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# Developing priority variables ("ecosystem Essential Ocean Variables" — eEOVs) for observing dynamics and change in Southern Ocean ecosystems

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ABSTRACT

Reliable statements about variability and change in marine ecosystems and their underlying causes are needed to report on their status and to guide management. Here we use the Framework on Ocean Observing (FOO) to begin developing *ecosystem Essential Ocean Variables* (eEOVs) for the Southern Ocean Observing System (SOOS). An eEOV is a defined biological or ecological quantity, which is derived from field observations, and which contributes significantly to assessments of Southern Ocean ecosystems. Here, assessments are concerned with estimating status and trends in ecosystem properties, attribution of trends to causes, and predicting future trajectories. eEOVs should be feasible to collect at appropriate spatial and temporal scales and are useful to the extent that they contribute to direct estimation of trends and/or attribution, and/or development of ecological (statistical or simulation) models to support assessments. In this paper we outline the rationale, including establishing a set of criteria, for selecting eEOVs for the SOOS and develop a list of candidate eEOVs for further evaluation. Other than habitat variables, nine types of eEOVs for Southern Ocean taxa are identified within three classes: state (magnitude, genetic/species, size spectrum), predator–prey (diet, foraging range), and autecology (phenology, reproductive rate, individual growth rate, detritus). Most candidates for the suite of Southern Ocean taxa relate to state or diet. Candidate autecological eEOVs have not been developed other than for marine mammals and birds. We consider some of the spatial and temporal issues that will influence the adoption and use of eEOVs in an observing system in the Southern Ocean, noting that existing operations and platforms potentially provide coverage of the four main sectors of the region — the East and West Pacific, Atlantic and Indian. Lastly, we discuss the importance of simulation modelling in helping with the design of the observing system in the long term.
Regional boundary: south of 30°S.

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**Contents**



## 1. Introduction

Assessments of status, variability and change in marine ecosystems are needed to inform management decisions for sustaining goods and services (see Table 1 for a glossary of terms used in this paper). Long-term observations of many attributes of these ecosystems are often lacking. This limits the capacity to report on changes in status, to identify key processes driving marine ecosystems, to judge the long-term effects of people on marine resources, food webs and biodiversity, to determine sustainable levels of activities, such as fisheries, and to assess

**Table 1**
A glossary of terms used in this paper.

| *Term* | Context |
|---|---|
| *Change* | Restricted in this paper to mean any difference in the status or function of a system that is of interest to society, policy-makers, managers and scientists |
| *Status* | The condition of an ecosystem property or the ecosystem as a whole. Measures of status can include mean, variability or other short and long-term aspects of an ecosystem's dynamics (e.g. seasonal cycles, decadal oscillations). Thus, status includes the relative abundances of components (habitats, taxa), the processes by which those components interact with other physical, chemical and biological components of the ecosystem and the subsequent dynamics and variability in the components. |
| *Trend* | A general tendency or direction of change over time-scales longer than a few years. Such changes may be in the mean and/or variability of status, such as the frequency of extreme events. |
| *Step change* | A relatively large change that occurs over a short time period. |
| *Attribution* | The process of determining and assigning the cause of a trend. |
| *Future scenarios* | Possible changes in ecosystem status and trends in the future. |
| *Assessment* | The quantification (including the process leading to that quantification) of (i) status of ecosystem properties and the ecosystem overall, (ii) trends and/or step changes in those properties, (iii) attribution of trends and step changes to causes, and (iv) likely future scenarios for the ecosystems. |
| *Observation* | A quantity directly measured in the field and from which an eEOV may be derived. |
| *ecosystem Essential Ocean Variable (eEOV)* | The name has its origin in the Framework on Ocean Observing. An eEOV is a defined biological or ecological quantity which is derived from field observations. It would be expected to contribute significantly to assessments and be feasible to collect at appropriate spatial and temporal scales. Its utility arises from its contribution to the roles: (i) direct estimation of status, trends and/or attribution, and/or (ii) development of ecological models (e.g. qualitative, statistical/empirical, dynamic mathematical models) to support assessments. |
| *Indicators* | Indicators are defined as variables, pointers or indices of a phenomenon. |
| *Evaluation* | To judge or calculate the importance or performance of candidate eEOV in relation to criteria and qualities for pilot and mature EOVs. |

the risk of passing tipping points in the face of global changes to the oceans, and what action might be needed to stop this from occurring (IPCC, 2014; Kennicutt et al., 2014; Millennium Ecosystem Assessment, 2005; UN, 2016).

Ecosystems are characterised by many connections between the physical and chemical environment, habitats, diversity and food webs. Bottom-up (from lower trophic levels), competitive, and top-down (from higher trophic levels) processes may interact to influence, directly or indirectly, each of these components, which are also affected by global and local human activities (Fig. 1). Nine general classes of ecosystem properties may be used to make statements about status and trends (or step changes) in the ecosystem and the consequences of those changes: habitat, diversity, spatial distribution of organisms, primary production, ecosystem structure, production, energy transfer, and regional and global human pressures (Table 2). Scientists are expected to be able to make such statements, including disentangling the underlying causes of variability and change in marine ecosystems. Without this support, policy-makers lack a scientific basis to adopt measures that may be effective in achieving sustainability of ocean uses and avoiding tipping points. A well-structured observing system is essential to delivering these statements.

Observing status and trends of the global ocean has a long history. During the 1980s and 1990s, the World Ocean Circulation Experiment (WOCE) established an essential set of observations, including their standard methods and ocean transects to meet regional sampling requirements (Siedler et al., 2001). These observations have been continued by the CLIVAR and GO-SHIP repeat hydrography programmes, and have facilitated estimates of physical and chemical change and enabled the attribution of their causes (e.g. IPCC, 2013).

The OceanObs'09 Conference brought together hundreds of scientists "to build a common vision for the provision of routine and sustained global information on the marine environment sufficient to meet society's needs for describing, understanding and forecasting marine variability (including physical, biogeochemical, ecosystems and living marine resources), weather, seasonal to decadal climate variability, climate change, sustainable management of living marine resources, and assessment of longer term trends" (http://www.oceanobs09.net). The Framework for Ocean Observing (FOO; Lindstrom et al., 2012), was developed as a result of the outcomes of this conference and was used to reorganise the Global Ocean Observing System and to develop other observing systems. Many oceanic and atmospheric variables have been identified for regular measuring and reporting and are known as *Essential Ocean Variables* (EOVs) or *Essential Climate Variables* (ECVs). The FOO also provides a process for establishing candidate EOVs and developing them through stages (conceptual, pilot, mature) until final adoption in an observing system.

The question of what variables need to be routinely observed to enable assessments of status and trends (or step changes) in biological components of ecosystems, attribution of causality and projection of scenarios of change for the future is now receiving attention (Table 3). The terminology adopted by the FOO has been extended to include *ecosystem Essential Ocean Variables* (eEOVs): biological and ecological variables selected for regular measurement (defined below and in the glossary of terms in Table 1). The breadth of biological variables that could be measured is vast due to the complexities of habitats, species and their interactions, making it challenging to identify specific biological variables to be used in an observing system. The challenge of maintaining a common set of variables increases with increasing spatial scale, particularly at greater than regional scales (Hayes et al., 2015). How can a "backbone" time-series of measurements be established and adopted by the international scientific community, upon which more specific measurements can be added or synthesised when needed?

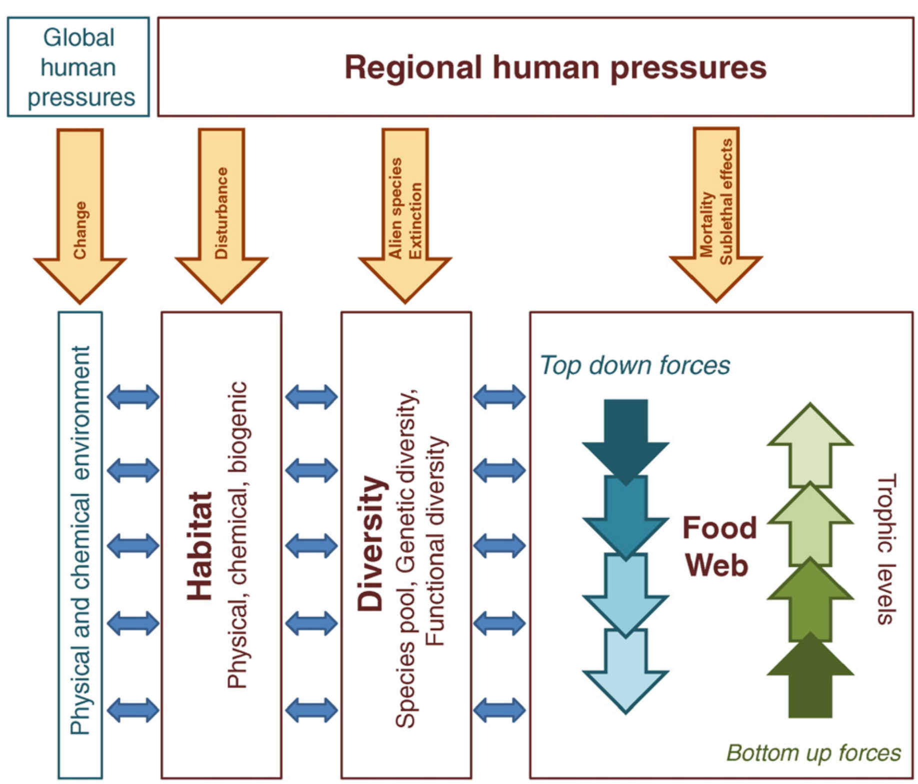


**Fig. 1.** Illustration of the relationships between general components of the Southern Ocean marine ecosystem — Habitat, Diversity, Food Web and Human Pressures. Horizontal blue arrows indicate the connections, including feedbacks, between the components. For example, habitats are a potentially dynamic combination of physical, chemical and biological processes, such as biogenic reefs. Downward orange arrows show the effects of global and regional human pressures in the system. The food web can be considered as a number of trophic levels, each of which will be impacted by both bottom-up and top-down forces. The number of blue arrows indicates that changes in habitats, diversity and food webs may occur at any trophic level, potentially giving rise to both bottom-up and top-down effects in the food webs (modified from Constable et al., 2014). Ecosystem properties relating to these general components are described in Table 2.

