Manuscript Details

Manuscript number	MARSYS_2019_9
Title	Observations and models to support the first Marine Ecosystem Assessment for the Southern Ocean (MEASO)
Article type	Review Article

Abstract

Assessments of the status and trends of habitats, species and ecosystems are needed for effective ecosystem-based management in marine ecosystems. Knowledge on imminent ecosystem changes (climate change impacts) set in train by existing climate forcings are needed for adapting management practices to achieve conservation and sustainabililty targets into the future. Here, we describe a process for enabling a marine ecosystem assessment (MEA) by the broader scientific community to support managers in this way, using a MEA for the Southern Ocean (MEASO) as an example. We develop a framework and undertake an audit to support a MEASO, involving three parts. First, we review available syntheses and assessments of the Southern Ocean ecosystem and its parts, paying special attention to building on the SCAR Antarctic Climate Change and Environment report and the SCAR Biogeographic Atlas of the Southern Ocean. Second, we audit available field observations of habitats and densities and/or abundances of taxa, using the literature as well as a survey of scientists as to their current and recent activities. Third, we audit available system models that can form a nested ensemble for making, with available data, circumpolar assessments of habitats, species and food webs. We conclude that there is sufficient data and models to undertake, at least, a circumpolar assessment of the krill-based system. The auditing framework provides the basis for the first MEASO but also provides a repository (www.SOKI.aq/display/MEASO) for easily amending the audit for future MEASOs. We note that an important outcome of the first MEASO will not only be the assessment but also to advise on priorities in observations and models for improving subsequent MEASOs.

Keywords	Antarctica, conservation, ecosystem-based management, CCAMLR,

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Suggested reviewers	Jeroen Ingels, Andrea Pinones, Irene Schloss

Submission Files Included in this PDF

File Name [File Type]

Brasier et al. JMS Letter to editor.docx [Cover Letter]

Brasier Models and Obs for MEASO 20190119 First submission.docx [Manuscript File]

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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
The data will be made available on our Southern Ocean Wiki page (http://soki.aq), our data sheets are being finalised and will be made available on publication.

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18th January 2019

Editor, Journal Marine Systems

Dear Editor

Please see our submitted review article entitled “Observations and models to support the first Marine Ecosystem Assessment for the Southern Ocean (MEASO)” for consideration as a publication in the Journal of Marine Systems special issue “Integration” following the presentation of our work at the ACOMO 2018 Workshop in Australia.

In this manuscript we use the Southern Ocean as a case study to illustrate the information that would be compiled, and the methods used to develop, an integrated, overarching marine ecosystem assessment (MEA) for use by policy makers. The aim of MEASO is to provide a consensus report on status and trends in Southern Ocean habitats, species and foodwebs to identify the risks of climate change impacts and how policy- and decision-makers may need to adapt management systems. In this paper, we provide an ‘audit’ of the materials and methods available to produce the first MEASO later in 2019. More specifically we review the observations (surveys and syntheses) and system-level models that would be available in a nested ensemble approach to the assessment.

We believe our manuscript fits well within the “Observations and models” sub-theme of the special issue and would like to thank you for considering our manuscript for publication with the Journal of Marine Systems.

Yours faithfully

Madeleine Brasier

Lead and corresponding author

Antarctic Climate and Ecosystems Cooperative Research Centre

Observations and models to support the first Marine Ecosystem Assessment for the Southern Ocean (MEASO)

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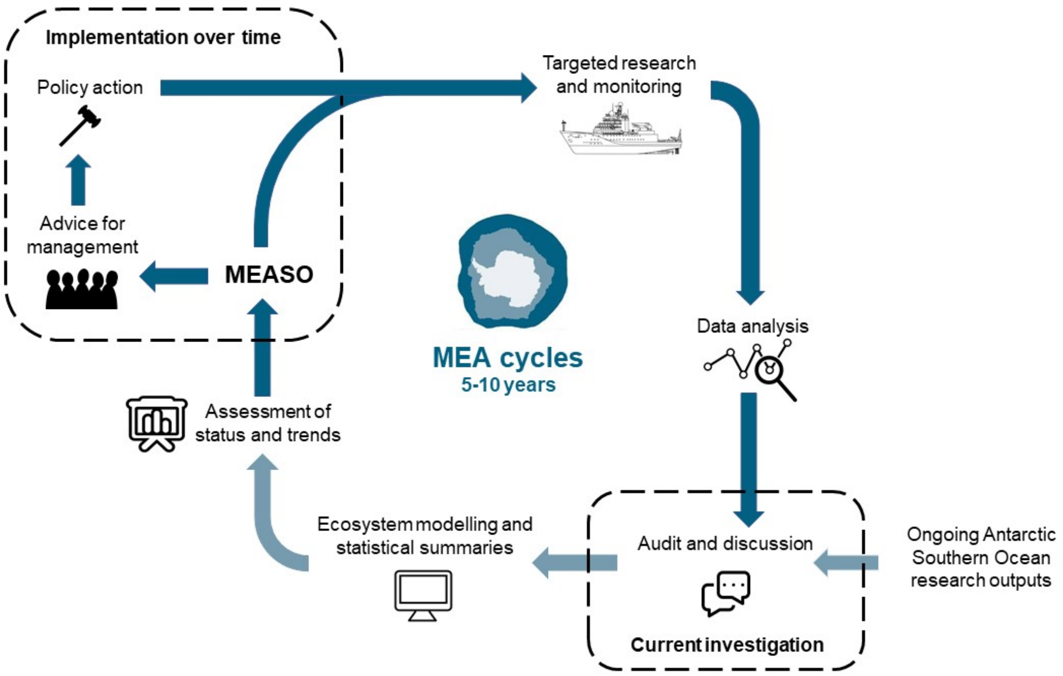
Abstract

Assessments of the status and trends of habitats, species and ecosystems are needed for effective ecosystem-based management in marine ecosystems. Knowledge on imminent ecosystem changes (climate change impacts) set in train by existing climate forcings are needed for adapting management practices to achieve conservation and sustainabililty targets into the future. Here, we describe a process for enabling a marine ecosystem assessment (MEA) by the broader scientific community to support managers in this way, using a MEA for the Southern Ocean (MEASO) as an example. We develop a framework and undertake an audit to support a MEASO, involving three parts. First, we review available syntheses and assessments of the Southern Ocean ecosystem and its parts, paying special attention to building on the SCAR Antarctic Climate Change and Environment report and the SCAR Biogeographic Atlas of the Southern Ocean. Second, we audit available field observations of habitats and densities and/or abundances of taxa, using the literature as well as a survey of scientists as to their current and recent activities. Third, we audit available system models that can form a nested ensemble for making, with available data, circumpolar assessments of habitats, species and food webs. We conclude that there is sufficient data and models to undertake, at least, a circumpolar assessment of the krill-based system. The auditing framework provides the basis for the first MEASO but also provides a repository (www.SOKI.aq/display/MEASO) for easily amending the audit for future MEASOs. We note that an important outcome of the first MEASO will not only be the assessment but also to advise on priorities in observations and models for improving subsequent MEASOs.

Graphical Abstract



Highlights

- Initial audit of data, models and results on status of Southern Ocean biota
- This audit will inform the first Marine Ecosystem Assessment for the Southern Ocean (MEASO)
- An ensemble of models can be used for circumpolar assessments of krill based system
- MEASO-1 will identify risks of climate change impacts and needs for management

Keywords

Antarctica, conservation, ecosystem-based management, CCAMLR,

1. Introduction

Assessments of the state of marine ecosystems and the causes of change in these systems are becoming very important for marine nations and internationally (e.g. Nymand-Larsen et al. 2014; Constable et al. 2017). They will enable managers to understand how change in habitats, species, communities, and foodwebs (hereafter referred to collectively as 'ecosystem changes') may give rise to change in marine ecosystem services. Moreover, managers need to consider the potential for multiple causes of change from different societal uses (sectors) of marine ecosystems; there is an increasing need to develop multi-sectoral management systems that can appropriately adjust those sectors causing change. An imminent and pressing challenge is to develop management systems that will facilitate the adaptation of sectors to expected future changes, such as those caused by climate change and ocean acidification.

At present, marine ecosystem assessments are mostly undertaken on a case-by-case basis when managing individual, or a small set of, 'activities' such as fisheries, pollution, and coastal engineering. They are generally based on empirical assessments from field observations. Typically, the combined effects across all activities are not directly assessed and managed, nor are the potential effects of climate change and ocean acidification included in these assessments individually or collectively. The latter effects are more often considered separately and heuristically based on reviews of disparate results in the existing peer-reviewed scientific literature, which we term 'derivative assessments'. The most comprehensive derivative assessments for the marine environment are those by the Intergovernmental Panel on Climate Change and the Global Ocean Assessment.

A scientific process is needed that directly assesses the potential for combined and cumulative effects and, particularly, can examine how those effects might continue in the short-to medium term future. The reason for assessing the future is that many effects may not be evident at the time of the assessment, although the drivers may have set them in train and made them unavoidable in the future. In the case of climate change and ocean acidification and based on the Earth system changes wrought by the ozone hole and its recovery, these changes may be two to three decades hence (IPCC, 2014).

Several important issues arise when attempting to consider and manage multiple drivers of effects, and the resulting cascading changes in ecosystems. Firstly, climate change and ocean acidification are not solely 'bottom up' drivers impacting on productivity of marine ecosystems. Species other than primary producers may be affected by changes in the physical and chemical systems. As a result, there may be 'top down' drivers that cause shifts in the structure and function of ecosystems as well (e.g. Johnson et al 2011). Secondly, some parts of the ecosystem will be better studied than others because science tends be more focussed on species or processes of direct interest to specific activities, such as fisheries. Lastly, future trajectories of the ecosystem may be difficult to foresee due to short time series of data or insufficient data to make empirical projections under climate change scenarios.

Ecosystems models provide the means to overcome these issues by enabling the integration of disparate datasets and knowledge of processes in order to examine the interactions of effects from different activities and from climate change and ocean acidification (Melbourne-Thomas et al. 2017). They will be central to developing realistic scenarios for the future (Constable et al. 2017).

1.1. What is a marine ecosystem assessment?

A marine ecosystem assessment (MEA) aims to bring together available data and knowledge from the scientific literature and different management bodies to, with the aid of models where possible, assess ecosystem status and change. Where possible, the relative importance of different stressors in causing that change will be assessed. Assessments of change will include historical change to the present, as well as providing realistic projections of change into the short-to-medium term future. The results are envisaged to directly support end-users, particularly policy makers, in adapting their work to ecosystem changes that may not be readily apparent in their jurisdiction but could impact on their objectives. Thus, a MEA aims to provide an overarching and integrated assessment, which has the flexibility and coverage enabling it to be adapted and useful to the needs of individual end-users, as well as providing context for derivative assessments and fisheries stock assessments (Figure 1).

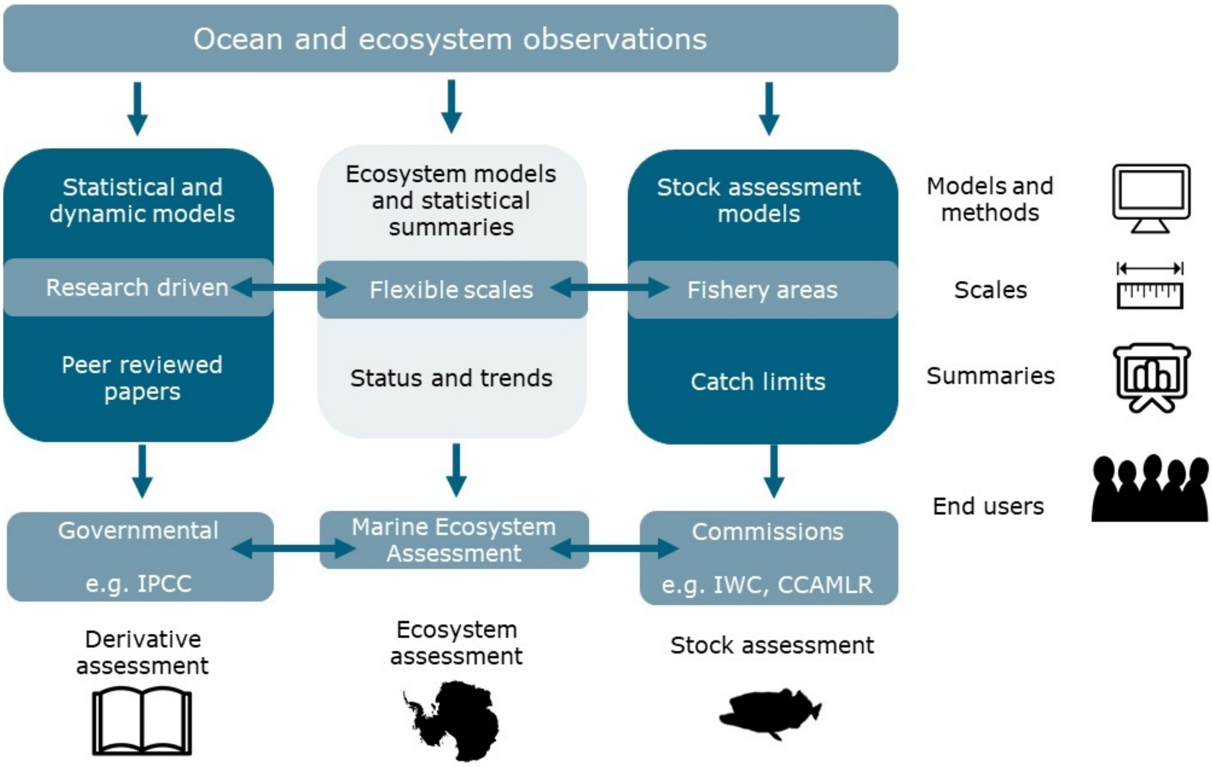


Figure 1. Comparison of the types of assessments undertaken for marine ecosystems, including the roles of observations and models within the workflows of the different assessments. Marine Ecosystem Assessments provide context for derivative and stock assessments (sideways arrows). In this example we use Antarctica as a region of interest.

Here, we use the Southern Ocean as a case study to illustrate the information that would be compiled and the methods used to develop an integrated, overarching assessment – a Marine Ecosystem Assessment for the Southern Ocean (MEASO). The need for regular assessments of change of marine ecosystems around Antarctica and in the Southern Ocean (ASO ecosystems) has been identified by the Antarctic Treaty Consultive Meeting (ATCM, 2015), the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (CCAMLR, 2015; SC-CCAMLR 2011), the Scientific Committee on Antarctic Research (SCAR) (Kennicutt et al. 2014; Turner et al. 2009; Turner et al. 2014) and in the work of the Intergovernmental Panel on Climate Change (IPCC

2014; Nymand-Larson et al. 2014). A MEASO is intended to be a consensus report on status and trends in Southern Ocean habitats, species and foodwebs, drawing on the experience, results and methods of the broader ASO research community. Figure 2 illustrates how a regular MEASO process is intended to interact with policy makers. The MEASO cycle would operate similar to an IPCC cycle, over 5-10 years. The work would be expected to benefit from published syntheses and collaborations amongst researchers across the spectrum of existing research activities, as well as from observations from long-term monitoring programs, e.g. the Southern Ocean Observing Sytem. Where possible, statistical and dynamic modelling would be used to assess the status and trends of habitats, species and food webs. The synthesis report would then provide summaries for use by policy-makers and other end-users.In addition, the synthesis would identify important priorities for advancing future assessments.

