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Title **Assessing status and change in Southern Ocean ecosystems**

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Abstract

A great challenge for Southern Ocean ecosystem science is to assess the status and trends of Southern Ocean marine ecosystems overall, against which change in ecosystem structure and function can be unambiguously assessed in the future. This challenge includes being able to assess the likelihood of different states in the future. These requirements are needed by different bodies regionally and globally for making tactical decisions, such as catch limits and conservation requirements in the Commission for the Conservation of Antarctic Marine Living Resources, and to provide strategic advice, such as in the Intergovernmental Panel on Climate Change. There are three subsidiary questions to this challenge:

1. How should status and trends in those ecosystems be assessed and reported and how will the likelihood of future states be assessed?
2. What are the gaps in knowledge that are required to be able to undertake these assessments?
    a. what is the current status of Antarctic and Southern Ocean ecosystems overall?
    b. what are the critical processes, mechanisms and feedbacks that directly influence the population responses of biota to change in their habitats?
3. What observations need to be taken that will indicate a change in state of those ecosystems and provide suitable input to, validation or correction of assessments?

This paper summarises international initiatives and their current activities aimed at delivering circumpolar ecosystem assessments.

Background

Southern Ocean ecosystems have been changing since the near extirpation of seals starting in the 1800s and the overexploitation of many whale species and benthic finfish in the mid-20th century. Since the late 1960s, significant changes to Southern Ocean habitats, probably resulting from the depletion of ozone over the Antarctic, have been observed including increased westerly winds (Turner et al. 2009b) and a movement south of their location indicated by the Southern Annular Mode (Turner et al. 2009a), the extent and timing of sea ice advance and retreat, (although varying greatly from positive to negative regionally (Stammerjohn et al. 2008, Turner et al. 2009a); abrupt loss of ice shelves (Cook et al. 2005, Cook et al. 2010); freshening of Antarctic Bottom Water and surface waters near the continent, a southward shift in the Antarctic Circumpolar Current fronts, along with a changed eddy field (Meredith et al. 2006, Sallee et al. 2009, Sokolov et al. 2009). Increased CO_2 in the atmosphere has also led to a decrease in ocean pH (Turner et al. 2009a). The Southern Ocean is expected to substantially change in the coming decades as a result of climate change and ocean acidification (Turner et al. 2009a).

In recent decades, changes in biota and the potential role of change in habitats have been identified (e.g. the role of sea ice, Massom et al. 2010) but the actual mechanisms of change remain poorly understood for many components of the ecosystem (Constable et al. submitted). The prognoses for change in the structure and function of Antarctic and Southern Ocean ecosystems in response to climate change and recovery of marine mammals are regionally specific due to regional differences in the manifestations of climate change (Constable et al. submitted). For example, a switch from a krill-based food web to a copepod- and fish-based food web in times of low krill abundance (Waluda et al. 2010, Murphy et al. 2012c) suggests that the latter may become more common in the future in the south Atlantic (Shreeve et al. 2009, Trathan et al. 2012). The prognosis for Antarctic krill overall is ambiguous, as factors that could impact directly on krill vary regionally, and because they are able to adapt physiologically and behaviourally (Schmidt et al. 2011). New research also shows that larval krill survival may be negatively affected by increasing ocean acidity (Kawaguchi et al. 2011), adding further complexity to these assessments.

Some key trends in distribution and abundance of bird populations (penguins and flying birds) have been linked to recent change (e.g. Barbraud et al. 2001, Forcada et al. 2005, Jenouvrier et al. 2005, Trathan et al. 2012). However, the ecological pathways of impact on marine mammals and birds may be difficult to determine because higher predator populations are less sensitive to small-scale spatial and temporal variability of lower trophic levels, e.g. the contrasting changes in Adelie and other penguin populations (Trivelpiece et al. 2011, Nicol et al. 2012, Smith Jr. et al. 2012).