**Table 2**
General Ecosystem Properties that assist in addressing questions regarding status, trends, attribution and likely future scenarios for marine ecosystems.

| | Ecosystem Property | Description | Examples of significant changes |
|---|---|---|---|
| Spatial arrangements of taxa | 1. Habitat | The distribution of physical, chemical and biological attributes that, combined, influence the types and ecologies of taxa in the region. This includes biogenic habitats, such as reefs, and biological modification of the physical–chemical properties of an area. | Seasonal variability, ocean variability over years, disturbance by ice scour, biotic disturbances or other biologically mediated change, such as through bio-engineers, or by direct or indirect disturbance from human activities, such as dredging or fishing. |
| | 2. Diversity | Diversity of species and genotypes, including species composition and functional diversity, which may occupy the different suites of habitats. | Adaptation and extinction may cause changes in diversity. |
| | 3. Spatial Distribution of Organisms | Geographic and depth distributions of organisms that may affect the degree to which organisms overlap in space. It also includes the degree of connectivity of taxa across the region. | Range changes may occur as a result of trends in the distribution of habitats. |
| Food-web structure and function | 4. Primary production | Production of organic material by photosynthetic and chemosynthetic autotrophs. | Changes in the taxonomic composition of autotrophs, such as shifts from large diatoms to smaller nanoplankton. |
| | 5. Structure | Abundances of taxa in space and time, related to patchiness of the organisms, along with size structure of populations and functional groups, relationships between biota, and processes/responses that give rise to structure. | Change in relative abundances or feeding interactions of some species may lead to trophic cascades, or regime shifts. |
| | 6. Production | Productivity of different levels of the food web in a region. This may include factors that affect productivity such as non-trophic interactions and disease. | Productivity of individual species may change as a result of changes in one or more of the other ecosystem properties. |
| | 7. Energy Transfer | Efficiency in transferring/utilising energy in the food web, which will need to account for spatial and temporal overlap of consumers and resources, which in turn will be affected by habitat characteristics and behaviour. This relates to production. | Changes in the relative importance of different energy pathways, such as shifts from the krill-based food web to the copepod-fish food web. |
| Human pressures | 8. Regional | Human activities directly interacting with one or more of the local ecosystem properties. Primary human pressures in the Southern Ocean are fisheries, tourism and pollution. Shipping is a secondary human pressure in this case. | Change can arise from shifts in social, economic, governmental priorities and regulations, or through advances in technology |
| | 9. Global | Human activities distant from the local ecosystem but giving rise to local change. | The effects of climate change and ocean acidification |

One role of eEOVs would be consistent with the role of indicators in ecosystem-based management (Garcia and Staples, 2000), which are used widely, including in a pressure-state-response framework (Fulton et al., 2005; Jennings, 2005; Rice and Rochet, 2005). In this case, eEOVs would be those variables that reliably indicate changes in state as a result of specific pressures from human activities. Often, these variables are intended to be directly useful to policy-makers and scientists, and for communicating change (e.g. Hayes et al., 2015). More than one eEOV will be required for many types of assessment of change.

A second role for eEOVs relates to the development of models (Table 1), although this has not received as much attention (but see Peters, 1991). Many types of models may be used in assessments of change, attribution of causality, and the consequences of change. Unless otherwise specified, we use the term 'model' to represent the variety of conceptual-qualitative, statistical-empirical, and dynamic mathematical models (for a review of the types of models and their uses see Fulton and Link, 2014). Dynamic models may be used for retrospective evaluation of the effectiveness of alternative management actions to achieve a range of socio-economic–ecological objectives in the face of unexpected events that have actually occurred. Further, dynamic models can be used to assess the likelihood of different ecosystem states, including past and future states. eEOVs enable scientists to control and validate the behaviour of models. For empirical models, eEOVs may include important covariates or other variables in an analysis. For dynamic models, eEOVs may include important state or process variables for fitting or validating models or as drivers of models. In this second role, eEOVs can be used to discriminate between alternative models, thereby enabling better assessments over time.

### *1.1. What is an eEOV?*

There is a hierarchy in data from field observations (called 'subvariables' and 'supporting variables' in biogeochemical EOVs — Anon, 2014), to using algorithms to transform the data into quantities useful to ecologists (e.g., Chlorophyll *a* (Chl *a*) concentration from ocean colour, density of mesopelagic fish and krill from acoustic observations), to results of more complex statistical or dynamic models that are used to provide assessments of relevant ecological properties that would be useful to managers and policy-makers (Fig. 2).

In this paper, we treat eEOVs as defined biological or ecological quantities derived from field observations, rather than being a product of an assessment (as defined in Table 1). Their importance will be determined by how well they contribute to assessments of Southern Ocean ecosystems. eEOVs should be feasible to collect at meaningful spatial and temporal scales. Some eEOVs might be measurable by several different methods, or new or improved methods might emerge over time. The specification of an eEOV must provide standard requirements to be met to help ensure that the eEOVs can be compared in space and time. Importantly, an eEOV will have a defined unit of measurement; e.g., density, proportions of taxa in the diet, foraging locations, habitat area, and autoecological rates. For example, ocean colour could be observed in the field by measuring the relative intensities of reflected light at specified wavelengths, and these observations would then be converted into a "Chlorophyll *a*" eEOV using an algorithm that quantitatively relates ocean colour to Chl *a* density. Chl *a* could then be used with other eEOVs to estimate primary production, an ecosystem property.

**Table 3**
International activities aimed at determining biological variables to be measured routinely in the long term.

| Activity | Organisation/group | Web site |
|---|---|---|
| CCAMLR Ecosystem Monitoring Program | CCAMLR | www.ccamlr.org/en/science/ccamlr-ecosystem-monitoring-program-cemp |
| IndiSeas: evaluating effects of fishing on status of marine ecosystems, using a suite of indicators | UNESCO-IOC, EUR-OCEANS | www.indiseas.org |
| The Global Ocean Observing System Biology and Ecosystems Panel (GOOS Bio-Eco) | UNESCO-IOC, WMO, UNEP, ICSU | www.ioc-goos.org |
| Deep Ocean Observing Strategy (DOOS) | UNESCO-IOC, WMO, UNEP, ICSU | www.ioc-goos.org |
| Group on Earth Observation Biodiversity Observation Network (GEOBON) | iDiv, NASA, UNEP-WCMC, GBIF, ASEAN Center for Biodiversity, UNESCO-IOC, MOL, SASSCAL | www.geobon.org |
| Integrated Atlantic Ocean Observing System (AtlantOS) | EU H2020 Consortium | www.atlantos-h2020.eu |
| Arctic Biodiversity Assessment (ABA) | Arctic Council | www.arcticbiodiversity.is |
| Arctic Regional Ocean Observing System (Arctic ROOS) | NERSC, SMHI, Ifremer, IMR, IOPAS, NIVA, DMI, MERCATOR, DAMTP, AWI, FMI, IUP, MET Norway, NIERSC, NPI, GIUB, FCOO | www.arctic-roos.org |
| The Long-term-Ecological Research network (LTER) | International Consortium | www.lternet.edu |

ASEAN Centre for Biodiversity (www.aseanbiodiversity.org).
AWI — Alfred-Wegener-Institut für Polar- und Meeresforschung.
DAMTP — University of Cambridge, Department of Applied Mathematics and Theoretical Physics.
DMI — Danish Meteorological Institute.
FCOO — Danish Defence Centre for Operational Oceanography.
FMI — Finnish Meteorological Institute.
GBIF — Global Biodiversity Information Facility (www.gbif.org).
GIUB — Geophysical Institute at University of Bergen.
ICSU — International Council for Science (www.icsu.org).
iDiv — German Centre for Integrative Biodiversity Research (www.idiv.de).
IFREMER — Institute Français de Recherche pour l'Exploitation de la Mer.
IMR — Institute of Marine Research in Norway.
IOPAS — Institute of Oceanology, Polish Academy of Sciences.
IUP — University of Bremen, Institute of Environmental Physics.
MERCATOR — Mercator Océan.
MET Norway — Norwegian Meteorological Institute.
MOL — Map of Life (www.mol.org).
NASA — National Aeronautics and Space Administration (www.NASA.gov).
NERSC — Nansen Environmental and Remote Sensing Center.
NIERSC — Nansen International Environmental and Remote Sensing Center.
NIVA — Norwegian Institute for Water Research.
NPI — Norwegian Polar Institute.
SASSCAL — Southern African Science Service Centre for Climate Change and Adaptive Land Management (www.sasscal.org).
SMHI — Swedish Meteorological and Hydrological Institute.
UNEP — United National Environment Programme (www.unep.org).
UNEP-WCMC — United Nations Environment Program — World Conservation Monitoring Centre (www.unep-wcmc.org).
UNESCO – IOC – Intergovernmental Oceanographic Commission (www.ioc-unesco.org).
WMO — World Meteorological Association (www.wmo.int).