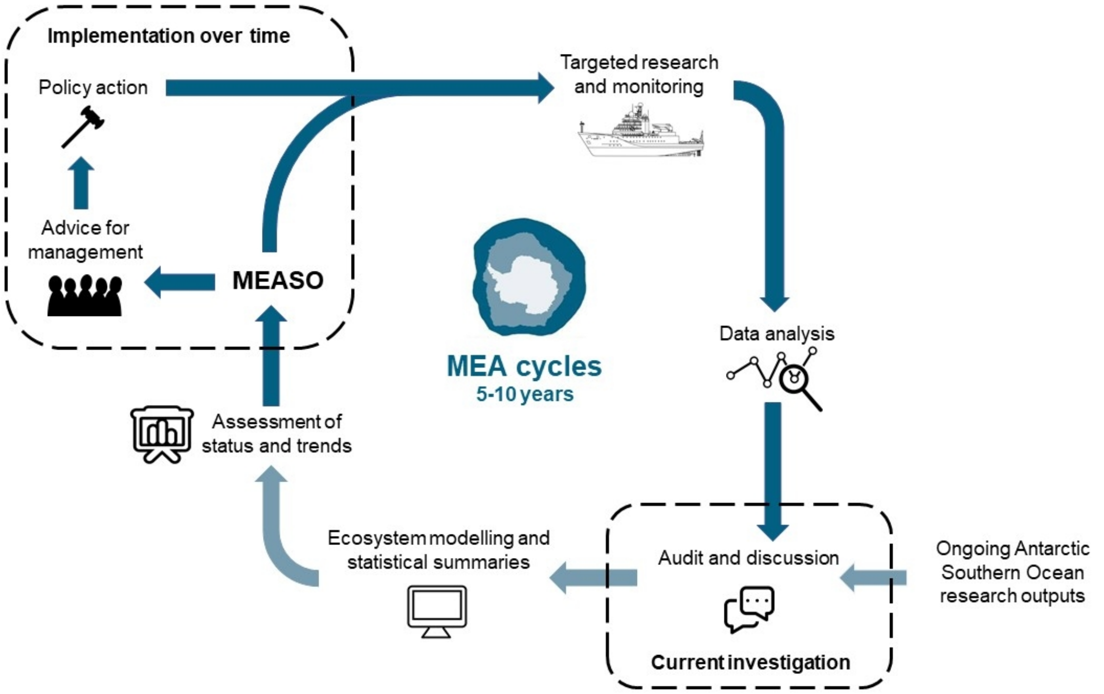


Figure 2. The processes and work flow in a Marine Ecosystem Assessment (MEA) using the Marine Ecosystem Assessment for the Southern Ocean (MEASO) regarding the management region around Antarctica as an example. The dashed box in the lower right corner indicates the starting point of the first MEASO, to which this paper contributes by providing an audit of available knowledge, data, syntheses and models. Future audits might include identifying new or advanced data sets, assessment methods and models, and any assessments that may have been undertaken since the previous MEASO. The dashed box in top left corner demonstrates the potential interaction of MEAs with policy-makers. MEASO is envisaged to be an ongoing process, where each MEASO will advise on priorities for future research and monitoring to improve subsequent MEASOs.

The first MEASO begins half way through the cycle and aims, through implementation of a first assessment, to establish processes and priorities for more comprehensive MEASOs in future. In this paper, we provide an ‘audit’ of the materials and methods available for the first MEASO. While this audit is comprehensive it is not intended to be exhaustive; our focus is on establishing a framework (using the Southern Ocean Knowledge and Information Wiki, www.soki.aq, as a repository) that can easily be amended and updated for future assessments.

Specifically, we start by summarising existing syntheses and derivative assessments on status and trends of habitats, species and food webs, including establishing spatial and temporal scales of reporting. Secondly, we document the types of observations available for assessing status and analysing trends, as well as the types of information that can be assembled for better understanding the pressures on different taxa in the ecosystem. In this section, we consulted researchers to better understand the data available and the scope of species-specific and assemblage-level assessments that may be undertaken. Thirdly, we summarise the status of models that could be used in a MEASO. Lastly, we identify the scope of the analyses that might be undertaken now, without substantially more research effort, to assess the status and trends in Southern Ocean ecosystems in a MEASO.

2. Syntheses of ecosystem status and trends

2.1. SCAR Antarctic Climate Change and the Environment report

The Scientific Committee on Antarctic Research (SCAR) has supported a number of efforts to provide syntheses on Antarctic and Southern Ocean science for policy makers. The Antarctic Environments Portal is one such initiative (https://www.environments.aq), where smaller syntheses may be found. A substantial synthesis on the effects of climate change on ASO systems – Antarctic Climate Change and the Environment (ACCE) - was undertaken by SCAR as part of the 2007-2009 International Polar Year (IPY) (Turner et al. 2009). The aim of ACCE was to describe how the physical climate system of Antarctica has varied over geological time and how environmental change during the instrumental period may affect biota (Convey et al. 2009). The 2009 report was largely focused on the West Antarctic Peninsula and how changes in sea-ice and primary production may affect ice-dependent species such as penguins and krill, as well the the sensitivity of biota in other habitats, including benthos. Each year SCAR prepares updates of the ACCE report that highlight the new advances in our knowledge relevant to different sections of the report and provide some direction on priorities for future research; updates are presented at the Antarctic Treaty Consultative Meeting and published online (see https://www.scar.org/policy/acce-updates/ for all ACCE updates).

2.2. Scientific Committee for the Conservation of Antarctic Marine Living Resources

The Scientific Committee for the Conservation of Antarctic Marine Living Resources (SC-CAMLR) has undertaken ecosystem syntheses on two occasions. In 2004, it held a Workshop on Plausible Ecosystem Models for testing approaches to krill management (SC-CAMLR, 2004). In 2008, it held a joint workshop with the Scientific Committee of the International Whaling Commission on Input Data for Antarctic Marine Ecosystem Models (SC-CAMLR, 2008). Expert groups provided syntheses on different taxa for publication in *CCAMLR Science* in 2012, including on phytoplankton (Strutton et al. 2012), zooplankton (Atkinson et al. 2012a), krill (Atkinson et al. 2012b), fish as predators of krill (Kock et al. 2012), ice-breeding seals (Southwell et al. 2012), and penguins (Ratcliffe and Trathan, 2012).

2.3. SCAR Biogeographic Atlas of the Southern Ocean

The SCAR Biogeographic Atlas of the Southern Ocean (De Broyer et al. 2014) was produced using data collected during the Census of Antarctic Marine Life voyages in the IPY 2007-2009 (content and data avaliable at http://data.biodiversity.aq/). It is one of the major contributors to our current knowledge of the biodiversity and biogeography of Southern Ocean biota. The Atlas collates 1.07 million occurrence records of 9064 validated species from ~434,000 distinct sampling stations, these are fundamental data in providing the necessary geospatial framework for marine biodiversity knowledge and understanding, and for assessing its gaps (De Boyer et al. 2014). The Atlas is now regarded as a milestone product of 21st Century Antarctic Science (De Broyer and Koubbi 2015). Examples of its use include the following. According to Google Scholar, it has been cited in 95 publications between 2015-2018. It has contributed to major publications reviewing knowledge of climate change impacts on Antarctic ecosystems (e.g. Constable et al. 2014a; Chown et al. 2015) and potential ecological change under future conditions (Griffiths et al. 2017). In addition it has been used to advise future monitoring, management and conservation of ASO ecosystems (e.g. Gutt et al. 2017; Koubbi et al. 2017; Cavanagh et al. 2016; Constable et al. 2016; Xavier et al. 2016) including contributing to supporting scientific information for spatial management measures in CCAMLR (Teschke et al. 2014).

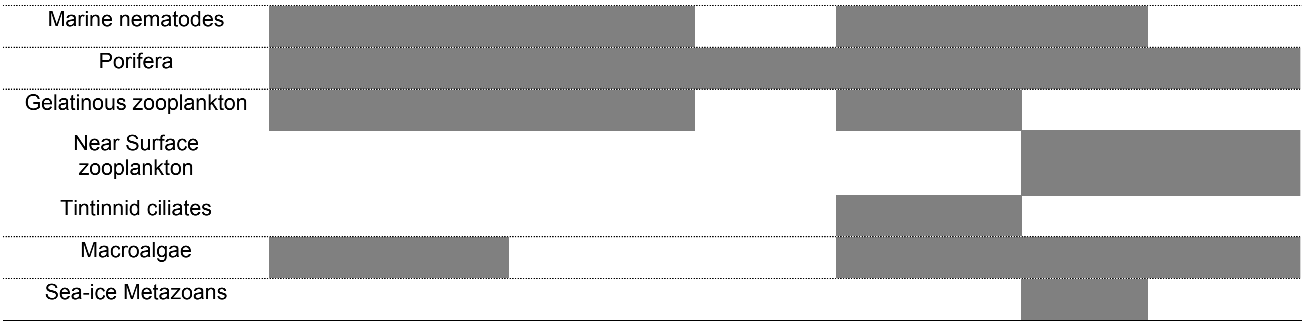
Table 1 summarises how the Atlas may be updated with more recent information. Trends in new research across taxa within the ASO include taxonomic, biogeographic, ecological and physiological studies. Information provided by the Atlas editorial team, many of the original lead authors of the chapters of the Atlas, along with literature reviews that we undertook was summarised into 7 sub-topics in the table. Not surprisingly, the advances in genetic technologies have results in many of the taxonomic groups undergoing revision, as well as enabling better understanding of spatial populations structures and food web linkages in the region. Many respondents provided general comments on the advances in science related to the Atlas including:

- Our knowledge of the evolution of Antarctic fauna and the environmental factors that have governed distribution over time suggest that the evolutionary models used in the Atlas may need to be reassessed (Crame pers. comms.).
- Statistical methods used to derive the distribution modelling of species have not significantly advanced since publication, but additional methods should be considered if analyses re-run. However, for some taxonomic groups our knowledge of species distribution, trophic ecology and physiology have advanced with respect to environmental drivers which should be integrated into future modelling analysis (Saucede pers. comms).
- Advances in remote observations technologies including satellites (plankton) and aerial and tracking studies (top predators) have provided more reliable data for use in biogeographic study that previous data sources (Alvain and Ropert-Coudert pers. comms.).

The Atlas team are in the process of creating an online version of the Atlas, which will display the original content of the Atlas but with integrated R code (in Bookdown, https://bookdown.org/yihui/bookdown/) to map the most recent records (Van de Putte, pers. comm.).

Table 1. Expected research findings by taxa achieved since the publication of the SCAR Biogeographic Atlas of the Southern Ocean (de Broyer et al 2014). Coloured cells indicate new research available. Columns show how new research could be used to update the relevant chapters: Taxonomic re-evaluation (previous taxonomic classifications have been altered); species discovery (previously undescribed morphological or cryptic species); invasive species (species previously considered non-Antarctic have now been recorded within the Southern Ocean); species shift (evidence of species shifts within the ASO e.g. the poleward movement); sample coverage (additional samples are now available from previously un-sampled locations or un-sorted material increasing spatial coverage within the ASO); ecological (improved understanding of ecological traits, e.g. diet, habitat, reproduction, which may change distribution of taxa now or in the future); physiological (insights into physiological traits, e.g. acclimation or adaptation to changing temperature or acidity, which might influence distributions). Taxonomic experts who provided information for this table are acknowledged at the end of this manuscript.

Taxa	Taxonomic re-evaluation	Species discovery	Species shift	Sample Coverage	Ecological	Physiological
Polychaetes		■		■	■	
Bryozoa		■		■	■	■
Ascidian	■	■		■	■	■
Benthic Hydroids	■	■		■	■	
Stylasteridae	■	■	■	■	■	■
Antarctic Hexacorals	■	■	■			
Harpacticoid copepods	■	■	■			
Pycnogonida	■	■			■	■
Benthic Ostracoda	■	■				
Benthic Amphipods		■			■	■
Isopoda		■		■	■	
Cumacea		■		■	■	
Crabs and Lobsters		■		■	■	■
Shrimps						
Pelagic Copepods		■	■	■	■	■
Halocyprid Ostracods					■	
Hyperiidea amphipods				■		
Euphausiids					■	■
Lysianassoidea amphipods	■	■		■	■	
Tanaidacea				■		
Asteroidea	■			■	■	■
Crionoids				■	■	
Echinoids	■	■		■	■	■
Fish	■			■	■	
Benthic foraminifera	■	■			■	
Gastropoda	■	■		■	■	
Bivalvia		■			■	■
Octopuses	■				■	■
Pteropods					■	■
Squid	■				■	■



2.4. Other Reports

A number of bodies under the auspices of the United Nations have developed syntheses on ASO ecosystems. These include the Intergovernmental Panel on Climate Change (IPCC) and Regular Process for Global Reporting and Assessment of the State of the Marine Environment (World Ocean Assessment). The most recent regional reports from each are those by IPCC Working Group II on Polar Regions in 2014 (Nymand-Larson et al. 2014) and by the World Ocean Assessment in 2016 on high-latitude ice and the biodiversity dependent on it (Rice and Marschoff, 2016). An IPCC Special Report on the Oceans and Cryosphere in a Changing Climate has a Polar Regions chapter examining the effects of climate change on polar regions, including ecosystems due for release in 2020.

Several major research projects have also resulted in dedicated journal issues with specific publications on different taxa and processes (e.g. Brant and Ebbe 2007, Hofmann et al. 2011) whilst others have focused on the physical environmental changes and how these may affect biota now (e.g. Rogers et al 2012; Murphy et al 2013; Constable et al. 2014a; Chown et al. 2015) and under future conditions (Griffiths et al. 2017). Some papers have developed syntheses along with advice for future monitoring, management and conservation of ASO ecosystems (e.g. Xavier et al. 2015; Cavanagh et al. 2016; Constable et al. 2016; Gutt et al. 2017; Koubbi et al. 2017).