Why good estimates of change are needed

Despite the historical changes to the ecosystem, the Southern Ocean remains the easiest region to separate the ecosystem impacts of climate change and ocean acidification from direct anthropogenic effects - many other regions have continuing and confounding effects of pollution, catchment and coastal zone modification and fisheries (Constable et al. 2009). A monitoring and assessment programme in the Southern Ocean would play an important role in evaluating and estimating the magnitudes and rates of change in global marine ecosystems, testing predictions from climate model scenarios of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2001, Meehl et al. 2007, Rosenzweig et al. 2007) and, thereby, provide a sound basis for signalling future changes in ecosystems in the Southern Ocean and beyond. Identifying changes in ecosystem productivity and dynamics is fundamental to achieving ecologically sustainable Antarctic krill fisheries and the conservation of Antarctic marine life as a whole (Constable and A.J. 2011, Murphy et al. 2012a, Murphy et al. 2012b).

A great difficulty in interpreting the cause of changes is the absence of integrated measurements of a suite of variables across the range of physical and biological properties of Antarctic and Southern Ocean ecosystems (Murphy et al. 2008, Constable et al. 2009, Rintoul et al. 2011). Moreover, attention needs to be given to estimating how regional differences and intra- and inter-annual variability may impact the use of these indicators for assessing long-term trends in the ecosystems (Constable and A.J. 2006, 2011). Conversely, the regional differences of climate change impacts on habitats in the Southern Ocean provide opportunities for determining how changes in habitats (positive and negative) will impact on ecosystems as a whole.

Future impacts of climate change on marine ecosystems are being predicted using a combination of expert views and simulation models (Hitz et al. 2004, Sarmiento et al. 2004). Predictions to date have focussed on shifts in distribution and abundance of biological populations in marine systems driven by temperature (Harley et al. 2006). However, both abiotic and biotic changes and responses are expected to be significantly more complex (Melbourne-Thomas et al. 2013). For example, survival and condition of many organisms may be more affected by changes in ocean chemistry or by disruptions to food-web dynamics than by changes in temperature (Harley et al. 2006, Clarke et al. 2007, Constable et al. submitted).

Observations are needed to unambiguously validate the conclusions from modelling and forecasting studies. Such a programme is essential for monitoring how the role of Southern Ocean ecosystems in the Earth System is changing, as well as for appropriately setting both ecosystem-based catch limits for krill and finfish species in the region (SC-CAMLR 2011) and conservation requirements for threatened, endangered or recovering species, such as whales and albatross.

The Challenge

The great challenge is to assess the status and trends of Southern Ocean marine ecosystems overall, against which change in ecosystem structure and function can be unambiguously assessed in the future. This challenge includes being able to assess the likelihood of different states in the future. There are three subsidiary questions to this challenge:

1. How should status and trends in those ecosystems be assessed and reported and how will the likelihood of future states be assessed?
2. What are the gaps in knowledge that are required to be able to undertake these assessments?
    a. what is the current status of Antarctic and Southern Ocean ecosystems overall?
    b. what are the critical processes, mechanisms and feedbacks that directly influence the population responses of biota to change in their habitats?
3. What observations need to be taken that will indicate a change in state of those ecosystems and provide suitable input to, validation or correction of assessments?

International Context

A number of current international initiatives provide the means for coordinating this work. The ability to undertake integrated circumpolar ecosystem programmes of this kind is demonstrated by past successful programmes such as BIOMASS (El-Sayed 1994) and, more recently, the International Polar Year (Krupnik et al. 2011). The biogeographic atlas forms an important milestone in helping deliver what is needed to estimate change in Southern Ocean ecosystems. The current initiatives are outlined here.

Scientific Committee for the Conservation of Antarctic Marine Living Resources (SC-CAMLR)

SC-CAMLR (http://www.ccamlr.org/en/science/science) provides scientific advice to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR; Constable et al. 2000). As part of its remit, it coordinates the CCAMLR Ecosystem Monitoring Program (CEMP; Agnew and J. 1997). At present, CEMP has a primary focus on monitoring ecosystem components that affect or are affected by Antarctic krill, *Euphausia superba*. This is because krill is the focus of the largest fishery in the Southern Ocean, and therefore, changes in krill abundance/distribution could impact on most marine mammal and bird species in the region because of their dependence on Antarctic krill as prey.

Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED)

ICED (http://www.iced.ac.uk) is an international programme that aims to determine the major controls on the dynamics of Southern Ocean ecosystems and the potential for feedbacks as part of the Earth System (Murphy et al. 2008). It is associated with the Scientific Committee on Antarctic Research (SCAR), the Scientific Committee on Oceanic Research (SCOR) and other international programmes. It is part of the International Geosphere-Biosphere Programme's "Integrated Marine Biogeochemistry and Ecosystem Research" project (IGBP IMBER).

ICED has three main scientific objectives, which are (i) to understand the structure and dynamics of ecosystems in the Southern Ocean and how they are affected by, and feedback to, climate processes, (ii) to understand how ecosystem structure and dynamics interact with biogeochemical cycles in the Southern Ocean, and (iii) to determine how ecosystem structure and dynamics should be incorporated into management approaches for sustainable exploitation of living resources in the Southern Ocean.

Its core activity areas will directly contribute to assessing status and trends of Southern Ocean ecosystems and providing a capability for assessing the likelihood of future states. These core activities include the development of ecosystem models, synthesis of historical datasets and the development and coordination of fieldwork.

ICED has a project, the Southern Ocean Sentinel, hereafter termed 'the Sentinel', which will utilise the models and field activities in an ongoing integrated programme to assess status, trends and likelihood of future states of Southern Ocean ecosystems as a whole. It has close synergies with other international initiatives within the Southern Ocean science community, as well as the broader Earth System community.

ICED is closely linked to another IMBER programme, Climate Impacts on Oceanic Top Predators (CLIOTOP), particularly in relation to its work on marine mammals. The general objective of CLIOTOP (http://www.imber.info/index.php/Science/Regional-Programmes/CLIOTOP) is to organise a large-scale worldwide comparative effort aimed at elucidating the key processes involved in the impact of both climate variability (at various scales) and fishing on the structure and function of open ocean pelagic ecosystems and their top predator species. The ultimate objective is the development of a reliable predictive capability for the dynamics of top predator populations and oceanic ecosystems that combines both fishing and climate (i.e. environmental) effects. CLIOTOP is in its second phase with an emphasis on developing scenarios of the evolution of oceanic ecosystems under anthropogenic and natural forcings in the 21st century (Hobday et al. 2013).

Future Earth

Future Earth is a new 10-year international research initiative that is intended to "develop the knowledge for responding effectively to the risks and opportunities of global environmental change and for supporting transformation towards global sustainability in the coming decades" (see http://www.icsu.org/future-earth). Future Earth is being developed by an alliance of partners that includes the International Council for Science (ICSU), Belmont Forum, International Social Science Council, UNEP, as well as others. Future Earth is intended to replace the existing structure that is composed of the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme (IHDP) and DIVERSITAS. The IGBP will end in late 2014 and plans for a synthesis phase have begun. The IHDP and DIVERSITAS are also planning synthesis and phase-out activities. The World Climate Research Programme (WCRP) is a partner in Future Earth, but will retain it present structure and independence.

A Future Earth transition team has been established and tasked with providing a plan for the merger of the IGBP, IHDP and DIVERSITAS that will retain the science being done through the core projects of these programs and also maintain their science communities and networks. An interim director for Future Earth will soon be appointed as will a Scientific Committee; both will guide the development and transition of the international global environmental change programmes towards Future Earth.

All of the existing core projects of IGBP, IHDP and DIVERSITAS have been invited to join Future Earth. The projects that wish to make this transition are now considering new research directions that fall under the three Future Earth research themes of:

- Dynamic Planet - Observing, understanding, projecting Earth and societal system trends, drivers and processes, and their interactions; anticipating global thresholds.
- Global Development - Providing the knowledge for sustainable, secure and fair stewardship of food, water, health, energy, materials and other ecosystem services.
- Transformation towards Sustainability - Understanding and evaluating strategies for governing and managing the global environment across scales and sectors, and transformations to move towards a sustainable Future Earth.

The Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Programme of IGBP is planning its transition to Future Earth. The IMBER Project is convening an Open Science Meeting in June 2014 in Bergen, Norway. The goals of this conference are to highlight IMBER research results, promote integrated syntheses, and develop a plan for the next phase of IMBER science, in the context of Future Earth. More information is available at www.imber.info/index.php/Meetings.