The Southern Ocean Observing System (SOOS) is developing a set of variables to address 6 themes (Meredith et al., 2013; Rintoul et al., 2011), on heat and freshwater balance, overturning circulation, ice sheet stability and sea level rise, carbon uptake, sea ice and biological systems. It aims to coordinate the observations required for estimating these essential variables throughout the Southern Ocean. In 2014, with the Scientific Committee on Oceanic Research (SCOR) and the Scientific Committee on Antarctic Research (SCAR), and supported by the International Council for Science, SOOS coordinated a workshop hosted by Rutgers University, USA. This workshop aimed to (i) consider a framework for eEOVs for the Southern Ocean that would support the biology theme of SOOS and (ii) identify potential candidates for eEOVs.

In this paper, we outline a process for choosing candidate biological variables for adoption as eEOVs (hereafter termed 'candidate eEOVs'), and how candidate eEOVs could be progressed to final adoption as eEOVs, according to the process described by the FOO. We consider some of the spatial and temporal factors that will influence the implementation of eEOVs in an observing system, and discuss the importance of simulation modelling in helping with the design of the observing system in the long term. We then consider the ecosystem properties of the Southern Ocean and existing observing activities in the region. Lastly, we identify a range of candidate eEOVs that emerge from that experience, including many already being measured, and how they may be further developed for the region.

## 2. Choosing and implementing a set of essential variables

An observing system must have sufficient eEOVs to provide robust foundations for assessments of status and trends of ecosystem properties and development of scenarios for the future. Yet, it will not be practical or even desirable to measure and monitor everything; the observing system must be selective to be economically sustainable and logistically feasible. Efficiencies may be gained by using representative species or measurements, reference locations, or relative rather than absolute measures. These, and other, factors will need to be considered when evaluating eEOVs for inclusion in an observing system.

The inclusion of eEOVs in ocean observing systems will be an evolving process. The FOO (Lindstrom et al., 2012) argues that eEOVs to be given priority for development are those that would have high impact from their use and are feasible to adopt with existing technology and knowledge. We use the term 'utility' in place of 'impact' in order to avoid confusion with the use of the latter term in ecological and environmental science. These terms are intended to relate to an eEOV's utility in assessments of status and trends, attribution of causality, and in projections of future scenarios for marine ecosystems (Table 1). Feasibility relates to how efficiently and reliably the required eEOV quantity can be estimated. Feasibility is determined by (i) the availability in time and space of platforms, sensors and sampling equipment; (ii) the ability to standardise results; and (iii) the timely processing of the measurements. Feasibility is influenced by the costs associated with each of

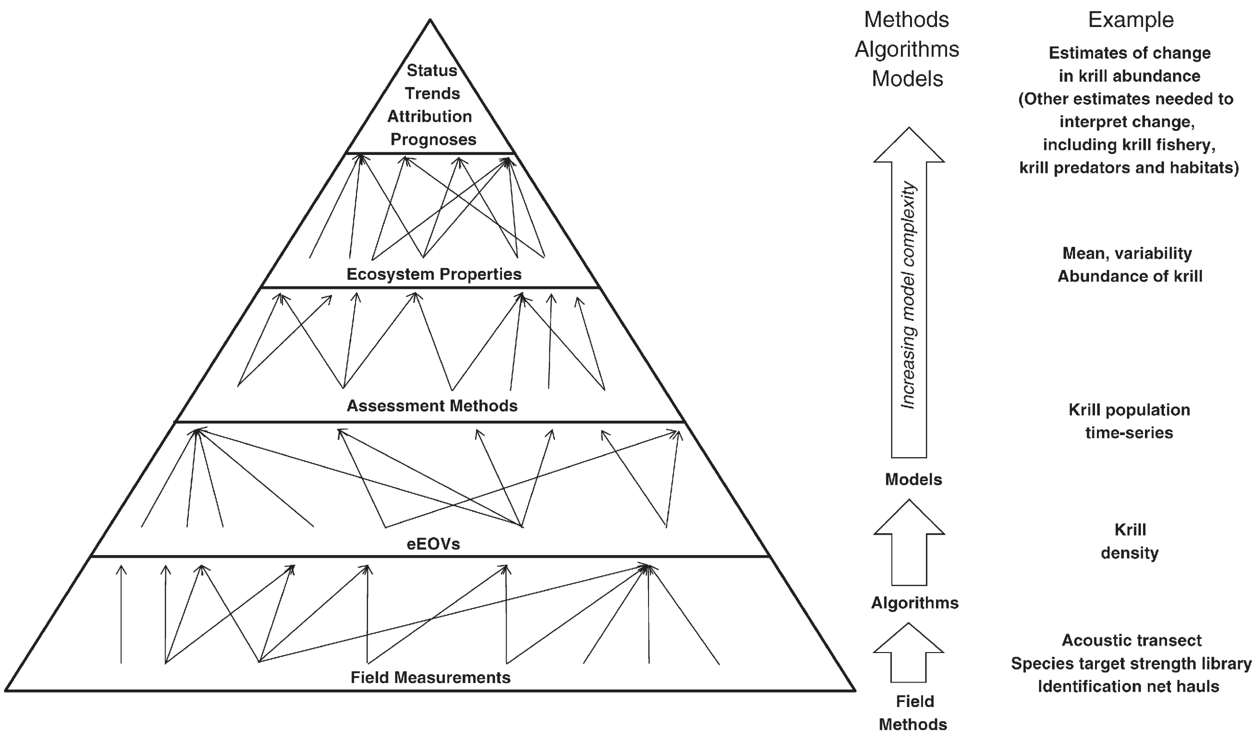


**Fig. 2.** Hierarchy of the process required to move from discrete field observations to products that facilitate assessments of status and trends of ecosystems, attribution to causes, and likely future scenarios. The interplay between data collection by example and different types of analytical procedures (algorithms, statistics, dynamic models) is shown to the right. The triangle illustrates that the process may have 1-to-1 relationships between each level but, more likely, will have many elements from a lower level contributing to fewer synthetic elements at the next level, and that, on the whole, there is a general reduction in the number of elements from one level to the next. The observing system would have standard units to be achieved for eEOVs, which may require the specification of standard field methods. The example for the Southern Ocean illustrates how observations of the acoustic backscatter can deliver estimates of density (eEOV) that help assess change in ecosystem properties.

these factors, as well as the ability to coordinate an effective network of activities across operations. For example, efficiencies may be gained when combining capabilities on single platforms, such as the deployment of conductivity–temperature–depth recorders on animal trackers to observe oceanographic conditions coupled with foraging activities of the marine mammals and birds (Costa et al., 2008; Hindell et al., 2003).

eEOVs will vary in their spatial and temporal sampling requirements. For example, populations of top predators may not need to be measured every year, given their longevity, but seasonal and interannual variation in primary production means that phytoplankton standing stock may need to be estimated monthly or annually at times suitable for the measurement of the phenomena. Also, some eEOVs might benefit from a flexible sampling regime. In this case, they may be initially implemented with relatively coarse spatial or temporal field sampling designs, with planned finer sampling resolution when appropriate signals are detected. The sampling may then return to the coarser resolution after a specified period, or if a counter-signal has been observed. This could be the case when relating surface primary production to pulsed energy inputs to benthic assemblages. For some Antarctic assemblages, pulses of energy inputs may arise as a result of irregular timing of the formation of polynyas in heavy sea ice. Sampling would need to occur when the polynyas form but not at other times. This could also be the strategy for better resolving the consequences of extreme events, such as Antarctic ice shelf collapse.

These considerations of the roles of eEOVs, along with their utility and feasibility, form the basis for establishing criteria for deciding whether specific variables are eEOVs for SOOS. Criteria for establishing indicators, particularly for the effects of fishing, have been detailed over the last 15 years (e.g. Hayes et al., 2015; Jennings, 2005; Rice and Rochet, 2005). Building on this work, the criteria we consider important for eEOVs for the Southern Ocean are given in Table 4.

An eEOV would be expected to be developed through three stages of readiness identified by the FOO (Lindstrom et al., 2012): conceptual to pilot to mature.

Conceptual eEOVs are candidates determined to have reasonable potential of meeting many criteria in Table 4; few candidates will meet all requirements. Qualitative modelling of key ecosystem quantities and processes can help identify the role that a specific eEOV will play (e.g. Hayes et al., 2015). The process for curating data will also need to be identified and tractable.

Conceptual eEOVs would then be evaluated further according to criteria in Table 4. The logistics and cost of the spatial and temporal sampling required to meet the criteria would be determined and evaluated for their acceptability. For example, variables aimed at signalling ecosystem change will need to have a suitable signal-to-noise ratio for the resources that could be committed to measuring them. Of course, measurements of some variables may become less expensive over time, through improved or cheaper technologies.

Realistic options for field designs can be evaluated using case-studies based on existing data or field studies. For example, suitable time series with spatial coverage are available from the west Antarctic Peninsula and the Scotia Sea (Ducklow et al., 2013; Kavanaugh et al., 2015; Rogers et al., 2012), as well as from satellite products and model re-analyses. These data can be used to estimate possible spatial distributions of the values of field measurements at different times. These distributions are then sampled according to possible field designs for collecting the observations, taking account of variation in the implementation of the design from one sampling event to the next. In this way, the statistical properties of the data arising from different designs can be assessed, as well as whether the eEOV will provide a suitable foundation for particular assessments of ecosystem properties. Candidate eEOVs determined to be feasible and cost-effective will be regarded as 'pilot'.

