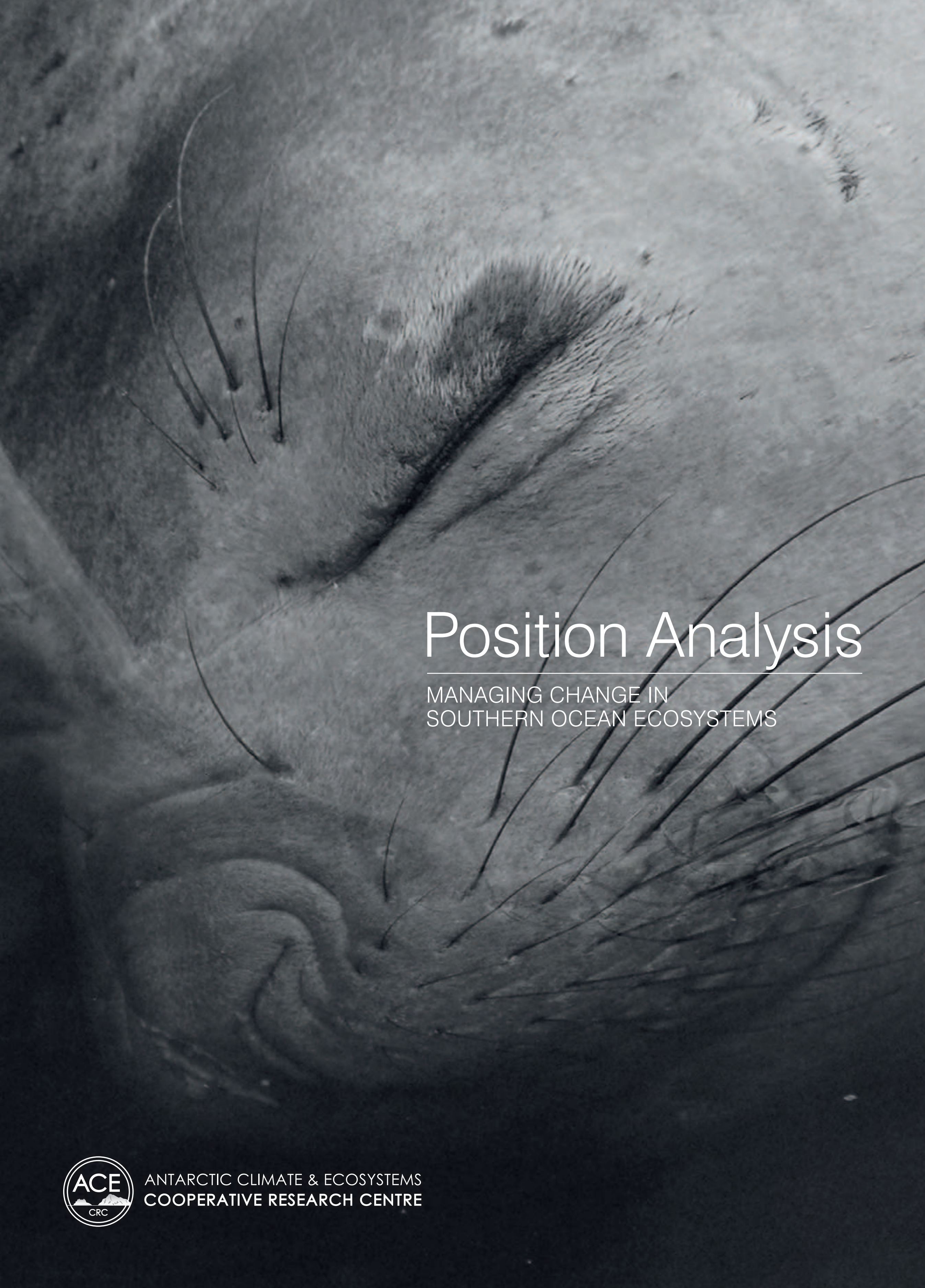


Position Analysis

MANAGING CHANGE IN
SOUTHERN OCEAN ECOSYSTEMS

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

Australian Government
Department of Industry and Science

Business Cooperative Research Centres Programme

Position Analysis: Managing change in Southern Ocean Ecosystems

ISSN: 1835-7911

Antarctic Climate & Ecosystems
Cooperative Research Centre
Private Bag 80, University of Tasmania
Hobart Tasmania 7001

Tel: +61 3 6226 7888
Fax: +61 3 6226 2440
Email: enquiries@acecrc.org.au
www.acecrc.org.au

Cover image: A female southern elephant seal sleeps in a rock pool on Macquarie Island. Credit: Rowan Trebilco

The Antarctic Climate & Ecosystems CRC is Australia's primary vehicle for understanding the role of the Antarctic region in the global climate system, and the implications for marine ecosystems. Our purpose is to provide governments, industry and the public with accurate, timely and actionable information on climate change and its likely impacts.

Document citation: Constable, A.J., Melbourne-Thomas, J., Trebilco, R., Press, A.J., Haward, M. (2017) ACE CRC Position Analysis: Managing change in Southern Ocean ecosystems. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia. 39 pp.

Australian Government
Department of the Environment

Australian Government
Department of the Environment and Energy
Australian Antarctic Division

Australian Government
Bureau of Meteorology

ANTARCTIC GATEWAY PARTNERSHIP

NIWA
Taihoro Nukurangi

CSIRO

AWI ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

UNIVERSITY of TASMANIA

Scientific Contributors

Andrew J. Constable
Jessica Melbourne-Thomas
Rowan Trebilco
Anthony J. Press
Marcus Haward

This document aims to:

- Update the Australian Government and the community on the latest developments in research into the impacts on climate change on Southern Ocean ecosystems
- Explain the techniques that are being used, those that are being developed and the future development of tools capable of reflecting the complexity of climate change impacts on Southern Ocean ecosystems
- Explain the international framework underpinning this work
- Identify issues for consideration in policy development

Contents

At a glance: For a rapid summary, read the Introduction and Background, the centre-spread summarising key messages, and the Benefits of meeting the challenge.
Note: Key terms and concepts are highlighted in bold.

Rowan Trebilco

Rowan Trebilco

1

INTRODUCTION AND BACKGROUND

Marine ecosystems are integral to the health of our planet and to humankind. As the Earth's largest ecosystem, the oceans provide us with a enormous variety of vital 'services', from sequestering atmospheric carbon to providing a major source of nutrition and natural resources. These ecosystems are changing and will continue to change over the coming century as climate change, ocean acidification and commercial pressures continue to modify ocean habitats. Minimising such impacts on ecosystem services is one challenge for governments and regulators. A further and important challenge is to identify how policy and regulatory frameworks may need to adapt to prospective impacts in a timely manner, such that the resilience of these ecosystems is retained, ecosystem services are conserved and, with sufficient warning, rapid upheavals in how we use the ecosystems are minimised.

Climate change poses greater difficulties for policy makers and managers than the usual forms of environmental management because the effects of actions are not seen immediately, or even in the foreseeable future. The experience of the rate of recovery of the ozone hole and the associated changes to ecosystems suggests that ecosystems will take many decades to change in response to changes in greenhouse gas emissions.

To ensure ecosystem services are sustained in the face of future change, we need:

1. robust early-warning indicators of change
2. robust assessments of the likelihood of different future states of ecosystem services given different management options or scenarios, and
3. mechanisms for adjusting management options to take account of new information.

Humpback whales.

Christopher Michel

Clockwise from left: emperor penguins, a single Antarctic krill and a juvenile icefish.

This position analysis outlines how these three needs can be met for Southern Ocean ecosystems by building a number of policy-relevant scientific capabilities. The Southern Ocean is remote from most of the world's population, but has attracted interest since the late 18th Century for harvesting, science, wilderness and, most recently, conservation. It is no less important than other ocean basins – in fact it could be used as a model for sustaining ecosystem services and climate change adaptation elsewhere in the world.

Following the background to this analysis, Part A summarises the current knowledge on change in Southern Ocean ecosystems. Part B details the key scientific questions on which policy-makers need advice, the primary scientific capabilities needed to address those questions and how these capabilities can be delivered. In conclusion, it describes the benefits to Australia of meeting this challenge.

Southern Ocean ecosystems are important globally and regionally

The Southern Ocean, defined here as waters south of the Subtropical Front (Figure 1), is important in the Earth System, accounting for about 40% of the total global ocean uptake of anthropogenic CO_2 [2]. Prior to the 18th century, it was the most significant region supporting marine mammals [40] and is home to most species of albatross and penguin. It also has a very short food chain supporting higher predators.

Exploitation of biota has wrought significant change historically and will likely remain as the dominant human activity across the region for decades to come. At present, fisheries in the region target Antarctic krill, Patagonian and Antarctic toothfish and mackerel icefish. Antarctic krill is the most likely species to sustain very high catches in the region, although the fishery is

A CRITICAL HYPOTHESIS FOR POLICY AND SCIENCE TO ASSESS:

- Southern Ocean ecosystems will be impacted this century, in a non-linear manner and with outcomes differing between regions, resulting overall in a substantial reduction of the relative importance of the krill energy pathway before 2100.

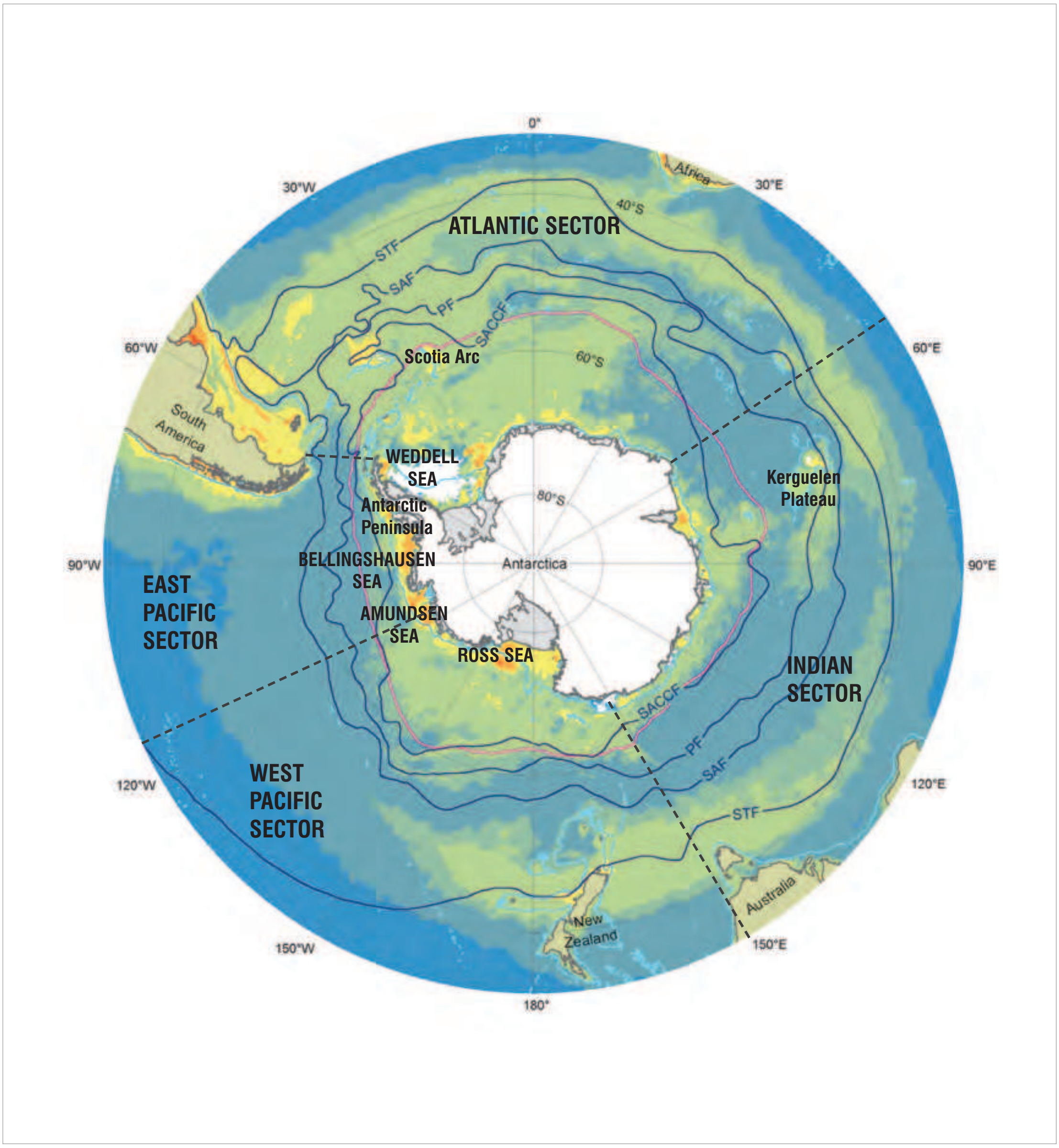
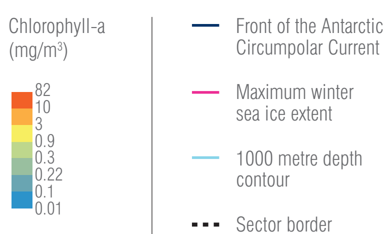


FIGURE 1: Important physical features that shape the ecosystems of the Southern Ocean include the positions of major frontal features (dark blue lines) and sea ice cover (pink line shows the average maximum winter extent over the past 10 years) (after Deppeler & Davidson, 2017[20]). These physical features play an important role in shaping patterns of productivity, as illustrated by the near-surface chlorophyll-a concentration (from Moderate-Resolution Imaging Spectroradiometer, Aqua satellite estimates from austral summer seasons between 2002/03 and 2015/16). Major sectors can be distinguished based on differences in the physical environment (Constable et al 2014), delineated here by dashed lines.



currently operating at a low level (approximately 2% of the total catch limit) but increasing. This fishery may become one of the top 10 wild-caught fisheries in the world in terms of biomass production [59]. Catch limits for Antarctic krill are currently set by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which is responsible for conserving the biota and ecosystems of the Southern Ocean [7], and amount to 8.695 million tonnes. These estimates are considered ecologically sustainable at present, although mechanisms to avoid local impacts of the fishery are still needed and any future changes in system productivity would require adjustments to the catch limits [7]. The catch limits are likely to increase solely as a result of improved methods for estimating abundance from acoustic data from ship-based surveys [57]. If taken in full, catches at the limit would be 11% of the global wildfish fisheries production in 2011 (78.9 million tonnes)[23]. By contrast, Peruvian anchovetta, which is currently the largest single species fishery, accounts for only 5 % of annual global landings.