Southern Ocean Observing System (SOOS)

SOOS (http://www.soos.aq) was established to better coordinate routine observing of the Southern Ocean in order to improve our ability to detect and interpret Southern Ocean change across a range of variables and disciplines (Rintoul et al. 2011). It has associations with all international programmes undertaking scientific research in the Southern Ocean. SOOS has six overarching themes in its strategy: (1) the role of the Southern Ocean in the planet's heat and freshwater balance, (2) the stability of the Southern Ocean overturning circulation, (3) the role of the ocean in the stability of the Antarctic ice sheets and their contributions to sea level rise, (4) the future and consequences of Southern Ocean carbon uptake, (5) the future of Antarctic sea ice, and (6) the impacts of global change on Southern Ocean ecosystems. The sixth theme is complementary to ICED Southern Ocean Sentinel and will be important in observing trends in Southern Ocean ecosystems.

Scientific Committee on Antarctic Research (SCAR) programmes

SCAR (http://www.scar.org) has a number of programs contributing to understanding change in the Southern Ocean.

The SCAR Life Sciences programme helps coordinate priorities for Antarctic ecosystem research. These priorities have generally centred on understanding the patterns of biodiversity in Antarctica and the Southern Ocean, and the drivers of change in structure and dynamics of ecosystems. Recently, two programmes have been adopted to further this work. The State of the Antarctic Ecosystems (AntEco) programme aims to explain the biodiversity of Antarctica, how it evolved/arrived in the region, its ecology and threats to its persistence in the region. The Antarctic Thresholds – Ecosystem Resilience and Adaptation (Ant-ERA) programme aims to determine the biological processes in

Antarctic ecosystems and to define the thresholds for biota along with their resistance and resilience to change.

SCAR also has a Southern Ocean Continuous Plankton Recorder Survey (SO-CPR), which was established in 1991 to map the spatio-temporal variation in biodiversity, distribution and abundance of plankton (Hosie et al. 2003). It is a key component of the Southern Ocean Observing System, and is a founding contribution to the Global Alliance of CPR Surveys (GACS, www.globalcpr.org), which allows Southern Ocean observations to be placed in a global context.

Council of Managers of National Antarctic Programs (COMNAP)

COMNAP (https://www.comnap.aq) is the international association of National Antarctic Programs, formed in 1988. National Antarctic Programs are those organizations that have responsibility for delivering and supporting scientific research in the Antarctic Treaty Area on behalf of their respective governments and in the spirit of the Antarctic Treaty. Stations in the Antarctic Treaty Area in 2011 are shown in **Error! Reference source not found.**. The purpose of COMNAP is to develop and promote best practice in managing the support of scientific research in Antarctica. It does this by: (i) serving as a forum to develop practices that improve effectiveness of activities in an environmentally responsible manner; (ii) facilitating and promoting international partnerships; (iii) providing opportunities and systems for information exchange; and (iv) providing the Antarctic Treaty System with objective and practical, technical and non-political advice drawn from the National Antarctic Programs' pool of expertise.

Platform for collaboration and communication: SOKI

The recently established Southern Ocean Knowledge and Information (SOKI) wiki (http://soki.aad.gov.au) can be used in the further elaboration of work on this theme. It is being used by the Southern Ocean ecosystems scientific community to develop collaborations, projects and research tools as well as providing a publicly accessible repository for reference material on biota, ecosystems, standard methods and so on. SOKI also aims to provide a forum for researchers to exchange and link information, ideas and commentaries with respect to this material. It is designed to enable straightforward and efficient management of information content, input and updating of new information, extraction of information, and involvement of a community of users. SOKI is divided into five main spaces: (i) ecological knowledge, (ii) ecological review and application, (iii) research tools and activities, (iv) SOKI administration and (v) frequently asked questions.

These spaces are determined around the questions 'What do we know and what are the key gaps and uncertainties?', 'How is the knowledge used?' and 'What research is being done, by whom and how?', followed by administration of the site and FAQs that provide the user guide.