**Table 4**
Criteria for assessing utility and feasibility of eEOVs for the Southern Ocean Observing System. Individual eEOVs do not need to meet all criteria.

| Criterion | Feasibility, utility | Description |
|---|---|---|
| Signal change in ecosystem properties | Utility | Changes in the eEOV or related derived products are likely to be robust indicators of changes in the properties of the ecosystem, despite variability. |
| Contribution to developing and/or applying models investigating change and attribution | Utility | eEOVs can be used to validate, fit or parameterise models in order for those models to represent the ecosystem realistically, or components thereof (at various scales), with dynamics that are suitable for investigating change and attribution to cause. |
| Understanding for policy-makers and the public | Utility | Some eEOVs may improve understanding of dynamics and change, particularly to better explain changes in critical eEOVs. |
| Alignment with other eEOVs | Utility, feasibility | Some eEOVs will need to be sampled concurrently with others in order to disentangle trends from variability (e.g. covariates), to help differentiate between alternative models or to help attribute changes to a cause. Here, essential ocean variables from other disciplines may also be important. |
| Ability to be connected to historical (legacy) datasets, thus extending the time-series into the past | Feasibility, utility | Some eEOVs will help connect historical datasets with new datasets, thereby potentially lengthening the time-series of observations important for assessing change in ecosystem properties. These eEOVs may not be needed after the connection has been completed. |
| Potential to be adapted through time | Feasibility, utility | Improved knowledge and greater capacity for observations may result in an improved sampling design underpinning the eEOV. The signal derived from the eEOV needs to be robust to changes in the methods or design of data collection or, at least, can be standardised to maintain the comparability of legacy data. Similarly, the utility of the eEOV may be greater as the time-series increases. |
| Can be sampled at space and time scales appropriate to the task | Feasibility | Limited sampling in space and/or time may result in confounded signals, e.g. differences in the eEOV may be due to different locations being sampled at different times rather than a temporal trend. |
| Sufficiently high signal-to-noise ratio | Feasibility, utility | Have low sampling error, adequately captures the variability of the eEOV, and that a signal (trend) can be detected in the time scale required. |
| Potential for adaptive sampling | Feasibility | Coarse-grain sampling until a signal is observed to institute fine-grain sampling and then later revert to coarse-grain sampling when a counter-signal is observed. |

Mature eEOVs will have clearly defined standards to be met by the data, as well as policies for the storage and availability of the data. Most importantly, mature eEOVs will be expected to have a high, long-term utility (Table 1). This utility will be determined by the reliability of the data stream, including the quality of the data, the spatial and temporal coverage of the measurements achieved, and whether the signal can be detected above the noise of measurement error and variability. Mature eEOVs and their associated sampling designs will also be required to fulfil the requirements expected by scientists and managers.

The process for evaluating the long-term utility of an eEOV could take a long time if it were done by trial and error; time and resources could be wasted if chosen variables are found to have negligible or low utility. Instead, advances in dynamic simulation models of marine ecosystems, combined with existing time-series, provide a faster process for testing the performance of observing systems and the utility of eEOVs under plausible scenarios (Constable and Doust, 2009; Henson et al., 2016; Fulton and Link, 2014; Masutani et al., 2010). This process, using case studies and model simulations, is illustrated in Fig. 3.

Scenarios may include hypothesised or modelled time-series of different plausible futures, such as under climate change (e.g. rising temperatures at specified rates) (Fig. 3a; Constable et al., 2014; Murphy et al., 2012; Nymand Larson et al., 2014), but can also include simulating historical time series. The latter retrospective analyses can reveal which combinations of variables would have been most useful in detecting known changes in sufficient time for good decisions to be made on managing the marine environment.

An ecosystem model is used to simulate the scenarios to give time series of ecosystem properties and eEOVs (Fig. 3b). The proposed observing system (regular line transects, occupied stations, adaptive glider routes, trawl surveys, and/or ships-of-opportunity taking underway observations such as active acoustics) is simulated to sample from the ecosystem at appropriate spatial and temporal scales (Fig. 3c). The simulated measurements are then used for assessments of the ecosystem properties. The eEOVs and estimated ecosystem properties are then compared to their actual values from the ecosystem model; the difference between the estimated and actual values is a measure of the performance of the observing system. While the effect of spatial and temporal variability on the estimates of eEOVs and ecosystem properties may be explored first, the effects of missing some samples or having errors in locations and/or times of sampling can also be explored to test the effects of uncertainty in funding or resourcing in the long term (Fig. 3d).

The performance of the observing system may be judged according to the measures that would quantify the criteria in Table 4, including accuracy and precision of individual eEOVs or ecosystem properties or trends in either of these (Fig. 3e). A further consideration is the cost of implementing the observation system; there be insufficient resources for some eEOVs to achieve good performance against some criteria. Decisions will need to be made on the minimum performance requirements to be met by an observing system; for example, some variables may need to be estimated with a minimum level of accuracy while others may only require a minimum level of precision.

Many trials of a scenario may be needed to adequately explore the range of behaviours of the system in order to test that eEOVs are reliable, irrespective of the sequence of events that may occur. For example, variation in the dataset may arise from different conditions at the start of the time-series of observations, ecological dynamics, variation in space and time, as well as the random behaviours (errors) of the observing system. Trials for a scenario may also include varying the structure of the ecosystem to test how robust the observing system is to uncertainty in knowledge about the ecosystem. In addition, the performance of a prospective observing system can be evaluated across many future scenarios for the ecosystem, for example, different rates of change, multiple stressors and the like. The design of the observing system can then be adjusted until the minimum performance requirements are likely to be met despite the random variability and errors in any one scenario, and, most importantly, despite which scenario eventuates.

No single observing system design will achieve the best performance for all eEOVs, given the resources available to the observing system. The aim will be to find an observing system that satisfactorily meets the requirements across all eEOVs, which will likely require their prioritisation. In the future, this simulation process can be used to evaluate how to add to the observing system in a cost-effective manner should new resources become available; for example, how to improve measurements of lower priority eEOVs or to help determine the cost-effective implementation of new eEOVs.

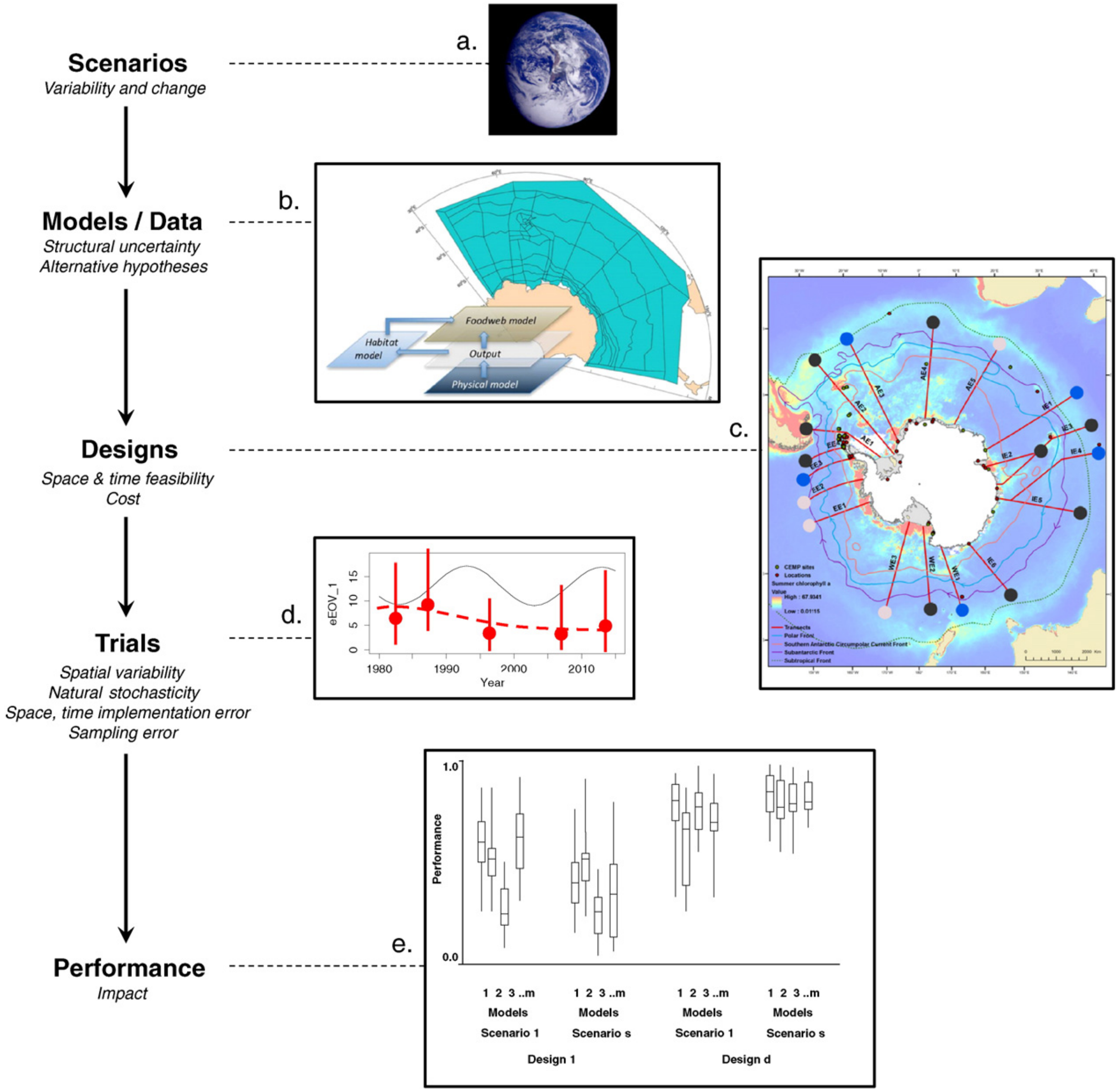


**Fig. 3.** Important steps in the process for evaluating candidate eEOVs using case studies and model simulations (see text for explanation). a. Scenarios derived from hypothesised or modelled time-series of global or regional physical forcings. b. Models/data used to generate time-series of ecosystem properties, represented here by a schematic of a coupled end-to-end ecosystem model for the Indian Sector of the Southern Ocean, based on physical, habitat and food web sub-models. c. Alternative sampling designs in space and time for measuring the candidate eEOVs and tested against the criteria in Table 4 (Fig. 5 is reproduced here showing a possible design based on current field capability). d. Trials of a design used to generate a time-series of observed eEOVs using the proposed sampling design(circles with error bars and a fitted dashed line) to compare with the actual time-series of the quantities in the model (solid line). e. The performance of a design, with the figure showing the performance (box plots illustrate variability in performance across many randomised trials) of 2 field designs for 2 plausible future scenarios and based on 4 different plausible models of the ecosystem.