Rowan Trebilco

Juvenile southern elephant seals on Macquarie Island.

The comparative simplicity of the Southern Ocean ecosystem provides an opportunity to better understand the ramifications of climate change on ecosystems at large scales, identifying positive and negative feedbacks. Also, different parts of the Southern Ocean (sectors in Figure 1) are expected to experience different changes in physical habitats, which will provide opportunities for large scale comparisons of ecosystem responses to different physical regimes. Overall, this will improve our ability to hone and validate models that will be used by policy-makers to forecast the likelihood of different future states [63].

Further, polar ecosystems are expected to experience many substantive changes in the physical environment before other regions of the globe. Early changes such as these may be used to trigger adaptation responses to imminent changes elsewhere.

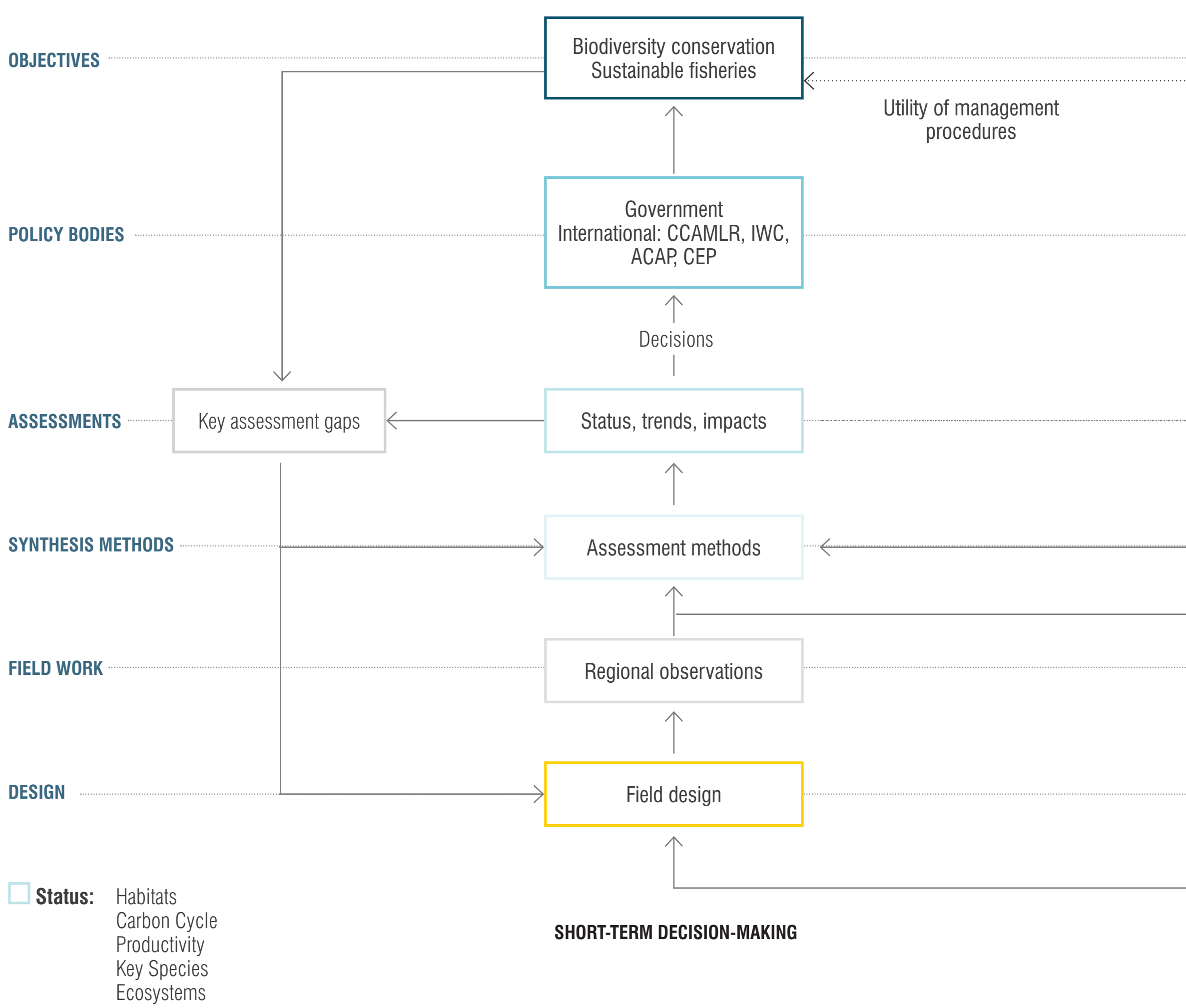
Rowan Trebilco

Southern Ocean mesopelagic fish are key prey for many predators including penguins, seals and larger fish.

Polar ecosystems are currently the least impacted ecosystems on the planet – in terms of the direct effects of current human activities in the region – and may remain so if the current comprehensive management regimes are able to respond to the requirements for conserving changing ecosystems in the future. This makes the Southern Ocean a perfect laboratory for monitoring the effects of climate change and acidification on marine ecosystems if fisheries and other activities are managed in such a way as to maintain the scientific values of this laboratory.

How does science fit into management?

Science has an integral role to play in the management of marine ecosystems. Figure 2 illustrates the links between science and policy. Policy objectives provide the top level of requirements for the relationship between policy and science,



with a separation of short-term tactical needs to manage current day direct interactions of people with ecosystems (left half of the chart) from the strategic needs for adjusting human-ecosystem interactions in the longer term (right half of the chart). For tactical needs, science tends to be oriented towards field observations and assessments of status and trends of the ecosystem and impacts from human activities. For strategic needs, science is currently more focused on processes as well as models that can assess the potential for ecosystems to change and what future states may arise. However, science cannot neatly be divided between tactical and strategic needs. Each depends on the other for producing advice.

The priority for science based on policy needs will be for research that reduces important uncertainties and gaps in assessments. Important uncertainties and gaps are the

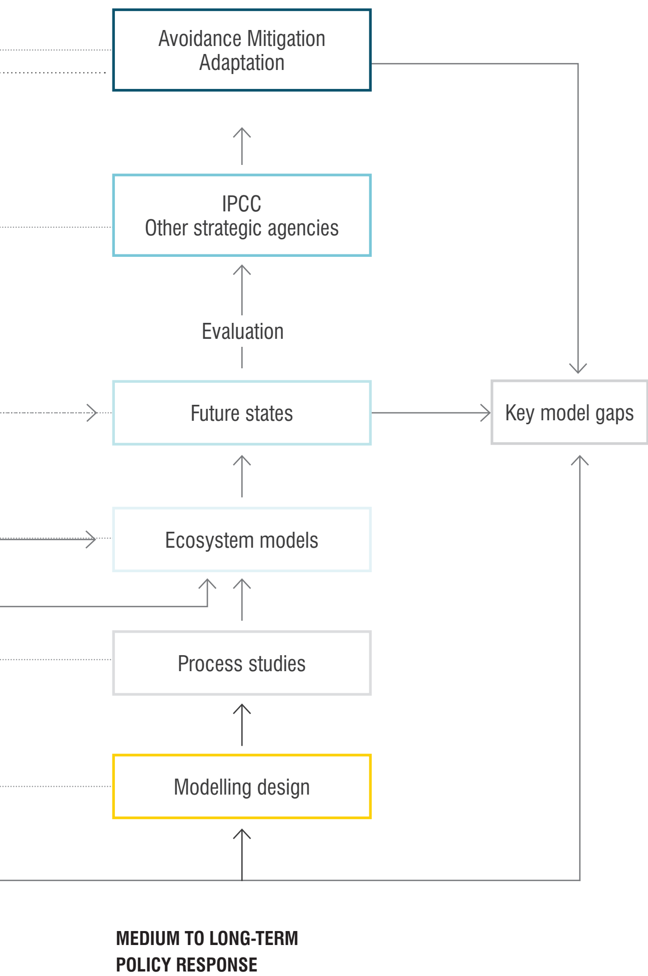
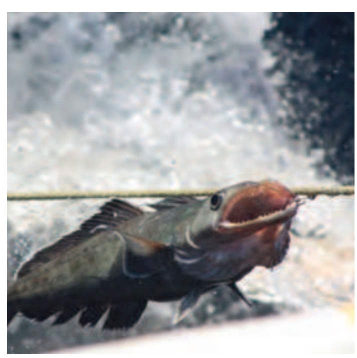


FIGURE 2: Linkages of science and policy in the management of marine ecosystems. Ecosystem objectives relate to maintaining the status of key attributes of the ecosystem (dark blue boxes). Gaps in the capability of assessments and models to assist the policy regimes (top half) drive the science to support policy (bottom half). The left column of activities relate to short-term decision-making while the right column relates to work to develop a medium to long-term policy response. Delivery into policy requires designing and evaluating how to address gaps, undertaking the field and laboratory work, developing the methods for synthesis and assessments and then undertaking the assessments themselves.



James Moir Clark

An Antarctic toothfish is hauled on board a commercial fishing vessel in the Southern Ocean.

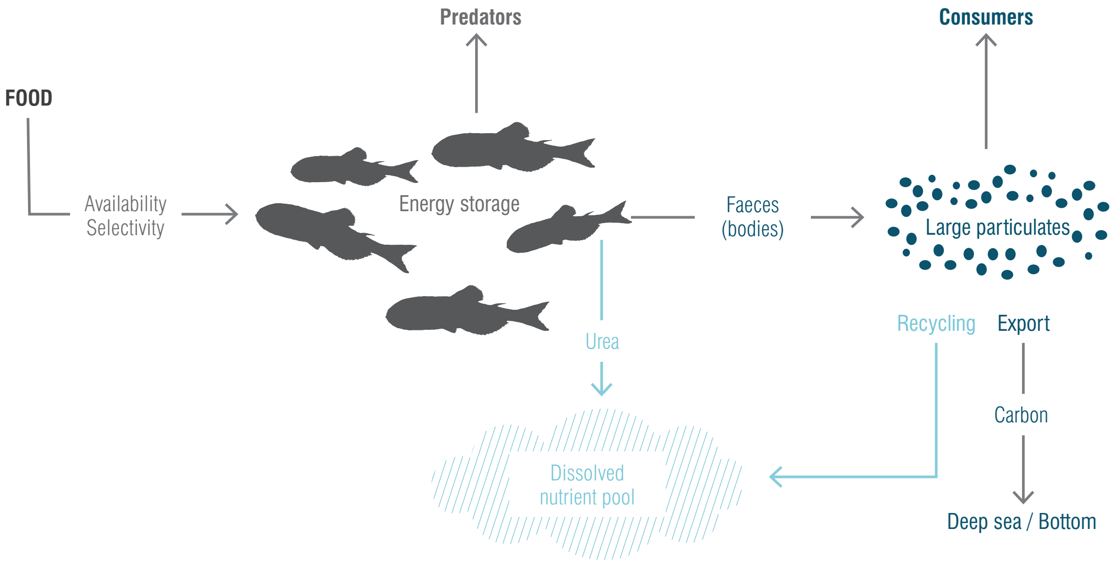


FIGURE 3: The role of an organism in an ecosystem. An organism ingests food based on what is available, and food preferences (usually smaller organisms or, in the case of plants, nutrients from the nutrient pool). Not all food is assimilated into the organism. Waste food is ejected as faeces which, depending on its size, may sink to deeper water, contributing to carbon sequestration or feeding bottom-dwelling (benthic) species. Some of the faeces may be ingested by other organisms and/or recycled into the dissolved nutrient pool by bacteria. Nitrogenous metabolic waste is released into the nutrient pool. The organism may be consumed by higher predators or suffer mortality from other agents. The combined result of all of the trophic interactions shown by gray arrows is the energy pathways that make up foodwebs as shown in Figures 4 and 6.

attributes of the assessments that substantially reduce confidence in policy bodies achieving their objectives. That said, the achievement of the high-level objectives will also be determined by the ability of management systems to adapt to the uncertainties in the available science.

Why do foodwebs matter to changing ecosystems?

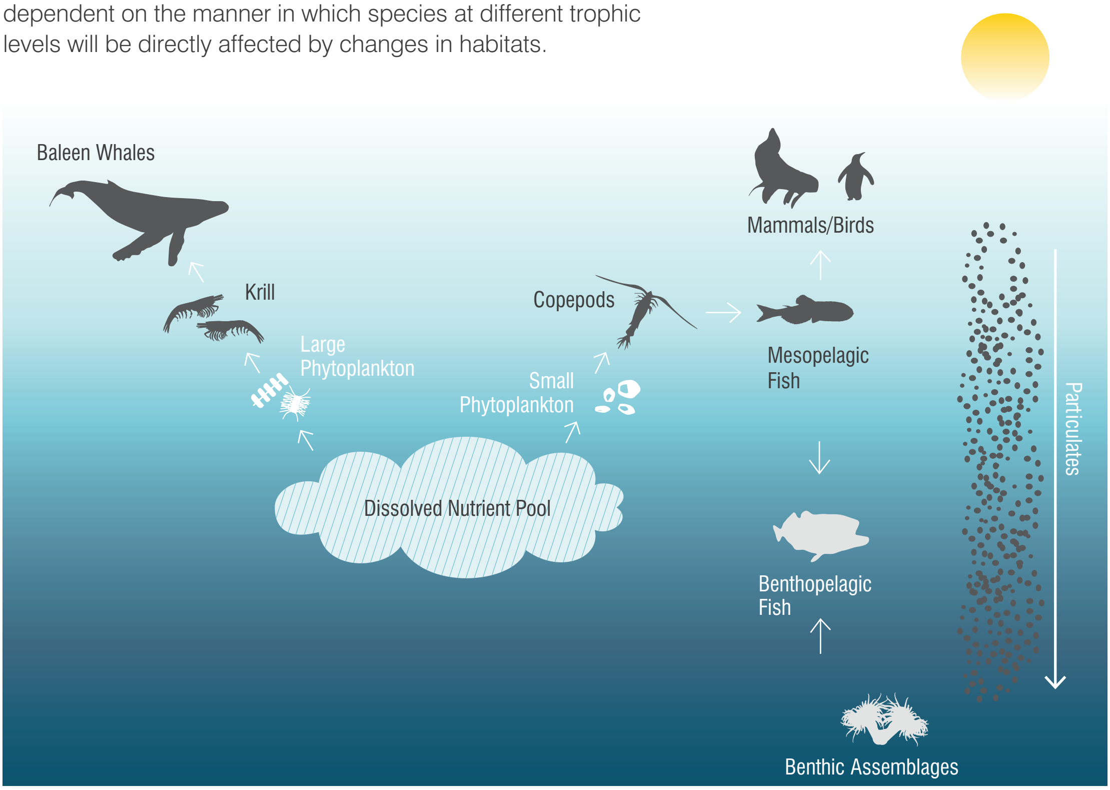
The biomass of a species, whether it be phytoplankton or whales, is dependent on the food eaten by the species, giving rise to production (body growth and reproduction), and by the loss of biomass through consumption by predators or other factors that impact on survivorship (which may include features of its habitat or diseases and the like)(Figure 3). These relationships are not static, even hour to hour.