3. Observations to support MEASO

3.1. Field Programmes

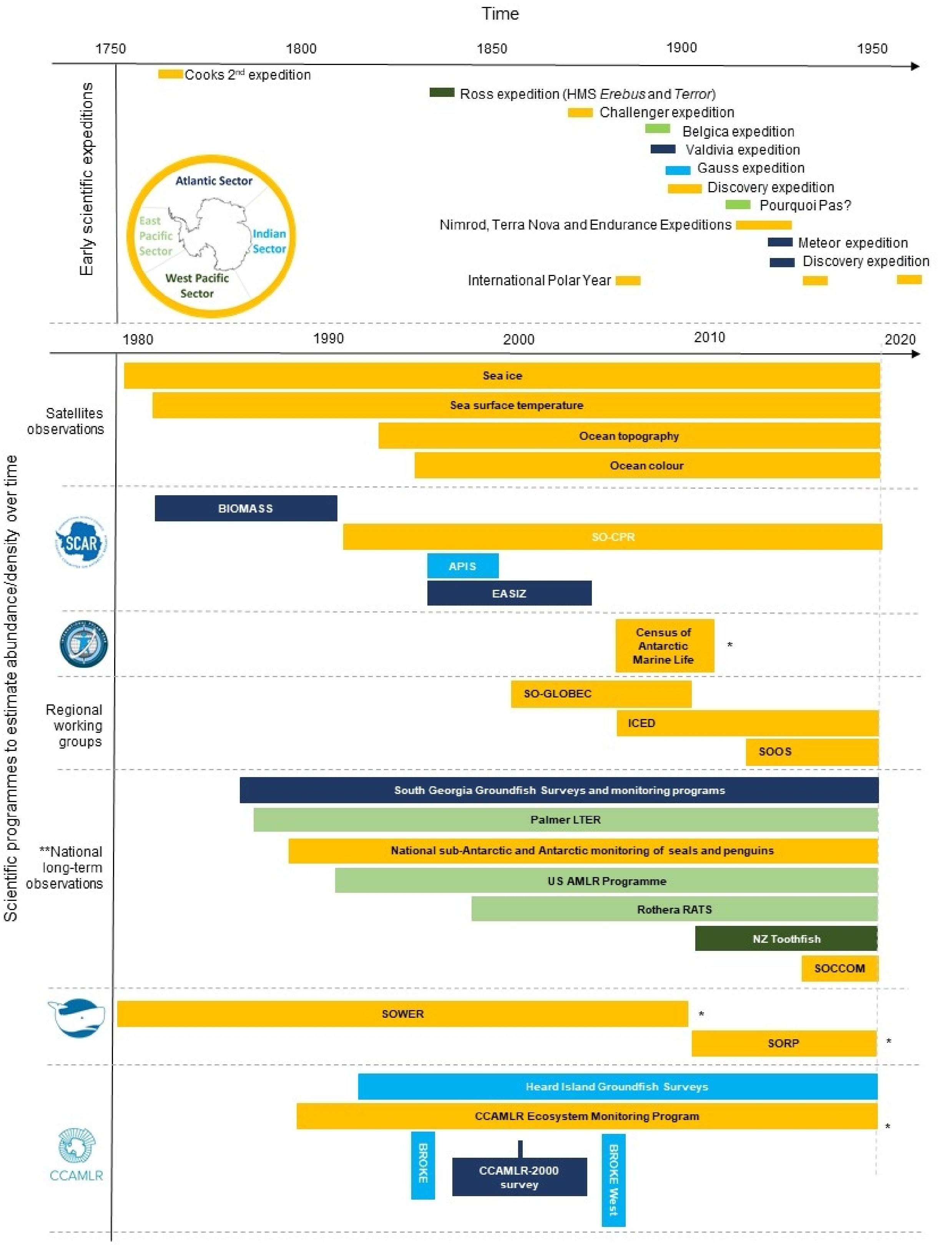
Scientific observations within the ASO commenced in the late 1800s with the first Challenger expedition, shortly followed by the first International Polar Year initiatives and the Belgica and Discovery expeditions (Figure 3). These early expeditions formed the foundation for benthic and pelagic species records in the Southern Ocean (Griffiths, 2010). In 1981 the first large-scale international research project, BIOMASS (Biological Investigations of Marine Antarctic Systems and Stocks) took place (El-Sayed et al. 1994). In 1978 satellite technologies were implemented to observe the variability and trends in Antarctic sea ice (Cavalieri and Parkinson, 2008). Since then satellites have also been used to monitor sea surface temperature, ocean topography and ocean colour (a proxy for chlorophyll concentration, Johnson et al. 2013). These combined with ongoing oceanographic research assist in characterising the changing pelagic habitats of the ASO.

Many ASO research programmes have targeted Antarctic krill and krill-dependent predators, especially whales. For example, the BROKE and BROKE-West expeditions were designed to improve our understanding of krill dynamics within east Antarctica (Nicol et al. 2000; 2010) whilst the CCAMLR-2000 Survey (also CCAMLR-2000 Krill Synoptic Survey) was initiated to improved estimates of krill biomass in the Atlantic sector of the Southern Ocean (Trathan et al. 2001). The outcomes of these programs were used by CCAMLR to set precautionary catch limits for the krill fishery (Hewitt et al. 2004). CCAMLR has established an ecosystem monitoring program (CEMP) for monitoring krill-dependent species, which at present focusses on land-based predators (Agnew, 1997). It also provides for regular assessments of the status of fish stocks based on tagging and groundfish surveys (see Fishery Reports - https://www.ccamlr.org/en/publications/fishery-reports).

The CEMP was established in 1987 with national research agencies contributing data, as available, to the CCAMLR Secretariat. CEMP uses standardised methods to monitor 8 indicator species considered dependent on Antarctic krill. These species include the adélie penguin (*Pygoscelis adeliae*), chinstrap penguin (*P. antarctica*), gentoo penguin (*P. papua*), macaroni penguin (*Eudyptes chrysolophus*), black-browed albatross (*Thallasarche melanophrys*), Antarctic petrel (*Thalassoica antarctica*), cape petrel (*Daption capense*) and the Antarctic fur seal (*Arctocephalus gazella*). CEMP is developed from national contributions to individual programs.

General coordination is provided through the CCAMLR Working Group on Ecosystem Monitoring and Management.

Ecosystem-oriented research programs and monitoring have been of increasing importance over the last few decades. Many are focussed on biogeochemistry or kirll-based food webs . Long term observation programmes such as the Palmer Long Term Ecological Research (LTER, http://pal.lternet.edu/) and the Rothera Time Series (RaTS, https://www.bas.ac.uk/project/rats/) collect sustained observations within the vicinity of national research stations. These programmes collect oceanographic, biochemical and biological data to investigate inter-annual variation and climate change impacts on the Antarctic ecosystem. Other programmes are more fisheries oriented such as for the UK at South Georgia (krill, toothfish, icefish), Australia at Heard Island and McDonald Islands (toothfish, icefish) and Macquarie Island (toothfish), France at Kerguelen Islands (toothfish, icefish) and Crozet Islands (toothfish), South Africa at Prince Edward & Marion Islands (toothfish), and New Zealand, UK and Norway in the Ross Sea (toothfish). Land-based predators are extensively monitored on many subantarctic islands, including South Georgia, Crozet, and Kerguelen.



* Programmes have a circumpolar approach and outlook but individual surveys may have targeted specific regions or sites. See SOKI pages for details.
** Programmes not associated with the listed international monitoring schemes

Figure 3. Timeline including often-cited examples of the major scientific observations within the Antarctic Southern Ocean ecosystem from early scientific observations and modern survey and sampling programmes. Including Scientific Committee for Antarctic Research (SCAR) lead programmes: BIOMASS - Biological Investigations of Marine Antarctic Systems and Stocks (1981-1991), SO-CPR – Souther Ocean Continuous Plankton Recorder, EASIZ - Ecology of the Antarctic Sea Ice Zone (1994-2004), APIS - The International Antarctic Pack Ice Seals Programme. Commission for the Conservation of Antarctic Living resources (CCAMLR) programmes: CEMP - CCAMLR Ecosystem Monitoring Programme, BROKE - Baseline Research on Oceanography, Krill and the Environment. International Polar Year (IPY) programmes and CAML - Census of Antarctic Marine Life (2005-2010). International Whaling Commission (IWC) programmes: SOWER - Southern Ocean Whale and Ecosystems Research Programme (1978-2009), SORP - Southern Ocean Research Partnership. Regional working groups: SO-GLOBEC - Southern Ocean Global Ocean Ecosystems Dynamics, ICED - Integrating Climate and Ecosystem Dynamics in the Southern Ocean, SOOS - Southern Ocean Observing System. National long-term observation examples including: LTER - Long-term Ecological Research Programme, AMLR - Antarctic Marine Living Resources, RATS - Rothera Antarctic Time Series, SOCCOM - Southern Ocean Carbon and Climate Observations and Modelling project. Details of additional CEMP sites and ongoing monitoring see https://www.ccamlr.org/en/science/cemp-sites.

Many of the field programmes shown in Figure 3 were international research efforts consisting of multiple expeditions within different regions of the ASO. The Census of Antarctic Marine Life, which ran from 2005-2010, coordinated 18 major research voyages to the Antarctic and the Southern Ocean during the 2007-2009 International Polar Year (Schiaparelli et al. 2013), many of which targeted unsampled regions, for example the deep-sea benthos within the Amundsen and Bellingshausen Seas (Linse et al. 2013). Overall the CAML voyages sampled about 350 sites within the ASO collecting pelagic, demersal and benthic fauna using a variety of sampling gears (Stoddart, 2010). The species data collected during CAML voyages were deposited in SCAR-MarBIN (Scientific Committee on Antarctic Research Marine Biodiversity Network, now biodiversity.aq) data portal, containing data for over 14 000 species.

Since BIOMASS, Southern Ocean GLOBEC provided the impetus to develop internationally co-ordinated, integrated studies of the krill-based food web (Hofmann et al. 2011). In 2008, it morphed into the IMBER and SCAR program, Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) (Murphy et al. 2008), with a continued focus on process studies, as well as a new emphasis in developing ecosystem models (Murphy et al. 2012).

The Southern Ocean Observing System was established as a partnership between SCAR and the Scientific Committee on Oceanic Research to develop sustained observing of essential physical, chemical and biological variables to underpin research and monitoring of the region (Rintoul et al 2011; Meredith et al 2013; Constable et al 2016; Newman et al, submitted). Although in its infancy, SOOS is beginning to provide mechanisms for retrieving data for the purposes of a MEASO. Its development of regional working groups (Newman et al, submitted) will enable further implementation of co-ordinated field observations identified as important to MEASO in the future.

3.2. Taxon-level assesments

In its simplest form, an assessment of the status and trends of a species can be derived from abundance data of taxa over time (Constable et al. 2014b). Here we review the potential spatial and, in the case of pelagic taxa, temporal coverage of species-specific assessments within the published literature and where assessments have been undertaken by management bodies (Table 2, Table 3). At this stage, we did not review the utility of the assessments for the purposes of MEASO; while our review here is not exhaustive, the number of assessments indicated for each taxonomic group indicate the relative attention given to each group. The assessments varied in the amount of data included. Some were derived from long-term data sets that may help identify trends in species abundance/density over time. Others were "snapshots" of a species that may be used as an indicator of status but not trends. Our results highlight the real differences in coverage between taxa and between sectors. Ideally a MEASO would be based on circumpolar assessments of abundance or density but, at present, this only exists for a limited number of species (Klekociuk and Wienecke 2016). Only few locations/regions are well sampled across the spectrum of taxa. Some types of areas, such as the deep-sea benthos, are only poorly sampled (Brandt et al. 2014).

Some of the earliest species-level studies within the ASO focused on krill and marine mammals, dating back to the early 20th Century during the sealing and whaling eras. This was followed by a rise in scientific estimates of krill abundance between 1930 and 1980 (Pauley et al. 2000) and an interest in their potential relationship between krill abundance and large-scale oceanographic processes (for a review of early works see Priddle et al. (1988) and for the earliest fisheries data see Fedulov et al. (1996)). For birds and marine mammal's quantitative abundance data was scarce until the 1970s and close to non-existent prior to the 1950s (Croxall et al. 1992). Crude estimates of seal and whale populations are suggested in Laws et al. (1977). In many early works the methodologies are unpublished or at best unreliable.

Species-level abundance or density data have been compiled in recent decades for a number of species, including zooplankton (from SO-CPR surveys; https://www.scar.org/science/cpr/home/) for Antarctic krill (raw data iin KRILLBASE; https://www.bas.ac.uk/project/krillbase/#data), Adelie penguins (colongy counts; http://www.penguinmap.com/) whales (assessments; https://iwc.int/status), albatross (assessments; http://acap.aq/en/acap-species), species with conservation assessments (IUCN red list; https://www.iucn.org/resources/conservation-tools/uicn-red-list-threatened-species) and in CCAMLR fishery reports by CCAMLR management area (https://www.ccamlr.org/en/publications/fishery-reports and supplementary information). Additional individual assessments have been submitted to the CCAMLR Working Group for Ecosystems and Marine Management. These can be found online and available on request, for example reports submitted for the Predator Survey Workshop in 2008 include reports of fur seal, flying bird and penguins abundance (https://www.ccamlr.org/en/wg-emm-psw-08).

These sources have varying degrees of quality-control. For some datasets, limited repeat observations may make trends difficult to estimate. Attention may need to be given to interannual variation associated with El Niño–Southern Oscillation (Trathan et al. 2003; Meredith et al. 2005; Fielding et al. 2014). Importantly, inconsistencies between surveys and/or sampling biases of different survey methods may need to be accounted for through standardisation procedures. These issues have been important to resolve in existing datasets, including standardisation across sampling methods and spatial and temporal coverage for Antarctic krill (in KRILLBASE; Loeb & Santora 2015; Cox et al 2018), Adelie penguins (Adelie penguin census repositiories; Southwell et al 2013) and ice-breeding seals (APIS repositories; Southwell et al 2012).

The general trends for taxonomic groups presented in Table 2 reflect conclusions in recent publications, noting that some groups summarise across species that, respectively, may have different trajectories. The MEASO process will need to avoid confounded results.

Table 2. Review of the spatial and temporal coverage of taxon-specific assessments for zooplankton, krill, fish and air breathing species in the Antarctic and Southern Ocean. Results include the number of assessments of status (abundance and density) that we found are publicly available, the relative spatial coverage of these assessments by region (see figure at bottom), the number of assessments that investigate trends over time presented with an indication of current trends. Earliest data refers to quantitative data in the published literature. Some example references are included here with the full list of references available on request.