At present, new users can go to the home page of SOKI and request access by following the links on the home page.

Approaches

In its simplest form, the status of Antarctic and Southern Ocean marine ecosystems is determined by the relative abundances of the different taxa, taking account of different habitats, trophic levels, and seasonal variability in abundance. Trends in populations need to be described in relation to sources of interannual variability, so that differences over time can be attributed to random events, or systemic changes (physical or biological) that may be cyclical or longer term trends. Relating observations to the true state of an ecosystem is a major challenge in an assessment. This is particularly true for analyses across many taxa, habitats and the varying temporal and spatial scales at which different components of the ecosystem operate. Techniques are usually employed so that not all taxa in an ecosystem need to be observed in order to assess biodiversity or the relative abundance of taxa at different trophic levels. However, some understanding is needed of how these summary observations relate to the overall status of taxa in the ecosystem.

Beyond the empirical data and assessments of status and trends, we also need an understanding of the key ecological processes (or "drivers", or "forcings) that directly or indirectly cause the ecosystem dynamics. This knowledge enables an understanding of the consequences of assessments for the Earth System, and also for achieving management objectives. The combination of knowledge on status, trends and processes, along with natural variability, enables the development of dynamic models of the ecosystem. These models can then be used to project from the current state to explore possible future states under various scenarios and therefore enable assessments of the likelihood that those states might arise in the future. This process can take account of historical perturbations, such as whaling and sealing, in assessing the likelihood of future states. For example, knowledge of the present status and ecology of whales provides the basis for determining the future trajectory of whales and their potential to directly and indirectly impact on other parts of the ecosystem.

1. Current status

Knowledge on the current state of Southern Ocean ecosystems is mostly derived from integrated ecosystem studies on the Antarctic Peninsula and South Georgia, along with expert syntheses across disparate data sets for other regions (Rogers et al. 2012, Constable et al. submitted). This can be combined with the benchmarking of the state of krill from the CCAMLR (2000) survey in the Atlantic Sector (Watkins et al. 2004), and the BROKE (1996; Nicol et al. 2000) and BROKE West (2006; Nicol et al. 2010) surveys in East Antarctica. Other work in the past decade also provides a solid foundation for identifying gaps and how to achieve a benchmark for Antarctic and Southern Ocean ecosystems as a whole, including a workshop held jointly between the Scientific Committees of CCAMLR and the International Whaling Commission (SC-CAMLR and SC-IWC 2008) and subsequent publications on primary production (Strutton et al. 2012), zooplankton (Atkinson et al. 2012b), krill (Atkinson et al. 2012a), finfish (Kock et al. 2012), penguins (Ratcliffe et al. 2011) and seals (Southwell et al. 2012).

Impacts on the physical environment of climate change are expected to differ between regions in the Southern Ocean. Synchronised studies between regions, in a similar way to that undertaken in World Ocean Circulation Experiment (Siedler et al. 2001), Southern Ocean GLOBEC (Hofmann et al. 2011) and the IPY (Krupnik et al. 2011), can provide a natural experiment to test hypotheses about direct and indirect ecosystem responses to changing physical environments. Apart from the southwest Atlantic and the west Antarctic Peninsula, the overall status of the marine ecosystems, as a foundation for assessing ecological dynamics and change, is not well known (Constable et al. submitted). The ICED Sentinel and SOOS are using existing regional datasets and programmes, synoptic data (e.g, from satellites and integrative models), and work in the SCAR Biogeographic Atlas to develop a means for benchmarking Southern Ocean ecosystems as a whole, towards developing integrated ecosystem measurements of status and trends in these ecosystems. It is envisaged that a coordinated field programme to benchmark the ecological status of Southern Ocean ecosystems could be developed for 2020 or soon after utilising satellite observations, ship-based transects and integrated studies (Figure 1) coupled with land-based programmes to monitor foraging activities and diets of seals, penguins and flying birds at key locations in the different regions.