Environmental factors can favour some kinds of phytoplankton over others, each of which, in turn, may be favoured as food by different herbivores. This can lead to the energy (carbon) being committed to different energy pathways through the foodweb, driven by the predator-prey relationships (Figure 4). In the past, Southern Ocean foodwebs were considered to be relatively simple and dominated by a short trophic pathway transferring primary production to top predators (whales) via krill. However, this is now recognised to be an over-simplification for much of the Southern Ocean and there is at least one other energy pathway that moves energy from smaller phytoplankton to top predators via copepods and small mesopelagic fishes. Toothfish, a primarily bottom-dwelling species, feed on mesopelagic fishes and squids during vertical feeding migrations. They also feed on species dependent on the bottom-dwelling (benthic) communities fuelled by the detrital (particulate) rain from surface waters. The relative importance of these different energy pathways in foodwebs has significiant implications for resource management, in particular the management of krill and toothfish fisheries in the Southern Ocean. There is therefore a clear need to understand and predict foodweb change for Southern Ocean ecosystems. For example, change in the relative importance of these energy pathways may see increases in krill and decreases in toothfish or vice versa.

In addition to moving through food chains, carbon can be lost to the deep sea (sequestration). This may arise through the transport of carbon dioxide in the water and by sinking of the tests (shells) and bodies of plants or animals (e.g. whale carcasses), and discarded waste products, such as faeces (Figure 3). Different species will have a different propensity to contribute to carbon sequestration, either because of their efficiency at using ingested carbon or by the potential for their wastes to be consumed or recycled in the foodweb (Figure 3). Thus, the production of a species (its capacity for storing energy as biomass) will be dependent on the efficiency of the pathway that provides its main source of energy.

Altogether, the dynamics of important species and carbon sequestration will be dependent on the structure and function of the foodweb as a whole. How these dynamics may change as a result of climate change and ocean acidification will be dependent on the manner in which species at different trophic levels will be directly affected by changes in habitats.

FIGURE 4: Simplified representation of the role of different energy pathways in foodwebs and carbon sequestration. The left pathway is regarded as an efficient pathway from nutrients to the top trophic level. The right pathway is less efficient with more intervening trophic levels and consequent loss of energy along the way. This pathway also shows possible linkages between the benthic (bottom) and pelagic (water column, notably epi- and mesopelagic) parts of the ecosystem. Carbon sequestration occurs when particulates sink to deep water and are not recycled into the pelagic foodweb (as shown in Figure 3).



PART A:
CURRENT KNOWLEDGE AND SCIENCE

2

WHAT ARE SOUTHERN OCEAN ECOSYSTEMS AND HOW ARE THEY CHANGING?

Southern Ocean ecosystems

Southern Ocean ecosystems comprise habitats, communities of interacting species, and foodwebs (Figure 5) that together perform functions or processes that we can consider as 'ecosystem services' (e.g. fisheries production, carbon sequestration, conservation values). Dominant features of the physical environment that define Southern Ocean habitats include the Antarctic Circumpolar Current (ACC) and its frontal systems, polar seasonality, and the annual advance and retreat of sea ice [6,10,11,27]. Phytoplankton productivity is contained within the region by the frontal systems, with highest production occurring in conjunction with shallow areas, linked to the supply of iron [76]. Along with the physical variables, the biomass of phytoplankton is also a measure of pelagic habitat quality.

Habitats in the Southern Ocean show latitudinal zonation from south to north due to the transitions between the Antarctic continental shelf, slope, deep ocean, and sub-Antarctic Islands. There is also longitudinal zonation associated with the subpolar Weddell and Ross seas, the Scotia Arc

Grey headed albatross nest in colonies on several sub-Antarctic islands in the Southern Ocean, including Macquarie Island, foraging for food in the open ocean.

RowanTrebilco

Primary drivers of ecosystem change

Temperature | Wind | Acidification | Harvesting

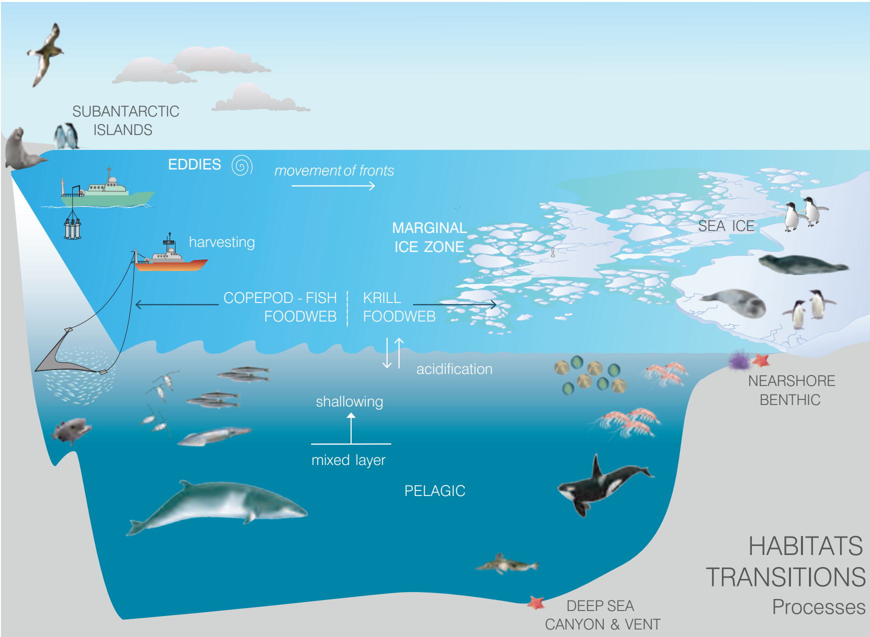
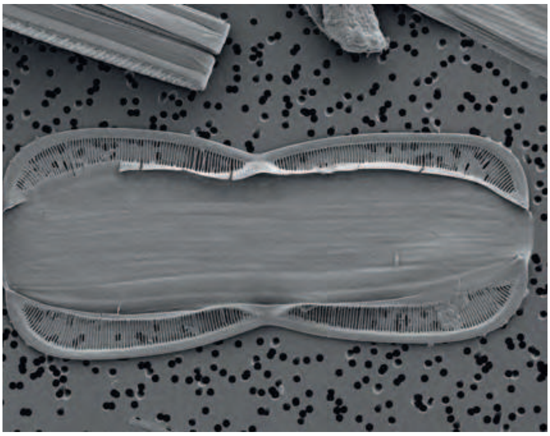
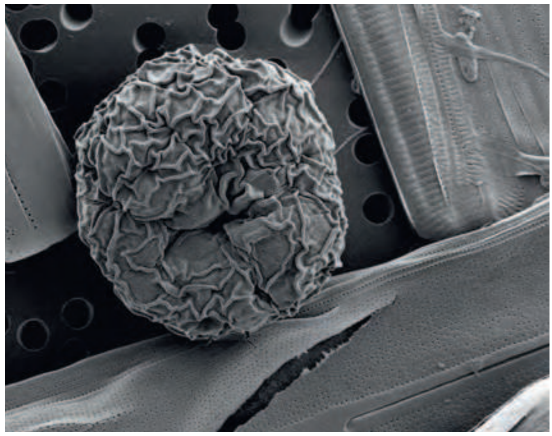


FIGURE 5: Illustration of the key features of Southern Ocean ecosystems (sub-Antarctic to left and Antarctic continent to right). The ecosystem transitions from a copepod-fish foodweb in the north to a foodweb dominated by Antarctic krill in the south. The seasonal cycle is dominated by the changing light and sea ice conditions. Future change in temperature, wind and acidification may drive a shallowing of the mixed layer depth in spring and summer, movement south of the fronts and greater concentrations of carbon dioxide in the surface waters. The marginal ice zone is expected to contract with increasing temperatures, although wind can play an important role in distributing the sea ice. Corresponding changes in the different organisms are shown in Table 1.

in the southwest Atlantic, the Kerguelen Plateau in the Indian sector, and the Macquarie Ridge and seamounts to the north of the Ross Sea in the western Pacific sector [27,35] (Figure 1). Superimposed on this topographical complexity is oceanographic complexity associated with the fronts and zones of the ACC, the shelf sea current systems, the subpolar gyres, and latitudinal variation in a number of other factors, most notably temperature, salinity and sea ice [86]. The interactions of all these factors result in substantial regional variation in both habitats as well as differences in the effects of climate change on ecosystems [10].

Productivity and food web dynamics in the Southern Ocean are dominated by the extreme seasonal fluctuations of irradiance and the dynamics of sea ice, along with temperature, carbonate chemistry and light due to deep vertical mixing [3,4,10,47,78]. Diatoms are the dominant primary producers, particularly in the coastal waters, and are also the primary contributors to the annual carbon flux in the region (Figure 6).





Jake Wallis

Southern ocean diatoms photographed using scanning electron microscope.

Antarctic marine food webs (Figure 6) are considered to be dominated by Antarctic krill, the adults of which range in size from 30-60mm and live for up to seven years [56]. Krill is the dominant consumer of large phytoplankton (diatoms) and small zooplankton and are themselves food for many of the fish, squid, marine mammals, penguins and flying birds in the Southern Ocean.

Other secondary producers (consumers of primary producers) are salps and copepods. The latter feed on smaller phytoplankton, and are consumed by smaller fish, such as myctophids. Food chains where most primary production reaches higher trophic levels via krill, copepods or salps represent, respectively, three energy pathways in these food webs.

The relative importance of krill varies regionally. They are dominant from the Bellingshausen Sea east through to the Weddell Sea and the Atlantic sector of the Southern Ocean [65]. In the Indian and southwest Pacific sectors of the Southern Ocean, the krill-dominated system lies to the south of the Southern Boundary of the ACC [61], while in the north the system is dominated by copepods (Figure 5). In the colder coastal waters over the continental shelf, including the shelf regions of the Ross Sea, Weddell Sea and Prydz Bay, the secondary producers are dominated by ice krill (smaller than Antarctic krill – *Euphausia crystallorophias*) and copepods [61,79]. Copepods are also found in the Atlantic sector but their relative importance to the food web only comes to the fore when krill are in low abundance. Those conditions may also favour salps.

In the open ocean zone (not covered by sea ice in winter), myctophids dominate the fish fauna with distributions showing a high degree of correlation with oceanographic features, particularly frontal zones that act as biogeographic barriers [6,22,33]. These fishes constitute the mid-trophic level between mesozooplankton and many top predators (seabirds, marine mammals, large fish and squid), and therefore are important influences on energy flows in these food webs [30]. They are particularly important in sub-Antarctic waters of the Indian Sector of the Southern Ocean.

Current changes and trends

Southern Ocean ecosystems have been changing as a direct result of human influence since the near elimination of Antarctic and subantarctic seals starting in the 1800s, followed by the overexploitation of many whale species and benthic finfish in the mid-20th Century [38]. The Southern Ocean will substantially change in the coming decades as a result of climate change and ocean acidification [6,10,28,88]. Increases in mid-water ocean temperature [26] and a possible reduction in the extent of sea ice of up to 30% [15,17,19] have occurred since the 1940s. Since the late 1960s, significant changes include increased westerly winds [89] as well as a southward shift in their location [88], extent and timing of sea ice advance and retreat (although varying

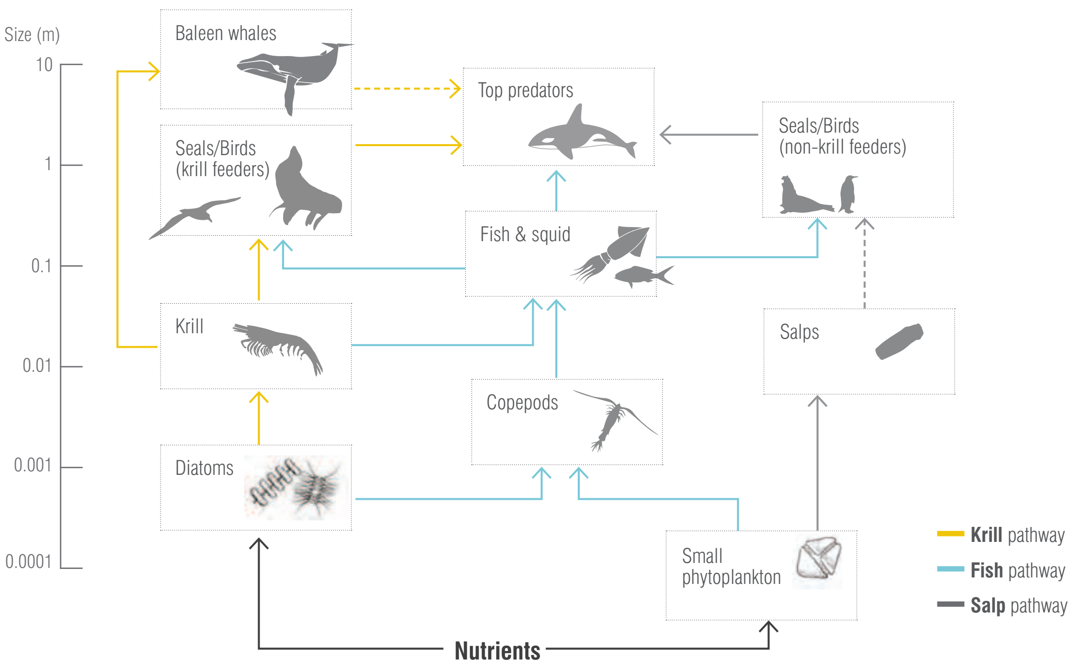


FIGURE 6: Generic Southern Ocean foodweb showing the different energy pathways based on the primary herbivores – Antarctic krill (yellow), copepods (blue), and salps (grey). The complexity of the food web is illustrated by the potential for some species to be dependent on more than one pathway. The dashed blue line indicates that the predators of salps are currently unknown. Vertical position indicates the approximate size of different organisms with the largest organisms at the top and the smallest at the bottom (the size bar on the LHS is on a log10 scale). Not shown here is the contribution of all organisms to the nutrient pool and carbon sequestration via sinking of whole dead individuals and ejection of waste products, as summarised in Figures 3 and 4.

regionally from positive to negative) [31,83,88], abrupt loss of ice shelves [13,14,75], freshening of the bottom water indicating a freshening of the surface waters, a southward shift in the ACC fronts, along with a changed eddy field [50,66,80] and an increase in ocean acidification [88].