Taxon	Status assessments	Spatial coverage	Trend assessments	Earliest data	Current trends*	Key references**
Plankton	166		?	1900s	? ? ? ?	Hosie et al. 2003; McLeod et al. 2010; Atkinson et al. 2012a;
Krill	42		15	1920s	~ ~ ~ ~	Nicol et al. 2000; Atkinson et al. 2004; Watkins et al. 2004; Fielding et al. 2014; Atkinson et al. 2016; Cox et al. 2018.
Mackerel Icefish	5		3	1970s	~ ? x x	De la Mare et al. 1998; Everson et al. 1999; North et al. 2005.
Toothfish	10		5	1980s	↓ ? ? x	Williams et al. 2002; Tuck et al. 2003; Hillary et al. 2006; Candy and Constable et al. 2008; Hanchet et al. 2010; Mormede et al. 2014; Day et al. 2015.
Baleen whales	17		7	1970s	x ↑ ↑ x	Branch and Butterworth. 2001; Branch 2006; Branch 2007; Leaper et al. 2008; Branch 2011.
Toothed whales	2		2	1970s	x x ? x	Kasamatsu et al. 2000; Branch and Butterworth 2001; Branch et al. 2004; Pitman et al. 2018.
Ice-breeding Seals	26		3	1970s	x ? x ?	Erickson and Hanson 1990; Wiemerskirch et al. 2003; Southwell et al. 2012.
Elephant Seals	22		22	1950s	↑ ? x ?	Laws (1994); McMahon et al. 2005; Hindell et al. 2016.
Fur Seals	17		14	1950s	↑ ↑ x ↑	Hucke-Gaete et al. 2004.
Adelie Penguin	19		15	1940s	? ↑ ↑ ↓	Croxall et al. 1988; Trivelpiece et al. 1990; Woehler and Croxall 1997; Micol et al. 2001; Croxall et al. 2002; Forcada et al. 2006; Dunn et al. 2016; Lyver et al. 2014; Lynch et al. 2012; Lynch and La Rue 2014; Southwell et al. 2015
Chinstrap Penguin	13		11	1950s	↓ x x ↓	Croxall et al. 1988; Trivelpiece et al. 1990; Woehler and Croxall 1997; Croxall et al. 2002; Forcada et al. 2006.
Emperor penguin	15		6	1940s	x ↓ ~ x	Kooyman and Mullins 1990; Jouventin and Weimerskirch 1990; Woehler and Croxall 1997; Croxall et al. 2002; Barber et al. 2007; Micol et al. 2001; Fretwell et al. 2012.
Gentoo penguin	9		10	1970s	↑ x x ?	Croxall et al. 1988; Woehler and Croxall 1997; Croxall et al. 2002; Forcada et al. 2006; Dunn et al. 2016; Dunn et al. 2018.
Macaroni penguin	4		2	1950s	↓ ? x x	Croxall et al. 1988; Woehler and Croxall 1997; Reid and Croxall 2001.
Antarctic and Cape Petrels	16		3	1960s	↓ ? x ?	van Franeker et al. 1999; van Franeker et al. 2001.
Black-browed Albatross	6		4	1960s	x ? x x	Woehler and Croxall 1997; Reid and Croxall 2001.

Observed trends
↑ Increase
↓ Decrease
− No change
~ Interannual-variation
? Contrasting data or local variation
X insufficient data/unknown

*based on most recent findings within the literature
**Full reference list available on SOKI

Data on Antarctic benthic communities has been assembled since the 1960s, recorded from mostly from trawl, dredge, corer and camera data (Gutt et al. 2013). However, the density of taxa has often not been recorded (Downey et al. 2012); the difficulties in collecting quantitative benthic samples mean that many studies are semi-quantiative at best (Clarke, 2008). Some equipment including the epibenthic sledge and camera technologies are able to generate quantitative abundance data for macro and megafauna species respectively (Gutt and Starmans, 2003; Brandt et al. 2007a; Post et al. 2017). Studies that assess trends over time are rare, usually in shallow water habitats close to research stations (E.g. Conlan et al. 2004; Stark et al. 2014). Table 3 summarises the coverage of benthic assessments by depth and sector. To date the greatest number of benthic studies have been conducted in the Weddell Sea, around the West Antarctic Peninsula and Ross Sea (Gutt et al. 2013)

Table 3. Review of the spatial and depth coverage of taxon-specific assessments for benthic species (not including fish) in the Antarctic and Southern Ocean. Results include the number of assessments of status (density) that we, the relative spatial coverage of these assessments by region (see figure at bottom), the number of assessments by depth. Earliest data refers to quantitative data in the published literature. Some example references are included here with the full list of references available on request.

Taxon	Status assessments	Spatial coverage	Depth coverage	Earliest data	Example references**
All benthos	108			1960	Dayton et al. 1974; Gutt et al. 2011.
Meiofauna	3			1980	Gutzmann et al. 2004.
Macrofauna	12			1970	Gutt et al. 2007; Glover et al. 2008; Brandt et al. 2014; Stark et al. 2014.
Megafauna	10			1980	Lockhart and Jones 2008.
Annelida	9			1970	Hilbig et al. 2006; Neal et al. 2018.
Cnidaria	2			1980	Waller et al. 2011.
Crustacea	14			1970	Brandt et al. 2007b; Brokeland et al. 2007; Kaiser et al. 2007, 2009.
Echinodermata	4			1980	Piepenburg et al. 1997; Manjon-Cabeza and Ramos 2003.
Foraminifera	5			1970	Cornelius and Gooday 2004; Majewski 2005.
Mollusca	7			1970	Clarke et al. 2007; Schiaparelli et al. 2014.
Porifera	5			1960	Dayton 1989; Gocke and Janussen 2013

Depth Distribution
Shelf (<1000 m)
Shelf-slope (0 - 3000 m)
Shelf-slope-basin (0 - >3000 m)
Basin (>3000 m)

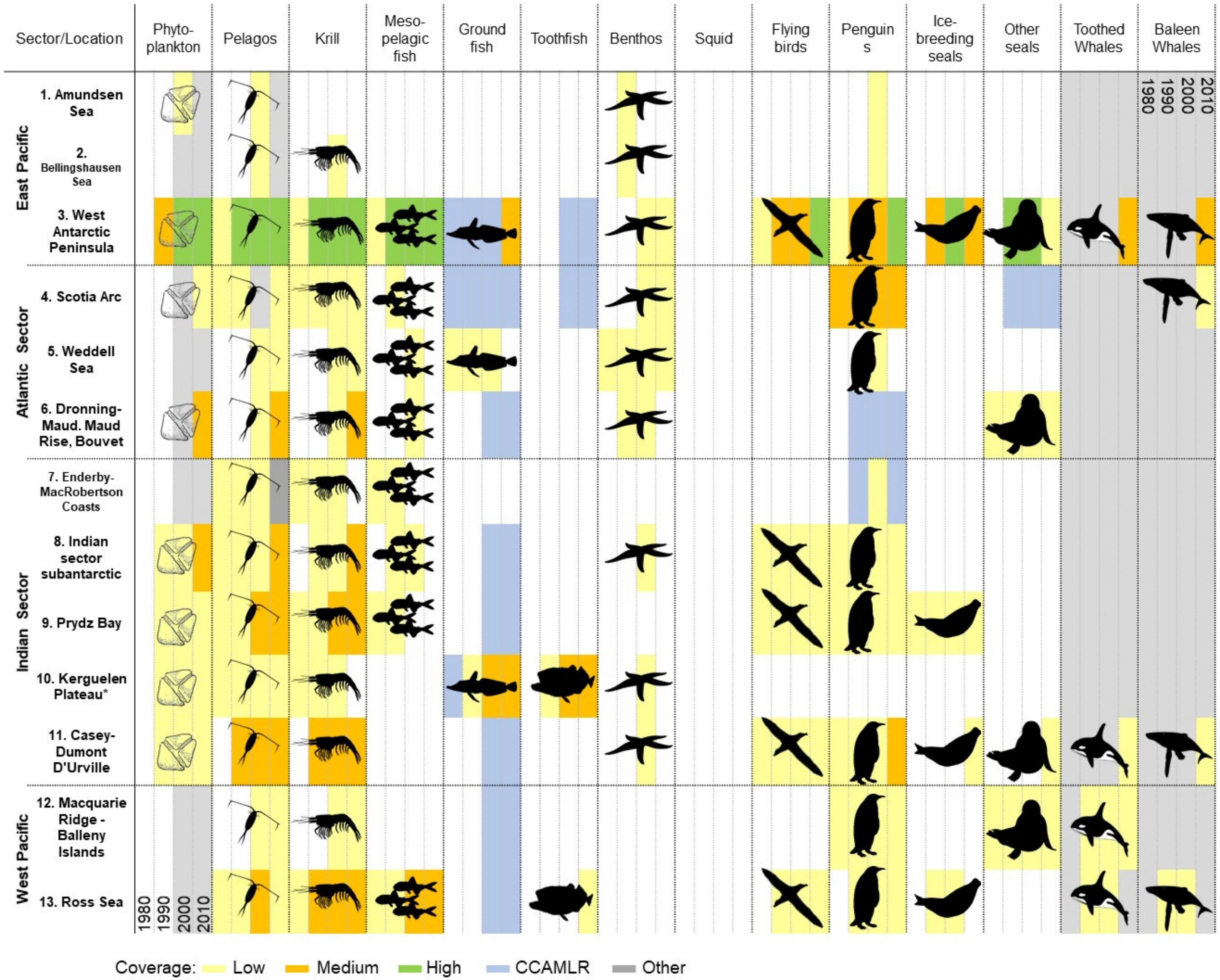
3.3. Consultation on research activities on density or abundance

In addition to the review of previous scientific surveys and sampling programmes from the literature and online sources, we consulted 92 scientists from 18 different countries for information on assessments of density/abundance of ASO taxa. The aim of this consultation was to determine the spatio-temporal coverage of research programs estimating abundance (or relative density) of taxa within the Southern Ocean in each decade from 1980 to the present. A total of 14 broad taxonomic groups sub-divided into 49 monitoring groups were listed within the consultation document over 13 different sites within the ASO (full instructions, taxonomic groups and data are provided in supplementary material).

Completed responses were received from 30 individuals from 13 of the targeted countries including (number of responses): Argentina (1), Australia (5), Canada (1), Chile (2), France (1), Germany (5), India (1), Italy (4), Japan (1), Russia (1), South Africa (2), United Kingdom (3) and the USA (3). Additional information was also provided by New Zealand, Australia and the USA. Others indicated that they were not able to contribute or had already contributed to previous responses for their nation. These data are available on SOKI and contributors acknowledged at the end of this manuscript.

The greatest survey coverage over time and taxa was recorded for the West Antarctic Peninsula, one of the most accessible regions of the ASO, whilst the main spatial gaps appear to be the Amundsen Sea, Bellingshausen Sea and Macquarie Ridge. The number of surveys generally increased with time in most regions reflecting the increase in Antarctic research capacity with time. Across taxa flying birds were not covered at locations generally away from coastal research stations and benthic taxa were not well represented. Such spatial biases, inherent when studying the Southern Ocean, are discussed in Griffiths et al. (2014). In previous research the most intense sampling tends to be at the more easily accessible locations e.g. close to research stations or the WAP and depths less than 1000 m. Taxonomic biases are somewhat easier to overcome, during the SCAR Biogeographic Atlas project there was a surge in species data recorded in online databases (Griffiths et al. 2011, 2014), however we still lack abundance data for many groups. These differences could reflect both the nature of scientific programmes or the success of the community-based survey approach.

Figure 4. Complied survey responses by taxa, location and region over time. Colour scheme for number of research programs measuring abundance: yellow (low 1-5), orange (medium 6-15); green (high >20). Grey shading indicates additional data available from circumpolar databases from SO-GLOBEC (phytoplankton and pelagos) and IWC (toothed and baleen whales). Blue shading indicates data within CCAMLR sources including fishery assesments (bathypelagic and ground-fish) and from CEMP monitoring sites (penguins and fur seals). The four cells within each taxon indicate time by decade from 1980 to 2010.



Sector/Location
Phyto-plankton
Pelagos
Krill
Meso-pelagic fish
Ground fish
Toothfish
Benthos
Squid
Flying birds
Penguins
Ice-breeding seals
Other seals
Toothed Whales
Baleen Whales
East Pacific
1. Amundsen Sea
2. Bellingshausen Sea
3. West Antarctic Peninsula
Atlantic Sector
4. Scotia Arc
5. Weddell Sea
6. Dronning-Maud. Maud Rise, Bouvet
Indian Sector
7. Enderby-MacRobertson Coasts
8. Indian sector subantarctic
9. Prydz Bay
10. Kerguelen Plateau*
11. Casey-Dumont D'Urville
West Pacific
12. Macquarie Ridge - Balleny Islands
13. Ross Sea
1980
1990
2000
2010
Coverage: Low Medium High CCAMLR Other

4. Models to support MEASO

Models underpin the scientific method (Peters 1991). The term 'model' is used in many ways (see Melbourne-Thomas et al., 2017), ranging from (i) heuristic discussions on a system and/or hypotheses of various complexities, to (ii) statistical models aimed at predicting the magnitude of one or more dependent variables based on a series of independent and related variables, to (iii) formal system-level structures linking objects (nodes – physical and chemical variables, species, human uses) by processes (edges – trophic interactions, physiological responses, competitive interactions), the behaviour of which are forced by system drivers (variables – seasonality, ENSO, climate change, fisheries). Hereafter, the latter system-level models are termed 'system models'. In this section, we focus on the system models, regarding that statistical models, which include species distribution models, underpin the species-specific analyses. System models are those that help identify causes and effects and consequent changes when the forcing variables change.

System models can be used to test outstanding hypotheses on the effects of change, develop plausible scenarios of current and future change given the data, and for undertaking more precise assessments of the status and trends of the ecosystem (and its likelihood) using estimation procedures (Murphy et al 2012; Melbourne-Thomas 2017). Ranging in complexity from single species to whole ecosystems (Table 4), system models provide scientists with a method for linking disparate studies on status of some important species with many other studies on processes and ecosystem interactions, thereby enabling complex system studies even though not all components of the system have been observed simultaneously. Thus, system models, couched in observations, can be used to explore the outcomes from multiple ecosystem interactions and perturbations and reporting the consequences to decision makers (Watters et al. 2013; Klein et al 2018). With the rise of ecosystem-based management practices, which are supported by CCAMLR (Constable

2004, 2011; Kock et al. 2007), the development of ecosystem models to investigate future climate, fishing and conservation scenarios are increasingly important (Gurney et al. 2014).

The main ecological and modelling challenges in the development of system models is summarised in Murphy et al. (2012). Some of the first ecological modelling applications within the Southern Ocean were based on Antarctic krill because of its importance to whales as well as its emerging importance as a target commercial species (see references in Hill et al 2006). Antarctic krill is a relatively well studied species, with much information on its growth rate, transport, and population dynamics which can be incorporated into models (Siegel 2016).

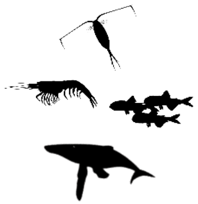
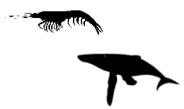
Early modelling studies investigated the interaction between krill aggregations and harvesting operations in attempt to utilise the krill catch rate as a proxy for abundance (Mangel, 1988; Butterworth 1988) whilst conceptual models provided qualitative descriptions of the food-web and model multi-species interactions (for references see Hill et al. 2006). Qualitative network models have since been used to examine directional responses of ecosystem components to perturbations, including the mechanisms behind observed changes and the impacts of model complexity on results (Melbourne-Thomas et al. 2012, 2013). This approach provides a quick yet substantial insight into system functioning (Levins 1996).