## 3. Candidate eEOVs for the Southern Ocean

The need for regular assessments of change in Antarctic marine ecosystems has been identified by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014; Nymand Larson et al., 2014), the Antarctic Treaty Consultative Meeting (ATCM, 2015), the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (CCAMLR, 2015a; SC-CAMLR, 2011), and SCAR (Kennicutt et al., 2014; Turner et al., 2009; Turner et al., 2013). The question that is important for managers is whether the ecology of the Southern Ocean is changing as a result of regional (e.g., fishing, pollution, tourism) and/or global (e.g., temperature, carbon dioxide) pressures, and how should managers respond in order to minimise unwanted impacts of these changes?

In this section, we summarise knowledge on the ecosystem properties of the Southern Ocean, and their sources of variability and change. We also describe existing efforts for establishing time-series of observations. We then identify candidate eEOVs for the region, including what we consider to be their state of readiness. Lastly, we discuss the available tools and processes that can be used to determine a mature set of eEOVs for SOOS.

### 3.1. Ecosystem properties of the Southern Ocean

Habitats of the Southern Ocean are well reviewed by Constable et al. (2014) and Gutt et al. (2015). Pelagic habitats are determined by a mix of ocean features, a general gradation of warmer waters in the north to colder waters in the south, delineated by a number of fronts in the west–east flow of the Antarctic Circumpolar Current, and overlaid in the southerly areas by the annual advance and retreat of sea ice (Fig. 4). Nearer to the coast is the east–west flow of the Antarctic Coastal Current, which is broken up by several jets and gyres, notably the Ross and Weddell gyres. Ice shelves, icebergs and glacier tongues create a variety of habitats on the continental shelf. Benthic habitats vary along the continental shelf and slope. Shallow water habitats also occur on the Scotia Arc, the Kerguelen Plateau and the Macquarie Ridge, as well as around other subantarctic islands and seamounts. These physical factors contribute to differing conditions in four different sectors of the region — the East and West Pacific, Atlantic and Indian (Constable et al., 2014).

The diversity of marine biota around Antarctica and in the Southern Ocean, and their spatial distribution, was the subject of intense investigation during the International Polar Year. A thorough compilation of results was published in the SCAR Biogeographic Atlas of the Southern Ocean (De Broyer et al., 2014). For many species, particularly benthos, zooplankton, fish and squid, the spatial distributions are not well described because of the limited coverage of fully quantitative samples; many records are difficult to analyse for relative abundance of different species and when species were not present (i.e. presence-only data).

Primary production is greatest on the continental shelf and near islands, submarine plateaux, banks and seamounts (Fig. 5). Iron supply and surface stratification are critically important to the magnitude of the seasonal blooms, which may vary in their timing depending on spring weather and the retreat of sea ice. The relative abundance of different phytoplankton species varies with location, with larger diatoms and the colonial form of the haptophyte *Phaeocystis antarctica* dominating the more productive areas and smaller species dominating elsewhere (Constable et al., 2014). The distribution of chlorophyll using ocean colour data from satellites shows the spatial variability in primary production. However, the algorithm for converting ocean colour into standing stock of phytoplankton and primary production needs to account for

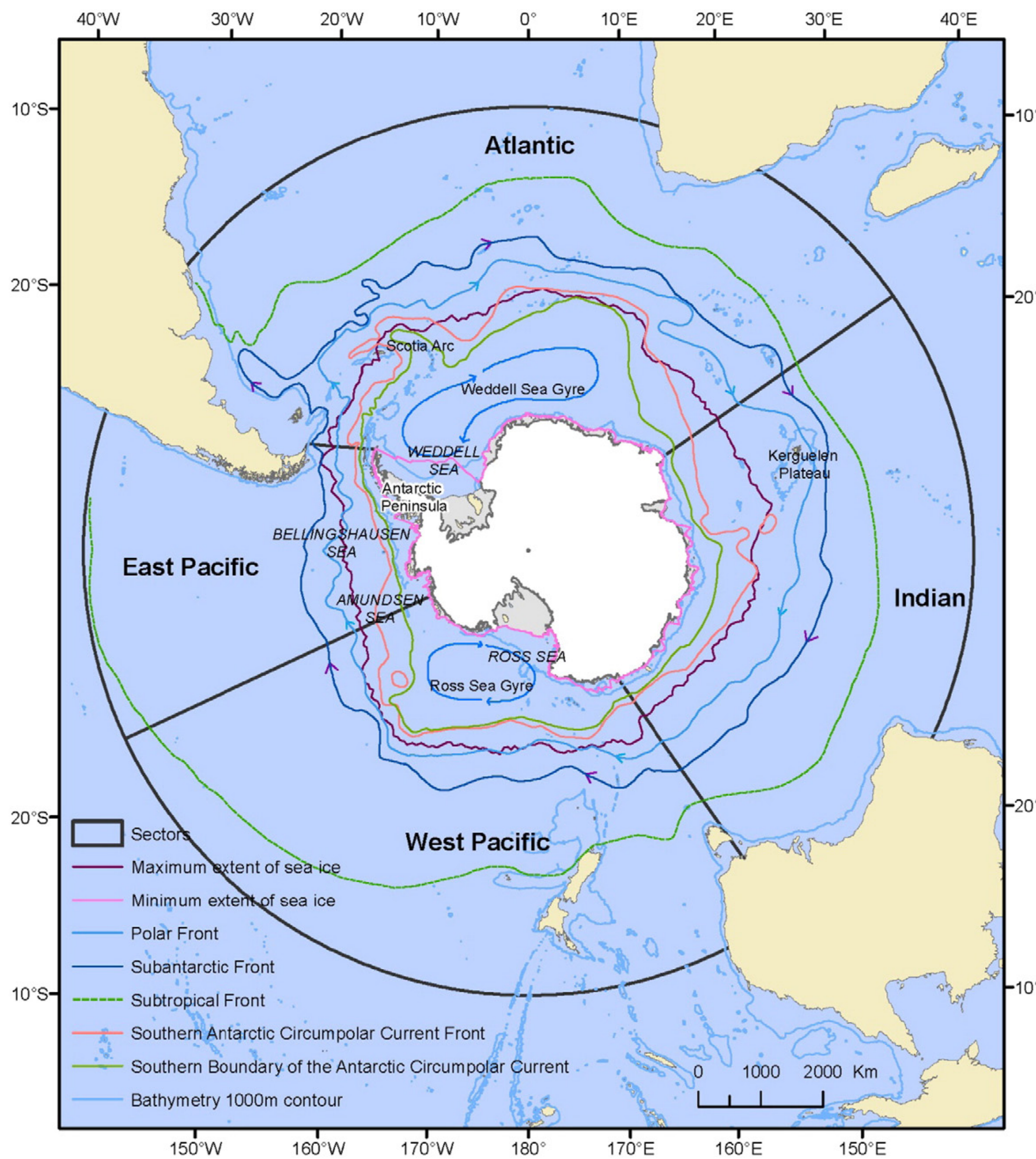


**Fig. 4.** Major physical features of the Southern Ocean, including key locations referred to in the text; major sectors differentiating the ecosystems; minimum and maximum extent of sea ice; the Subtropical, Subantarctic and Polar fronts, Southern Boundary of the Antarctic Circumpolar Current; and the 1000 m contour (Fig. 3 from Constable et al. (2014)).