Changes in the physical environment of the Southern Ocean constitute changes in habitats, which have implications for diversity and Antarctic marine foodwebs. As a result, climate change is expected to impact more than just primary production (phytoplankton); the diversity of species present in different areas is changing through changes in the spatial extent of different habitats. Also, the modification of habitats in some areas means that predator-prey interactions may be affected at different trophic levels of the food web or the production of some species may be affected by the energetic costs associated with living in modified habitats (e.g., changes in sea ice may change the feeding locations of ice-dependent predators). Thus, climate change can result in changes in species in lower trophic levels, thereby changing the production that reaches the higher trophic levels. It can also result in impacts on higher trophic levels which then alters the predation pressure on species at lower trophic levels.

While changes in biota have been identified in recent decades (Table 1), the mechanisms of change are generally poorly understood. Species that live near the surface, including zooplankton [34], may migrate southward as the ocean warms, but regional geography and oceanography may make the response more complex [84].

In the Scotia Sea, Antarctic krill, the best studied Southern Ocean pelagic species, had been estimated to have declined in density and this was attributed to a decline in sea ice [1], although these estimated changes have now been assessed as part of the variability in the system over time [42]. The switch from a krill-based food chain to a copepod and fish-based food chain in times of low krill abundance [55] is likely to be a result of poorer habitats and primary production available for krill in some years [10]. This suggests that if poorer habitats persist for longer in the future then the copepod and fish-based food chain may become more common [73,85]. The overall prognosis for Antarctic krill is ambiguous because: (i) factors that could directly impact them vary regionally, (ii) they use different habitat features at different times in their life-cycle (e.g. larvae and juveniles utilise sea ice habitat in winter [49]) and (iii) they are able to adapt to changing conditions physiologically and behaviourally [70]. New research is also showing that the survival of larval krill may be negatively affected by increasing ocean acidity [36,37] adding further complexity to these assessments.

Emperor penguins on sea ice in East Antarctica. These birds are the only animals that breed during the Antarctic winter.

Some key trends in distribution and abundance of bird populations (penguins and flying birds) have been linked to climate change impacts, including negative responses to warmer conditions [10]. However, the primary forces of change on higher predators may be difficult to untangle because higher predators can, except in extreme cases, have flexible responses, behaviourally and/or reproductively, to variability in prey and foraging habitat. This may mean that the responses of some populations may lag behind trends in prey or habitats and may be difficult to attribute to a particular cause if many factors are changing at the same time, such as may occur when changes in habitats affect different trophic levels in different ways [61,77,87].

A difficulty with these analyses is that, at present, there are no circumpolar assessments of the status of all the major taxonomic groups, although there has been substantial progress for some groups (e.g. penguins and seals) and across many groups in some areas, such as the Antarctic Peninsula and the Scotia Arc. This makes it difficult to determine what has happened to these ecosystems overall.

Expectations for the future

Southern Ocean habitats are expected to continue to change with further southward movement of ocean fronts, warming and freshening of the surface waters, and increased stratification [71]. These changes would be a result of the expected intensification of winds (through the Southern Annular Mode) and a southward expansion of the subtropical gyres [48]. This will also bring increased upwelling of warm, salty, nutrient-rich water, including increased incursions of warm Circumpolar Deep Water on to the Antarctic continental shelf

Taxon	Size (m)	UV	Temperature	Ocean acidification	Mixed Layer Depth	Sea-ice	Move with fronts	Eddies
Diatoms	0.0005	↓	↑		↑	↓	↑	
Flagellates (*Phaeocystis*)	0.0001	↑	↓		↓	↓	↑	
Microzooplankton	0.001	?	↑	?		↓	↑	
Bacteria & viruses	0.000001	↓	↑			↓	↑	
Zooplankton	0.005-0.01		↑				↑	
Salps	0.01-0.05					↓	↑	
Antarctic krill	0.05	↓	↓ Sub-Antarctic	↓		↑		
Nototheniid fish	0.1-0.5		↓					
Myctophid fish	0.05-0.1		↑				↑	
Oegopsid squid	0.05-5		↓?	↓?				
Southern Elephant seal	2-5					?		↑
Krill-eating seals	1-3				↓	↑?	↑	↑
King penguin	1						↑	↑
Emperor penguin	1.5					?		?
Adélie penguin	0.7				?	↑ no ice to lower ice conditions ↓ heavy ice conditions		
Macaroni penguin	0.7					↓		↑
Baleen Whales	>10					?		?
Flying birds	0.5-2					↑?	↑ ?	↑ ?
Benthic communities	0.1-0.5		↓ ?	↓ ?				

Table 1: Summary of known direct responses of biota to changes in physical parameters in Antarctica and the Southern Ocean (based on Constable et al. 2014). UV = ultraviolet radiation. Acidification includes altered carbonate chemistry and pH. Sea-ice includes consideration of thickness, concentration, and extent without differentiating the factor/s causing change in each group of organisms. An upwards arrow indicates a positive relationship (increase in the physical variable is expected to cause an increase in the taxon). A downward arrow indicates a negative relationship (increase in the physical variable is expected to cause a decline in the taxon). A question mark (?) indicates where there is likely to be a response but the direction is uncertain, i.e. the result may be variable in space, time or for specific taxa, or the evidence is equivocal. As physical factors vary in their direction of change between different sectors of the Southern Ocean, the responses in this table are used to interpret what specific directions of change may mean for the populations in a sector.

(for example see Sen Gupta *et al*. 2009 [71]). Sea ice is expected to decrease in both extent [5] and annual duration [45], although assessment models show that the sea ice prognosis remains one of the greatest uncertainties surrounding Southern Ocean habitats (there is still some discrepancy between observations and model simulations of Antarctic sea ice extent [31,45]). Further ice shelf disintegration may occur if rates of warming experienced in the Antarctic Peninsula area occur in other regions [68,75].

These changes in physical habitats are expected to result in a contraction southward of Southern Ocean ecosystems, a decline in krill, along with changes in higher predators. The manifestations of climate change impacts on ecosystems will vary between sectors, with southward shifts in habitats along the Antarctic Peninsula, increasing sea ice conditions in the Ross Sea but uncertain trajectories of change in East Antarctica.

The responses of biota will be governed by how easily the taxa can tolerate change within existing physiological flexibility, adapt to new environmental regimes or migrate to alternative sites that enable survival. The ultimate consequences of such changes are expected to go beyond shifts in species ranges and may result in novel functional organisation and dynamics of Southern Ocean food webs and potentially to reduced biodiversity. Importantly, foodweb-level change is difficult to predict because of the interactions between different energy pathways in the foodweb and the presence of feedbacks.

Finally, changes in Southern Ocean habitats will affect patterns of change in primary production and foodwebs. Pelagic species may migrate southward as the ocean warms and the winter sea ice extent reduces, but regional geography and oceanography may make the response more complex. Knowledge of the key habitat variables that limit the ranges of key species within food webs will be very important for determining whether marine food webs will contract polewards.

POSSIBLE CONSEQUENCES OF SHIFTS IN ENERGY PATHWAYS:

- decline in krill will reduce abundance of baleen whales and krill fishery production;
- increase in copepods may result in increased toothfish catch;
- increase in salps may increase carbon sequestration and food for benthic communities.

Jessica Melbourne-Thomas

A minke whale breathes through a lead in sea ice in East Antarctica. Minke whales have been seen hundreds of kilometres into heavy pack ice in the middle of winter.

SUMMARY OF KEY MESSAGES

	Current understanding/ capability	What needs to be done
Responses of key species	Responses of key species to individual habitat drivers are relatively well understood[10] (e.g. see Table 1).	There is a need to: – Better understand combined effects of multiple drivers and responses; – Evaluate the capacity of key species to adapt to environmental change.
Habitat change	Habitat change is relatively well understood at the broad scale, as are biological relationships with key habitat drivers (temperature, acidification, mixed layer depth, sea ice extent, sea ice duration, timing of sea ice advance and retreat, and the location of fronts and eddies).	There is a need for better methods to document and summarise habitat variability and change at scales that are meaningful to policy makers.
Foodweb structure	The krill-based food-chain is well described, and the importance of alternative energy pathways in Southern Ocean foodwebs has been established.	There is a need to better understand: – What factors cause differences in foodweb configuration and in the relative importance of key energy pathways (particularly pathways through mesopelagic fish and salps); – What the implications are for delivery of ecosystem service (carbon sequestration and productivity available for fisheries).

	Current understanding/ capability	What needs to be done
Assessing status and trends in ecosystems	We now understand the components/information that is needed to undertake a full assessment of Southern Ocean ecosystem status and trends.	The first circumpolar assessment of Southern Ocean ecosystem status and trends is being led by the ACE CRC and will culminate in a conference in Hobart in 2018 on a Marine Ecosystem Assessment for the Southern Ocean (www.measo2018.aq). Long-term integrated, circumpolar, biological observations need to be established to support assessments of change in the future (co-ordinated through Southern Ocean Observing System).
Estimating future states	No clear statements of ecosystem futures are currently available but two things are recognised to be needed for providing estimates of future ecosystem states: (i) dynamic ecosystem models, and (ii) an estimate of current state to provide a starting point for projections.	A set of dynamic models for Southern Ocean ecosystems are near completion. Further tools will be needed to down-scale these models to support management objectives for the region. Benchmarking of Southern Ocean ecosystems needs support and is planned for 2022.
Adapting management approaches	A consolidated framework for evaluating and adapting management strategies for changing Southern Ocean ecosystems is now available (see Figure 8).	Adaptive approaches need to be informed by scenarios for future change derived from coupling Earth System models and end-to-end ecosystem models, along with tools for downscaling these results to the management systems. These scenarios need to be evaluated against observations designed to help discriminate between them.

Rowan Trebilco

3

TIMELINE OF SOUTHERN OCEAN ECOSYSTEM RESEARCH, CHANGE AND MANAGEMENT

Scientific study of Southern Ocean ecosystems commenced in the early-mid 20th century. The Discovery Expeditions, International Geophysical Year and the advent of the Antarctic Treaty System and the accompanying Scientific Committee on Antarctic Research are landmark events. Although unconnected initially, the growth in large-scale coordinated scientific activity coincided with the emerging effects of climate change, ozone depletion and ocean acidification. Timing of key steps in the development of ecosystem research relative to ecosystem change is illustrated in Figure 7. A key point is that, by the time systematic scientific observations commenced, humans had already been exploiting Southern Ocean ecosystems for more than 150 years.

Marine ecosystem research has evolved from an initial emphasis on production, krill and whales at spatial scales often less than the sectors in Figure 1 to a point where the research community is endeavouring to take a more whole-of-ecosystem view at a spatial scale of at least sectors if not a synoptic circum-polar view. Nevertheless, patchy sampling of the biota, in space and time has meant that there are very few datasets from which we can identify the state of the ecosystem and the relationships between many of the physical, chemical and biological variables.

A number of censuses have helped contribute to circumpolar estimates of abundance of Antarctic krill[58,60 90], Adelie penguins[43,44,82], emperor penguins[24], pack ice seals[81], and baleen whales[41]. Time series of observations of different components of food webs became co-ordinated in the

1980s through activities in SCAR and the establishment of the ecosystem monitoring program of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) [9]. However, long-term observations integrated across all levels of the food web along with the physical environment have not been taken routinely in many locations, except in the vicinity of the West Antarctic Peninsula[21] and the Scotia Sea[54]. Most of this work is oriented towards krill-centred interactions. Few areas have data on the other energy pathways in the region. An assessment of pelagic and benthic biodiversity was undertaken by the Census of Antarctic Marine Life during the International Polar Year (CAML-IPY; 2007-2008) [39,69] leading to the SCAR Biogeographic Atlas of the Southern Ocean [16].

Recent reviews on the state of knowledge on the status of Southern Ocean ecosystems indicates an overall paucity of data and results available to examine the current and future impacts of climate change and ocean acidification on Antarctic food webs [10,62]. In particular, the IPCC Working Group II Summary for Policy Makers concludes there is only medium confidence around statements of ecosystem change for polar regions due largely to this lack of data to estimate whether change has occurred. The Summary for Policy Makers also indicates the need for enhanced monitoring, regulation and warning systems that achieve safe and sustainable use of ecosystem resources in these areas (see also the Millennium Assessment 2005[51] and the report of the Scientific Committee of CCAMLR in 2011[67]).

In 2003, ACE CRC added ecosystem capability to its biogeochemical capability with leading research on:

- key processes that influence krill dynamics and ecosystem ecology in East Antarctica,
- the role of sea ice in Southern Ocean ecosystems, and
- ecosystem assessments and modelling ecosystem futures.

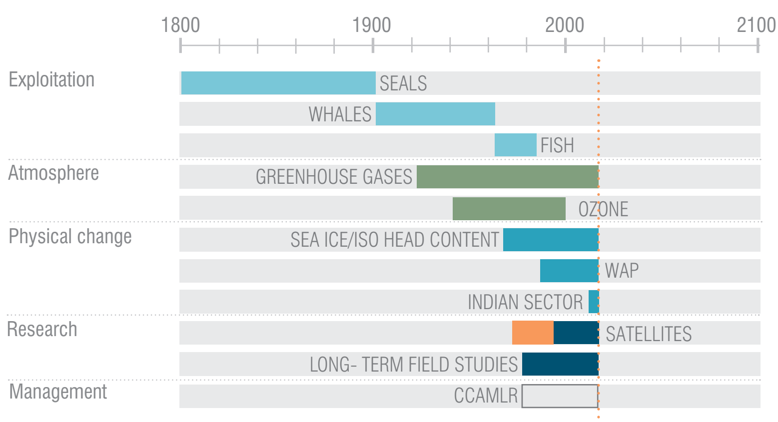


FIGURE 7: Timeline of exploitation, environmental changes, major international field programs, major long-term observing activities, and management (see text for details). Present day is indicated by the vertical red dotted line. Satellite data began with measurements of physical ocean variables (e.g. Sea Surface Temperature, orange part of bar) with ocean colour being measured alongside physical variables from 1997 (dark blue part of bar).