Quantitative food web and ecosystem models have also been developed to simulate responses to ecosystem perturbations including fishing (Fulton 2010). These include the widely used Ecopath with Ecosim, a mass balance model with a time dynamic simulation based on the functional groups within an ecosystem (Christensen and Walters 2004). Pinkerton et al (2010) used a similar framework to Ecopath but included key non-trophic transfers (e.g. seasonal release of material from sea-ice, vertical detrital flux) to investigate the ecosystem impacts of fishing in the Ross Sea.

More recently, end-to-end, or whole-ecosystem models, attempt to include all major relevant processes within the ecosystem, such as nutrient cycling, climate forcing, environmental variability and harvesting as well as representations of biological species/functional groups that include ecological processes such as feeding, growth, reproduction and dispersal (Fulton 2010; Murphy et al. 2012). An end-to-end modelling framework, Atlantis (Fulton et al. 2010, 2011) is currently under development for implementation in East Antarctica. This model will enable development of climate change scenarios for the regional ecosystem as well as evaluating different management and adaptation options for fisheries and other activities.

Table 4. Different modelling approaches used within Antarctic and Southern Ocean (ASO) ecosystems from physical and biogeochemical to whole ecosystem models, anticipated utility within the MEASO project, current ASO coverage and example references.

Model type	Description	Examples	Anticipated utility	Implementation	ASO Coverage	Example references
Qualitative models	Framework to examine ecosystem responses to press perturbation.	Qualiative network models	Understand linkages and feedback mechanisms.	West Antarctic Peninsula and aspatial.		Melbourne-Thomas et al. 2013; Goedegebuure et al. 2017.
Earth System	Simulation of physical, chemical and biological processes within the earth system. Can incorporate global climate models.	CMIP5 models	Provides forcings for regional models	Global with circum-Antarctic detail. Note, southern boundary may not be to the coast		Reviewed in Cavanagh et al. 2017
Regional Physical	Simulation of physical conditions within the Southern Ocean such as temperature, salinity and currents.	Ocean General Circulation Models (OGCM) Regional Ocean Modelling System (ROMS) Southern Ocean State Estiamte (SOSE)	Provides regional physical forcing for ecosystem models.	Ross Sea, West Antarctic Peninsula Indian sector		Dinnimen et al. 2011; Corney et al. in review; Mazloff et al. 2010
Regional Biogeochemical	Simulation of biogeochemistry in the Southern Ocean e.g. nutrient cycling, carbon uptake, productivity	Nutrient, phytoplankton, zooplankton and detritus (NPZD)	Understand different drivers that control the base ASO productivity.	All sectors, including pelagic and in sea ice		Pasquer et al., 2005; Saenz and Arrigo 2014; Vancoppenolle et al. 2010; Melbourne-Thomas et al. 2015; Priester et al. 2017

Single Species 	Simulation to understand the ecology of a single species based on current biological knowledge and environmental setting.	Krill examples: Advection, recruitment, relationship with physical drivers e.g. sea ice and climatic variation etc	Filling gaps in space and time, where we have patchy abundance data.	Mostly commercially exploited species (krill, seals, whales); Scotia Arc, South Georgia, West Antarctic Peninsula, Ross Sea, Indian Sector		Hofmann et al. 1998; Murphy et al. 2004; Thorpe et al. 2007; Wiedenmann et al. 2008; Jenouvrier et al. 2014.
Foodweb models 	Simulation of the trophic interactions within an ecosystem from primary producers to higher predators. Used to investigate the impacts of changes in primary production, fishing effort and species loss.	Mass balance Ecopath with Ecosim. Size spectrum models	Representation of food entire food web to explore relative importance of trophic linkages and the relative impact of different climate and fishing scenarios.	Ross Sea, Scotia Arc, South Georgia, West Antarctic Peninsula, Indian Sector		Mori and Butterworth 2004, 2005, 2006; Pinkerton et al. 2010; Hill et al. 2012; Ballerini et al. 2014; Gurney et al., 2014; McCormack et al, in prep.; Subramaniam et al, in prep
Benthic models 	Simulation of habitat complexity that shapes biological communities in benthic ecosystems, and roles in benthic-pelagic coupling		Explore dynamics of benthic assemblages in relation to iceberg scour, environmental change and fisheries	Weddell Sea, Scotia Sea Indian sector		Johst et al. 2006; Pothoff et al. 2006a, 2006b
Specific interaction models 	Dynamic models of the interactions between selected species within the ecosystem. Can provide quantitative information on ecosystem performance for use in management of human activities including fishing.	FOOSA SMOM EPOC	Subset a food web to specific primary interactions for exploring effects of environmental change or fisheries scenarios.	Mostly krill and krill predators (penguins, whales). Scotia Sea, circum-Antarctic		Constable 2005, 2008; Watters et al. 2013; Plaganyi & Butterworth 2015; Klein et al 2018; Tulloch et al 2018

Socio-ecological	Framework used to understand the interactions between societal, environmental and governmental factors.		To investigate policy-relevant scenarios that may contribute to adaptive conservation and management of marine social—ecological systems	Yet to be implemented in Antarctica.		
End to end models	These models include submodels on physics, chemistry, biology, human uses, economics and management. They are spatially structured and can resolve small time-steps (minutes) if needed. They enable exploration of direct and indirect effects of change in one or more components on the other elements of the system. Components can be modelled at different levels of complexity from pools to complex populations with behaviours.	Atlantis	Enable exploration of system-level scenarios of change as well as having methods for evaluating how well management and adaptation measures may work under various scenarios.	Currently being implemented for East Antarctica.		Melbourne-Thomas et al. In Prep;

East Pacific   Atlantic   Indian   West Pacific   Circumpolar

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Figure 5 illustrates how the different system models described in Table 4 might fit together in a nested, ensemble of models. While not all the available models described in Table 4 will be used in the initial MEASO, the aim will be to utilise scenarios of environmental change from Earth System models (Cavanagh et al. 2017), along with time-series of observations of physics, chemistry and biology, to drive regional food web and/or species models. These latter models can then be used to investigate the consequences, and their likelihoods, of the different scenarios on different parts of the ecosystem (see, for example, Klein et al 2018).

How might this work in practice?

Qualitative models are a useful means for developing a suitable, plausible network of interactions expected in an ecosystem model, linking physical, chemical and biological components. Once formed, a qualitative model can then be used to generate possible directions of change in different species/functional groups arising from press perturbations in different parts of the network, particularly in the physical and chemical components. For example, possible changes in the krill-based food web have been explored for the West Antarctic Peninsula (Melbourne-Thomas et al., 2013). Overall, this process can be used to simplify food web models in order to achieve computational efficiencies, in preparation for using the nested ensemble of models.

Earth System models can provide the state of habitat variables and primary producers across the Southern Ocean, although sea ice may not be well described at present (Cavanagh et al 2017). The ability for these models to represent the actual state of the Southern Ocean can be assessed as to their fit to time series of ocean observations; the relative ability for representing reality is termed ‘model skill’. Environmental scenarios from models with high skill will establish the base conditions for driving the regional food web and/or species models. The results for the different scenarios can be immediately used for looking at potential shifts in suitable habitats for different species under the different scenarios (e.g. krill eggs - Kawaguchi et al. 2013; krill larvae in sea ice – Melbourne-Thomas et al 2016; krill growth potential – Hill et al. 2013).

Time series of observations of physics, chemistry and biology can be used to establish the starting conditions for model assessments of projected changes under different scenarios. While end-to-end models take account of the interactions between physics, chemistry and biology when undertaking projections, singles species and food web assessments can be undertaken using a hierarchical approach to the models. For example, biogeochemical models can help bound the production in a region based on time-series (observations or model data) of the physical environment. The time-series of production can then be used as inputs to species-specific models or to underpin the productivity in a food web. Models such as Ecopath with Ecosim, can help ensure the starting conditions of the relative biomasses of species or functional groups are appropriate given the observed relative abundances amongst a subset of taxa. Thus, projections into the future will have plausibility given these initial calculations. For some regions and species, time-series of observations will enable species and food web models to be fit to the data, enabling a test of the plausibility of the models given the precision in the estimation of parameters.

Given the development of models to date, it will be possible to at least examine biological scenarios under different future environmental scenarios from Earth System models for Antarctic krill and krill-based food webs (e.g. some recent models available are Constable and Kawaguchi 2017; Murphy et al 2017).

Uncertainties in the outcomes of the projections arise from parametric uncertainty, natural variation and the role of extreme events in altering trajectories of different taxa. In addition, uncertainties can arise from different views of how the ecosystems work – structural uncertainty. Estimating the uncertainty in the consequences of the different scenarios will be an important part of the assessment (Constable 2004; Fulton, 2010; Link et al 2012). A further step in reducing uncertainties using this hierarchical, ensemble of models, combined with existing time-series of data, will be to evaluate how an observing system for Southern Ocean ecosystems might be improved to better contribute in the future to a subsequent MEASO (Constable et al., 2016).

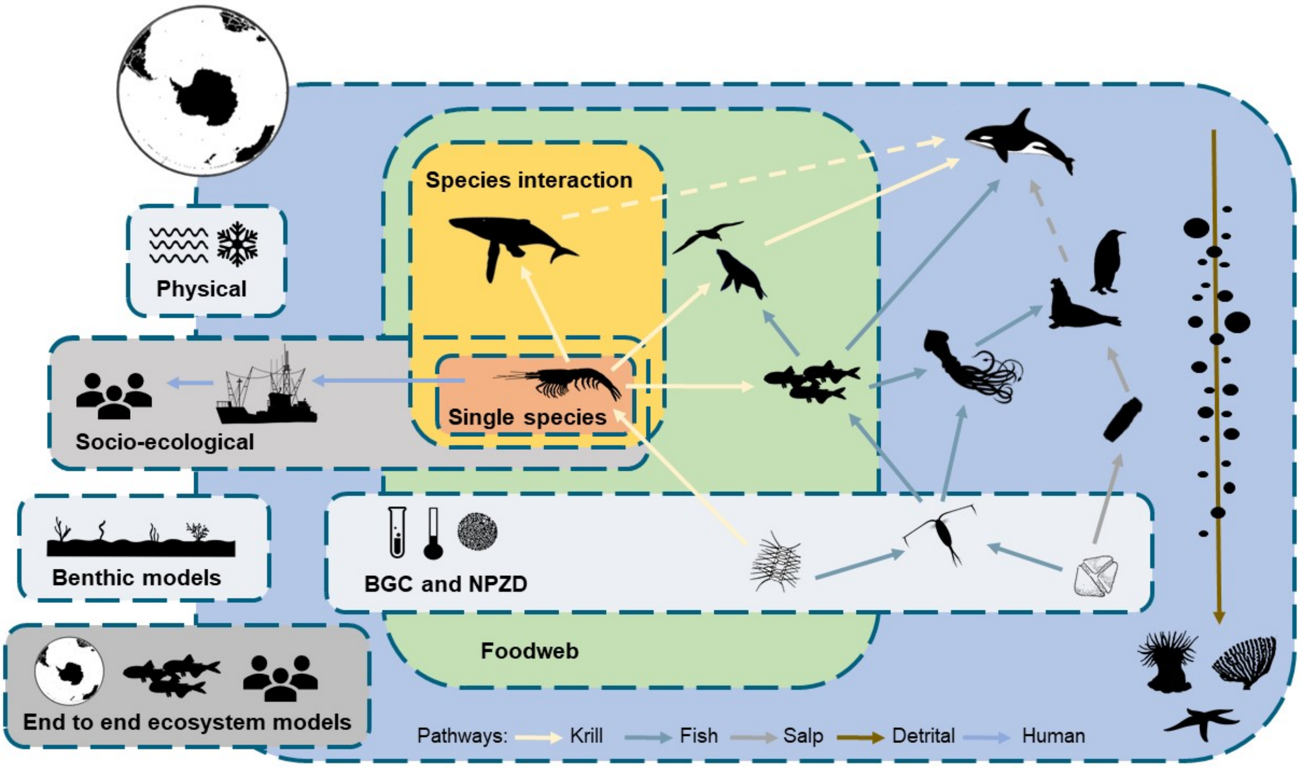

Figure 5. Single and integrated model approaches that could be used in marine ecosystem assessments. The generic Southern Ocean food web shown here represents different energy pathways and the most commonly studied species and interactions in model analyses.

5. Summary and future directions

Southern Ocean ecosystems cover a range of different physical and chemical environments with four different meridional sectors (ocean scale) and subantarctic and polar zonal divisions within sectors. The best studied sector is the East Pacific (West Antarctic Peninsula) followed by the Atlantic sector, both of which have had emphases on the Antarctic krill-based pelagic systems. Nevertheless, a nested ensemble of models with sufficient time series of observations are available to undertake circumpolar assessments of, at least, the Antarctic krill-based system. This can be achieved by applying available knowledge and general principles of interactions between physical, chemical and biological components of food webs.

We provide here a framework for auditing available data, syntheses and system models (incorporating knowledge of autecological and ecosystem processes) for a MEASO. This framework provides a means of easily collating works and information not yet included in our audit in order to make them available for future assessments. While we have had an emphasis on the scientific literature, it will be possible to use the auditing process in future to collate and make available data and models not yet or not able to be established in the literature.

An important task for MEASO will be to evaluate the degree to which future assessments may benefit from programs to fill in taxonomic gaps in data within each of the main sectors. Here, it will be important to consider how advice to end users, such as different management bodies, may be improved by filling in those gaps. As described in the use of the system models, it will be possible to evaluate how the ecosystem parts of the Southern Ocean Observing System could be improved by increasing spatial and/or temporal coverage of observations of particular taxa (Meredith et al 2013; Constable et al 2016). A major gap that can be identified by our audit here is the need to have greater coverage of observations and modelling of benthic systems, particularly as they may pertain to managing the interactions of fisheries with benthic habitats as well as the role of benthic habitats in the carbon cycle (e.g. Barnes et al 2018).

Technological advances have greatly increased our efficiency to obtain ecological data in the Southern Ocean. These advances include the use of genetics to identify species, study diversity, population connectivity and phylogeography (e.g. Grant et al. 2011; Cluas et al. 2014); stable isotope analysis in dietary analysis essential for foodweb studies (Raymond et al. 2011); acoustics, automated cameras and satellites to locate species and monitor populations (e.g. Fretwell et al. 2012; Southwell et al. 2013) as well as autonomous and remotely operated vehicles survey the most remote and ice-covered regions (Gutt et al. 2017). Our temporal coverage has also increased with a number of moored and remote observing systems, providing continuous and sustained data collection. The development of a network of long-term biological monitoring stations and survey transects within ASO ecosystems has been suggested and may be feasible with these technological advances (Griffiths et al. 2010; Constable et al. 2014, 2016). Importantly, the development of improved observing in the region is coordinated by the Southern Ocean Observing System (www.soos.aq).

Biological assessments began with the BIOMASS program of the Scientific Committee on Antarctic Research in the 1980s, followed by a series of assessments and the Census of Antarctic Marine Life in the International Polar Year leading to the SCAR Biogeographic Atlas of the Southern Ocean and the report on the Antarctic Climate Change and Environment. The Marine Ecosystem Assessment for the Southern Ocean is a further step in these assessments aiming to provide needed scientific advice to support the sustainable management and conservation of the region long in to the future.