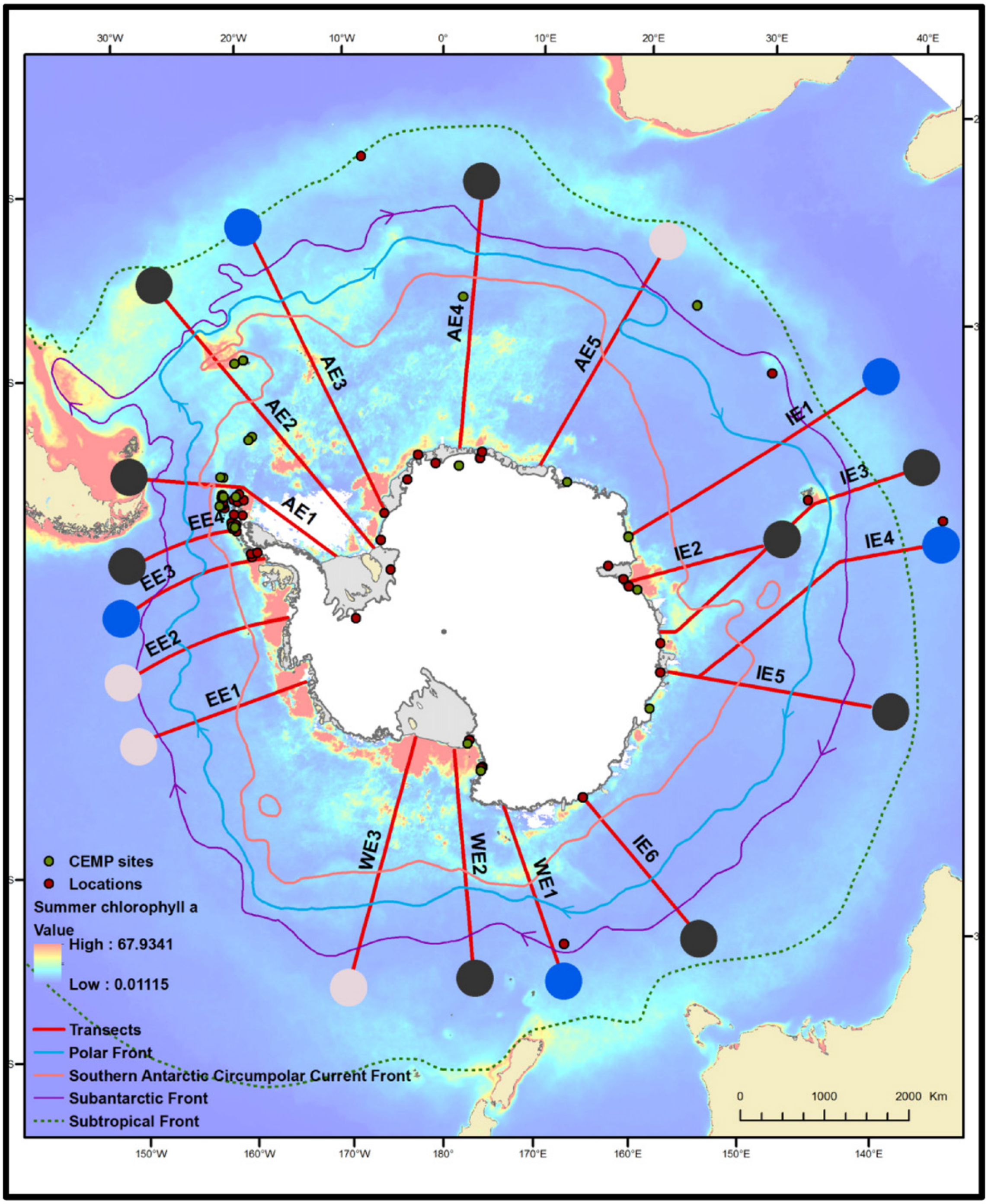


**Fig. 5.** Illustration of a potential design of field sampling for ecosystems in the Southern Ocean Observing System. The map of the Southern Ocean shows potential field capability at present, using satellites, land-based monitoring and possible transects that could be occupied routinely using shipping 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 (described in Constable et al., 2014). The second letter E = Ecosystem transect and then a number for identification.

several sources of error, which are more problematic for the Southern Ocean than elsewhere (Johnson et al., 2013; Strutton et al., 2012). These errors include the spatial and seasonal variability in the relative abundance of species (each of which comprise different relative proportions of chlorophyll), variability in the relationship of surface chlorophyll to the integrated depth profile of chlorophyll (including accounting for variation in the depths of the deep chlorophyll maximum and mixed layer resulting from ice melt and wind), and uncertainty in production from standing stock of different species under different conditions. A further source of error is the standing stock of algae found in and under sea ice, which is very poorly estimated at present but is known to be very abundant in some areas (Meiners et al., 2012).

Food-web structure results from the combination of habitat attributes, the supply and consumable size of organic inputs either as detritus or primary production, and the tolerances to different habitat conditions of species at different trophic levels (Constable et al., 2014; Murphy et al., 2012; Murphy et al., 2013). The most widely understood food chain is pelagic, comprising large diatoms-Antarctic krill- krill predators (whales, penguins, seals, fish) (SC-CAMLR, 2008). However, food chains based on smaller phytoplankton – zooplankton (copepods)

– fish – higher trophic levels occur both near the Antarctic continent and around subantarctic islands. These latter food chains and their relative importance in the region compared to Antarctic krill are poorly understood (Murphy et al., 2012; SC-CAMLR, 2008). Moreover, little information is available on benthic food chains, including benthic primary production, and the role of benthic-pelagic coupling on the Antarctic continental shelf.

The construction of Antarctic food webs and the spatial variability in these food webs is now being given attention (Murphy et al., 2012; Murphy and Hofmann, 2012). Increasingly, weaknesses are being identified in our understanding of energy transfer and productivity of different trophic levels (Hill et al., 2012; Melbourne-Thomas et al., 2013; Murphy et al., 2013; Pinkerton et al., 2010). Food-web structure and the relative importance of different energy pathways will be influenced by how well species respond to the marked seasonality of the habitats and interannual variation in this seasonality (Fig. 4 in Constable et al., 2014). This seasonality and variability varies with latitude and between different sectors of the Southern Ocean (Fig. 4; Constable et al., 2014; Murphy et al., 2012).

The diverse and unique ecosystems of the Southern Ocean have been affected by more than two centuries of regional human pressures, notably with the over-exploitation of whales, seals and finfish (SC-CAMLR, 2008). Fisheries for toothfish, icefish and Antarctic krill are at sustainable levels (SC-CAMLR, 2015a). Tourism and pollution may also add pressure within the region but would currently have localised effects in the nearshore/coastal environments, if such effects occur (Tin et al., 2009). Global human pressures are resulting in rapid changes in habitats through change in ocean temperature, winds, ocean acidification, UV radiation, and seasonal ice cover, although the degree and direction of change varies among different sectors of the region (Constable et al., 2014; Gutt et al., 2015).

### *3.2. Existing and emerging time-series of observations*

Existing time-series of observations provides the foundation for establishing a mature set of eEOVs; these observations show what is feasible to collect at present.

Circumpolar habitat measurements are available through the combination of physical variables from satellites (Stammerjohn et al., 2008), the Argo float programme (Dong et al., 2008), occupied oceanographic sections (Hood, 2009) and conductivity-temperature-depth recorders on seals and penguins (Costa et al., 2010; Costa et al., 2008; Hindell et al., 2003). Moorings and gliders are increasingly being used in some areas and now include biogeochemical measurements as well (Kahl et al., 2010; Kaufman et al., 2014; Schofield et al., 2013). Advances in Argo and other floats, including SOCCOM and PROVOR floats, will enable observations to extend to the deep sea and under ice and routinely include biogeochemical measurements (Kikuchi et al., 2007). These activities and developments suggest that eEOVs relating to the three-dimensional nature of habitats and primary production will be readily observed in the not too distant future.

Biological variables for the Southern Ocean have been measured since the time of the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) surveys coordinated by SCAR (El-Sayed, 1994). Other SCAR initiatives include the expansion of the use of continuous plankton recorders (CPR) for monitoring zooplankton, and more recently phytoplankton, through the Southern Ocean CPR Survey (Hosie et al., 2014; Hosie et al., 2003). The census of Antarctic pack-ice seals (Southwell et al., 2012) occurred in the 1990s-early 2000s and the Census of Antarctic Marine Life was undertaken as part of the International Polar Year (De Broyer et al., 2011; De Broyer et al., 2014). More recently, tracks of marine mammals and birds in the Southern Ocean are being compiled into central databases (Roquet et al., 2014; Raymond et al., 2014), as well as diets of different species (Raymond et al., 2011).

Since the establishment of its Secretariat, CCAMLR has been maintaining records of commercial catches of Antarctic species, including haul-by-haul catch, fishing effort and location data (CCAMLR, 2015b). CCAMLR also maintains reports of estimates of time-series of abundances of target species and, where possible, by-catch species, including benthos (https://www.ccamlr.org/en/publications/fishery-reports). Since the mid-1980s, CCAMLR has developed its CCAMLR Ecosystem Monitoring Program (CEMP: Agnew, 1997 — http://www.ccamlr.org/en/science/ccamlr-ecosystem-monitoring-program-cemp). The CEMP aims to establish monitoring sites for measuring the effects of krill fishing on krill and krill predators, and for differentiating these effects from those of environmental variability and change (see review in Constable, 2011).

Research on the ecology and abundance of whales occurs under the auspices of the Southern Ocean Research Partnership (http://www.marinemammals.gov.au/sorp) (Bell, 2015) and the Southern Ocean Whale and Ecosystem Research programme of the Scientific Committee of the International Whaling Commission (IWC) (Branch, 2007; Branch and Butterworth, 2001; Branch and Rademeyer, 2003).

A Workshop to Review Input Data for Antarctic Marine Ecosystem Models jointly hosted by the Scientific Committees of CCAMLR and the IWC (SC-CAMLR, 2008) reviewed the status of knowledge on many ecological properties of the Southern Ocean, including abundance, trends in abundance, habitat use and diet of many taxa, including phytoplankton biomass and primary production (Strutton et al., 2012), zooplankton (Atkinson et al., 2012b), Antarctic krill (Atkinson et al., 2012a), fish (Kock et al., 2012), penguins (Ratcliffe and Trathan, 2011), ice-breeding seals (Southwell et al., 2012), and whales (Leaper and Miller, 2011; Zerbini et al., 2010). Recently, large-scale censuses have been undertaken for emperor penguins (Fretwell and Trathan, 2009) and Adelie penguins (Lynch et al., 2012; Southwell et al., 2015).