PART B:
POLICY-ORIENTED SCIENCE FOR ESTIMATING CHANGE

4

THE POLICY CHALLENGES FOR ECOSYSTEM SCIENCE IN THE SOUTHERN OCEAN

Climate change is challenging ecosystem scientists to determine how ecosystems are changing, how fast they are changing and what capacity key biota have to buffer against the changes impacting them. For the Southern Ocean, the key overarching questions for ecosystems are:

Carbon uptake and storage:

- How will the uptake of anthropogenic CO^2 by the Southern Ocean be affected by climate change?
- How might changes in the food web influence that uptake?

Fisheries:

- How will Antarctic fisheries production be impacted by climate change?
- Could fisheries impact on the long-term resilience of Antarctic krill-based food webs to climate change effects?
- What management strategies are needed to ensure fisheries remain ecologically sustainable and do not contribute to undesirable shifts in ecosystem structure and function?

Conservation:

- How will climate change impact on marine mammals and birds in Antarctica and the Southern Ocean and will the recovery of depleted populations be impeded?

A scientist working in the wet lab on board RV *Aurora Australis* sorts mesopelagic fish species collected around the Kerguelen Plateau.

Rowan Trebilco

- What is the potential for a shift to a less productive and less efficient food web based on copepods and fish rather than krill?

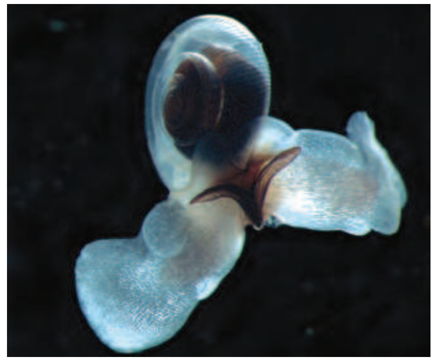
From a scientific perspective, these questions can be distilled into the following capabilities, which can then be used to address the different questions above:

Scientific Capability 1:
Status and trends of key biota and ecosystems

- Assessments of the current state of key biota and ecosystems, against which change in ecosystem structure and function can be measured.
- Estimation of changes in key biota and ecosystems, including attributing the causes of change, such as the effects of fishing and/or the effects of climate change.

Scientific Capability 2:
Estimation of the likelihood of future states

- Identification of critical processes, mechanisms and feedbacks that directly influence the population responses of biota to change in their habitats and the productivity and dynamics of the ecosystem generally.
- Assessments of the likelihood of future changes in biota and ecosystems under specific climate change and/or fishery scenarios.


Donna Roberts

One of the most common species of pteropod in the Southern Ocean, *Limacina helicina antarctica.*

Injecting science into decision-making

In managing ecosystems (as for managing complex systems in general), managers aim to achieve system objectives despite their uncertainties in knowledge. Uncertainties may stem from: (i) assumptions about how the system works (including the manner in which people interact with the system); (ii) knowledge about the state of the system and where it is heading; and (iii) the degree to which the future state of the system will be affected by random behaviour. In fisheries, these three components would be considered, respectively, as (i) the fish stock population parameters that are influenced by environmental conditions (e.g. growth, reproduction, natural mortality and fishing mortality), (ii) the current state and trajectory of abundance and stock structure relative to some reference level, and (iii) natural (stochastic) variability in the fish stock. In setting levels of human interaction, e.g. fishery catch limits, a manager needs to consider the risks of failing to meet the objectives as a result of uncertainties in the process. For a given catch, greater uncertainty means relatively higher risk. A precautionary approach entails maintaining a comparatively low level of risk.

Climate change is challenging ecosystem scientists to determine how ecosystems are changing

Control systems theory has been used to help assess the risks of a management strategy failing to meet the objectives in fisheries and ecosystem management as a result of uncertainties [18]. It can also be used to assess the trade-offs in risk between different scenarios, such as risks associated with different management actions governing catch and risks arising from different levels of scientific efforts to address the uncertainties in stock parameters, stock status, and dynamics. This approach can be extended to include scenarios for long-term change in environment as a result of climate change and ocean acidification. A systems approach such as this could also include how risk may be moderated by actions to avoid, mitigate or adapt to climate change and ocean acidification.

Figure 8 shows the interaction between management, industry and science in a "control system" for the case of fisheries. Even though we may not have perfect knowledge of the entire system, it is still possible to simulate (model) it based on the knowledge that we do have of the different components of the system and their interactions, including the ecosystem. Simulations can then be used to explore plausible scenarios and determine how management, science and industry may be adjusted in order to successfully meet the objectives with an agreed maximum level of risk [2].

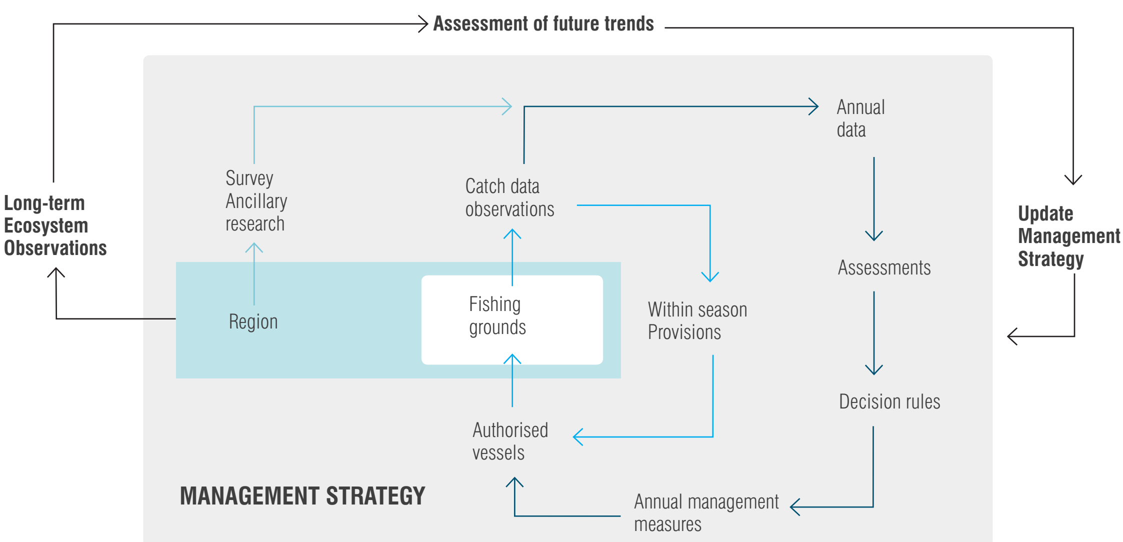


FIGURE 8: Adaptive management strategy showing short-term requirements of science for management and the longer-term requirement to achieve adaptation of the management system before problems arise (after Constable & Welsford 2011)[12]. The management strategy utilises data from the fishery and regular surveys in an assessment of the status of the stock. Catch limits and their spatial distribution are set according to pre-agreed decision rules that specify how the catch will be altered to achieve the objectives (e.g. long-term annual catch that will be consistent with the conservation requirements of the Convention on the Conservation of Antarctic Marine Living Resources). Annual management measures are then established and used to govern the authorised vessels. Some within-season provisions may be needed, such as keeping the by-catch rates within acceptable bounds. Annual assessments may be insufficient to determine when the management strategy may need to be adapted to changes in the ecosystem. A combination of long-term ecosystem observations and ecosystem models will be important for assessing future trends in the ecosystem and to signal when the management strategy may need to be adjusted in order for the objectives to be met in the long-term.

Using science to formulate objectives

Fisheries usefully illustrate how science can contribute to the formulation of objectives that can then be used for making decisions to manage human activities.

Management of fish stocks often assumes that:

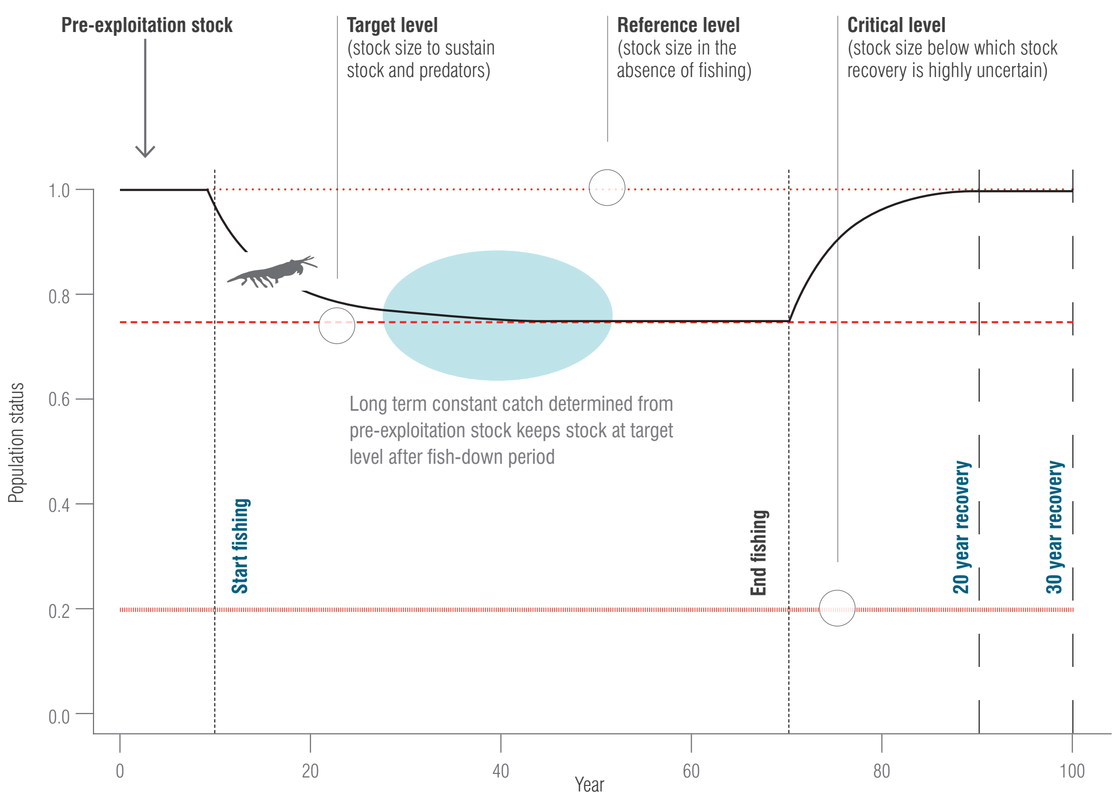
i) a stock biomass gravitates around a stable median level, despite its inherent natural variability

ii) if the biomass is exploited at a relatively constant rate, the new stable median value will be at a proportion of a median level prior to exploitation.

iii) biomass will recover to the pre-exploitation median over time, in the absence of fishing, no matter how depleted the stock may become.

At the ecosystem level (multiple stocks and species), the extension of these assumptions is that the ecosystem has an approximately equilibrium state that is very resistant to change. These principles are encapsulated in the decision rules for CCAMLR fisheries [9] and are illustrated for Antarctic krill in Figure 9.

FIGURE 9: Illustration of the principles embedded in the rules for determining long-term annual catch limits for Antarctic krill by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). The principles are based on the relative status of the population (spawning biomass) over years. The pre-exploitation median spawning stock biomass is the reference level (top red horizontal line) under constant system productivity. The target level for the spawning stock (middle red horizontal line) was determined to be 0.75 of the pre-exploitation level, based on an assumed level of requirements for krill predators and that recovery of the ecosystem needed to be able to occur in two to three decades (vertical long-dashed lines at 90 and 100 years) should fishing cease (fishing period indicated by vertical dotted lines; here fishing begins at year 10 ends at year 70). The decision rules also recognise the need to ensure the fishery has only a low chance of causing the stock to decline below the critical level (bottom red horizontal line), which was set at 20% of the pre-exploitation level. The solid black line indicates a stock trajectory based on a surplus-production model and a long-term annual yield by the fishery that satisfies the decision rules.



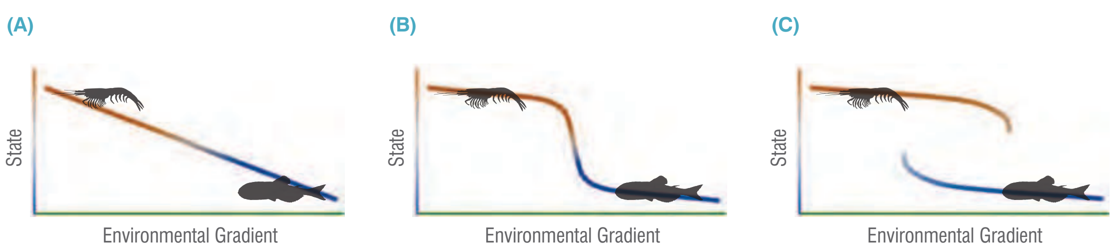
Why should policy-makers be concerned about how ecosystems respond to climate change?

Management approaches for fish stocks and marine ecosystems generally require that (i) the trajectory of a species is largely predictable, relative to the environment and to other species, and (ii) these relationships are measurable now. However, these requirements, together with the assumptions described above for the recovery of fish stocks, may not stand up to the reality of biological systems, particularly under climate change and ocean acidification. Acidification and climate change in particular may cause dramatic changes in the relationships between species, yielding unpredictable ecosystem states in the future.

There are three plausible scenarios for ecosystem change under climate change (Figure 10). The first of these is that, if the ecosystem changes in a consistent manner relative to environmental changes, then the long-term change may be wholly predictable based on estimates from recent observations (Figure 10a). Under this first scenario, if the environment is restored then we expect that the ecosystem will be restored as well. The second scenario is that the current rate of change in the ecosystem may not remain constant and that an abrupt, non-linear transition from the current ecosystem state to a new state may occur at some time in the future (Figure 10b). Under this scenario, restoring the environment will also result in the ecosystem being restored but with rapid restorative change at some point. The third scenario is one in which alternative stable states (hysteresis) are possible (Figure 10c); these states are hyperstable despite change in the environment. In this scenario, the ecosystem state deteriorates until a ‘tipping point’ is reached and the alternative state rapidly takes over. This alternative stable state then remains even if the environment returns to conditions that supported the other state in the past; restoring the ecosystem will require much more substantial environmental restoration or may not be possible within the constraints of restoration.

