in Marine Science 8 doi: 10.3389/fmars.2021.760731

76.
National Academies of Sciences Engineering and Medicine. 2017. Antarctic Sea Ice Variability in the Southern Ocean-Climate System: Proceedings of a Workshop. Washington, DC: The National Academies Press.

77.
Newman L, Hancock AM, Hofmann E, Williams MJM, Henley SF, et al. 2022. The Southern Ocean Observing System 2021-2025 Science and Implementation Plan. Zenodo: Southern Ocean Observing System. doi: 10.5281/zenodo.6324359

78.
Newman L, Heil P, Trebilco R, Katsumata K, Constable A, van Wijk E, et al. 2019. Delivering sustained, coordinated and integrated observations of the Southern Ocean for global impact. Frontiers in Marine Science doi: 10.3389/fmars.2019.00433

79.
Ottersen G, Constable AJ, Hollowed AB, Holsman KK, Melbourne-Thomas J, Muelbert MMC, et al. 2022. Climate change impacts on polar marine ecosystems: toward robust approaches for managing risks and uncertainties. Frontiers in Climate 3 doi: 10.3389/fclim.2021.733755

80.
Pallin LJ, Kellar NM, Steel D, Botero-Acosta N, Baker CS, Conroy JA, et al. 2023. A surplus no more? Variation in krill availability impacts reproductive rates of Antarctic baleen whales. Glob Chang Biol 29(8):2108-21. doi: 10.1111/gcb.16559

81.
Pearlman J, Bushnell M, Coppola L, Karstensen J, Buttigieg PL, Pearlman F, et al. 2019. Evolving and sustaining ocean best practices and standards for the next decade. Frontiers in Marine Science 6 doi: 10.3389/fmars.2019.00277

82.
Pinkerton MH, Boyd PW, Deppeler S, Hayward A, Höfer J, Moreau S. 2021. Evidence for the impact of climate change on primary producers in the Southern Ocean. Frontiers in Ecology and Evolution 9 doi: 10.3389/fevo.2021.592027

83.
Pinkerton MH, Hayward A. 2021. Estimating variability and long-term change in sea ice primary productivity using a satellite-based light penetration index. Journal of Marine Systems 221 doi: 10.1016/j.jmarsys.2021.103576

84.
Pinnegar JK, Hamon KG, Kreiss CM, Tabeau A, Rybicki S, Papathanasopoulou E, et al. 2021. Future Socio-Political Scenarios for Aquatic Resources in Europe: A Common Framework Based on Shared-Socioeconomic-Pathways (SSPs). Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.568219

85.
Press AJ. 2021. Science and policy interactions in assessing and managing marine ecosystems in the Southern Ocean. Frontiers in Ecology and Evolution 9 doi: 10.3389/fevo.2021.576047

86.
Press AJ, Constable AJ. 2022. Conservation Law in Antarctica and the Southern Ocean: the Antarctic Treaty System, conservation, and environmental protection. Australian Journal of International Affairs:1-19. doi: 10.1080/10357718.2022.2057920

87.
Press AJ, Hodgson-Johnston I, Constable AJ. 2019. Governing Marine Living Resources in the Polar Regions. The principles of the Convention on the Conservation of Antarctic Marine Living Resources: why its Commission is not a Regional Fisheries Management Organisation: Edward Elgar Publishing.

88.
Punt AE, Dalton MG, Cheng W, Hermann AJ, Holsman KK, Hurst TP, et al. 2021. Evaluating the impact of climate and demographic variation on future prospects for fish stocks: An application for northern rock sole in Alaska. Deep Sea Research Part II: Topical Studies in Oceanography 189-190 doi: 10.1016/j.dsr2.2021.104951

89.
Purich A, Doddridge EW. 2023. Record low Antarctic sea ice coverage indicates a new sea ice state. Communications Earth & Environment 4(1) doi: 10.1038/s43247-023-00961-9

90.
Purich A, England MH, Cai W, Sullivan A, Durack PJ. 2018. Impacts of Broad-Scale Surface Freshening of the Southern Ocean in a Coupled Climate Model. Journal of Climate 31(7):2613-32. doi: 10.1175/jcli-d-17-0092.1

91.
Rackow T, Danilov S, Goessling HF, Hellmer HH, Sein DV, Semmler T, et al. 2022. Delayed Antarctic sea-ice decline in high-resolution climate change simulations. Nat Commun 13(1):637. doi: 10.1038/s41467-022-28259-y

92.
Raphael MN, Handcock MS. 2022. A new record minimum for Antarctic sea ice. Nature Reviews Earth & Environment 3(4):215-6. doi: 10.1038/s43017-022-00281-0

93.
Reum JCP, Blanchard JL, Holsman KK, Aydin K, Hollowed AB, Hermann AJ, et al. 2020. Ensemble Projections of Future Climate Change Impacts on the Eastern Bering Sea Food Web Using a Multispecies Size Spectrum Model. Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.00124

94.
Roberts L, Kutay C, Melbourne-Thomas J, Petrou K, Benson TM, Fiore D, et al. 2021. Enabling enduring evidence-based policy for the Southern Ocean through cultural arts practices. Frontiers in Ecology and Evolution 9 doi: 10.3389/fevo.2021.616089

95.
Ropert-Coudert Y, Van de Putte AP, Reisinger RR, Bornemann H, Charrassin JB, Costa DP, et al. 2020. The retrospective analysis of Antarctic tracking data project. Sci Data 7(1):94. doi: 10.1038/s41597-020-0406-x

96.
Sarmiento JL, Gruber N, Brzezinski MA, Dunne JP. 2004. High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 427(6969):56-60.