Several national programmes have maintained long time-series of observations both at sea and at land-based colonies of penguins and seals, including the Long-Term Ecological Research site on the west Antarctic Peninsula (USA), the US-AMLR programme in the South Shetland Islands, and programmes in the Scotia Arc (UK, Norway). Long time-series of penguins have been maintained in the Ross Sea (USA, NZ, Italy), East Antarctica (France, Australia, Japan), Indian Ocean subantarctic (France, also including seals) and Pacific Ocean subantarctic (Australia, New Zealand).

More recently, CCAMLR is developing a means by which active acoustic data can be routinely collected by ships of opportunity, notably fishing vessels, for monitoring mesopelagic species, such as krill and myctophid fish. Further, international efforts are underway to develop a cost-effective, satellite method for monitoring seal and penguin populations from space (SOOS Working Group on Censusing Animal Populations from Space; http://soos.aq/activities/capability-wgs/caps-wg).

While many aspects of the Southern Ocean ecosystem have been measured at one time or another, there are few places other than the

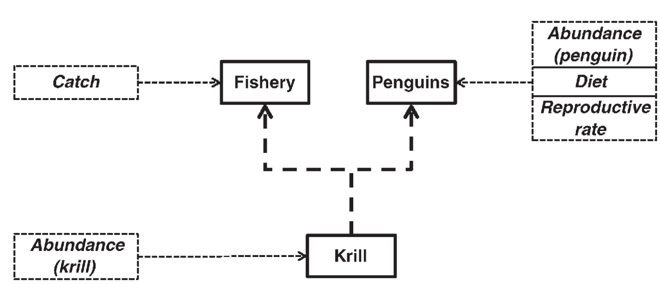


**Fig. 6.** Schematic diagram showing some ecosystem components (bold boxes) for which there are standard methods in the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (https://www.ccamlr.org/en/science/ccamlr-ecosystem-monitoring-program-cemp) — haul-by-haul catch reporting for the fishery, standard protocol for estimating density of krill using acoustics (Watkins et al., 2004), and the standard methods for penguins in the CCAMLR Ecosystem Monitoring Program (CEMP). The dashed arrows indicate linkages that are not regularly estimated. The dotted boxes with italicised names indicate parameters that could be considered as eEOVs. The dotted arrows show the aspects of the food web to which the eEOVs would relate.

Antarctic Peninsula and Scotia Arc where populations and processes are all routinely observed at the same time. A great challenge will be to establish sustained observing across sufficient eEOVs that take account of spatial, seasonal and inter-annual variability.

### 3.3. Candidate eEOVs

A number of candidate eEOVs for the Southern Ocean emerge from existing experience along with consideration of significant gaps in knowledge of the properties of the region.

The evolution of CEMP to facilitate management of the Antarctic krill fishery provides a practical foundation for considering the biological variables that would form the backbone of an observing system, from which assessments of change and attribution of these changes to their causes could then be made. CEMP collects data on krill, the krill fishery and krill predators (Fig. 6). Attention has mostly focussed on krill predators, although regular local surveys of krill occur on the west Antarctic Peninsula and in the Scotia Arc as well (Agnew, 1997; Constable, 2011).

These CEMP data have been summarised into ecosystem indices to help determine when significant changes may occur and to assist in attributing the cause of any change (Boyd and Murray, 2001; Constable et al., 2000; de la Mare and Constable, 2000). However, their use for decision making remains to be implemented. A difficulty in the application of these data is the need for greater spatial coverage of the annual monitoring (not all CEMP variables are measured at all sites and not all fishing locations have monitoring sites), and a better demonstration that the data can be used to link change in the magnitude of predator performance (mostly reproductive success) and the fishery's catch.

More recently, consideration is being given to how to use these types of data to disentangle the effects of fishing from the effects of environmental change (e.g. SC-CAMLR, 2011, 2015b), and how assessments of future ecosystem changes may facilitate adaptation of the fisheries to future conditions (Constable et al., 2014; Murphy et al., 2012). There is now recognition that environmental change may result in an increase in the relative importance of energy pathways alternative to those dependent on krill and, therefore, could result in a reduced abundance of krill (Constable et al., 2014). Further, changes in habitats may result in spatial shifts in the food web not due to the fishery (Constable et al., 2014).

The collection of eEOVs in the observing system will need to encompass sufficient attributes of the food web (including state and process variables) to satisfactorily underpin assessments of the status and trends of the system. For individual biota, 9 types of eEOVs can be used to assess the status of ecosystem properties in Table 2. These can be grouped as state variables, predator–prey linkages, or autecological processes. State variables include abundance, species composition and size spectra. Predator–prey linkages include the biological, spatial and temporal overlap of predators with prey, i.e. foraging timing and range, along with diet. Autecological eEOVs include annual phenology (e.g. timing of reproduction, migration), reproductive output and individual growth. A result of autecological processes is the export of detritus and the potential for recycling of nutrients from waste products. An example of how these eEOVs might be used in assessing ecosystem properties is where data on abundance, foraging and diet are used to assess the status of the part of a food web sustained by species targeted by fisheries, such as krill (Constable, 2001).

Fig. 7 illustrates how CEMP monitoring in Fig. 6 could be expanded to better fulfil the purposes of CCAMLR, particularly given the potential for alternative energy pathways other than through krill (Murphy et al., 2012). Importantly, we can identify in this analysis that not all processes or state variables need to be measured for all species in order to characterise the system and estimate the ecosystem properties. Also, when variables do not substantially vary or the relationships with other variables are well established then they need not be observed regularly, although checks may be made from time to time.

With these principles in mind, we identify candidate eEOVs for habitats and the major biotic groups in the Southern Ocean ecosystem — benthic species, pelagic and sea-ice taxa, and marine mammals and birds. We also identify candidate eEOVs for observing regional pressures on the ecosystem — fisheries, pollution, and tourism. These are summarised in Table 5. We have identified possible states of readiness of the candidates in Table 5 based on their current level of implementation, although these require further scrutiny according to the criteria

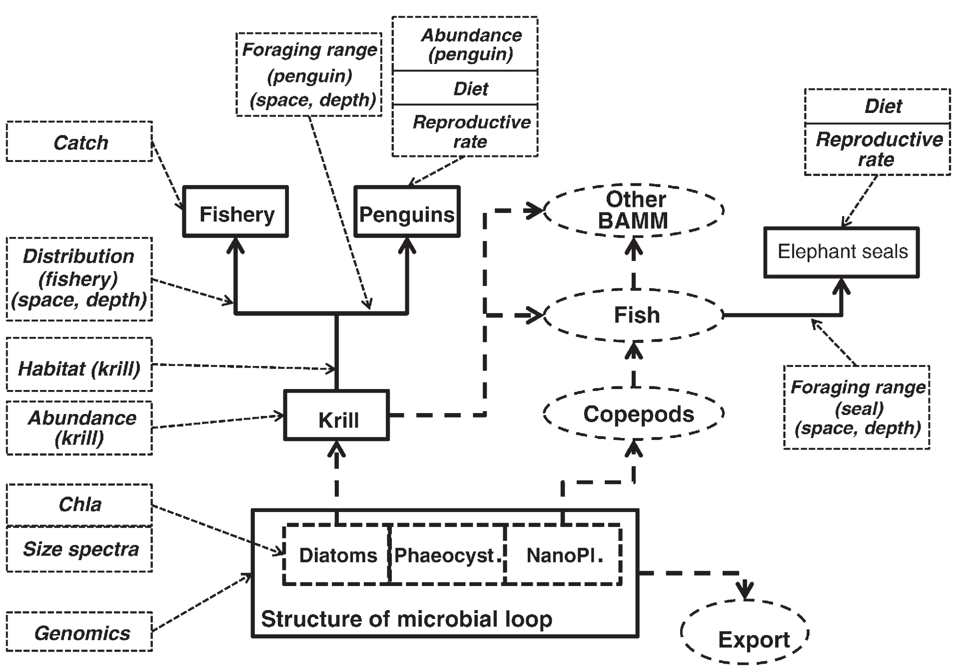


**Fig. 7.** Using eEOVs in ecological models: Example schematic showing how the main elements of a food web model that might use time-series of eEOVs to make the model realistic, either through validation procedures, model fitting or data assimilation. Solid boxes and arrows indicate components of the food web for which ecological properties could be assessed directly. Dashed arrows indicate linkages that may not be regularly observed. Dashed ovals indicate components of the model that may not be regularly estimated. The dotted boxes with italicised names indicate potential candidate eEOVs. Parameters in Fig. 6 are included in this diagram in the set of boxes for krill, fishery and penguins, illustrating how eEOVs can support a number of questions and approaches and use observations already being collected. Phaeocyst. = *Phaeocystis antarctica*. NanoPl. = Nanoplankton. BAMM = Birds and Marine Mammals.