Nonlinear transitions and hysteresis are of particular concern for management; an important goal in designing robust management approaches is to maintain the resilience of biological systems to help ensure that management actions do not precipitate phase shifts or alternative stable states.

FIGURE 10: Schematics showing the relationship between two alternative ecosystem states based on the dominant prey – Antarctic krill (orange) or mesopelagic fish (blue) – and an environmental gradient. Three plausible scenarios are shown: (a) a linear change in environmental gradient gives rise to a linear transition from Antarctic krill to mesopelagic fish. (b) a nonlinear transition from one state to the other occurs over a small change in the environmental gradient. (c) hysteresis occurs giving rise to two alternative stable states along the environmental gradient.

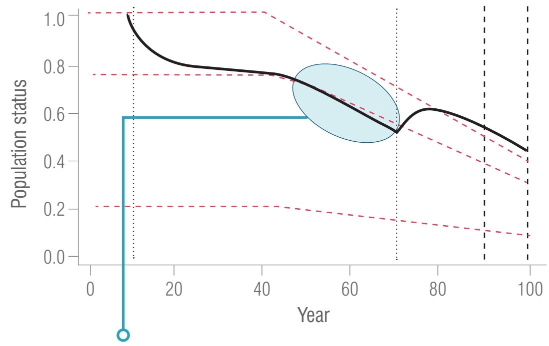


An important question for science – in supporting policy makers – is whether ecosystems (and species) have comparatively smooth relationships with environmental change or are prone to phase shifts or hysteresis.

The implications of these considerations for management of marine ecosystems is illustrated in Figure 11 using the Antarctic krill fishery managed by CCAMLR as an example. The three scenarios shown here relate to shifts in primary production, which would be expected to cause consequent shifts in production of krill. These simple scenarios do not directly consider the effects of krill predators on krill and how their relationship with krill may change under climate change.

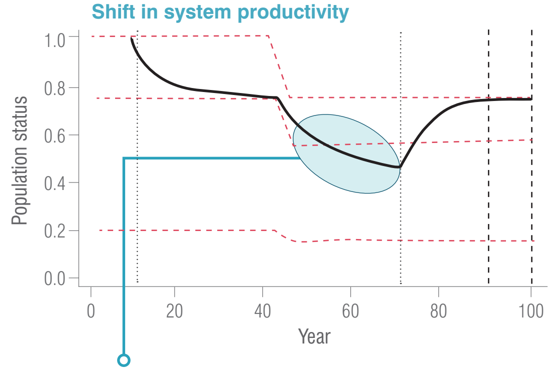
As Figure 11 suggests, knowledge of the status and trends of the ecosystem and its primary components are important challenges for managing and adapting to the future. Importantly, science can advise policy-makers on what is needed to discriminate between competing hypotheses on the future state of ecosystems and to accommodate these needs in determining how to adapt management strategies to satisfactorily achieve their objectives (Figure 8).

Declining system productivity



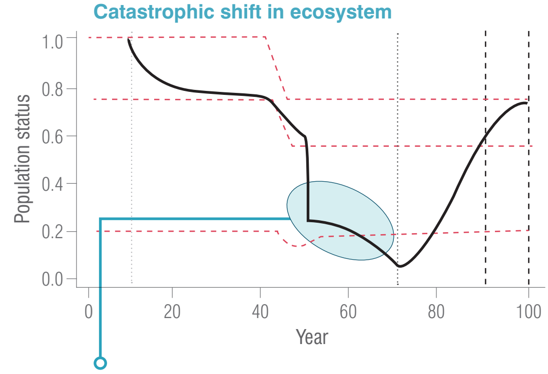
Decline in stock parallels decline in production.
Unchanged constant catch causes overfishing long-term.

Shift in system productivity



Unchanged constant catch causes overfishing below target level soon after step-change in production.

Shift in system productivity + Catastrophic shift in ecosystem



Unchanged constant catch causes critical levels of overfishing after catastrophic decline in stock from ecosystem pressures.

FIGURE 11: Scenarios indicating the consequences of possible future ecosystem changes on the effects of fishing on Antarctic krill and why long-term assessments of the status and trends of the ecosystem can enable adaptation before problems arise. In the first scenario there is an overall decline in production that manifests as a decline in the stock; population status is below the target level for a short period of time. In the second scenario there is step change in system productivity and an unchanged constant catch causes overfishing below the target level. The final scenario includes a catastrophic shift in the ecosystem coupled with a shift in system productivity (e.g. if krill production declined due to decreasingly favourable environmental conditions and recruitment failed catastrophically in one or more years); under this scenario the stock is reduced below the critical level and does not fully recover to the reference level after 30 years.

5

ASSESSING STATUS, TRENDS & FUTURE STATES

The state of an ecosystem can be summarised according to nine ecosystem properties [8]. These ecosystem properties relate to spatial arrangements of taxa (Habitat, Diversity [species pool], Spatial Distributions of Organisms), food-web structure and function (Primary Production, Structure [relative abundance of taxa and processes], Production [of different trophic levels], Energy Transfer), and human pressures (Regional, Global). Assessments of these properties can be used to facilitate decisions on how management strategies may need to be altered (Figure 8).

Regular field measurements are needed to provide the data for estimating the status of these ecosystem properties in different regions of the Southern Ocean and how they may be changing over time. Many of the measurements that are currently taken routinely relate to the physical environment. Biological indicators are only available for particular aspects of the ecosystem, most notably on the effects of fishing

An automated camera records an Adélie penguin colony at Whitney Point near Casey Station.

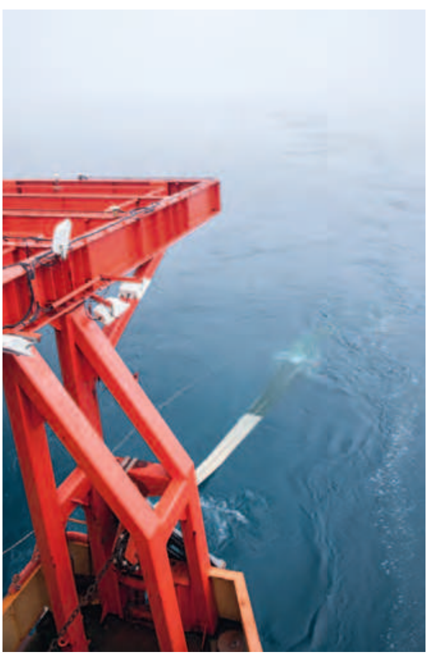
(see references cited in Shin *et al*. 2010) [72]. An approach for establishing a set of measurements to satisfactorily assess status and trends in Southern Ocean ecosystems is described in Constable *et al* (2016) [8]. The identification of *ecosystem Essential Ocean Variables* (eEOVs) will help this process. eEOVs are biological or ecological quantities derived from field observations in order to be able to estimate the ecosystem properties. They will often include abundances of those taxa that represent the primary dynamics of a food web, together with key elements of the ecology of these taxa, e.g. diet, reproduction and growth rates. Several different types of field measurements may be collected in order to estimate the eEOVs. For example, satellites can measure ocean colour, from which the concentration of Chlorophyll *a* is estimated. An algorithm is then used to convert these measures to an eEOV for phytoplankton abundance. Periodic measurements of the phytoplankton in the water help validate the continued use of the satellite-derived measurement of the eEOV.

Nisha Harris

Issues of uncertainty and attributing change to causes

The selection of eEOVs will need to balance their importance in monitoring ecosystem status and change, with the feasibility of their sustained measurement based on present and emerging observing technology. Marine ecosystems are inherently variable in space and time, often resulting in the need for long time series of data to differentiate change from natural variability. There will be a trade-off between the number of observations needed and the statistical power required for quantitative statements of change.

A mid-water trawl net is deployed from the RV *Aurora Australis* in the Indian sector of the Southern Ocean.



Rowan Trebilco

The Southern Ocean provides a large-scale natural experiment where the physical changes in habitats arising from climate change will differ between the sectors of the Southern Ocean in Figure 1. The East Pacific sector includes the West Antarctic Peninsula, which is one of the fastest changing marine regions on Earth with its loss of sea ice and ice shelves. The Atlantic sector includes the Scotia Arc, which is likely to experience significant shifts southwards of available krill habitat. The Indian sector includes the Kerguelen Plateau, which is experiencing southward movement of frontal systems that may result in substantial reductions of icefish populations. At the same time the sea ice environment in the Indian sector may be more favourable to predators, such as penguins, rather than less favourable, as is occurring on the Antarctic Peninsula. The West Pacific sector includes the Ross Sea, Balleny Islands and the Macquarie Ridge. Here, the sea ice environment is expected to increase. With concurrent studies in each of these four different treatments for climate change impacts, key processes and responses of Southern Ocean ecosystems to climate change will be able to be identified more easily.

The expansion of fisheries into important areas will potentially be a confounding factor for understanding climate change impacts on productivity and ecosystem dynamics. **Reference areas** in these main regions that are able to minimise the effects of fishing will be important for undertaking robust assessments of whether changes should be attributed to one or both of climate change and ocean acidification.

Changing resilience to extreme events

The shift from a food web dominated by krill to one dominated by copepods in the south Atlantic occurs because of rare but extreme events. The indirect effect of these events is failed reproduction by krill-dependent predators in those years. More frequent extreme events may make the system vulnerable to abrupt transitions or tipping points. Reference areas can help determine whether the frequency of extreme events may be changing and whether fisheries may alter the resilience of food webs to such changes.

Scenarios of the future

Population models for individual taxa are difficult to use to examine climate change impacts on species in the future because they lack the positive and negative feedbacks that may arise in food webs and ecosystems as a whole. Representations of Southern Ocean ecosystems in dynamic models are needed to validate the performance of individual population models but also to examine the likelihood of phase shifts or alternative stable states arising in the future, given the climate change scenarios predicted by Earth System models [52]. Moreover, these dynamic models can help explore the relative importance of global and regional pressures in explaining the current and future trends in these ecosystems.

These models need to be constructed in such a way that they will be free to re-organise the relative importance of taxa in the food webs and that tipping points could be an outcome in the simulation.

Future states will be determined by the starting conditions for the ecosystem (**benchmark**), scenarios for the primary drivers of the system (usually physical forcing variables) and the responses of the different taxa to those drivers and change in other taxa. Models can be validated by continuously fine-tuning critical parameters and states through repeated field observation and estimation of eEOVs. As the skill of a given model is improved in replicating existing data, its ability to project the likelihood of future states improves. Importantly, continued measurements of eEOVs provide the means by which predictions from the models can be verified; measurements in the future can be used for determining which models make good predictions and which do not. Ideally, several models would be used together in an 'ensemble'; contrasting the ensemble of models with field data shows which models are the most plausible given the data [29, 63]. The most reliable models, ie those that regularly give correct predictions, will be best for making decisions.

The likelihood of hypothesised futures can be tested with models and data.

The development of end-to-end (physics to higher predators) ecosystem models is considered a high priority in the Southern Ocean science community [52]. The ACE CRC is developing the Atlantis end-to-end ecosystem model [25] for simulating ecosystems in the Indian sector of the Southern Ocean (Figure 13).

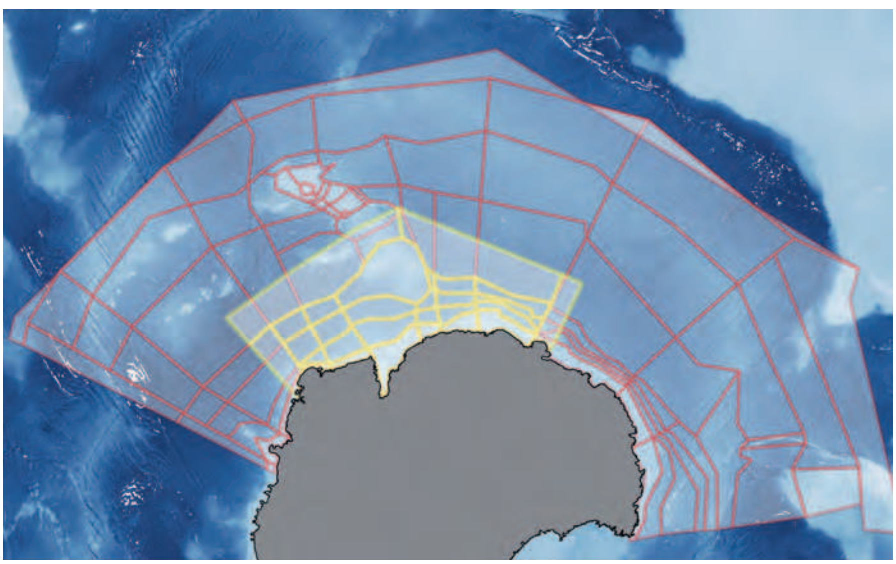


FIGURE 13: Domain of Atlantis[25] model being developed for Indian Sector of the Southern Ocean. Red lines indicate spatial polygons over the whole domain. Yellow lines indicate a smaller model being developed to test the model with existing data before the larger domain is completed.

Ernesto Trujillo

Fieldwork is a critical component of ecosystem assessment and monitoring.

6

A STRATEGIC APPROACH TO MEET THE CHALLENGE

Regular assessments of status and trends in Southern Ocean ecosystems are needed. A strategy to achieve these must include (i) identification of the quantities needed to indicate the status of an ecosystem, (ii) the field methods that would be used to take the measurements, (iii) a design of the field program to measure the status of the ecosystem in a region, (iv) a design of how often the measurements may need to be taken given the time scales of natural variation and change in the indicators being measured, and (v) an assessment methodology. Once the assessment methodology is determined, Southern Ocean ecosystems will need to be 'benchmarked' in order to provide a strong foundation for assessing future change.

At present, several large scale monitoring programs for assessing the current and future impacts of climate change on marine biodiversity and ecosystems are being developed. Internationally, the importance of large scale, integrated measurement programs is now recognised [32], particularly through the SCAR-SCOR Southern Ocean Observing System (SOOS) [64] and the IMBER program Integrating Climate and Ecosystem Dynamics (ICED) in the Southern Ocean [53].