97.
SCAR. 2022. SCAR Data Policy. Scientific Committee on Antarctic Research (https://www.scar.org/library/products/scadm/5767-scar-data-policy-2022/file/#:~:text=Data%20collected%20as%20part%20of,precision%20specified%20in%20the%20metadata).

98.
Seferian R, Berthet S, Yool A, Palmieri J, Bopp L, Tagliabue A, et al. 2020. Tracking Improvement in Simulated Marine Biogeochemistry Between CMIP5 and CMIP6. Curr Clim Change Rep 6(3):95-119. doi: 10.1007/s40641-020-00160-0

99.
Sergi S, Baudena A, Cotté C, Ardyna M, Blain S, d'Ovidio F. 2020. Interaction of the Antarctic Circumpolar Current With seamounts fuels moderate blooms but vast foraging grounds for multiple marine predators. Frontiers in Marine Science 7 doi: 10.3389/fmars.2020.00416

100.
Shu Q, Wang Q, Song Z, Qiao F, Zhao J, Chu M, et al. 2020. Assessment of Sea Ice Extent in CMIP6 With Comparison to Observations and CMIP5. Geophysical Research Letters 47(9) doi: 10.1029/2020gl087965

101.
Siegert MJ, Bentley MJ, Atkinson A, Bracegirdle TJ, Convey P, Davies B, et al. 2023. Antarctic extreme events. Frontiers in Environmental Science 11 doi: 10.3389/fenvs.2023.1229283

102.
Solomonsz J, Melbourne-Thomas J, Constable A, Trebilco R, van Putten I, Goldsworthy L. 2021. Stakeholder engagement in decision making and pathways of influence for Southern Ocean ecosystem services. Frontiers in Marine Science 8 doi: 10.3389/fmars.2021.623733

103.
SOOS DMSC. 2022. SOOS Data Policy. Zenodo. Southern Ocean Observing System Data Management Sub-Committee. doi: 10.5281/zenodo.6041433

104.
Steffen W, Leinfelder R, Zalasiewicz J, Waters CN, Williams M, Summerhayes C, et al. 2016. Stratigraphic and Earth System approaches to defining the Anthropocene. Earth's Future 4(8):324-45. doi: 10.1002/2016ef000379

105.
Swadling KM, Constable AJ, Fraser AD, Massom RA, Borup MD, Ghigliotti L, et al. 2023. Biological responses to change in Antarctic sea ice habitats. Frontiers in Ecology and Evolution 10 doi: 10.3389/fevo.2022.1073823

106.
Tittensor D, Eddy T, Lotze H, Galbraith E, Cheung W, Barange M, et al. 2018. A protocol for the intercomparison of marine fishery and ecosystem models: Fish-MIP v1.0. Geosci Model Dev 11:1421-42. doi: 10.5194/gmd-11-1421-2018

107.
Trebilco R, Melbourne-Thomas J, Sumner M, Wotherspoon S, Constable A. 2019. Assessing status and trends of open ocean habitats: A regionally resolved approach and Southern Ocean application. Ecological Indicators 107 doi: 10.1016/j.ecolind.2019.105616

108.
Tronstad S, Bricher P, Kool J, Pulsifer P, Putte AVd, Larsen JR, et al. 2021. Alignment of polar data policies: recommended principles. Report by a working group under Arctic Data Committee, Arctic Spatial Data Infrastructure, and Southern Ocean Observing System Standing Committee on Antarctic Data Management. https://zenodo.org/record/5734900#.ZIAdCy8RppR

109.
Turner J, Bindschadler R, Convey P, di Prisco G, Fahrbach E, Gutt J, et al., editors. 2009. Antarctic climate change and the environment: A contribution to the International Polar Year 2007-2008. Cambridge. : Scientific Committee on Antarctic Research (SCAR).

110.
United Nations Environment Programme. 2022. Emissions Gap Report 2022: The Closing Window — Climate crisis calls for rapid transformation of societies. Nairobi: UNEP.

111.
United Nations Office of Legal Affairs. 2021. The Second World Ocean Assessment: United Nations.

112.
Van de Putte AP, Griffiths HJ, Brooks C, Bricher P, Sweetlove M, Halfter S, et al. 2021. From data to marine ecosystem assessments of the Southern Ocean: achievements, challenges, and lessons for the future. Frontiers in Marine Science 8 doi: 10.3389/fmars.2021.637063

113.
van Putten I, Kelly R, Cavanagh RD, Murphy EJ, Breckwoldt A, Brodie S, et al. 2021. A decade of incorporating social sciences in the Integrated Marine Biosphere Research Project (IMBeR): much done, much to do? Frontiers in Marine Science 8 doi: 10.3389/fmars.2021.662350

114.
Warwick-Evans V, Constable A, Dalla Rosa L, Secchi ER, Seyboth E, Trathan PN. 2022. Using a risk assessment framework to spatially and temporally spread the fishery catch limit for Antarctic krill in the west Antarctic Peninsula: A template for krill fisheries elsewhere. Frontiers in Marine Science 9 doi: 10.3389/fmars.2022.1015851

115.
Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, et al. 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3:160018. doi: 10.1038/sdata.2016.18