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7. Acknowledgements

We thank the MEASO community for the contributions to and expressions of interest in the MEASO project during the 2018 MEASO meeting in Hobart, Tasmania (www.measo2018.aq).

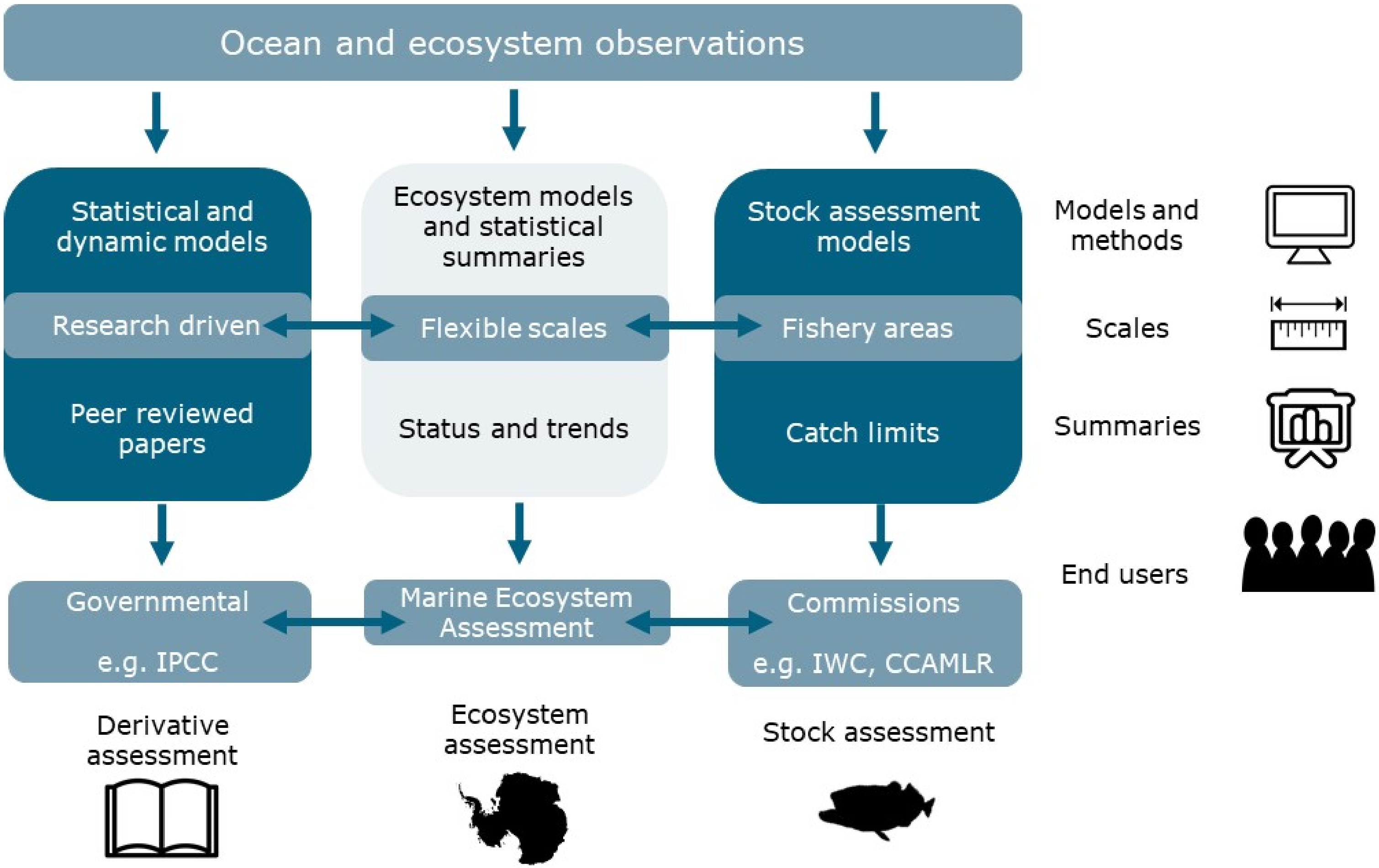
We would like to acknowledge the following international researchers who provided information regarding taxa-specific abundance surveys undertaken in Antarctica and the Southern Ocean by their national research agencies (the responses were used in the production of Figure 4) - by country: Irene Schloss (Argentina); Philippe Ziegler, John Kitchener, Karen Westwood, John van de Hoff, Colin Southwell, Nicole Hill, Andrea Walters (Australia); Evgeny Pakhomov (Canada); Cesar Cardenas, Humberto Gonzalez (Chile); Yan Ropert-Coudert (France); Julian Gutt, Santiago Pineda Metz, Bettina Meyer, Angelika Brandt, Helen Herr (Germany); Parli Bhaskar (India); Lillo Guglielmo, Iole Leonori, Marino Vacchi, Silvia Olmastroni (India); Tsuneo Odate (Japan); Matt Pinkerton (New Zealand); Azwianewi Makhado (South Africa); Martin Edwards, Phil Trathan, Sophie Fielding, Angus Atkinson (United Kingdom); Eileen Hofman, Christian Reiss, Oscar Schofield, Jefferson Hinke (United States of America).

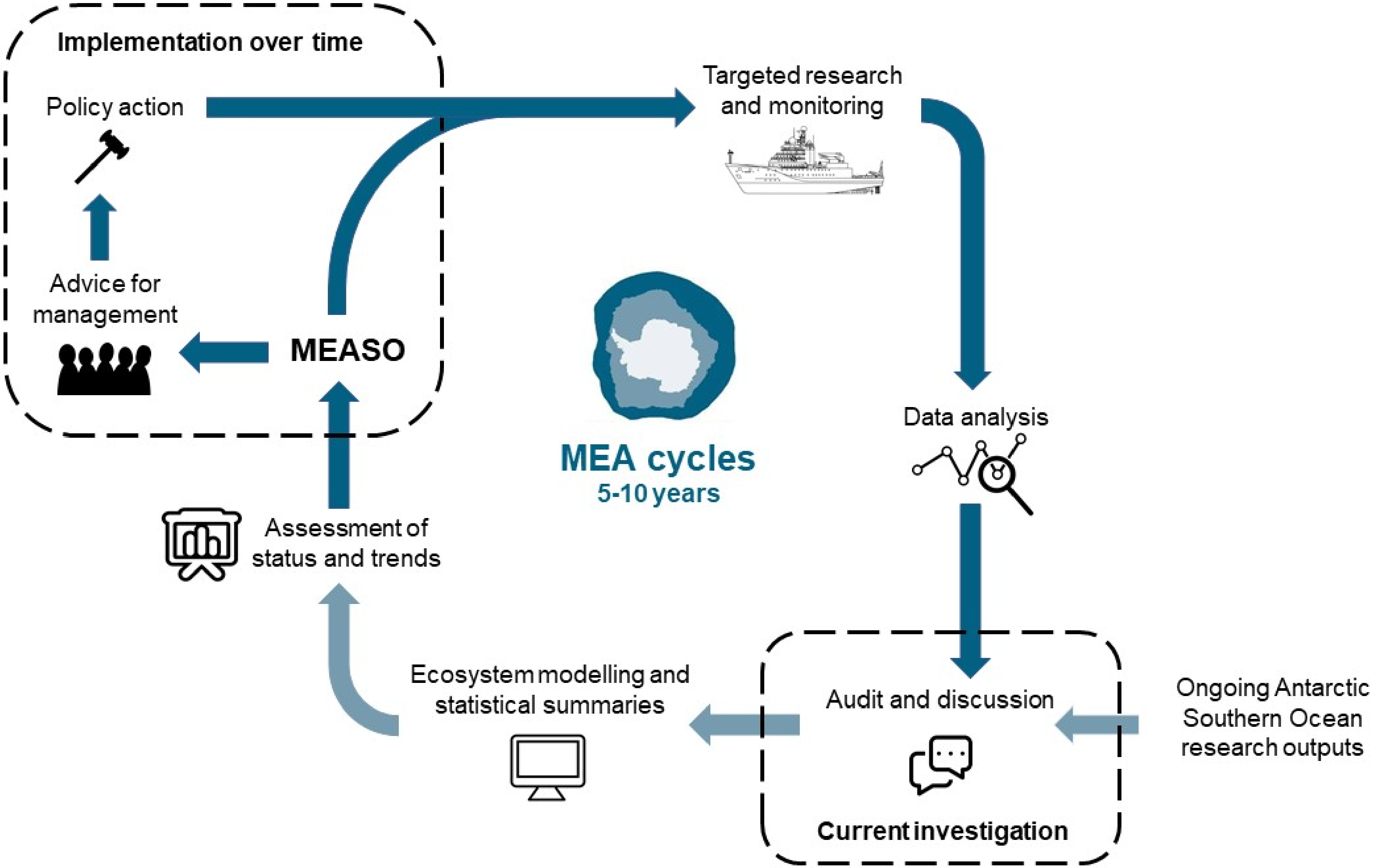
Additional thanks are due to lead and co-authors of the SCAR Biogeographic Atlas of the Southern Ocean who provide information regarding recent research in the field of research since the Atlas publication. With expertise: Séverine Alvain (Phytoplankton); Charles Amsler (Macroalgae); David Barnes (Bryozoa); Narissa Bax (Stylasteridae); Simone Brandão (Benthic Ostracoda); Alistar Crame (Antarctic Evolution); Bruno Danis (Asteroidea); Dhugal Lindsay (gelatinous zooplankton); John Dolan (Tintinnid ciliates); Rachel Downey (Porifera); Guy Duhamel (Fish); Kai H George (harpacticoid copepods); Andrew Gooday (Foraminifera); Huw Griffiths (Crabs and lobsters); Charlene Guillaumot (Asteroidea); Charlotte Havermans (Lysianassoidea amphipods); Graham Hosie (zooplankton); Falk Huettman (pelagic communities); Stefanie Kaiser (Isopoda); Juliana H. M. Kouwenberg (pelagic copepods); Sophie Mormede (distribution modelling); Camille Moreau (Asteroidea); Ute Mühlenhardt-Siegel (Cumacea); Alexandra Post (environmental setting); Ben Raymond (pelagic regionalisation); Estafanía Rodríguez (Antarctic Hexacorals); Yan Ropert-Coudert (birds and marine mammals); Thomas Saucède (echinoids); Stefano Schiaparelli (Gastropoda); Keri Swadling (sea-ice metazoans); José Xavier (squid) and Wolfgang Zeilder (Hyperiidea amphipods).

We are grateful to Australian Coastal and Oceans Modelling and Observations (ACOMO) for the opportunity to present our MEASO research at the 2018 ACOMO workshop and contribute to their special issue.

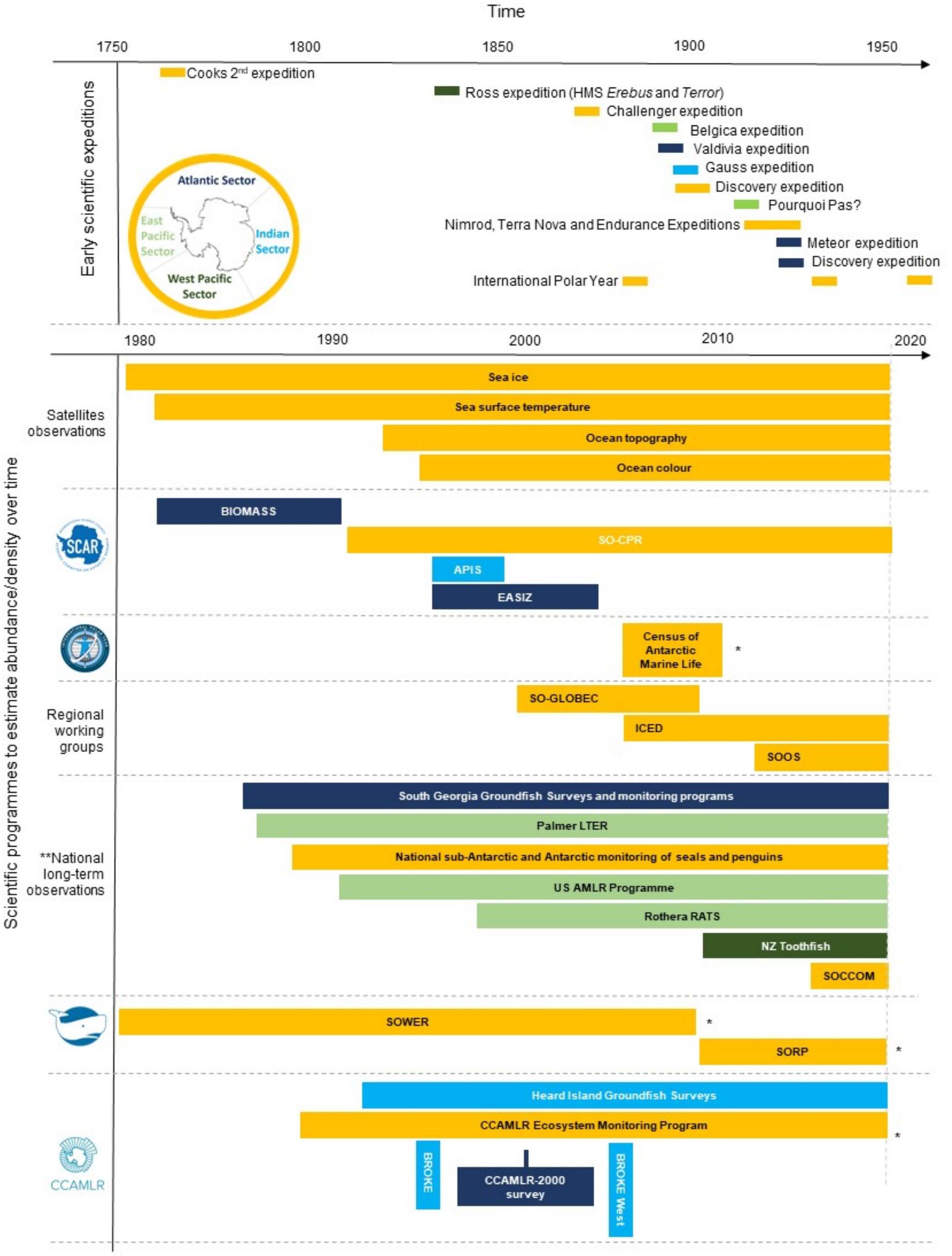
8. Funding

Funding for the MEASO conference and the development of materials for this paper were provided by: Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia; Pew Charitable Trusts, Washingto D.C., USA; World Wildlife Fund, Sydney, Australia, Austral Fisheries, Perth, Australia; Australian Longline, Hobart, Australia; National Institute for Polar Research, Tokyo, Japan; Coalition of Legal Toothfish Operators, Perth, Australia; Tasmanian Polar Network, Hobart, Australia.