2. Assessing status, trends and likelihood of future states

Methods for summarising the status and trends of ecosystems are in the process of being developed (SC-CAMLR 2008, Shin et al. 2010) and are now moving beyond summaries of the status of individual taxa to summaries of collective indices, such as size spectra (Jennings et al. 2005, Jennings et al. 2008). Some methods have been developed for combining multiple measures into a single index that can show time trends relative to specific causes of change (de la Mare et al. 2000). The challenge this technique raises, is how to determine which indices will reflect overall status of the ecosystems and provide useful summaries for describing trends that can be used by managers and policy makers (Fulton et al. 2005).

Ecosystem models are yet to be developed that can be used to assess the likelihood of future states, although the requirements for the models are now well established (SC-CAMLR 2004, SC-CAMLR and SC-IWC 2008, see Murphy et al. 2012a for discussion). Such models will also be useful for informing what observations need to be taken to measure trends in these ecosystems.

3. Observing change in Antarctic and Southern Ocean ecosystems

Regular integrated observations of Southern Ocean ecosystems are available on the western margins of the Antarctic Peninsula and from the Scotia arc. Land-based activities are available in other regions as part of the CCAMLR CEMP, or as regular monitoring activities such as at Kerguelen and Crozet Islands (e.g. Barbraud et al. 2012). Regular ship-based observations are also available (e.g., the Continuous Plankton Recorder Survey (Hosie et al. 2003); but these are mostly opportunistic and are not necessarily integrated with land-based observations or other ship-based activities. Observations of the physical system are generally further advanced than for biology (Rintoul et al. 2011). Improved integration of ecosystem observations along with improved coverage through CEMP, SOOS, and

ICED Sentinel will be central to improved assessments of status, trends and ecological processes in Southern Ocean ecosystems, as well as giving greater capacity for validating ecosystem models.

4. Critical ecosystem processes

Since the work of the BIOMASS programme in the 1980s (El-Sayed 1994), a number of internationally coordinated programmes have sought to better quantify the critical ecosystem processes in Southern Ocean such as factors affecting primary production (the role of iron) and the relative importance of different trophic pathways, the role of sea ice as habitat for krill and other biota, factors that affect the breeding phenology of marine mammals and birds and drivers of availability of prey. These have included Southern Ocean GLOBEC (Hofmann et al. 2011), the Discovery 2010 programme (Tarling et al. 2012), and most recently ICED (Murphy et al. 2008). This work is essential for providing the theoretical and quantitative underpinnings for the development of ecosystem models (Murphy et al. 2012a, Murphy et al. 2012b).

General

The IPY has provided a strong stimulus to setting up ongoing observations and assessments of status and trends in the Southern Ocean. Current work is leading towards an integrated field assessment of the ecological status of Southern Ocean ecosystems as a whole, using standard methods for biological monitoring. This will help standardise the relative differences between regions and provide consistent foundation against which future change will be measured. In this process, ecosystem models can not only support the assessments but will help provide a guide as to what measures need to be taken to indicate overall status of Southern Ocean ecosystems. It is envisaged that existing initiatives and further developmental work over the next 5 years will build on the programmes already underway for the west Antarctic Peninsula, Scotia Arc and CEMP. This work is expected to result in a fully integrated cost-effective programme to measure status and trends in Southern Ocean marine ecosystems overall that could begin with a benchmarking of these ecosystems around 2020.