An international work program through SCAR, SOOS, and ICED for assessing status and change in Southern Ocean ecosystems includes work to address the questions:

1. What is the current status of Southern Ocean ecosystems?
2. What measurements could be routinely used to assess change in different components of these ecosystems?
3. What models and statistical assessment methods can be used to estimate status and trends in these ecosystems and to forecast the likelihood of different states in the future?

An international conference, including a series of workshops, on a Marine Ecosystem Assessment of the Southern Ocean in 2018 is being organised and led by the ACE CRC. This conference aims to develop a quantitative assessment of the status and trends of habitats, species and foodwebs, as well as key drivers of change. It also will identify important gaps and priorities for future research on these assessments as well as the development of modelling and assessment methods to support them.

A key element for future assessments will be to benchmark the status of Southern Ocean ecosystems, possibly in 2022-23. In the first instance, available data will be used to conduct regional assessments and to help identify appropriate field strategies. A longer-term program is being developed to integrate satellite, ship and land-based observations along with those from autonomous platforms. For example, a transect design is being considered based on the oceanographic approach established by the World Ocean Circulation Experiment (WOCE) [74] but taking account of biological variability (Figures 14, 15) [8].

Advancing these research capabilities will enable a second more comprehensive ecosystem assessment by the end of the next decade (2030), enabling decadal re-assessments of status and trends of Southern Ocean ecosystems thereafter. Australia's work as part of international work programs contributes to increasing knowledge and understanding of the Southern Ocean ecosystem and also provides important base for national policy and management of fisheries and conservation of wildlife and biodiversity in its maritime jurisdiction.

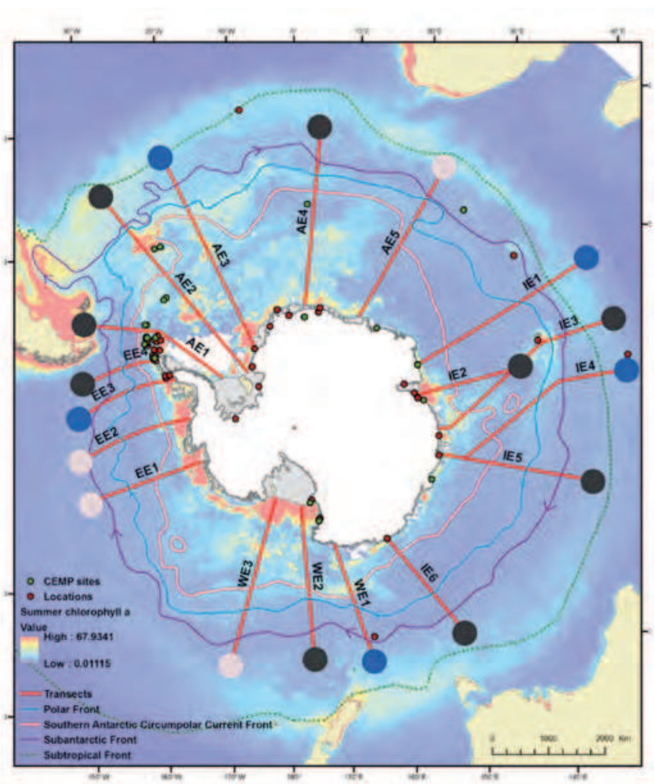


FIGURE 14: Illustration of a potential design of field sampling for ecosystems in the Southern Ocean Observing System. The map of the Southern Ocean shows potential field capability at present, using satellites, land-based monitoring and possible transects that could be occupied routinely using shipping in the region. Black circles indicate transects near where shipping operations exist. Blue circles are transects that may be possible with some deviations. Light circles are those transects that would be desirable but not near regular shipping routes.

The first letters on transects relate to sectors that may be used for assessments: E = East Pacific, W = West Pacific, I = Indian, A = Atlantic (Figure 1). The second letter E = Ecosystem transect and then a number for identification. (after Constable *et al*. 2016[8]).

7

BENEFITS OF MEETING THE CHALLENGE

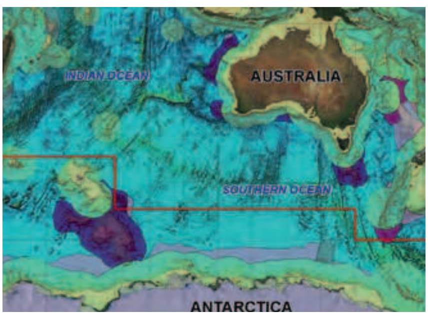


FIGURE 15: Australia's marine jurisdiction, showing the Exclusive Economic Zone and the Extended Continental Shelf areas. The CCAMLR boundary is shown with a red line.

Having the capacity to observe and assess status and trends of Southern Ocean ecosystems will provide the necessary long-term context of ecosystem change for bodies responsible for managing the region. For Australia, it will provide important assessments that underpin the management of fisheries and the conservation of wildlife and biodiversity in the Indian Sector of the Southern Ocean. Australia has a significant interest in that sector; 36% of its marine jurisdiction is in the Southern Ocean (not including the South Tasman Rise) (Figure 15). Research into change in these ecosystems is a high priority in the Australian Antarctic Science Program's Strategic Plan.

Australia's commitment to Southern Ocean ecosystem research developed from participation in the Biological Investigation of Marine Antarctic Systems and Stocks (BIOMASS), established by the Scientific Committee on Oceanography (SCOR) as the first large-scale, multinational research program focusing on the marine ecosystems and resources of the Southern Ocean. BIOMASS had direct and significant effects on discussions of these issues by parties to the Antarctic Treaty and within Antarctic Treaty forums, and directly shaped Australian research efforts in the Southern Ocean. This led to Australia's active leadership in the development of an innovative multi-species ecosystem approach to management, pioneered in what became the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). CCAMLR's focus on science-based conservation management provided early implementation of what has become known as the precautionary approach. Australia, as depository state for CCAMLR and an active member of its commission, has supported the ongoing evolution of 'the CCAMLR approach', its values and objectives.

The observation and assessment program provides a focus for ongoing science in the Southern Ocean. It provides a new direction and opens a range of opportunities for Australia, while addressing the key goals of the Australian Antarctic Program and reinforcing the longstanding bipartisan statements of Antarctic policy interests. These opportunities develop from the fact that Australia (or any other party) alone cannot achieve the stated objectives for the Southern Ocean. This program is built on international cooperation and collaboration in logistics (including ship and air time), science projects and work in international forums, within and outside the Antarctic Treaty System. It provides a further opportunity providing a significant foundation for Australia's policy objectives for managing climate change impacts, fisheries and conservation in the region.

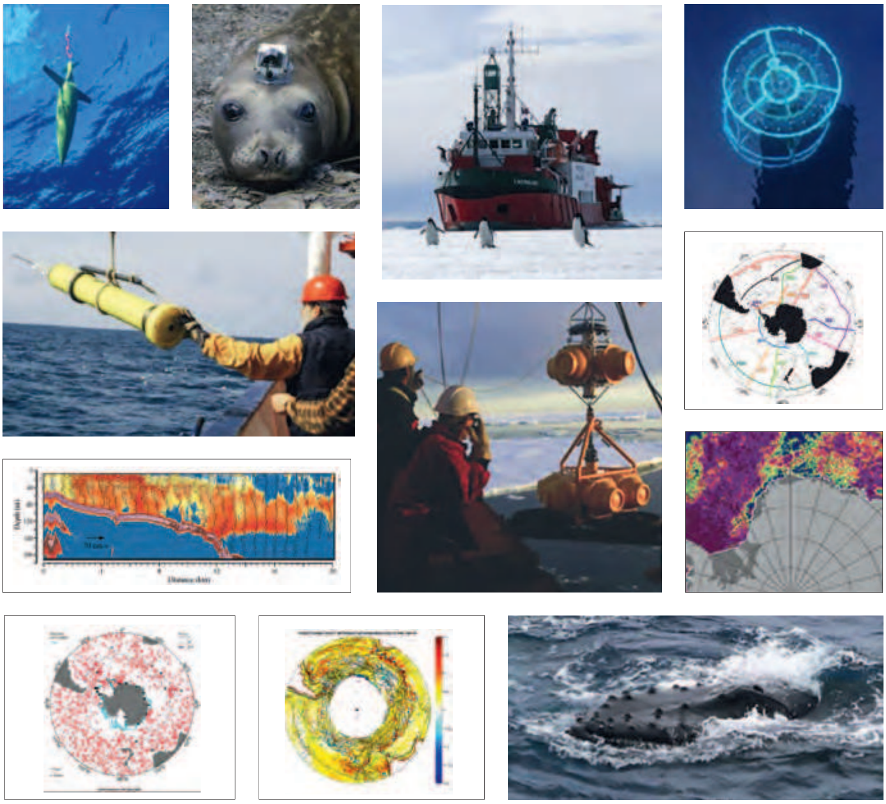


FIGURE 16: Types of technologies that could be used to monitor indicators of Southern Ocean ecosystems, including remote sensing (satellites, moorings, gliders), underway measurements (such as the continuous plankton recorder, surface phytoplankton and acoustic measurements of krill, fish and other schooling organisms), ship-based station observations using CTDs and net sampling, land-based studies of the population dynamics, foraging and diet of seals and seabirds, and fully integrated remote/ship/land studies.

GLOSSARY

Benchmark: A comprehensive assessment at a single point in time, to serve as a point of reference for future assessments of change.

Benthic: On or near the sea-floor.

Benthopelagic: A term used to describe organisms that are bottom-associated but move up into the water column to forage (e.g. Patagonian toothfish).

Control system: A system that regulates/controls the behaviour of other, component systems; in this context an overarching framework to link science and fisheries management.

Copepods: Small crustaceans, generally ranging between 100 μm and 6 mm in length, which form a dominant component of mesozooplankton communities on a global scale. Their high abundance makes them key contributors to secondary production in Southern Ocean ecosystems.

Ecosystem: Linkages of physics, chemistry and biology as a whole system, the function of which is characterised by the flow of energy through the major pathways (food chains). Services such as carbon sequestration and and fisheries provision are a by-product.

Food web: The network of trophic links (inter-connected food chains) among taxa or groups in an ecosystem.

Habitat: The physical and biological factors that define the environment in which an organism lives (e.g. for Antarctica – sea ice habitat, benthic habitat, pelagic habitat).

Marginal ice zone: The part of the Sea Ice in the Southern Ocean that is substantially affected by the open-ocean (e.g. where the ice pack is impacted by ocean swell and currents). The maginal ice zone may extend tens or hundreds of kilometres from the ice-edge, and retreates poleward as the ice melts in the spring/summer then advances equatorward in the winter each year.

Myctophids: Fishes between 5-20 cm that are noted in many oceans comprising 'feed layers' between the surface and 800m deep. These are often referred to as mesopelagic fish.

Pelagic (epi, meso, bathy): In the open-ocean. In the pelagic zone, the water column is typically split into epipelagic, mesopelagic, and bathypelagic zones – which are often defined as 0–200m, 200–800m, 800–2000m respectively. These terms are used to describe both the zones, and the organisms that inhabit them (e.g. mesopelagic fish – the fish that inhabit the mesopelagic zone).

Reference areas: Areas in which one or more activities or impacts are deliberately excluded so that they can provide a point of reference for the state of areas where these activities continue. Reference areas are important because traditional before/after comparisons have limited use in evaluating impacts under changing environmental conditions.

Tipping point: The point at which a system shifts between alternative stable states[91]. Beyond a tipping point the new alternative stable state will remain even if the environment returns to conditions that supported the previous state in the past.

Trophic level: The position that an organism occupies in a food chain.