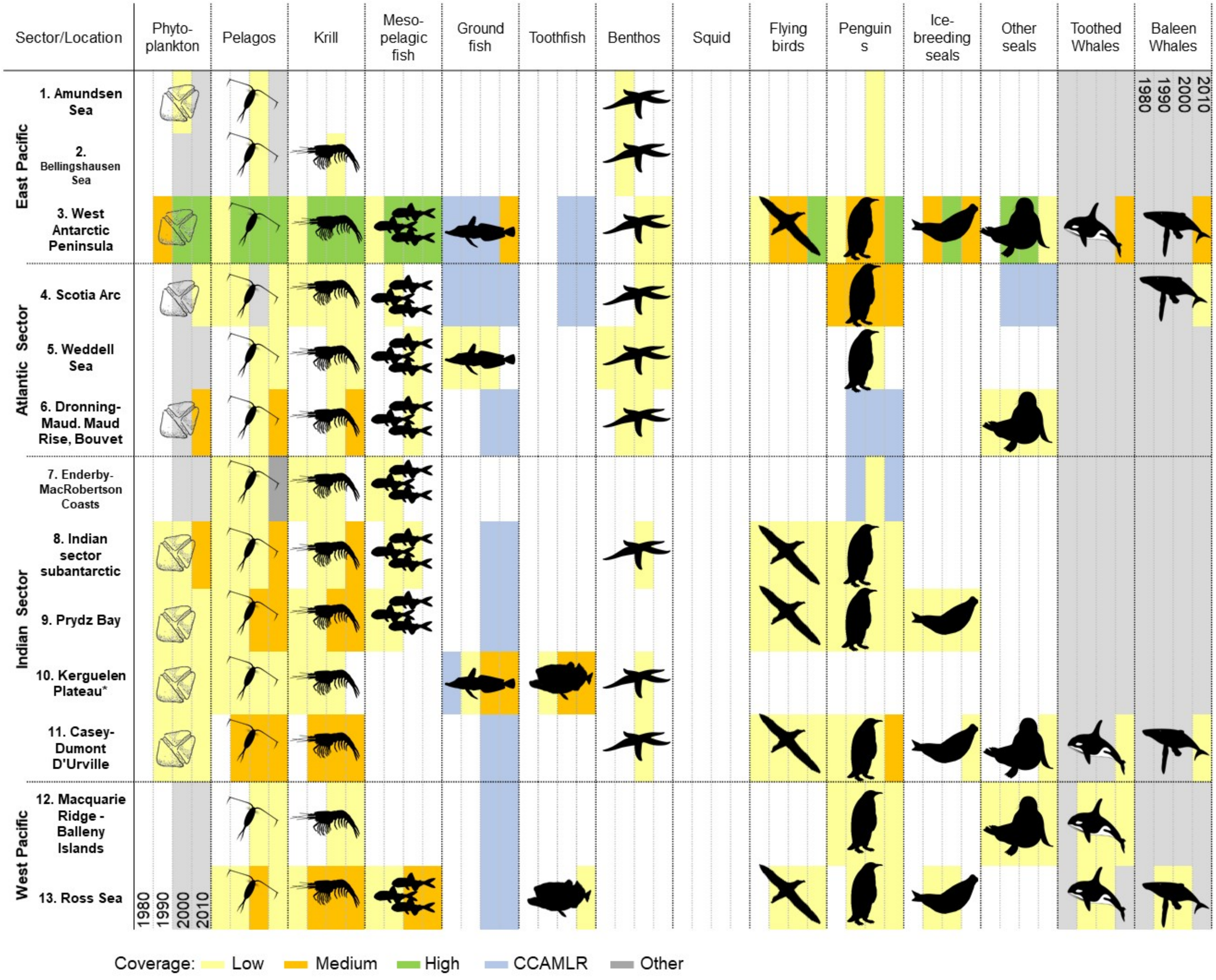

Ocean and ecosystem observations
Statistical and dynamic models
Research driven
Peer reviewed papers
Ecosystem models and statistical summaries
Flexible scales
Status and trends
Stock assessment models
Fishery areas
Catch limits
Models and methods
Scales
Summaries
End users
Governmental
e.g. IPCC
Marine Ecosystem Assessment
Commissions
e.g. IWC, CCAMLR
Derivative assessment
Ecosystem assessment
Stock assessment



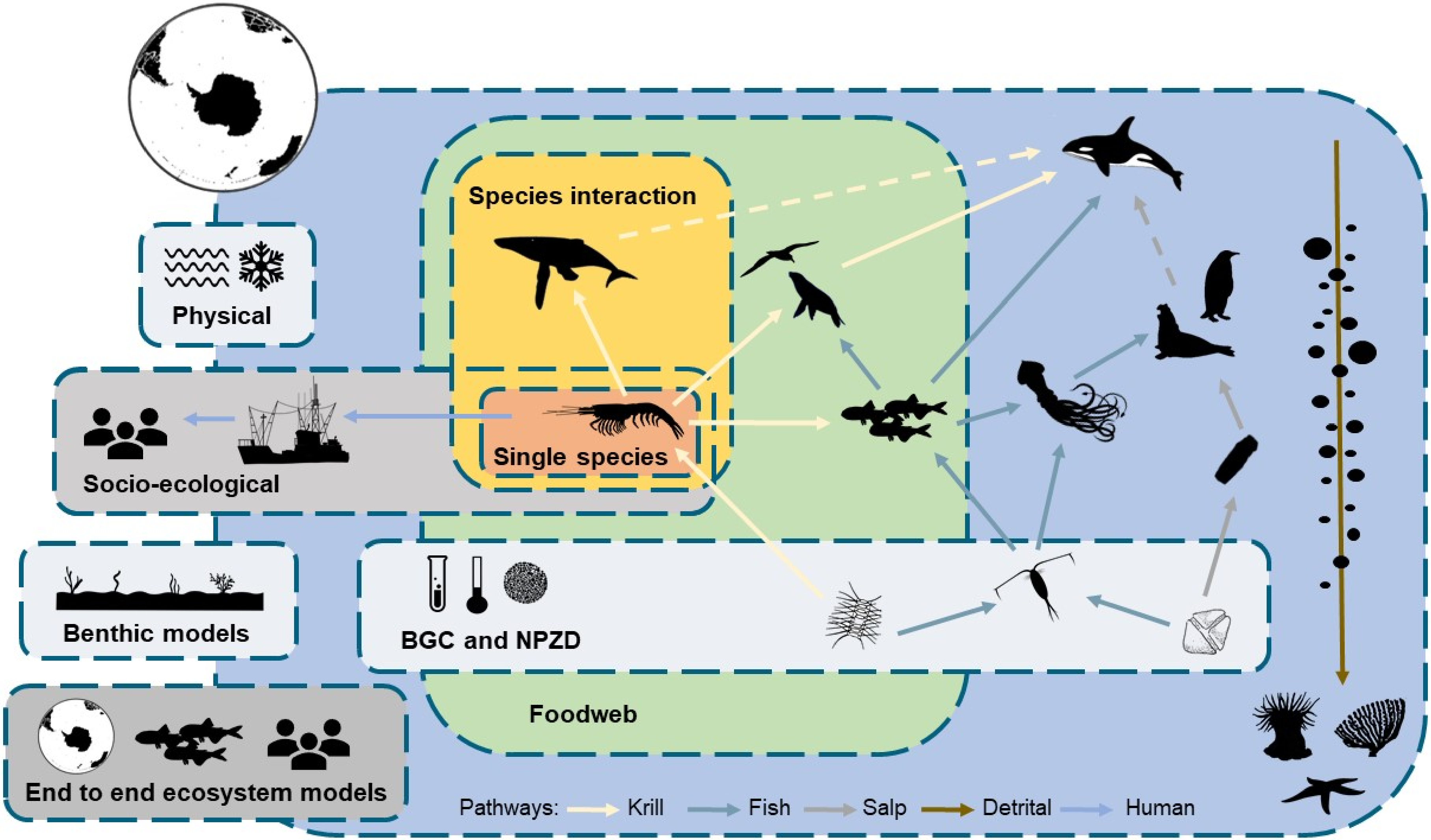
Implementation over time
Policy action
Targeted research and monitoring
Advice for management
MEASO
MEA cycles
5-10 years
Data analysis
Assessment of status and trends
Ecosystem modelling and statistical summaries
Audit and discussion
Current investigation
Ongoing Antarctic Southern Ocean research outputs



* Programmes have a circumpolar approach and outlook but individual surveys may have targeted specific regions or sites. See SOKI pages for details.
** Programmes not associated with the listed international monitoring schemes



Sector/Location
Phyto-plankton
Pelagos
Krill
Meso-pelagic fish
Ground fish
Toothfish
Benthos
Squid
Flying birds
Penguins
Ice-breeding seals
Other seals
Toothed Whales
Baleen Whales
1980
1990
2000
2010
East Pacific
1. Amundsen Sea
2. Bellingshausen Sea
3. West Antarctic Peninsula
Atlantic Sector
4. Scotia Arc
5. Weddell Sea
6. Dronning-Maud. Maud Rise, Bouvet
Indian Sector
7. Enderby-MacRobertson Coasts
8. Indian sector subantarctic
9. Prydz Bay
10. Kerguelen Plateau*
11. Casey-Dumont D'Urville
West Pacific
12. Macquarie Ridge - Balleny Islands
13. Ross Sea
1980
1990
2000
2010
Coverage: Low Medium High CCAMLR Other



Species interaction
Physical
Socio-ecological
Single species
Benthic models
BGC and NPZD
Foodweb
End to end ecosystem models
Pathways: Krill Fish Salp Detrital Human

Taxa	Taxonomic re-evaluation	Species discovery	Species shift	Sample Coverage	Ecological	Physiological
Polychaetes		■		■	■	
Bryozoa		■		■	■	■
Ascidian	■	■		■	■	■
Benthic Hydroids	■	■		■	■	
Stylasteridae	■	■	■	■	■	■
Antarctic Hexacorals	■	■	■			
Harpacticoid copepods	■	■	■			
Pycnogonida	■	■			■	■
Benthic Ostracoda	■	■				
Benthic Amphipods		■			■	■
Isopoda		■		■	■	
Cumacea		■		■	■	
Crabs and Lobsters		■		■	■	■
Shrimps						
Pelagic Copepods		■	■	■	■	■
Halocyprid Ostracods					■	
Hyperiidea amphipods				■		
Euphausiids					■	■
Lysianassoidea amphipods	■	■		■	■	
Tanaidacea				■		
Asteroidea	■			■	■	■
Crionoids				■	■	
Echinoids	■	■		■	■	■
Fish	■			■	■	
Benthic foraminifera	■	■			■	
Gastropoda	■	■		■	■	
Bivalvia		■			■	■
Octopuses	■				■	■
Pteropods					■	■
Squid	■				■	■
Marine nematodes	■	■		■	■	
Porifera	■	■	■	■	■	■
Gelatinous zooplankton	■	■		■		
Near Surface zooplankton					■	■
Tintinnid ciliates				■		
Macroalgae	■			■	■	■
Sea-ice Metazoans					■	

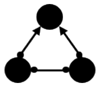
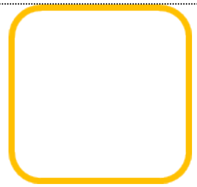
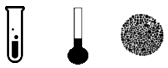
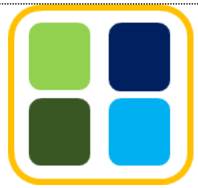
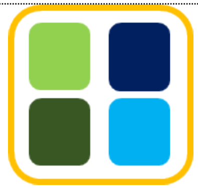
Taxon	Status assessments	Spatial coverage	Trend assessments	Earliest data	Current trends*	Key references**
Plankton	166		?	1900s	? ? ? ?	Hosie et al. 2003; McLeod et al. 2010; Atkinson et al. 2012a;
Krill	42		15	1920s	~ ~ ~ ~	Nicol et al. 2000; Atkinson et al. 2004; Watkins et al. 2004; Fielding et al. 2014; Atkinson et al. 2016; Cox et al. 2018.
Mackerel Icefish	5		3	1970s	~ ? x x	De la Mare et al. 1998; Everson et al. 1999; North et al. 2005.
Toothfish	10		5	1980s	↓ ? ? x	Williams et al. 2002; Tuck et al. 2003; Hillary et al. 2006; Candy and Constable et al. 2008; Hanchet et al. 2010; Mormede et al. 2014; Day et al. 2015.
Baleen whales	17		7	1970s	x ↑ ↑ x	Branch and Butterworth. 2001; Branch 2006; Branch 2007; Leaper et al. 2008; Branch 2011.
Toothed whales	2		2	1970s	x x ? x	Kasamatsu et al. 2000; Branch and Butterworth 2001; Branch et al. 2004; Pitman et al. 2018.
Ice-breeding Seals	26		3	1970s	x ? x ?	Erickson and Hanson 1990; Wiemerskirch et al. 2003; Southwell et al. 2012.
Elephant Seals	22		22	1950s	↑ ? x ?	Laws (1994); McMahon et al. 2005; Hindell et al. 2016.
Fur Seals	17		14	1950s	↑ ↑ x ↑	Hucke-Gaete et al. 2004.
Adelie Penguin	19		15	1940s	? ↑ ↑ ↓	Croxall et al. 1988; Trivelpiece et al. 1990; Woehler and Croxall 1997; Micol et al. 2001; Croxall et al. 2002; Forcada et al. 2006; Dunn et al. 2016; Lyver et al. 2014; Lynch et al. 2012; Lynch and La Rue 2014; Southwell et al. 2015
Chinstrap Penguin	13		11	1950s	↓ x x ↓	Croxall et al. 1988; Trivelpiece et al. 1990; Woehler and Croxall 1997; Croxall et al. 2002; Forcada et al. 2006.
Emperor penguin	15		6	1940s	x ↓ ~ x	Kooyman and Mullins 1990; Jouventin and Weimerskirch 1990; Woehler and Croxall 1997; Croxall et al. 2002; Barber et al. 2007; Micol et al. 2001; Fretwell et al. 2012.
Gentoo penguin	9		10	1970s	↑ x x ?	Croxall et al. 1988; Woehler and Croxall 1997; Croxall et al. 2002; Forcada et al. 2006; Dunn et al. 2016; Dunn et al. 2018.
Macaroni penguin	4		2	1950s	↓ ? x x	Croxall et al. 1988; Woehler and Croxall 1997; Reid and Croxall 2001.
Antarctic and Cape Petrels	16		3	1960s	↓ ? x ?	van Franeker et al. 1999; van Franeker et al. 2001.
Black-browed Albatross	6		4	1960s	x ? x x	Woehler and Croxall 1997; Reid and Croxall 2001.