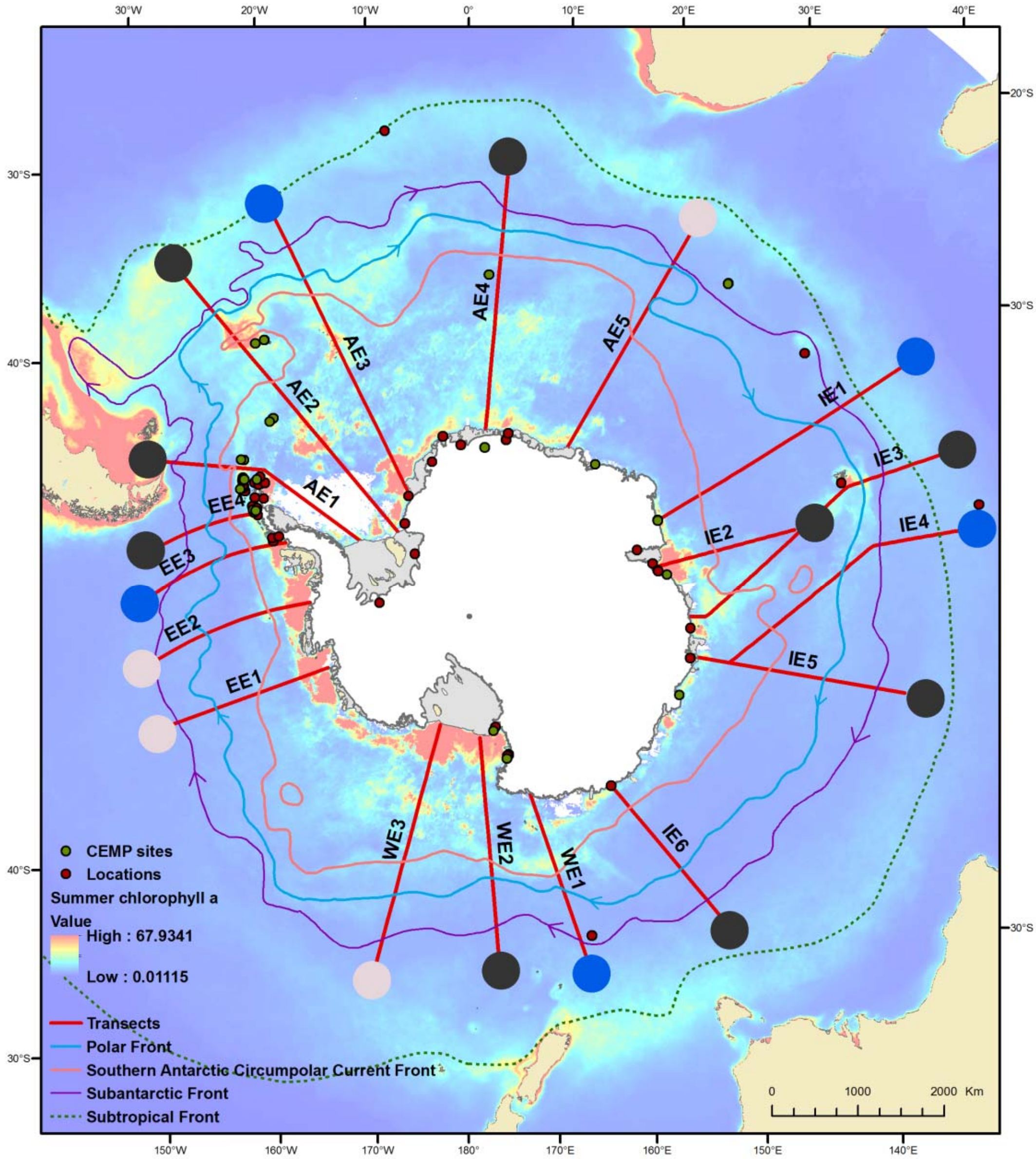

Figure 1 Map of mean summer chlorophyll *a* showing transects (red lines) and locations being investigated for measuring biological and ecosystem parameters in the Southern Ocean. Sectors are for circumpolar assessments of status and change, which are divided into polar and temperate. Transects take account of latitudinal and longitudinal variation in primary production and in regional differences in biology and food webs and the latitudinal range of oceanic, cryospheric and atmospheric conditions, including spatial variation in productivity, in each region. Initials indicate regions and transect numbers: EE = East Pacific sector ecosystem transect; AE = Atlantic sector ecosystem transect; IE = Indian sector ecosystem transect; WE = West Pacific sector ecosystem transect. Registered sites for monitoring in the CCAMLR Ecosystem Monitoring Program are shown. Locations are coastal bases or other possible research locations. Large dots show the degree of feasibility that existing operations in the region may be used as ships of opportunity for taking underway measurements along transects. Dark blue dots represent transects that could be feasible for repeated sampling within current operational activity. Lighter blue dots represent transects that could be done repeatedly but with some operational adjustments. Light dots represent desirable transects but not easily undertaken within the current operations.

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