**Table 5**
Candidate ecosystem Essential Ocean Variables (eEOVs) for Southern Ocean ecosystems to be evaluated against criteria in Table 4 and for their utility in delivering assessment results for Southern Ocean ecosystems. *Indicates initial candidates — when available, example field observations are included in place of asterisk. Note that the scale of sampling is proposed at the level of detail indicated in the component description; that is, species are listed when that level of detail is intended for eEOVs, otherwise the expectation is at the functional group level at this stage. Some of these candidate eEOVs are illustrated in Fig. 7. CEMP = CCAMLR Ecosystem Monitoring Program Standard Method (the number of the method is given). Colours reflect readiness (subject to evaluation against the criteria) of the eEOV as conceptual (red), pilot (yellow), mature (green) (grey cells indicate measures that will not be developed; white cells indicate candidates to be developed).

| | Type of eEOV | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **State** | | | **Predator–prey** | | **Autecology** | | | | **Regional pressures** | | |
| | **Abundance / density / magnitude** | **Genetic / species composition** | **Size spectrum (body size)** | **Foraging range** | **Diet** | **Phenology** | **Reprod–uctive rate** | **Individual growth rate** | **Detritus export/ import** | **Fishery catch** | **Pollution** | **Tourism** |
| **Related Ecosystem Properties (EPs)** | **1,2,3,4,5,6,8** | **1,4,5,6,7,8** | **1,2,4,5,8** | **2,4,5,8** | **2,3,4,5,8** | **2,3,4,8** | **2,4,8** | **2,4,8** | **1** | **3,8** | **8** | **8** |
| **1. Physical habitats** | | | | | | | | | | | | |
| PAR | Optical sensors | | | | | | | | | | | |
| Sea water | | | | | | | | | | | | |
| Temperature | * | | | | | | | | | | | |
| Mixed–layer depth | * | | | | | | | | | | | |
| Fronts & eddies | * | | | | | | | | | | | |
| Nutrients | * | | | | | | | | | | | |
| Oxygen | * | | | | | | | | | | | |
| pH | * | | | | | | | | | | | |
| Sea ice | | | | | | | | | | | | |
| Thickness | | | | | | | | | | | | |
| Concentration | Satellite | | | | | | | | | | | |
| Benthic | | | | | | | | | | | | |
| Sediment | | | | | | | | | | | | |
| Biogenic habitats | | | | | | | | | | | | |
| Land–based Colonies | | | | | | | | | | | | |
| Weather | * | | | | | | | | | | | |
| Snow cover | * | | | | | | | | | | | |
| **2. Benthic species** | | | | | | | | | | | | |
| Sessile taxa | * | * | * | | | | | | * | Haul reports | | |
| Mobile invertebrates | * | * | * | | | | | | | Haul reports | | |
| Fish | * | * | * | | * | | | | | Haul reports | | |
| **3. Pelagic & sea ice taxa** | | | | | | | | | | | | |
| Primary Producers & microbial loop | Colour spectrum (e.g. Chl *a*), underway/ under–ice net and bottle sampling, CPR | Genomics<br>net/bottle sampling HPLC | Underway/ under–ice image analysis | | | | | | * | | | |
| Krill | Acoustics, nets | | Net sampling | | Isotope signature | | | | | Haul reports | | |
| Zooplankton | CPR<br>nets | CPR<br>Genomics | CPR<br>Nets | | Isotope signature | | | | | | | |
| Mesopelagic fish | Acoustics, nets | Net sampling | Net sampling | | Isotope signature | | | | | Haul reports | | |
| Other fish | Net surveys | | | | Isotope signature | | | | | Haul reports | | |
| **4. Marine mammals and birds** | | | | | | | | | | | | |
| Adelie, Chinstrap, Gentoo (*Pygoscelis* spp) penguins | Counts –ground aerial, UAVs CEMP A3<br>satellite | Ground observations | CEMP A1; CEMP A6; CEMP A7 | Trackers;<br>CEMP A5 | Isotope signature; CEMP A8 | Remote camera observations; CEMP A9 | CEMP A2 CEMP A4 | | | | | |
| King, Emperor (*Aptenodytes* spp) penguins | Counts –ground aerial, UAVs<br>satellite | Ground observations | | Trackers | Isotope signature | Remote camera observations | | | | | | |
| Humpback (baleen) whales | Visual surveys | Visual surveys | | Trackers | Isotope signature | | | | | | | |
| Crabeater (Pack ice) seals | Satellite, UAVs | | | | Isotope signature | | | | | | | |
| Antarctic fur and southern elephant (Land–based) seals | Counts –ground aerial, UAVs<br>satellite | | | Trackers; CEMP C1 | Isotope signature | Remote camera observations | CEMP C1 | CEMP C2 | | | | |
| Flying birds | CEMP B1; CEMP B5 | | | | CEMP B4; CEMP T1 | | CEMP B2; CEMP B3; CEMP B6 | | | | | |
| **5. Human pressures** | | | | | | | | | | | | |
| Fisheries | Effort | | | Effort locations | | | | | | Haul reports | | |
| Pollution | Coastal point–source, dumping, spills | | | Spread pf coastal point–source, dumping, spills | | | | | | | Discharge reports | |
| Tourism | Visitor numbers, ship traffic | | | Visitor locations, ship traffic | | | | | | | | Activity reports |

outlined above. Where established, the methods currently used for collecting the data are indicated.

Habitat measurements are now well known and include photosynthetically active radiation (PAR), temperature, sea-surface stratification (mixed layer depth), currents and eddies, nutrients, oxygen, pH and sea-ice concentration and thickness. Benthic habitats include geomorphology (substratum type) and the coverage by biogenic habitats. For marine predators on land, the extent of a colony may be influenced by availability of nesting habitat and reproductive success could be affected by environmental conditions on land such as weather and snow cover.

The most well-developed eEOVs relate to phytoplankton and marine mammals and birds, although the units of measurements to be achieved remain to be internationally agreed upon in many cases. This is the reason most candidate eEOVs are identified to be at the conceptual level, or are yet to be developed. CEMP parameters are well developed field methods but are shown here as pilot because of the need to evaluate them against the aforementioned criteria (Table 4) before being considered mature.

The monitoring of regional human pressures (fisheries, pollution, tourism) is well advanced in the Antarctic Treaty System and these are regarded as mature eEOVs.

### 3.4. Progressing mature eEOVs for the Southern Ocean Observing System

The next step in consolidating eEOVs for the Southern Ocean will be to evaluate each of the candidates in Table 5 against the criteria in Table 4. This work will be facilitated by harnessing existing experience in ecosystem assessments and modelling for the Southern Ocean (Murphy et al., 2012; Turner et al., 2009; Turner et al., 2013) and other marine ecosystems (Fulton and Link, 2014; Fulton et al., 2014; Perry et al., 2010; Shin and Shannon, 2010). Scenarios for change in Southern Ocean ecosystems have been summarised in Constable et al. (2014) and Nymand Larson et al. (2014). Dynamic simulation models to represent these ecosystems are being developed and implemented (Murphy et al., 2012), and future scenarios are being established for investigating climate change impacts on the Southern Ocean (Gutt et al., 2015). Following appropriate tuning, the models and scenarios can be used to evaluate the degree to which uncertainty in ecosystem structure and dynamics may affect signals from candidate eEOVs as part of an observing system in the future. This evaluation will need to be supported by developing appropriate metrics of ecosystem properties derived from eEOVs, including methods to visualise and simplify complex results.

Circumpolar coverage for many candidate eEOVs in the Southern Ocean will be feasible when considered in relation to available field capabilities (Fig. 5). A number of the main areas of production in the Southern Ocean, extending from the continent to the subantarctic, are frequently occupied by resupply and marine science vessels. These include the (i) West Antarctic Peninsula—Drake Passage, (ii) Weddell Sea—Scotia Arc, (iii) Maud Rise—Bouvet Island, (iv) Prydz Bay—Kerguelen Plateau, and (v) Ross Sea—Macquarie Ridge.

## 4. Concluding remarks

Ecosystem essential ocean variables should collectively provide the foundation upon which scientists and managers can build programmes to identify change, attribute that change to its cause(s) and distinguish between alternative models for ecosystem futures. The Rutgers Workshop on eEOVs in 2014 made substantial progress towards developing an observing system for Southern Ocean ecosystems. The challenge now is to demonstrate which candidate eEOVs need to be given priority for investment in the long term because it will not be possible to regularly measure all candidates in Table 5 with sufficient spatial and temporal coverage. The adopted eEOVs would be expected to be mature in their development, have known implementation requirements (feasible field design) and be widely utilised.

Other than habitat variables, nine general types of eEOVs were identified within three classes: state (magnitude, genetic/species, size spectrum), predator–prey (diet, foraging range), and autecology (phenology, reproductive rate, individual growth rate, detritus). Most candidates for the suite of Southern Ocean taxa relate to state or diet. Candidate autecological eEOVs have not been developed other than for marine mammals and birds. A challenge will be to determine whether autecological eEOVs could be developed for lower trophic levels, given known variation in growth and reproductive rates, say, for Antarctic krill (Hill et al., 2013; Kawaguchi et al., 2006).

The state of readiness of many of these candidate eEOVs is currently at the conceptual or pilot stage rather than mature. In cases where candidate eEOVs are already regularly being observed and used, the experience should allow them to progress more rapidly through a case-study review to become pilot or, where the future requirements have been evaluated and the preferred sampling design has been articulated, mature eEOVs.

Simulation models to evaluate the performance of these candidates under different future scenarios will be important for deciding which eEOVs will have the greatest utility and should be adopted as mature eEOVs (Fulton and Link, 2014; Hayes et al., 2015). This process must include testing of field designs and provide a means of resolving competing demands for limited field operations. International coordination (Cai et al., 2015) through SOOS (Meredith et al., 2013) will be essential for delivering a strong foundation for assessing status, trends, attribution and likely future scenarios for Southern Ocean ecosystems. The next step in the process to reduce the set of candidate eEOVs for SOOS in Table 5 could be a workshop involving CEMP and SOOS scientists (among others), in which they would focus on the readiness of the candidate eEOVs.

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