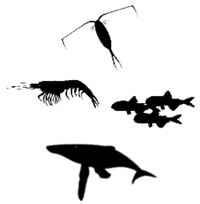
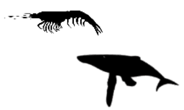
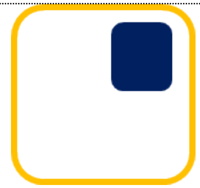
Observed trends
↑ Increase
↓ Decrease
− No change
~ Interannual-variation
? Contrasting data or local variation
X insufficient data/unknown

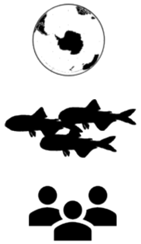
***based on most recent findings within the literature**
****Full reference list available on SOKI**

Taxon	Status assessments	Spatial coverage	Depth coverage	Earliest data	Example references**
All benthos	108			1960	Dayton et al. 1974; Gutt et al. 2011.
Meiofauna	3			1980	Gutzmann et al. 2004.
Macrofauna	12			1970	Gutt et al. 2007; Glover et al. 2008; Brandt et al. 2014; Stark et al. 2014.
Megafauna	10			1980	Lockhart and Jones 2008.
Annelida	9			1970	Hilbig et al. 2006; Neal et al. 2018.
Cnidaria	2			1980	Waller et al. 2011.
Crustacea	14			1970	Brandt et al. 2007b; Brokeland et al. 2007; Kaiser et al. 2007, 2009.
Echinodermata	4			1980	Piepenburg et al. 1997; Manjon-Cabeza and Ramos 2003.
Foraminifera	5			1970	Cornelius and Gooday 2004; Majewski 2005.
Mollusca	7			1970	Clarke et al. 2007; Schiaparelli et al. 2014.
Porifera	5			1960	Dayton 1989; Gocke and Janussen 2013

Depth Distribution
Shelf (<1000 m)
Shelf-slope (0 - 3000 m)
Shelf-slope-basin (0 - >3000 m)
Basin (>3000 m)

Model type	Description	Examples	Anticipated utility	Implementation	ASO Coverage	Example references
Qualitative models 	Framework to examine ecosystem responses to press perturbation.	Qualiative network models	Understand linkages and feedback mechanisms.	West Antarctic Peninsula and aspatial.		Melbourne-Thomas et al. 2013; Goedegebuure et al. 2017.
Earth System 	Simulation of physical, chemical and biological processes within the earth system. Can incorporate global climate models.	CMIP5 models	Provides forcings for regional models	Global with circum-Antarctic detail. Note, southern boundary may not be to the coast		Reviewed in Cavanagh et al. 2017
Regional Physical 	Simulation of physical conditions within the Southern Ocean such as temperature, salinity and currents.	Ocean General Circulation Models (OGCM) Regional Ocean Modelling System (ROMS) Southern Ocean State Estiamte (SOSE)	Provides regional physical forcing for ecosystem models.	Ross Sea, West Antarctic Peninsula Indian sector		Dinnimen et al. 2011; Corney et al. in review; Mazloff et al. 2010
Regional Biogeochemical 	Simulation of biogeochemistry in the Southern Ocean e.g. nutrient cycling, carbon uptake, productivity	Nutrient, phytoplankton, zooplankton and detritus (NPZD)	Understand different drivers that control the base ASO productivity.	All sectors, including pelagic and in sea ice		Pasquer et al., 2005; Saenz and Arrigo 2014; Vancoppenolle et al. 2010; Melbourne-Thomas et al. 2015; Priester et al. 2017
Single Species 	Simulation to understand the ecology of a single species based on current biological knowledge and environmental setting.	Krill examples: Advection, recruitment, relationship with physical drivers e.g. sea ice and	Filling gaps in space and time, where we have patchy abundance data.	Mostly commercially exploited species (krill, seals, whales); Scotia Arc, South Georgia,		Hofmann et al. 1998; Murphy et al. 2004; Thorpe et al. 2007; Wiedenmann et al. 2008; Jenouvrier et al. 2014.

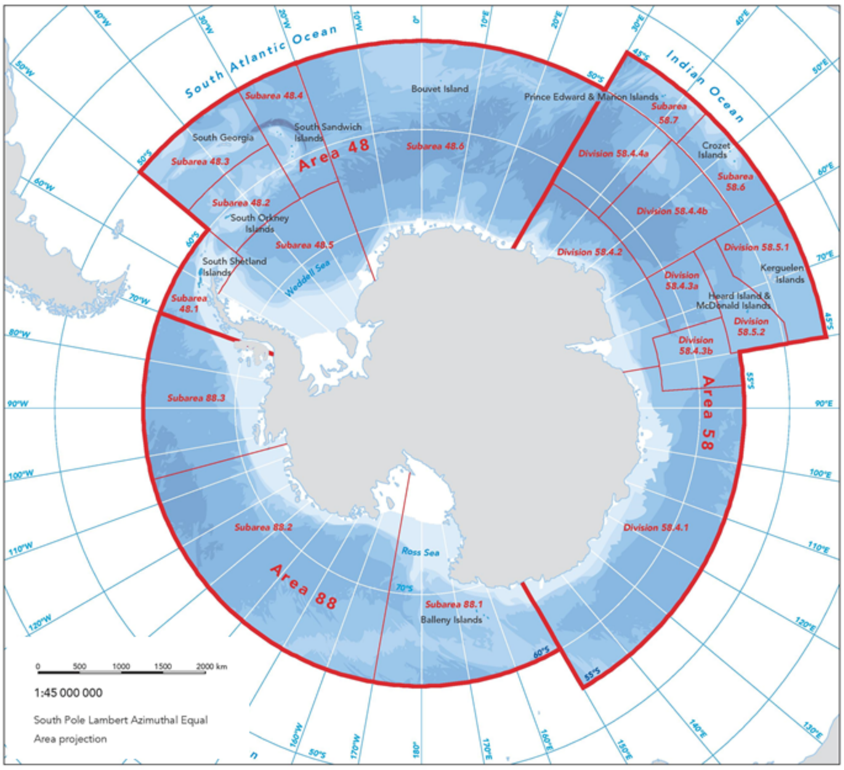
		climatic variation etc		West Antarctic Peninsula, Ross Sea, Indian Sector		
Foodweb models 	Simulation of the trophic interactions within an ecosystem from primary producers to higher predators. Used to investigate the impacts of changes in primary production, fishing effort and species loss.	Mass balance Ecopath with Ecosim. Size spectrum models	Representation of food entire food web to explore relative importance of trophic linkages and the relative impact of different climate and fishing scenarios.	Ross Sea, Scotia Arc, South Georgia, West Antarctic Peninsula, Indian Sector		Mori and Butterworth 2004, 2005, 2006; Pinkerton et al. 2010; Hill et al. 2012; Ballerini et al. 2014; Gurney et al., 2014; McCormack et al, in prep.; Subramaniam et al, in prep
Benthic models 	Simulation of habitat complexity that shapes biological communities in benthic ecosystems, and roles in benthic-pelagic coupling		Explore dynamics of benthic assemblages in relation to iceberg scour, environmental change and fisheries	Weddell Sea, Scotia Sea Indian sector		Johst et al. 2006; Pothoff et al. 2006a, 2006b
Specific interaction models 	Dynamic models of the interactions between selected species within the ecosystem. Can provide quantitative information on ecosystem performance for use in management of human activities including fishing.	FOOSA SMOM EPOC	Subset a food web to specific primary interactions for exploring effects of environmental change or fisheries scenarios.	Mostly krill and krill predators (penguins, whales). Scotia Sea, circum-Antarctic		Constable 2005, 2008; Watters et al. 2013; Plaganyi & Butterworth 2015; Klein et al 2018; Tulloch et al 2018
Socio-ecological 	Framework used to understand the interactions between societal, environmental and governmental factors.		To investigate policy-relevant scenarios that may contribute to adaptive conservation and management of marine social—ecological systems	Yet to be implemented in Antarctica.		

End to end models 	These models include submodels on physics, chemistry, biology, human uses, economics and management. They are spatially structured and can resolve small time-steps (minutes) if needed. They enable exploration of direct and indirect effects of change in one or more components on the other elements of the system. Components can be modelled at different levels of complexity from pools to complex populations with behaviours.	Atlantis	Enable exploration of system-level scenarios of change as well as having methods for evaluating how well management and adaptation measures may work under various scenarios.	Currently being implemented for East Antarctica.		Melbourne-Thomas et al. In Prep;

East Pacific Atlantic Indian West Pacific Circumpolar

Brasier et al. Supplementary information

1. CCAMLR Convention Areas used to define coverage of fishery reports, adapted from: https://www.ccamlr.org/en/document/organisation/map-camlr-convention-area with Fishery reports and stock assessments publicly available from the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (https://www.ccamlr.org/en/publications/fishery-reports-archive).



Species	CCAMLR Convention area	Site	Region	Reports since
Champsocephalus gunnari Mackerel icefish	48.3	South Georgia	Atlantic	2004
	58.5.2	Heard Island	Indian	2004
Dissostichus spp. Toothfish	88.1; 88.2	Balleny Islands and Ross Sea*	West Pacific	2004
	48.3	South Georgia	Atlantic	2004
	58.5.1	Kerguelen Island	Indian	2004
	58.5.2	Heard Island	Indian	2004
	58.6; 58.7	Prince Edward Island	Atlantic	2004
	58.6	Crozet	Atlantic	2004
	48.6	Bouvet Island and surrounds*	Atlantic	2006
	58.4.1	Indian Ocean*	Indian	2006
	58.4.2	Prydz Bay area*	Indian	2006
	58.4.3a; 58.4.3b	*	Indian	2006
	58.4.4a; 58.4.4b;	**	Indian	2009
	48.4	South Sandwich Islands***	Atlantic	2009
Krill	48	Weddell sea; West Antarctic Peninsula	Atlantic; West Pacific	2015
	58		Indian Ocean	2015
	88		East and West Pacific	2015

*exploratory, **fishery closed, *** no report 2013

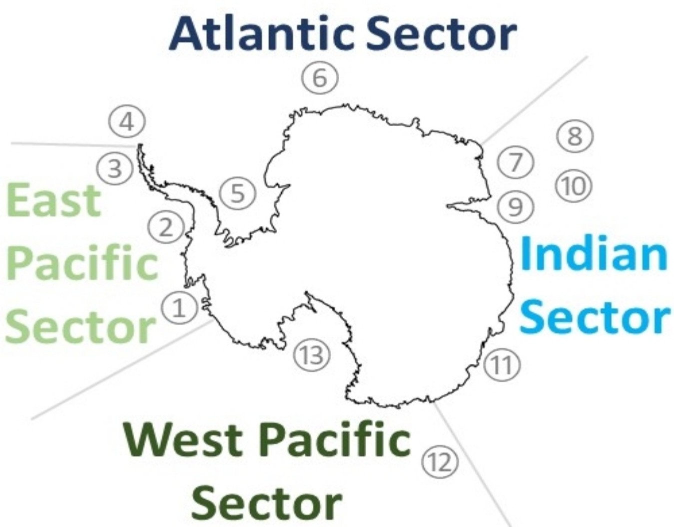
2. ASO coverage based on expert judgement

We consulted 92 scientists from 18 different countries for information on assessments of density/abundance of ASO taxa. The aim of this consultation was to determine the spatio-temporal coverage of research programs estimating abundance (or relative density) of taxa within the Southern Ocean in each decade from 1980 to the present. A total of 14 broad taxonomic groups sub-divided into 49 monitoring groups (listed in the table below) within the consultation document over 13 different sites within the ASO (shown in the map below).

Benthos	**Phytoplankton**	**Pelagos**	**Krill**	**Mesopelagic fish**
Benthic filter feeders	Diatoms	Amphipoda	Antarctic krill	Myctophids
Benthic deposit feeders	Other phytoplankton	Copepods	Other krill	Silverfish Antarctic
Benthic infauna	Other protozoans	Other pelagic invertebrates		
Benthic octopus		Salps		
Benthic predator/scavenger invertebrates				

Groundfish	**Toothfish**	**Squid**	**Flying birds**	**Penguins**
Icefish mackerel	Toothfish Antarctic	Squid	Albatross	Aptenodyte emperor
Icefish other	Toothfish Patagonian		Petrels	Aptenodyte king
Bathypelagic fish			Skuas	Eudypte macaroni
Skates			Other seabirds	Eudypte rockhopper
				Eudypte royal
				Pygoscelid Adelie
				Pygoscelid chinstrap
				Pygoscelid Gentoo

Ice Breeding Seals	**Other Seals**	**Baleen Whales**	**Toothed Whales**
Crabeater seal	Antarctic fur seal	Baleen blue	Toothed dolphins & ziphiids
Leopard seal	Elephant seal	Baleen humpback	Toothed Orca
Ross seal	Other seals/sealions	Baleen minke	Toothed sperm
Weddell seal		Baleen other	



Where:

1. Amundsen Sea
2. Bellingshausen Sea
3. West Antarctic Peninsula
4. Scotia Arc
5. Weddell Sea
6. Dronning-Maud, Maud Rise, Bouvet.
7. MacRobertson-Enderby
8. Indian Sector Subantarctic
9. Prydz Bay
10. Kerguelen Plateau
11. Casey to Dumont D'Urville
12. Balleny Islands, Macquarie Ridge
13. Ross Sea

Estimates of abundance or density could have been obtained from land-based, sea-based or remotely sensed activities over local to regional scales. We asked that the data identified should be suitable for regional assessments of status and trends in the surveyed taxa. For ease of contribution, respondents were asked to indicate the number of surveys undertaken using numerical bins (1, 2-5, 6-10, >10) or simply that they have conducted surveys on specific taxa at a specified location. An additional aim of this research community approach was to measure the level of international engagement with the MEASO project and to identify potential contributors and experts for future regional working groups in the later stages of the MEASO project (see section 5.2).

3. Glossary and acronyms

AMLR - Antarctic Marine Living resources

APIS – The International Antarctic Pack Ice Seals Programme

ASO – Antarctic Southern Ocean

BIOMASS - Biological Investigations of Marine Antarctic Systems and Stocks (1981-1991)

BROKE - Baseline Research on Oceanography, Krill and the Environment

CEMP – CCAMLR Ecosystem Monitoring Programme

CCAMLR – Commission for the Conservation of Antarctic Marine Living Resources

CCAMLR-2000 Survey – CCAMLR 2000 Krill Survey in the Atlantic Sector of the Southern Ocean

EASIZ - Ecology of the Antarctic Sea Ice Zone (1994-2004)

ICED - Integrating Climate and Ecosystem Dynamics in the Southern Ocean

IPY – International Polar Year

IWC - International Whaling Commission

LTER - Long-term Ecological Research Programme

MEASO – Marine Ecosystem Assessment for the Southern Ocean

RATS - Rothera Antarctic Time Series

SCAR – Scientific Committee for Antarctic Research

SCAR MarBIN - Scientific Committee on Antarctic Research Marine Biodiversity Network, now biodiversity.aq

SO-CPR – Southern Ocean Continuous Plankton Recorder

SOKI – Southern Ocean Knowledge WIKI

SOCCOM - Southern Ocean Carbon and Climate Observations and Modelling

SOOS - Southern Ocean Observing System

SORP - Southern Ocean Research Partnership

SOWER - Southern Ocean Whale and Ecosystems Research Programme (1978-2009)

SO-GLOBEC - Southern Ocean Global Ocean Ecosystems Dynamics