REFERENCES

1 Atkinson, A. *et al.* (2004) Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature* 2996, 1-4.
2 Bindoff, N. *et al.* (2011) *Position analysis: Climate change and the Southern Ocean*. 27 (The Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart).
3 Boyd, P. W. *et al.* (2012) Mapping phytoplankton iron utilization: Insights into Southern Ocean supply mechanisms. *Journal of Geophysical Research* 117, C06009, doi:10.1029/2011jc007726.
4 Boyd, P. W. *et al.* (2008) Climate-mediated changes to mixed-layer properties in the Southern Ocean: assessing the phytoplankton response. *Biogeosciences* 5, 847-864.
5 Bracegirdle, T. J. *et al.* (2008) Antarctic climate change over the twenty first century. *Journal of Geophysical Research* 113, D03103, doi:10.1029/2007jd008933.
6 Constable, A. & Doust, S. (2009) *Southern Ocean Sentinel - an international program to asses climate change impacts on marine ecosystems: report of an international workshop, Hobart, April 2009*. (ACE CRC, Commonwealth of Australia & WWF-Australia).
7 Constable, A. J. (2011) Lessons from CCAMLR on the implementation of the ecosystem approach to managing fisheries. *Fish and Fisheries* DOI: 10.1111/j.1467-2979.2011.00410.x.
8 Constable, A. J. *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.
9 Constable, A. J. *et al.* (2000) Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). *ICES Journal of Marine Science* 57, 778-791.
10 Constable, A. J. *et al.* (2014) Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. *Global Change Biology* 20, 3004-3025, doi:10.1111/gcb.12623.
11 Constable, A. J. *et al.* (2003) Southern Ocean productivity in relation to spatial and temporal variation in the physical environment. *Journal of Geophysical Research* 108, 1-10.
12 Constable, A. J. & Welsford, D. C. (2011) *Developing a precautionary, ecosystem approach to managing fisheries and other marine activities at Heard Island and McDonald Islands in the Indian Sector of the Southern Ocean*. in *The Kerguelen Plateau: marine ecosystem and fisheries* (eds G. Duhamel & D.C. Welsford) 233-255 (Société Française d'Ichtyologie).
13 Cook, A. *et al.* (2005) Retreating glacier fronts on the Antarctic Peninsula over the past half century. *Science* 308, 541–544.
14 Cook, A. & Vaughan, D. (2010) Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *Cryosphere* 4, 77-98.
15 Curran, M. *et al.* (2003) Ice core evidence for Antarctic sea ice decline since the 1950s. *Science* 302, 1203-1206.
16 De Broyer, C. & Koubbi, P. (eds) (2014) *SCAR Biogeographic Atlas of the Southern Ocean*. (SCAR).
17 de la Mare, W. (2009) Changes in Antarctic sea-ice extent from direct historical observations and whaling records. *Climate Change* 92, 461-493.
18 de la Mare, W. K. (1998) Tidier fisheries management requires a new MOP (management-oriented paradigm). *Reviews in Fish Biology and Fisheries* 8, 349-356.
19 de la Mare, W. K. (1997) Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records. *Nature* 389, 57-60.
20 Deppeler, S. L. & Davidson, A. T. (2017) Southern Ocean Phytoplankton in a Changing Climate. *Frontiers in Marine Science* 4, doi:10.3389/fmars.2017.00040.
21 Ducklow, H. *et al.* (2012) *The marine system of the western Antarctic Peninsula*. in *Antarctic Ecosystems* (eds AD Rogers, NM Johnston, EJ Murphy, & A Clarke) 121-159 (Blackwell Publishing, Ltd).
22 Duhamel, G. & Welsford, D. (eds) (2011) *The Kerguelen Plateau: marine ecosystem and fisheries*. (Société Française d'Ichtyologie).
23 FAO. (2012) The State of the World's Fisheries and Aquaculture 209 (FAO, Rome).
24 Fretwell, P. T. & Trathan, P. N. (2009) Penguins from space: faecal stains reveal the locations of emperor penguin colonies. *Global Ecology and Biogeography* 18, 543-552.
25 Fulton, E. A. *et al.* (2011) Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish and Fisheries* 12, 171-188, doi:10.1111/j.1467-2979.2011.00412.x.
26 Gille, S. (2008) Decadal-scale temperature trends in the Southern Hemisphere Ocean. *Journal of Climate* 21, 4749-4765.
27 Grant, S. *et al.* (2006) Bioregionalisation of the Southern Ocean: Report of Experts Workshop, WWF- Australia and ACE CRC. (Hobart, September 2006).
28 Gutt, J. *et al.* (2015) The Southern Ocean ecosystem under multiple climate change stresses - an integrated circumpolar assessment. *Global Change Biology* 21, 1434-1453, doi:10.1111/gcb.12794.
29 Hilborn, R. & Mangel, M. (1997) *The Ecological Detective: confronting models with data*. (Princeton University Press).
30 Hill, S. L. *et al.* (2012) A foodweb model to explore uncertainties in the South Georgia shelf pelagic ecosystem. *Deep-Sea Research Part Ii-Topical Studies in Oceanography* 59, 237-252.
31 Hobbs, W. R. *et al.* (2016) A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change* 143, 228-250.
32 Hofmann, E. (2009) Southern Ocean GLOBEC Research and the Future. *Antarctic Science* 21, 411-411, doi:10.1017/s0954102009990484.
33 Hulley, P. A. & Duhamel, G. (2009) A review of the lanternfish genus Bolinichthys Paxton, 1972 (Myctophidae). *Cybium* 33, 259-304.
34 Hunt, B. & Hosie, G. (2005) Zonal structure of zooplankton communities in the Southern Ocean South of Australia: results from a 2150 km continuous plankton recorder transect. *Deep-Sea Research I* 52, 1241-1271, doi:10.1016/j.dsr.2004.11.019.
35 Kaiser, S. *et al.* (2009) Biodiversity of the Amundsen Sea (Southern Ocean): spatial patterns of richness and abundance in shelf isopods. *Marine Biodiversity* 39, 27-43.
36 Kawaguchi, S. *et al.* (2013) Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Clim. Change*, doi:10.1038/nclimate1937.
37 Kawaguchi, S. *et al.* (2011) Will krill fare well under Southern Ocean acidification? *Biology Letters* 7, 288-291.
38 Kock, K.-H. *et al.* (2007) Fisheries in the Southern Ocean: an ecosystem approach. *Philosophical Transactions of the Royal Society B-Biological Sciences* 362, 2333-2349, doi:10.1098/rstb.2006.1954.
39 Krupnik, I. *et al.* (eds) (2011) *Understanding Earth's Polar Challenges: International Polar Year 2007–2008. University of the Arctic, Rovaniemi, Finland ; CCI Press, Edmonton, Canada and ICSU/WMO Joint Committee for IPY 2007–2008.*
40 Laws, R. M. (1977) Seals and whales of the Southern Ocean. *Philosophical Transactions of the Royal Society of London* 279, 81-96.
41 Leaper, R. *et al.* (2008) A review of abundance, trends and foraging parameters of baleen whales in the Southern Hemisphere. Working Paper CCAMLR-IWC-WS-08/04 to CCAMLR IWC Workshop to review input data for Antarctic Marine Ecosystem Models, 11-15 August 2008, Hobart, Tasmania. 51.
42 Loeb, V. J. & Santora, J. A. (2015) Climate variability and spatiotemporal dynamics of five Southern Ocean krill species. *Progress in Oceanography* 134, 93-122.
43 Lynch, H. *et al.* (2012) Spatially integrated assessment reveals widespread changes in penguin populations on the Antarctic Peninsula. *Ecology* 93, 1367–1377.
44 Lynch, H. J. & LaRue, M. A. (2014) First global census of the Adélie Penguin. *The Auk* 131, 457-466, doi:10.1642/AUK-14-31.1.
45 Maksym, T. *et al.* (2012) Antarctic Sea Ice - a polar opposite? *Oceanography* 25, 140-151.
46 Marr, J. W. S. (1962) The natural history and geography of the Antarctic krill (*Euphausia superba* Dana). *Discovery Reports* 32, 33-464.
47 Massom, R. A. & Stammerjohn, S. E. (2010) Antarctic sea ice change and variability – physical and ecological implications. *Polar Science* 4, 149-186.
48 Meijers, A. J. S. *et al.* (2012) Representation of the Antarctic Circumpolar Current in the CMIP5 climate models and future changes under warming scenarios. *Journal of Geophysical Research-Oceans* 117, 12008-12008.

49 Melbourne-Thomas, J. *et al.* (2016) Under ice habitats for Antarctic krill larvae: Could less mean more under climate warming? *Geophysical Research Letters* 43, 10322-10327.

50 Meredith, M. & Hogg, A. (2006) Circumpolar response of Southern Ocean eddy activity to a change in the Southern Annular Mode. *Geophysical Research Letters* 33, L16608, doi:doi:10.1029/2006GL026499.

51 Millennium Ecosystem Assessment. (2005) *Ecosystems and Human Well-being: Biodiversity Synthesis*. 86 (World Resources Institute).

52 Murphy, E. J. *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.

53 Murphy, E. J. *et al.* (eds) (2008) *Integrating Climate and Ecosystem Dynamics in the Southern Ocean: A Circumpolar Ecosystem Program: Science Plan and Implementation Strategy. GLOBEC Report No. 26, IMBER Report No. 2*.

54 Murphy, E. J. *et al.* (2013) Comparison of the structure and function of Southern Ocean regional ecosystems: The Antarctic Peninsula and South Georgia. *Journal of Marine Systems* 109, 22-42, doi:10.1016/j.jmarsys.2012.03.011.

55 Murphy, E. J. *et al.* (2007) Spatial and temporal operation of the Scotia Sea ecosystem: a review of large-scale links in a krill centred food web. *Philosophical Transactions of the Royal Society B-Biological Sciences* 362, 113-148, doi:10.1098/rstb.2006.1957.

56 Nicol, S. (2006) Krill, currents, and sea ice: *Euphausia superba* and its changing environment. *BioScience* 56, 111-120.

57 Nicol, S. & Brierley, A. (2010) Through a glass less darkly—new approaches for studying the distribution, abundance and biology of euphausiids. *Deep-Sea Research II* 57, 496–507.

58 Nicol, S. *et al.* (2000) Estimates of circumpolar abundance of Antarctic krill based on recent acoustic density measurements. *CCAMLR Science* 7, 87-99.

59 Nicol, S. *et al.* (2011) The fishery for Antarctic krill – recent developments. *Fish and Fisheries*, DOI: 10.1111/j.1467-2979.2011.00406.x.

60 Nicol, S. *et al.* (2010) BROKE-West, a large ecosystem survey of the South West Indian Ocean sector of the Southern Ocean, 30E–80E (CCAMLR Division 58.4.2). *Deep-Sea Research II* 57, 693-700.

61 Nicol, S. & Raymond, B. (2012) *Pelagic Ecosystems in the Waters off East Antarctica (30° E–150° E)*. in *Antarctic Ecosystems: An Extreme Environment in a Changing World* (eds AD Rogers, NM Johnston, EJ Murphy, & A Clarke) 243-254 (John Wiley & Sons, Ltd).

62 Nymand Larson, J. *et al.* (2014) *Chapter 28: Polar Regions*. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Report of Working Group II* Vol. 2 (eds C.B. Field & R.B. Barros) 71 pp. (Intergovernmental Panel on Climate Change).

63 Peters, R. H. (1991) *A Critique for Ecology*. (Cambridge University Press).

64 Rintoul, S. *et al.* (2011) *The Southern Ocean Observing System: initial science and implementation strategy*. 90 (SCAR-SCOR).

65 Rogers, A. *et al.* (eds) (2012) *Antarctic Ecosystems: An Extreme Environment in a Changing World*. (John Wiley & Sons, Ltd).

66 Sallee, J. B. *et al.* (2010) Zonally asymmetric response of the Southern Ocean mixed-layer depth to the Southern Annular Mode. *Nature Geosci* 3, 273-279

67 SC-CAMLR. (2011) Report of the thirtieth meeting of the Scientific Committee (SC-CAMLR XXX), Annex 4, Report of the Working Group on Ecosystem Monitoring and Management. (CCAMLR, Hobart, Australia).

68 Scambos, T. *et al.* (2003) *Climate-induced ice shelf disintegration in the Antarctic Peninsula*. in *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives* Vol. 79 (eds E Domack *et al.*) 79 – 92 (AGU).

69 Schiaparelli, S. *et al.* (2013) *The Census of Antarctic Marine Life: the first available baseline for Antarctic marine biodiversity*. in *Adaptation and evolution in marine environments Volume 2: the impacts of global change on biodiversity* (eds C. Verde & G. di Prisco) 3-19 (Springer-Verlag).

70 Schmidt, K. *et al.* (2011) Seabed foraging by Antarctic krill: Implications for stock assessment, bentho-pelagic coupling, and the vertical transfer of iron. *Limnology and Oceanography* 56 1411–1428.

71 Sen Gupta, A. *et al.* (2009) Projected Changes to the Southern Hemisphere Ocean and Sea Ice in the IPCC AR4 Climate Models. *Journal of Climate* 22, 3047-3078, doi:10.1175/2008jcli2827.1.

72 Shin, Y.-J. & Shannon, L. J. (2010) Using indicators for evaluating, comparing and communicating the ecological status of exploited marine ecosystems. 1. The IndiSeas project. *ICES Journal of Marine Science* 67, 686–691.

73 Shreeve, R. *et al.* (2009) Feeding ecology of myctophid fishes in the northern Scotia Sea. *Marine Ecology-Progress Series* 386, 221-236, doi:10.3354/meps08064.

74 Siedler, G. *et al.* (2001) *Ocean circulation and climate: observing and modelling the global ocean*. Vol. 77 (Academic Press).

75 Siegert, M. (2017) Glaciology: Vulnerable Antarctic ice shelves. *Nature Clim. Change* 7, 11-12, doi:10.1038/nclimate3189.

76 Smetacek, V. & Nicol, S. (2005) Polar ocean ecosystems in a changing world. *Nature* 437, 362-368.

77 Smith, W. O., Jr. *et al.* (2012) *The Ross Sea Continental Shelf: regional biogeochemical cycles, trophic interactions, and potential future changes*. in *Antarctic ecosystems: an extreme environment in a changing world* (eds AD Rogers, NM Johnston, EJ Murphy, & A Clarke) 213-242 (J. Wiley and Sons).

78 Smith, W. O., Jr. & Comiso, J. C. (2008) Influence of sea ice on primary production in the Southern Ocean: A satellite perspective. *Journal of Geophysical Research* 113, C05S93, doi:10.1029/2007jc004251.

79 Smith Jr., W. *et al.* (2012) *The Ross Sea Continental Shelf: regional biogeochemical cycles, trophic interactions, and potential future changes*. in *Antarctic ecosystems: an extreme environment in a changing world* (eds AD Rogers, NM Johnston, EJ Murphy, & A Clarke) (J. Wiley and Sons).

80 Sokolov, S. & Rintoul, S. R. (2009) Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts. 2: Variability and relationship to sea surface height. *Journal of Geophysical Research* 114, 1-15, doi:10.1029/2008JC005248.

81 Southwell, C. *et al.*(2012) A review of data on abundance, trends in abundance, habitat use and diet of ice-breeding seals in the Southern Ocean (submitted to the 2008 Joint CCAMLR-IWC Workshop). *CCAMLR Science* 19, 49–74.

82 Southwell, C. *et al.* (2017) Large-scale population assessment informs conservation management for seabirds in Antarctica and the Southern Ocean: A case study of Adélie penguins. *Global Ecology and Conservation* 9, 104-115.

83 Stammerjohn, S. *et al.* (2008) Trends in Antarctic annual sea ice retreat and advance and their relation to El Nino–Southern Oscillation and Southern Annular Mode variability. *Journal of Geophysical Research* 113, CO3S90, doi:10.1029/2007JC004269.

84 Trathan, P. & Agnew, D. (2010) Climate change and the Antarctic marine ecosystem: an essay on management implications. *Antarctic Science* 22, 387-398.

85 Trathan, P. *et al.* (2007) Environmental forcing and Southern Ocean marine predator populations: effects of climate change and variability. *Philosophical Transactions of the Royal Society B- Biological Sciences* 362, 2351-2365.

86 Tréguer, P. & Jacques, G. (1992) Dynamics of nutrients and phytoplankton and fluxes of carbon, nitrogen and silicon in the Antarctic Ocean. *Polar Biology* 12, 149-162.

87 Trivelpiece, W. *et al.* (2011) Variability in krill biomass links harvesting and climate warming to penguin population changes in Antarctica. *Proceedings of the National Academy of Sciences of the United States of America* 108, 7625-7628.

88 Turner, J. *et al.* (eds) (2009) *Antarctic climate change and the environment: A contribution to the International Polar Year 2007-2008*. (Scientific Committee on Antarctic Research (SCAR)).

89 Turner, J. *et al.* (2009) Strong wind events in the Antarctic. *Journal of Geophysical Research* 114, 18103-18103.

90 Watkins, J. L. *et al.* (2004) The CCAMLR 2000 Survey: a multinational, multi-ship biological oceanography survey of the Atlantic sector of the Southern Ocean. *Deep Sea Research Part II* 51, 1205-1213.

91 Conversi, A. *et al.* (2014). A holistic view of marine regime shifts. *Philosophical Transactions of the Royal Society B: Biological Sciences* 370.

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE