Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) programme: Report of the ICED-CCAMLR Projections Workshop, 5-7 Apr 2018

Murphy, Eugene (UK), Johnston, Nadine (UK), Corney, Stuart, (Aus) and Reid, Keith (CCAMLR) including workshop participants and contributors Atkinson, Angus (UK), Belchier, Mark (CCAMLR), Bellerby, Richard (Nor/China), Bindoff, Nathan (Aus), Cavanagh, Rachel (UK), Constable, Andrew (Aus), Costa, Daniel (USA), Eddy, Tyler (Can), Emmerson, Louise (Aus), Grant, Susie (UK), Groeneveld, Jürgen (Ger), Hill, Simeon (UK), Hobbs, William (Aus), Hofmann, Eileen (USA), Jackson, Jennifer (UK), Kawaguchi, So (Aus), Korczak-Abshire, Malgorzata (Pol), Lenton, Andrew (Aus), Meijers, Andrew (UK), Melbourne-Thomas, Jessica (Aus), Newman, Louise (Aus), Nicol, Steve (Aus), Piñones, Andrea (Chile), Reiss, Christian (USA), Santos, Mercedes (Arg), Tarling, Geraint (UK), Trathan, Philip (UK), Trebilco, Rowan (Aus), Watters, George (USA), Welsford, Dirk (Aus), Zhu, Guoping (China)

SC-CAMLR-XXXVII, Hobart, Aus

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Abstract

Climate change will alter the structure and functioning of Southern Ocean ecosystems, affect the ecosystem services they provide, and therefore require development of conservation and management strategies. A collaborative Workshop between the Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) programme and CCAMLR brought together a range of ecologists, physical and ecological modellers and fisheries scientists to consider the potential impacts of climate change on Antarctic krill in Area 48. The key outcomes of the Workshop for SC-CAMLR include:

- Area 48 is a region of high natural variability and scenarios of future changes in physical, chemical and ecological drivers are highly uncertain. Global climate models do not currently resolve key ocean and sea ice processes at scales relevant to predictions for Area 48;
- The position of the Polar Front is highly constrained and is not expected to change by 2100;
- Under a high emissions scenario the warming and loss of sea ice is expected to result in a reduction in the abundance and biomass of krill in northern areas of the Scotia Sea but an increase in abundance to the south around the Antarctic Peninsula and Weddell Sea. However, the resilience and adaptive capacity of krill to withstand such changes is poorly determined;
- The combined effects of changing sea ice and krill abundance will result in shifts in the distribution of the various krill-dependent species, with more polar species constrained farther south. These changes are also likely to result in substantial changes in the structure of the food web that may occur rapidly as particular biological thresholds are reached;
- CCAMLR would benefit from investment in the development of high-resolution physical-biological models and improved models of krill recruitment processes, underpinned by mechanistic understanding to resolve recruitment processes during the winter and the role of sea ice;
- Sufficient data are available to underpin the scenarios from this workshop. Uncertainty around the susceptibility of krill in Area 48 to future climate change can and should be incorporated into projections in order to scope potential outcomes for krill;
- Existing models and approaches developed for Area 48 to assess potential impacts and risks of fishing on krill and the dependent predators are a useful basis for developing models that can

incorporate the implications of climate change in a precautionary approach into CCAMLR management.

The Workshop noted the importance a joint approach between ICED and CCAMLR to improve scenarios and ecosystem models and develop quantified model projections of ecosystem change in support of decision making for conservation and management.

1. Introduction and scientific background

ICED

Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) is an international multidisciplinary science programme aimed at understanding the response of Southern Ocean ecosystems to natural and anthropogenic change and feedbacks to the wider Earth System (Murphy *et al.*, 2008, www.iced.ac.uk). The programme was developed in conjunction with the Scientific Committee on Oceanic Research (SCOR), the International Geosphere-Biosphere Programme (IGBP), CCAMLR and the Scientific Committee on Antarctic Research (SCAR), and is now a regional programme of SCOR and Future Earth's Integrated Marine Biosphere Research (IMBeR, formerly IMBER). ICED's coordinated circumpolar analyses are focused on understanding climate interactions in the Southern Ocean, the implications for ecosystem dynamics, the impacts on biogeochemical cycles, and the development of sustainable management and conservation measures.

Developing ICED and CCAMLR joint activities

ICED has strived to ensure that the science it generates is relevant to conservation and management decisions for the Southern Ocean. CCAMLR, its Scientific Committee (SC-CAMLR), and the Committee for Environmental Protection (CEP) have also formally recognised the importance of climate change information in the development of future conservation and management measures in the Southern Ocean. For example, the CCAMLR resolution 30/XXVIII (2009) on climate change "*Urges increased consideration of climate change impacts in the Southern Ocean to better inform CCAMLR management decisions*" and "*Encourages the commitment of all CCAMLR Parties to actively contribute towards relevant science initiatives, such as the Integrating Climate and Ecosystem Dynamics science program, and the Southern Ocean Sentinel program, which will contribute information needed to improve CCAMLR management actions*".

As part of this ongoing effort, ICED has recently engaged with SC-CAMLR (and its Working Group on Ecosystem Monitoring and Management, WG-EMM), the CEP, SCAR and the Southern Ocean Observing Programme, SOOS (of which Southern Ocean Sentinel is now a part) to identify mutual science priorities that can be jointly addressed (SCAR, 2016, United Kingdom 2016, 2017, Murphy *et al*., 2016, 2017). SCAR has also highlighted these issues and has generated assessments of Antarctic change. In response, these groups agreed on the value of pursuing joint activities with ICED (Grant and Penhale, 2016 a, b, and c; SC-CAMLR 2016 a and b, 2017).

Developing scenarios and projections for Area 48

At the CCAMLR WG-EMM-2016 meeting in Bologna, ICED proposed specific joint science areas and activities with CCAMLR to support decision-making, including involvement in an ICED workshop on projections of ecosystem change (Murphy *et al.*, 2016). In response to this (and noting the request from the 2016 Joint CEP-SC-CAMLR Workshop for the clear articulation of research questions) WG-EMM identified three key questions related to the potential effects of climate change on krill and krill fishing to which ICED science could contribute (SC-CAMLR 2016b, Annex 6, para 6.25):

i. *What are plausible scenarios for changes in the krill population in the Scotia Sea over the next 2 to 3 decades?*

ii. *How might changes in the extent of seasonal sea-ice affect the accessibility of krill fishing areas?*

iii. *What is the magnitude of change in krill and the krill-based food web that could be agreed to have occurred using current data sources?*

Based on discussions during and following that meeting, it was agreed (WG-EMM 2016, SC-CCAMLR 2016) that the ICED projections workshop could address these questions by focussing on the Antarctic Peninsula and Scotia Sea region (CCAMLR Area 48). This is a vital area for CCAMLR as it was one of the fastest warming parts of the planet over the second half of the last century (Turner *et al.* 2016) and is also where the Antarctic krill fishery operates. With that framework, the title, aims and objectives of this Workshop were developed (Murphy *et al.,* 2017) and subsequently agreed by WG-EMM (at their 2017 meeting) and endorsed by SC-CAMLR (SC-CAMLR, 2017). Although the Workshop was designed to consider how climate change and associated uncertainties could be included in CCAMLR decision-making for Area 48, it would also form a first step in an ongoing longer-term process to develop projections of the impacts of change on other species and regions across the Southern Ocean.

2. Workshop aims and objectives

This Workshop brought together a range of ecologists, physical and ecological modellers, and fisheries scientists to consider the development of projections of the impacts of climate change upon krill in Area 48, and to provide advice to enable CCAMLR to plan for and adapt to the consequences. The Workshop aimed to clarify the limitations in available knowledge and approaches to ensure that communication of projections of ecosystem change include associated uncertainties. It further aimed to identify priority activities between ICED and CCAMLR to ensure an ongoing iterative process to continue with this joint work. The specific objectives of the workshop were to:

1. *Assess the potential drivers of change (within three decades and over the 21st century) in the ecosystems in the Scotia Sea and Antarctic Peninsula region of the Southern Ocean (Area 48);*
2. *Assess potential future sea-ice change in Area 48 and the potential impacts on availability of krill to predators and the fishery;*
3. *Examine alternative approaches to modelling and projecting changes in distribution, abundance and biomass of Antarctic krill in Area 48.*

These objectives provide the basis for addressing the first two questions raised by WG-EMM-2016 (above), and form an important pre-cursor activity to consideration of its third question.

The Workshop took place at the CCAMLR Headquarters in Hobart, Tasmania, Australia between the 5th and 7th April 2018. An interim summary report of the main activities and outcomes of the Workshop prepared by the convenors, and acknowledging the Workshop participants, was presented to WG-EMM-2018 (Murphy *et al.* 2018). A scientific paper based on the results of the Workshop is also being prepared for publication to an international peer-reviewed journal.

3. Workshop operation

The workshop agenda and list of participants are given in Appendix I and II, respectively. A range of summary reports (Appendix III) produced ahead of the workshop provided participants with background information on aspects of past, current and future changes in the physics, chemistry and biology of ecosystems within Area 48 to support discussions. Information on regional ecosystems and key groups and species includes the northern Antarctic Peninsula (AP) ecosystem (Reiss, Jones and Watters, WS-SR-1-2018), and zooplankton (Johnston, Atkinson and Tarling, WS-SR-2-2018), krill (Murphy, Reiss and Hofmann, WS-SR-3-2018), fish (Belchier, WS-SR-4-2018), seals and seabirds (Costa, WS-SR-5-2018), and whales (Jackson, WS-SR-6-2018) across Area 48. Trebilco, Melbourne-Thomas, Constable and Murphy (WS-SR-7-2018) provides a summary of regional ecosystem models. Information on the krill fishery includes an overview of the history, development and changes in regional catch distributions (Reid, WS-SR-8-2018), and consideration of the influence of krill ecology on fishery operations (Nicol and Kawaguchi, WS-SR-9-2018). Belchier (WS-SR-4-2018) also provides information on finfish fisheries. Aspects relating to variability, change and potential future impacts on Southern Ocean ecosystems includes the dynamics of sea ice in Area 48 (Hobbs, WS-SR-10-2018) and the impacts of ocean acidification on phytoplankton (Bellerby, WS-SR-11-2018) and krill (Kawaguchi, WS-SR-12-2018). Cavanagh, Corney, Meijers, Hobbs, Lenton, Bracegirdle and Bindoff (WS-SR-13-2018) provide an extensive summary of the status of scenarios of change in key physical drivers. Hobbs (WS-SR-10-2018) also provides a summary of sea ice scenarios for Area 48. Aspects of monitoring and management include an overview of the development of a sustained biological observation network and its role in assessing ecological change (Constable, Newman, Swart, Schofield, Williams, Bricher, WS-SR-14-2018). Grant, Santos and Capurro (WS-SR-15-2018) discuss the implications of future climate change for the development and monitoring of marine protected areas. Constable (WS-SR-16-2018) and Watters and Hill (WS-SR-17-2018) consider the inclusion of climate change scenarios in krill management models, including the Krill Yield model currently used by CCAMLR.

To fulfil the Workshop aims and objectives, participants engaged in a mixture of plenary and breakout discussions (detailed in Appendix I). These activities reviewed existing scientific information needed to develop projections of change, including key uncertainties in developing ecological projections, agreed a preliminary set of qualitative projections (in the form of statements) on the likely future states of the krill-centred ecosystem, and prioritised future work required to develop quantitative model projections of changes in krill in Area 48 driven by climate change by 2050 and 2100.

4. Outcomes

Substantial knowledge has been gathered from extensive research over the last three decades, which has included dedicated field efforts, and process and modelling studies in Area 48. However, a number of important uncertainties in ecological processes still remain, including uncertainties from observations, conceptual and numerical model formulations, parameter estimates, model evaluation, appropriate consideration of spatial and temporal scales, and the potential for biological adaptation. Evaluations of the susceptibility of the krill-centred ecosystem in Area 48 to future climate change need to incorporate the uncertainty from climate change projections (including scenario uncertainty, model uncertainty and internal model variability, model bias and resolution). They must also incorporate the uncertainty in ecological processes. The workshop agreed a preference for an approach that evaluates risks (based on the magnitude and probability of change) and incorporates uncertainty, rather than specific predictions of the trajectories of the krill-centred system under future climate change scenarios, as an appropriate way to deal with uncertainty at present. There will be substantial benefits to refining the uncertainties in the near future, particularly through a concerted effort to develop high skill ecosystem models and through field programs to measure the key rates and mechanisms affecting krill, notably within the sea-ice zone.

Current changes in the Southern Ocean are often difficult to attribute to particular climate or ecological processes. There are currently few relevant ocean biological time series available and they are too short to provide information to quantify the rate of changes and range of variability of many oceanic variables and biological communities. Extensive international efforts are developing systems to observe and detect change but these will take some years to fully develop. In the interim, better mechanistic understanding will be important for informing the development of models, projections of change and the testing of management approaches to deal with climate change.

If global changes occur at the high-end of the rates being projected, large ecological changes are expected across much of the Southern Ocean. The Southern Ocean is, however, naturally highly variable and so it is likely to take a number of decades for ecological observation series to be of sufficient length and coverage to be highly definitive about causal mechanisms. These are complex systems in which responses to change are likely to be spatially variable, highly non-linear, and interactive feedbacks on multiple scales make it unlikely that simple attributions (i.e. of ecological change to climate change) will be possible. Model projections of future ecological changes are urgently required for analysing the likelihood of different outcomes; they are the only way that a potential range of impacts of climate change (under a range of emissions scenarios) with all the associated uncertainties can be assessed. This will require alternative model formulations that can be used to assess uncertainties and risks associated with different future scenarios and management strategies. Central to the development of projections for CCAMLR will be the requirement for uncertainties to be expressed, assessed, and communicated to allow the risks associated with different change scenarios and management strategies to be evaluated.

The following sections outline the Workshop’s assessment of current knowledge of change, its uncertainties and approaches to developing qualitative and quantitative projections of ecological change that could potentially be used as a basis for evaluating the risks of future climate change in Area 48 and facilitating conservation and management decisions.

4.1 Developing scenarios of key drivers

Scenarios of key physical and chemical drivers

The workshop noted the major features of Area 48, which encompasses a range of different ecosystems and drivers. Discussions highlighted the complexity and spatial and temporal variability in drivers across Area 48. The topography and bathymetry associated with the AP and the Scotia Arc affects atmospheric and oceanic interactions generating marked variability over multiple scales. These processes influence ocean currents and sea ice dynamics to the west and east of the AP and across the Scotia and Weddell Seas, making it one of the most variable regions of the Southern Ocean. It is also an area of marked variation in biogeochemical processes, from the sea-ice dominated low-production regions of the Weddell Sea, through the regions of natural iron fertilisation around the AP and the Scotia Arc, to the large phytoplankton bloom area north-west of South Georgia. Area 48 has also shown some of the most marked decadal changes in air and ocean temperatures, ice shelves and sea ice within the entire Southern Ocean over the past century. Analyses of the physical processes generating those changes has highlighted the importance of both regional and global processes. As a result, Area 48 is one of the main areas of focus of ongoing research into the impacts of climate change in the Southern Ocean.

Despite this complexity the Workshop agreed that potential future physical and chemical drivers of change in krill populations within Area 48 by 2050 and 2100 (Objective 1) would include winds, sea surface temperature (SST), sea ice, ocean circulation, mixed layer depth (MLD) and pH. Details of the physical and chemical drivers, their properties, and examples of their ecological importance in pelagic food webs of the Southern Ocean are given in Supplementary Table 3 of Cavanagh et al. (2017) and Bellerby et al. (WS-SR-11-2018 and In prep). The importance of ecological drivers (e.g. primary production, predator impacts, whale recovery) and changes in market forces and technology of the krill fishery were also noted and these are covered in the following sections. The Workshop agreed that the impacts of future changes in these drivers are also likely to reflect the complexity in spatial and temporal variability already seen in Area 48, and would include relatively local and small-scale processes.

The Workshop discussed the range of available projections (from outputs of IPCC-class climate models) of physical and chemical drivers for the Southern Ocean that are relevant to Area 48. A key goal of ICED in recent years has been to develop a consistent series of scenarios of key physical and chemical drivers across the Southern Ocean (based on available projections) as a common resource for use in ecological studies. The ICED Scenario Workshop (*Southern Ocean food webs and future scenarios: Furthering our understanding of the response of Southern Ocean ecosystems to change*, Cambridge, UK, Nov 2013) and outputs including Cavanagh *et al.* (2017) highlighted challenges and recommendations for using projections based on current IPCC-class climate models to develop such scenarios, recognising their limitations and capabilities. Overviews of the latest research and status of qualitative and quantitative physical projection development across the Southern Ocean prepared by Cavanagh *et al.* (WS-SR-13-2018), and an assessment of observed changes and status of projection development (particularly sea ice) across Area 48 prepared by Hobbs (WS-SR-10-2018), provided a useful context for the Workshop's consideration of future scenarios specifically for Area 48. Those documents also include important discussions of uncertainties and caveats of current physical projections, which we do not repeat here, but emphasize that they are crucial for understanding the implications for scenario development. Figure 1 provides a general view of the physical changes expected by 2100 from the CMIP5 model analyses (Meijers, 2014).

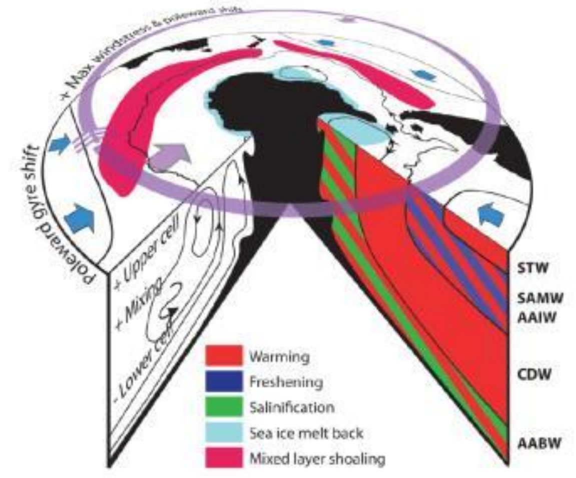

Figure 1. Schematic of changes in Southern Ocean by 2100 where there is reasonable agreement across the CMIP5 ensemble. From Meijers (2014).

The Workshop focussed on the current projections of key drivers that are known to be directly or indirectly important for krill in Area 48, and for which information is available (see Figure 2 as an example). As identified earlier, these were winds, sea ice, SST, ocean circulation, MLD and pH. Particular emphasis was placed on projections of sea ice, given its importance for krill and other ecosystem components within Area 48 (Objective 2). The Workshop also considered the importance of other variables for which projections are either poorly developed or not available (e.g. primary production- an ecological driver). The Workshop considered the limitations and uncertainties of these projections and ways to improve their development for producing scenarios for Area 48. It was noted that the Southern Ocean is a challenging region to study and is subject to considerable variability, both natural and anthropogenic. The ability of the current set of models reported upon by the latest IPCC assessment report (CMIP5) to accurately resolve key dynamical processes (e.g. sea ice, ice sheet/shelf melt, ocean circulation, including aspects of ACC and coastal circulation, MLD, westerly wind jets, as well as phytoplankton- see next section) and their variability, is hampered by the limited availability of suitably long observational time-series, limited understanding of these processes in addition to complex ocean-atmosphere-ice feedbacks across the Southern Ocean (and at finer regional scales). As a result, uncertainty is high for many existing centennial projections of key metrics (and hence drivers). There is also a high level of variability between current projections for the Southern Ocean, which makes it difficult to have confidence in even circumpolar averages for many properties. Regional trends should therefore be interpreted with extreme care. Qualitative scenarios of key drivers were developed with that note of caution (see also Hobbs WS-SR-10-18 and Cavanagh *et al.,* WS-SR-13-18). Despite their uncertainties and caveats, we consider that the regional scale-view of current model projections provide the basis for useful future scenarios of physical and chemical change in Area 48 for assessing potential impacts on Antarctic krill, the wider ecosystem and the fishery.

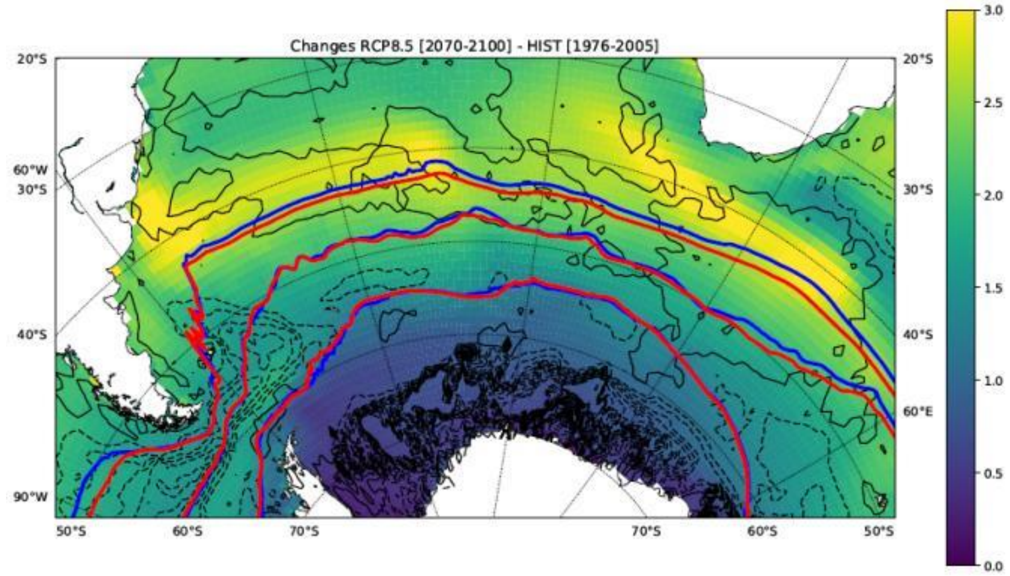

Figure 2. An example of an available scenario of SST (details are provided in WS-SR-13-18, which also notes major issues of model capacity and uncertainty): CMIP5 modelled changes in CCAMLR Area 48 averaged between 2070-2100 relative to 1976-2005 under the RCP8.5 forcing scenario. Colour indicates SST (^{o}C), contours are September MLD (dashed is shoaling, 25m contours) and bold lines indicate the positions of the present (blue) and projected (red) northern and southern boundaries of the Antarctic Circumpolar Current (ACC), and the position of the ACC transport core (Sub Antarctic Front/Polar Front).

Impacts of key drivers on krill, predators and the krill fishery

Krill

Understanding of the regional dynamics of krill was summarized by Murphy *et al.* (WS-SR-2-2018). Aspects of its distribution in the Southern Ocean and within Area 48 are shown in Figure 3. The Workshop considered the mechanistic impacts of key drivers on future krill biological processes including reproduction/recruitment, growth, mortality and their influence on distribution, abundance and biomass in Area 48 (Table 1). The impact of each individual driver was considered separately but the impacts of multiple drivers are likely to be synergistic.

Drivers deemed important, and for which we have reasonably good information, included winds, sea ice, SST, ocean circulation, MLD, and pH. Other drivers (e.g. oxygen, nutrient concentrations, food availability/phytoplankton, competition, predation, pathogens/parasites) are also important but either information on them is sparse or the mechanisms by which they affect krill processes are not clear. Some drivers have a direct influence (e.g. ocean temperatures and sea ice), while others have indirect effects (e.g. winds- via their influence on circulation or sea ice distribution). As outlined in the above section, drivers vary across Area 48, particularly SST, sea ice cover and primary production. The different drivers influence krill population processes at different life cycle stages (from larvae to adults) through a range of direct and indirect effects, resulting in spatial variation in krill demographics and population dynamics. Future impacts on krill processes are therefore likely to be spatially and temporally variable across the region.

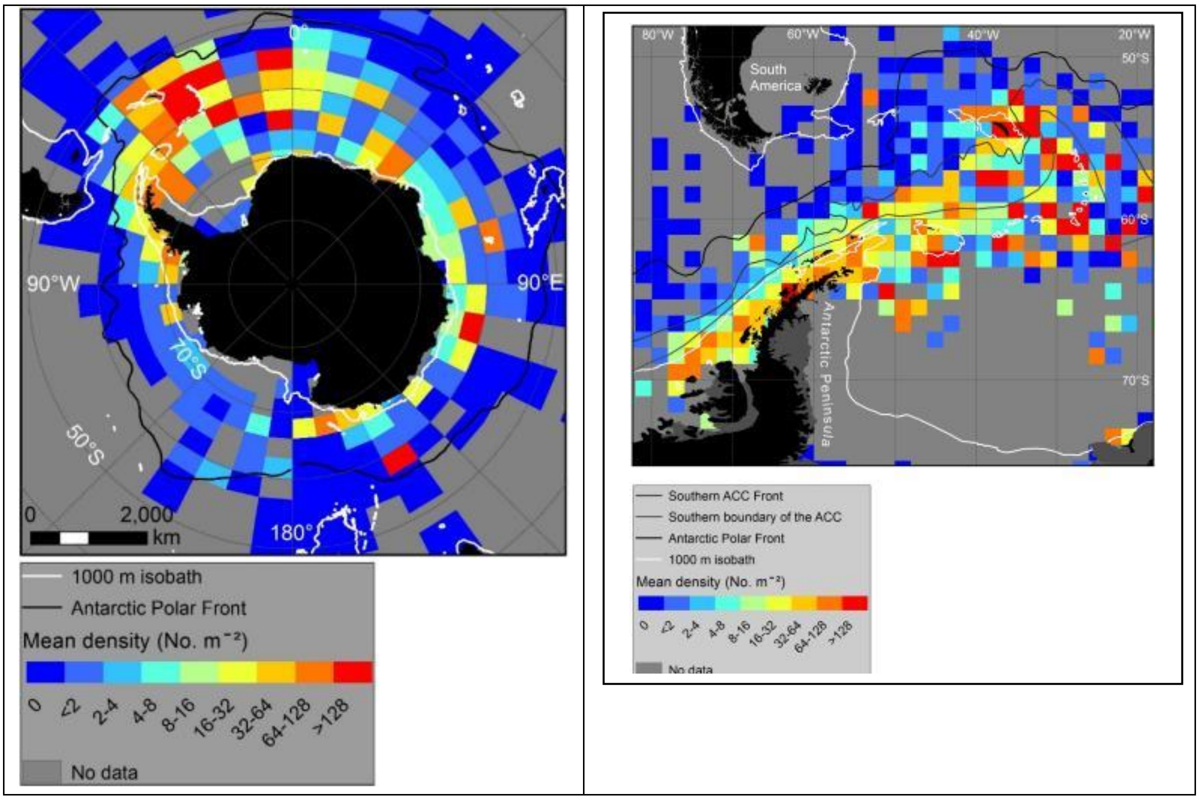

Figure 3. Probability maps of Antarctic krill distribution (a) around the Southern Ocean, and (b) at the Antarctic Peninsula and across the Scotia Sea. Data from KRILLBASE (Atkinson et al. 2017), normalised for different sampling methods, seasons and times of day. Note that the maps are based on data collected over seven decades with the level of sampling effort varying between grid cells.

Recruitment is the most important process determining the distribution and abundance of krill, however, knowledge of the mechanistic relationships determining krill recruitment across Area 48 is limited. There is a particular lack of understanding of how sea ice influences recruitment and the spatial connectivity of populations.

Bottom topography is an important influence on krill distribution and abundance, particularly in continental shelf areas. While topography is not temporally variable it does have an important role in influencing ocean currents, which are projected to move under climate change. The extent to which topographic-ocean current interactions are directly important in maintaining local krill populations is, however, unclear. Bathymetry is also an important aspect in constraining the spawning habitat, assuming a depth requirement of 1000 m for eggs to sink and develop.

Krill and related ecosystem models

The Workshop considered status and form of available krill models (e.g. life cycle, process and population dynamic models), their previous application in Area 48 (Table 2), and their suitability for coupling with driver scenarios. A variety of krill models have been developed and generally used at the subregional or regional scale. Some of these have been used to simulate the consequences of specific climate forcings. The current suite of models contains functional representations of many processes which may be incorporated in new model structures. Many of these processes, including recruitment, mortality and trophic interactions are poorly understood and even the better-understood processes may not be generalizable across regions. Nonetheless, a preference for evaluating risk rather than making explicit predictions has already been established, and this is an appropriate way to deal with uncertainty. The required form and scale of a model depends on the question being asked, and a strategic approach may be necessary to move from the current suite of models focused on a limited scales and processes to a set of models equipped to address the priority questions at the appropriate scales.

Krill predators

The Workshop discussed the potential impacts of physical change on predator populations and the impacts of predators on krill. Although predator populations in the Southern Ocean are changing (WS-SR-04-18, WS-SR-05-18, WS-SR-06-18), and some drivers have been identified, the mechanisms involved are poorly understood. Changes in predator populations will affect krill directly (through predation) and indirectly through food web changes. In particular, recovery of whales is likely to be important in changing the distribution of demand for krill and hence also mortality, which will also influence distribution and abundance. Such changes are likely to result in shifts in the structure of predator communities.

The krill fishery

A general summary of the history and operation of the krill fishery was given by Reid (WS-SR-08-18). The main driver of change during the history of the krill fishery has been socio-economic decisions independent of the fishery and external to the Southern Ocean. Catch levels in the fishery were highest in the early 1980s at greater than 400,000 t. Current catch levels are between 200,000 and 300,000 t. This represents less than 1% of the precautionary catch limit.

The increase in fishing in the Bransfield Strait over the last decade may be related to changes in sea ice concentration and timing of the seasonal advance and retreat, but recent changes in fishing technology have enabled fishing in areas of some ice cover. Norwegian fishing vessels operate using the ‘continuous fishing system’ under ice conditions that would not be possible using conventional trawling. Nets deployed by the continuous fishing system can remain submerged for several days, allowing the vessel to wait until it is in ice-free water before retrieving them. A conventional trawler, however, needs to retrieve its net 5-10 times a day, and cannot operate in sea ice areas. The Workshop also discussed the biological and ecological factors influencing the catch operations, which may be subject to future change (WS-SR-09-2018). Examples of these included the quality of krill preferred by certain economical markets which can dictate the preferred timing of fishing and the technologies deployed.

The locations where the krill fishery operates are dictated by a range of economic, technological, regulatory, biological and physical drivers. This makes it difficult to predict how the fleet will behave in a changing climate. More interactions between scientists and fishing operators will allow a better understanding of fleet behaviour.

4.2 Developing projections of ecosystem change

Qualitative projections

The workshop combined the information on the available *scenarios of physical and chemical drivers* with knowledge of *the impact of drivers on krill, predators and the fishery* to develop qualitative projections of ecosystem change (Figure 4). The aim is to use the information as a basis for developing ecosystem models that can project quantitative changes in krill populations in Area 48 (see Quantitative projections below). The qualitative projections were developed as a series of statements that summarised our current view. These were based on scenarios of key drivers within Area 48 by 2050 and 2100 using low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emissions scenarios. Key scenarios and projections based on the Workshop discussions are given below.

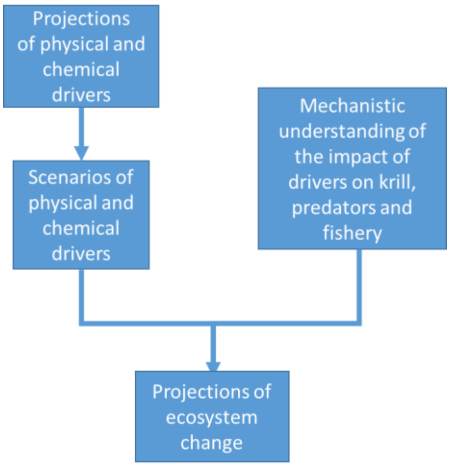

Figure 4. Steps to developing projections of ecological change

Scenarios of physical and chemical change

The Workshop highlighted that the current suite of projections (based on current global CMIP5 models) of key physical and chemical drivers for the Southern Ocean are poorly constrained and highly uncertain. The area around the AP is the one of the most variable regions of the Southern Ocean and the tip of the peninsula is one of the most complex regions of the Southern Ocean. The global climate models assessed in CMIP5 are too low in spatial resolution (i.e. they are >100km) to resolve many of the key physical processes around the AP and within Area 48, which occur over scales of less than 10km. These processes include aspects of sea ice, ice shelf, upwelling, cross-shelf exchange, connectivity and retention processes. In addition to this Area 48 is an atmospherically highly variable region, which is strongly influenced by the position and intensity of the climatological centre of low pressure in the Amundsen-Bellingshausen Sea region – the Amundsen Sea low (ASL). The intensity and position of the ASL is crucial to determining the impacts of the atmospheric variation on ocean and sea ice to the west and east of the AP. Although these factors make it difficult to generate comprehensive scenarios of changes in physical and chemical drivers in Area 48 with definitive levels of confidence (*sensu* IPCC, e.g. Mastrandrea 2010), the following represent the Workshop's consensus based on evaluation of the best available evidence (a complete list of scenarios and their basis is provided in Table 3, curly brackets references these). Unless otherwise stated, the scenarios relate to Southern Ocean-scale changes. In general, there is lower confidence in oceanographic statements in areas closer to the continent:

- **Winds:** Circumpolar westerly wind strength is expected to intensify by 2100 and the centre of the most intense winds is expected to shift southwards as a result of an increasingly positive Southern Annular Mode (SAM). The impact of these changes on the ocean and sea ice in Area 48 is uncertain {PCS1};
- **Sea ice:** Sea ice projections over the next few decades are highly uncertain, and current CMIP5 models indicate that signals of change will not be distinguishable from model variability until after ~2050. By 2100, sea ice area in the Southern Ocean is expected to reduce by >30%, and within Area 48 sea ice concentration is likely to be reduced in both winter and summer, but the dynamics are uncertain {PCS 2-8};
- **SST:** SST projections over the next few decades are highly uncertain, and current CMIP5 models indicate that signals of change will not be distinguishable from model variability until after ~2050. By 2100, warming of the surface ocean between 1°C and 3°C is expected under the highest emissions scenarios. {PCS 9-11};
- **Ocean circulation:** The position of the Polar Front is highly constrained and is not expected to change in the coming century, even under the highest emissions scenario. The surface manifestation of the front is variable. The warming and freshening influence of circumpolar deep water (CDW) upwelling along the western AP is expected to continue in association with a more positive SAM. {PCS 12-17};
- **Ocean stratification:** Ocean stratification is expected to increase in Area 48 by 2100 {PCS 18};
- **MLD:** A strong increase in stratification will lead to spatially variable shallowing of the mixed layer by 2050, with a SO average 40m by 2100. Shoaling over subareas 48.1 and 48.2 is expected to be smaller than the mean trend. Shoaling of the MLD will likely lead to reduction in nutrient circulation and supply to upper layers. {PCS 19-22};
- **pH:** pH is expected to decrease in the coming decades in direct proportion to rising atmospheric CO_2 concentrations. The largest decrease is expected in the upper ocean. Most of the SO is expected to be under-saturated (with respect to aragonite) by around 2030 and fully under-saturated by 2100. A strong south-north gradient in the progression of aragonite under-saturation from 2030 onwards is also expected {PCS 23};
- **Extreme climate-related events:** Changes in the frequency and magnitude of extreme climate-related events (e.g. upwelling events, very high air or sea temperature events, or low sea ice concentration) that can lead to high impacts on ecosystems may occur across Area 48 {PCS 24}.

Projections of ecological change

The Workshop highlighted major gaps in current understanding of food web interactions, distribution and abundance, population dynamics, and key life cycle processes of species in the krill-centred ecosystem across a range of spatio-temporal scales. It also highlighted the lack of understanding of the mechanistic processes by which key drivers impact Southern Ocean ecosystems. Although these factors make it difficult to generate comprehensive projections of ecological change in Area 48, under the scenarios outlined in Table 3 (and their issues), with definitive levels of confidence (*sensu* IPCC, e.g. Mastrandrea 2010), the following represent the Workshop's consensus based on evaluation of the best available evidence. A complete list of ecological projections and their basis is provided in Table 4, curly brackets reference these:

Primary Production

- Increases in primary production are indicated by the end 2100 for the region south of 50°S. It is likely there will be changes in phytoplankton community structure but there is low confidence in what those changes will be {EP 1}.

Krill

- A general southward shift of the favourable krill habitat is expected as a result of warming of the surface ocean. Sea temperatures in excess of 5°C are unsuitable for adult krill and larval survival. Zooplankton (including various other species of krill) exhibit the ability to adapt to different thermal conditions which may modify responses and outcomes. The resilience or long-term adaptive capacity of krill to different thermal conditions is unknown {EP 2-4};
- Sea ice is important (but probably not essential) for larval survival and recruitment. It is a habitat for larvae during winter and a refuge from predators. Krill larvae are strongly associated with sea ice and transported with the sea ice as it moves. Adult krill also make use of the under-ice environment during winter. A decline in sea ice is expected to result in changes in availability of refugia and consequently survival rates of krill. Changes in sea ice distribution and movements are likely to result in changes in krill dispersal and recruitment locations {EP 5, 6};
- Krill growth, reproduction, recruitment and mortality are expected to be impacted by multiple effects, which will be spatially and temporally variable across Area 48. The adaptive capacity of krill is unknown, but this species is a highly successful generalist that is likely to show a high degree of resilience. Synergistic effects are likely between temperature and ocean acidification and stresses will have different effects on different life stages {EP 7-12};
- Changes in the magnitude of primary production, plankton community composition and the winter availability of ice algal production will affect food availability for krill- a crucial aspect for understanding the responses of krill to climate change. Current projections suggest that primary production will increase, but these projections are highly uncertain and poorly constrained. Although temperature will increase stressors in the north, these may be ameliorated by changes in primary production {EP 13, 14}.

Other ecosystem changes

- Major ecological changes in response to climate change may occur in the next 30 years, but will be difficult to distinguish form natural variability {EP 15};
- Not all potential future changes will be negative. Many species are likely to have a reasonable level of resilience and adaptive capacity because the ecosystems naturally exhibit high variability.

As ranges shift southwards, populations of more polar species will increase in the south. In more northern regions, biodiversity may increase as a result of increased survival of sub-Antarctic species. Benthic connections are also important for krill, and with enhanced productivity, these communities and hence pelagic-benthic interactions may increase {EP 16};

- The increase in whale numbers through the recovery of exploited populations is likely to already be having a significant effect in some parts of Area 48. Projected increases in whale numbers are likely to cause increased competition among different predators and hence declines in some other predator populations. This will be a natural consequence of the recovery of whale populations. The effects of whale recovery are likely to occur on similar decadal time scales to the effects of climate change {EP 17};
- Changes in krill distribution may affect interactions between krill predators; including competitive interactions. There will be different responses from predators depending upon the strength of their association with sea ice. Changes in krill abundance as a result of climate change may be exacerbated by top down predation impacts in areas of intense demand for krill during the breeding season. There are likely to be substantial changes in the numbers and species composition of penguins across colonies in the western AP. This will reflect shifting distributions and does not necessarily mean overall populations will decline. For example, populations of Adélie penguins are likely to increase in more southern regions as these become the most favourable habitats {EP 18, 19};
- Changes in distribution and relative abundance of species will generate shifts in food webs. A southward shift of the centre of krill abundance would result in changes in food web structure. Copepods or salps may increase in relative abundance compared to krill in more northern regions. This would result in shifts in dominant energy pathways away from krill, with implications for the transfer efficiency to higher predators. Fish-based energy pathways are more likely to be important in areas where krill abundance declines. Salp-based systems may not support large numbers of higher trophic level predators {EP 20, 21};
- Northern areas of the Scotia arc, such as around South Georgia, may experience more incursions of sub-Antarctic zooplankton and fish. Species that are currently observed infrequently following warm water intrusions may be observed more frequently and become established. Non-native species may also be introduced into Area 48 via tourism, fishing, research or other vessels. Understanding of the environmental constraints on such species is limited. The potential for invasion by larger fish species requires attention {EP 22, 23};
- Changes in seasonality will affect the phenology and timing of food web interaction processes, e.g. food availability for larval krill and fish {EP 11};

Fishery change

- Changes in sea ice dynamics may allow new areas within Area 48 to become accessible for fishing, including the western AP region (Subarea 48.3). This may also lead to changes in shipping arrangements and ports to better access the fishing area {EP 25};
- Changes in seasonality may affect the operation of the fishery and hence access to krill that are of a favourable condition for market purposes. If winter sea ice declines, the fishery is likely to

explore newly exposed areas or remain for longer in established grounds in subareas 48.1 and 48.2 that are currently seasonally closed by sea ice {EP 26};

- Major future changes in the krill fishery are expected to be driven by global issues external to the Southern Ocean, including conservation decision making, socio-economic drivers and geopolitics {EP 27}.

Key points for CCAMLR

In formulating these qualitative ecological projections, and in order to develop and refine them in the future, the Workshop highlighted a range of scientific issues and ways in which they could be addressed. These centred around improving the scenarios upon which they were based, and increasing understanding of food web interactions, distribution, population dynamics and key life cycle processes of krill (particularly recruitment, which is a key driver of variability in krill across the region, and its links to sea ice) across a range of spatio-temporal scales, the mechanistic impacts of drivers on krill, and the systematic development of krill population models and high spatial resolution ecosystem models. Key points include:

- Current projections of physical and chemical change in the Southern Ocean are poorly constrained and highly uncertain. This makes it difficult to develop scenarios for Area 48. The use of a standard set of high spatial resolution regional physical models (forced by global models such as those in CMIP5) that resolve Southern Ocean processes better than current global models will be useful for understanding and communicating potential impacts of change. In addition, it will be useful for ICED and CCAMLR to maintain dialogue with WCRP and IPCC in future CMIP Phases and Assessment Rounds to encourage the improvement of global (and possibly regional) models that adequately resolve Southern Ocean processes that are key to interpreting and projecting ecological responses;
- A focused effort is required to improve understanding of the population dynamics of krill. This requires enhanced year-round study and monitoring in more regions within Area 48. Improving understanding of recruitment processes and the links between krill recruitment and sea ice is crucial. A particular focus is required on the northwest Weddell Sea, Bransfield Strait and South Orkney regions as the krill and ecosystem processes in this area influence wider AP and Scotia Sea processes;
- The impacts of multiple stressors (e.g. temperature, ocean acidification and oxygen) on different life stages of krill requires further study;
- Information is required on the life cycle processes and constraints of a range of key species and food web processes to improve understanding of how changes in krill populations will affect, and be affected by, wider ecosystem responses to change;
- Food availability is crucial for understanding the responses of krill to climate change. Appropriate operational biogeochemical models are not available to resolve phytoplankton dynamics regionally. Key processes within biogeochemical models (e.g. the iron cycle, sea ice processes) that determine food availability require further development and validation;

- A strategic approach is required to build models of the population processes of krill across Area 48. In addition, high-spatial resolution (<3km) physical models are required for key regions (particularly the tip of the AP, around the South Orkney Islands and South Georgia). Engagement and dialogue between ICED and CCAMLR, and physical modellers developing such high-resolution models will be beneficial in encouraging and supporting appropriate models;
- The current view of many of the observed ecological changes in Area 48 over the last 50 years is that it is difficult to distinguish long-term change from the natural variability of the system. To improve understanding of the impacts of variability and change in the region a systematic approach to development of observation and monitoring is required. This should be developed in association with MEASO and SOOS;
- An improved understanding of whale population recovery and its impact upon krill populations is required. Continued development of collaborations with IWC colleagues will be useful;
- Developing feedback management approaches that can encompass alternative projections of change with uncertainties to assess risk will be important. These will need to be able to consider alternative adaptation approaches and trade-offs in decision making. This will also require a clarification of the objectives of conservation and management so that different outcomes can be assessed;
- Current models and approaches for management of the krill fishery developed in WG-EMM provide a useful basis for development of adaptive management approaches for krill to encompass the potential future climate change impacts.

Quantitative projections

In addition to qualitative projections, the Workshop considered priorities for achieving quantitative model projections of changes in krill populations in Area 48 for 2050 and 2100 (Objective 3). Scientific priorities include modelling, data, observation and fieldwork to improve:

- Understanding of key drivers of change;
- Physical and chemical projections and agreed scenarios of key drivers;
- High-resolution regional models;
- Understanding of krill population dynamics and development of models;
- Krill-centred ecosystem models.

Physical and chemical scenarios

Development of ecological projections of the distribution and abundance of krill and the wider ecosystem will require agreed future scenarios of key drivers that can be used to drive krill and ecosystem models. These include scenarios for physical, chemical and ecological variables (e.g. phytoplankton and recovery of whale populations).

The Workshop considered a range of scientific priorities to improve current physical and chemical projections, and the data, observations and fieldwork that underpin them (Table 5). This included development of an agreed set of quantitatively derived physical and chemical scenarios, with appropriate assessments of caveats and uncertainties. This will necessitate continued close collaboration with the wider global physical and chemical modelling communities and colleagues involved in IPCC CMIP to identify key environmental variables and ensure that appropriate model outputs are generated and stored. This will also require a longer-term ongoing iterative process of scenario development and agreement as the physical and chemical projections, that provide their basis, are developed and refined.

The current generation of global CMIP models are too low in spatial resolution to resolve many of the key physical processes that are a major influence on krill population and ecosystem processes within Area 48. To generate projections at the relevant scales, high resolution (<5km) physical (ocean and ice) and biogeochemical models that better resolve local and regional Southern Ocean processes are required. These regional models can be used in combination with output from lower resolution (CMIP and non-CMIP) models (providing forcing and boundary conditions) to generate regional projections.

Improving knowledge of sea ice and its influence on the dynamics of krill populations is a priority. Developing analyses of sea ice habitats based on available data will be a useful first step. This will form part of the assessment activities being undertaken by MEASO (in conjunction with SOOS) to develop long-term sustained observing systems including for sea ice environments. Improving understanding of sea ice as a habitat for krill and how it changes seasonally and regionally is also crucial. This has been identified as a priority for ICED, which is developing plans for a major international collaborative multi-disciplinary field programme to examine the role of sea ice in Southern Ocean ecosystems. This aims to undertake studies in a number of areas around the Southern Ocean during crucial periods in winter-spring and autumn-winter. This would be a multi-ship effort over a number of seasons, utilising the next-generation of ice-capable polar research ships, and involve extensive deployment of autonomous observation systems to examine ocean, sea ice and ecological systems.

Mechanistic understanding

Development of quantitative projections of krill will also require improved understanding of the mechanistic impacts of drivers and their synergistic effects on different life cycle stages of krill and the wider ecosystem (Table 6). This can be achieved through process and experimental studies. Such studies will also generate the required parametrisation of functional relationships and models. Detection and management of change in these ecosystems will also require assessment of their status and sustained observations in close collaboration with MEASO activities.

As we have noted, understanding of krill population processes remains poor and requires a much more focussed set of field and experimental studies to provide the data required to develop models of local and region processes. Processes influencing local and regional recruitment are particularly crucial in determining changes in krill abundance. This will require extensive sampling of seasonal changes in population processes and particularly spawning production, larval overwintering survival. As noted above, a key focus for that work will be the role of sea ice ecosystems in maintaining krill larvae and their importance to adult krill. Determining the key drivers of krill recruitment, beyond SST and sea ice extent is also important. For example, an understanding of how changes in temperature throughout the water column affect different life cycle stages of krill, what characteristics of sea ice environments are important for larval krill during winter. Such information is required to inform the dialogue with those involved in generating projections (IPCC) to ensure that future assessments are capable of providing appropriate model outputs.

Ecological models

There are no agreed standard models of krill population dynamics or wider ecosystem processes that can be used to generate projections. A range of different model formulations are available and will be required to examine and test alternative hypotheses of the factors that influence krill recruitment, distribution, and the structure and functioning of ecosystems (Murphy et al. 2012). In order to explore many of these aspects, a systematic development of krill population models is needed. In addition, models that link different model structures together to consider the interactive effects of change on krill and the wider ecosystem are needed. This will be crucial for informing decision making within CCAMLR. As part of these activities high spatial resolution ecosystem models that can be used to explore the fine scale and two-way impacts of change within ecosystems are needed. Such fine scale models can provide an important basis for quantitative assessment of the alternative spatial management strategies in key areas of change. Much of the work noted in this section will require continued close collaboration between ICED and CCAMLR.

The workshop also noted that the models and approaches that WG-EMM have developed for Area 48 in assessing potential impacts of fishing on krill and the dependent predators provide a useful basis for developing models that can incorporate the implications of climate change into CCAMLR management. Developing projections and models will be a useful focus for the next stage of collaborative activities between ICED and CCAMLR.

In addition to the collaborations outlined above, the Workshop also noted a range of other collaborations between ICED and CCAMLR to build on the outputs of this workshop (Table 7 and below).

5. Post workshop outputs

The preliminary outcomes were presented to the Southern Ocean community immediately following the workshop at the Marine Ecosystem Assessment of the Southern Ocean conference (MEASO2018, Hobart, Australia, 9-13 Apr 2018), the ICED SSC meeting, and the Integrated Marine Biosphere Research project (IMBeR) SSC meeting, which were both held in Hobart either side of MEASO2018. Preliminary outcomes were also disseminated to the Scientific Committee for Antarctic Research community (SCAR, and presented at POLAR2018, Davos, Switzerland 25-23rd Jun 2018). Results will be disseminated to the Committee for Environmental Projection (CEP), for presentation at the 2019

Antarctic Treaty Consultative Meeting. Results will also be disseminated beyond the Southern Ocean community via IMBeR (of which ICED is a regional programme), as part of Future Earth and SCOR. The outputs of this Workshop will also contribute to an ICED session (in collaboration with MEASO) that will be held at the IMBeR Open Science Conference, Brest 2019. This will include CCAMLR (and other stakeholders) and is aimed at considering ways to improve research on understanding and projecting changes in Southern Ocean ecosystems relevant to conservation and management decisions.

Potential scientific peer-reviewed papers that could be generated by individuals or groups were also identified. These included a paper that summarises rationale, outcomes, and opinions generated in this workshop with policy makers (i.e. resource managers and the IPCC) as a key focal audience. There was also support for presenting the summary reports (that were collated prior to and in specific support of this workshop) in a format that makes them widely accessible to science and policy makers, for example through the Antarctic Environments Portal or other peer-reviewed journal.

6. Summary

The Workshop successfully addressed the major objectives, assessing potential drivers of change (including sea ice), considering the potential impacts on krill and the availability of krill to predators and the fishery, and examining approaches for modelling and projecting ecosystem change in Area 48.

The area around the AP, the northern Weddell Sea and across the Scotia Sea is one of the most complex oceanographic regions of the Southern Ocean. This complexity is reflected in the spatial variability of the ecosystem structure. It is also a region of high natural inter-annual and decadal variability. This variability dominates signals in even the longest available biological times series. Projections of physical and chemical change across the region are highly uncertain.

Under a high emissions scenario the warming and loss of sea ice is expected to result in a reduction in the abundance and biomass of krill in northern areas of the Scotia Sea but increases in the south around the AP and Weddell Sea. However, the resilience and adaptive capacity of krill to withstand such changes is poorly determined. The combined effects of changing sea ice and krill abundance will result in shifts in the distribution of the various krill dependent species, with more polar species constrained farther south. These changes are also likely to result in substantial changes in the structure of the wider food web and it is possible that these may occur rapidly as particular biological thresholds are reached.

The Workshop highlighted our poor understanding of many key biological processes and particularly the importance of sea ice in influencing krill recruitment. Many of the key physical processes that determine krill availability to predators and the fishery occur at relatively small spatial scales (<10 km). The Workshop emphasized the need for the systematic development of krill population process models and high-resolution physical-biological models to provide the basis for developing quantitative projections and management procedures.

The expected changes in species distributions and reconfiguration of food webs (as krill abundance declines in some areas but increases in others) will require adaptation of conservation and management procedures. The models and approaches that WG-EMM have developed for Area 48 for assessing potential impacts of fishing on krill and the dependent predators are a useful starting point for developing models that can consider and incorporate climate change. Observation series are unlikely to be sufficient to detect change and attribute the causes to particular mechanisms in the next 10-15 yrs. This necessitates a precautionary approach that incorporates all aspects of uncertainty associated with generating ecological projections, allowing uncertainties in outcomes under different conservation and management strategies to be assessed.

This first ICED-CCAMLR Projections Workshop has provided an initial, mainly qualitative, assessment of the potential impacts of climate change on krill, their predators and the fishery in Area 48, and considered the implications for including climate change in decision making for conservation and management. The Workshop identified a series of new activities where ICED and CCAMLR can engage in strategic collaboration to develop quantitative projections in support of decision-making, including an iterative process of quantitative projection development in association with the IPCC assessment cycle. Activities for 2019 and 2020 to further these collaborations are currently being discussed and a scientific paper based on the results of the workshop is also being prepared for publication.

Acknowledgements

The meeting was supported by ICED, IMBeR, SCOR, CCAMLR and the British Antarctic Survey. The organisers are also grateful for the support provided by Andrew Constable and the MEASO2018 meeting organisers, and the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC).

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Table 1. Impacts of key drivers on Antarctic krill in Area 48.

Driver	**Impacts on krill biological processes**			**Impacts on krill populations**		**Impacts on availability of krill to predators (incl. fishery)**	**Comments**
	Growth	**Recruitment**	**Mortality**	**Distribution**	**Abundance**		
Sea ice	**Larvae** Growth through availability of food from late winter to early spring when ice algae start to grow under ice (Meyer and Teshke 2016; Kawaguchi 2016). Enhance spring bloom as sea ice retreats through stratification. Positive effects on boosting egg production, and also provide food for larvae to enhance transition into juvenile. Timing of ice retreat important (Kawaguchi 2016).		**Larvae** Complexity of structure of underside of sea ice provides good habitat for overwintering. Probably less mortality through predation. Loss of complex ice will have negative effect on their survival (Meyer et al. 2017)			Increased access for winter krill fishery (Kawaguchi et al. 2009)	Relative importance of sea ice as providing refugee vs providing good food is unclear and probably varies between region as well as season. Dictates access for fishery. Change in sea ice dynamics may allow other areas in Area 48 to become accessible for fishing, even western Antarctic Peninsula region (Area 88.3). It may also change shipping arrangements and ports to better access the fishing area. However, fishery also tends to target predictable fishing grounds
Ocean temperature	Has an optimum **Adults** Dome shape 0.5° C is optimal (Atkinson et al. 2006) 5 °C upper, and -1.5 ° C lower threshold	**Developmental decent & ascent** Higher temperature means faster development and hence shallower development	+ve Not much information but the patterns are likely to be same as growth (whether increased energy demand due to	Increase stress at margins of distribution Krill can swim horizontally and vertically to avoid unfavourable temperature	Uncertain. Probably same pattern as growth…	-ve with low confidence If temp affect recruitment, then will consequently impact availability. Colder the better for fishery. Seasonality	Plasticity of krill biology need to be looked into. In long term (across a number of generations) they may be able to adapt and do fine.

	Larvae Faster development and higher growth rate (Ikeda 1984 Ross et al. 1988) Balance between higher energy demands vs amount of food available (Meyera et al 2009, 2016, 2017) Need to address this through experimental approach	In turn may be more vulnerable to predation due to their shallow distribution **Survival for the first year** Require enough food to meet the increased energy demand at increased temperature. If this is potentially met, survival rate is likely to decrease	increased temperature are not met).	Poleward contraction of habitat range (Hill et al., 2013), but the main distribution is determined by bathymetry (canyons and so on) Bathymetry is also important for the habitat for early development: need enough depth (1000m) for eggs to sink			In any region there are not enough age-1 krill found to sustain self-sustaining population. Where are the young krill? Krill in high temperature region may grow much faster and therefore size range of age-1 krill be larger than lower temperature region. Temperature-Growth relation should be revisited for better model population dynamics of krill More lipid accumulation may probably be needed to overwinter as energy demand during winter may increase
Ocean acidification	**Adults** Cost of living will be higher in high CO2 environment. Higher energy required to sustain their growth	**Egg production** Energy diverted from egg production due higher cost of living Embryonic development interrupted at increased CO2 in the habitat. (>1000ppm)		Parts of Southern Ocean may become less favourable for reproduction (due to lowering of hatch rates) by 2100			Synergistic effect of temperature and ocean acidification. Impacts of multiple stressors (Temp, OA) on krill need to be studied
Primary production: Food availability (upwelling and BGC)	+ve,	+ve (via fecundity)	Adults reasonably robust to starvation, larvae are not	Important control on mesoscale distribution	Possibly indirect via aggregation	+ve	Processes underlying pp reasonably well represented in GCMs chl-*a* outputs form CMIP5 models not reliable

							Better estimates required, and pp functional groups. Future pp uncertain, spatially complex
Mixed layer depth							Shallower mixed layer, lower nutrient supply, reduced primary production Egg sinking depth
Predation	? (probably not)	?	-ve	Uncertain (not primary driver at area 48 scale)	-ve	Uncertain Possibility of positive feedback and facilitation	
Chronology (desynchronization)	-ve	-ve (indirect)	-ve	-ve (habitat shrinkage)	-ve	-ve	Applies specifically to adults
Interspecific competition (from salps)				Uncertain – may constrain distribution	-ve (uncertain)	-ve (uncertain)	
Pathogens/parasites	-ve	-ve	-ve	Would affect	-ve	-ve	
Advection-dispersal							
Behaviour-dispersal							
Oxygen							Less important

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Table 2. Status of Antarctic krill and relevant ecological models.

Reference	Model description	Modelling group	Developments required to couple with scenarios of key drivers	Comments
Kawaguchi et al. 2007	A conceptual model describing seasonal cycle of krill physiology that provides a framework for future studies and highlights the importance of its link to the timings of the environmental conditions. The model highlights the importance of the amount of sea ice algae available in the lead up to the reproductive season, and the timing of sea ice retreat in relation to the period when krill become physiologically ready to start their ovarian cycle. The overall length of the primary production season dictates the length of the period during which the ovarian cycles are sustained	AAD	Conceptual only – see next row for numerical implementation	
Piñones & Fedorov 2016	Vertically resolved embryo-development model embedded in 3D temperature, salinity fields, to assess survival of early life stages	Centro IDEAL	Already used with prognostic temperature, salinity	Circumpolar projections
Constable & Kawaguchi 2017	An energetics moult-cycle (EMC) model that combines energetics and the constraints on growth of the moult-cycle. This model flexibly accounts for regional, inter- and intra-annual variation in temperature, food supply, and day length. The EMC model provides results consistent with the general expectations for krill growth in length and mass, including having thin krill, as well as providing insights into the effects that increasing temperature may have on growth and reproduction	AAD/ACE CRC	Ready	Has been applied to Area 48. Includes a review of krill growth and life history models
Ryabov et al. 2017	This population model identifies intraspecific competition for food as the main driver of the krill cycle, while external climatological factors possibly modulate its phase and synchronization over large scales. The model indicates that the cycle amplitude increases with reduction of krill loss rates. Thus, a decline of apex predators is likely to increase the oscillation amplitude, potentially destabilizing the marine food web, with drastic consequences for the entire Antarctic ecosystem	AWI/University of Oldenburg	Ready	Has been applied to subarea 48.1
Groeneveld et al. 2015	Individual based model incorporating effects of photoperiod and food availability effects on activity and development	AWI/UFZ	Not temperature dependant	Used to examine implications of sea ice timing for individual survival and development

Watters et al. 2013	Spatially resolved, ecosystem dynamics model, incorporating krill-predator fishery interactions. Considers various uncertainties. Used to evaluate fishery management options	WS-AMLR-BAS	Has been extended to incorporate temperature effects on krill mean size (Klein et al. 2018), and can include environmentally forced krill recruitment	Has been applied to Area 48
Murphy & Reid 2001	Demographic model	BAS	Applied to analyses size structure	
Reid 2002	Demographic model	BAS	Applied to analyses of growth and size structure	
Murphy et al. 2007	Demographic model	BAS	Used to examine impact of climate fluctuations on size structure and biomass. Has been developed to explore scenarios	Applied to analyse Area 48 population dynamics in Area 48.3
Various	Ecopath/Ecosim	Various	Dynamic implementation- Bottom up forcing	Has been applied to sub regions of Area 48

AAD = Australian Antarctic Division, ACE CRC = Antarctic Climate & Ecosystems Cooperative Research Centre, AMLR = US Antarctic Marine Living Resource, AWI = Alfred Wegener Institut, BAS = British Antarctic Survey, Centro IDEAL = Centro de Investigacion Dinamica de Ecosistemas Marinos de Atlas Latitudes, UFZ = The Helmholtz-Centre for Environmental Research GmbH – UFZ

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Table 3. Scenarios of physical and chemical change in the Southern Ocean*. Refer to https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf and Appendix IV for guidance on IPCC calibrated language where used

Statement ID	Statement category	Scenario	Associated information	References
PCS1	Winds	Poleward shift and strengthening of annual mean circumpolar westerlies is projected to continue: 10% over 21st century (3% for RCP4.5)	Southern Annular Mode (SAM) has become increasingly positive, resulting in westerly winds shifting poleward and strengthening. Strengthening of the polar vortex. Westerly wind jet is biased too strong and too far north. Uncertainty in strength projections linked to sea ice biases. The impact of projected changes in these winds on the ocean and sea ice within Area 48 is uncertain	Marshall et al. 2003; Meijers et al. 2012; Bracegirdle et al. 2013; Meijers 2014; Bracegirdle et al. 2018; see WS-SR-13-2018 for further detail
PCS2	Sea ice	Persistent and ongoing decrease in sea ice cover (including areas where cover is currently increasing) is *likely*. Increased precipitation may cause freshening and reduced occurrence of Weddell polynya	There has been an overall increase in sea ice cover, most pronounced in period of growth. However, this overall trend masks significant regional variation. Regional trends include: increased cover in Ross and Weddell Seas, decreased cover in Amundsen and Bellingshausen seas. Changes in timing largely follow same patterns. Enhanced sea ice export believed to be due to changes in winds, notably more positive SAM. *Low confidence* in sea ice projections, especially for Weddell Sea (e.g. *low confidence* in ability of models to represent coastal circulation and understanding of future ice sheet/shelf melt)	Stammerjohn et al. 2012; Massom et al., 2013; Turner et al. 2013; de Lavergne et al. 2014; Bracegirdle et al. 2015; Hobbs et al. 2016; Haumann et al. 2016; Cavanagh et al. 2017; see WS-SR-13-2018 for further detail
PCS3	Sea ice	By 2100 sea ice area in the Southern Ocean is expected to reduce by >30% in winter (*medium confidence*). Summer sea ice extent and duration is *likely* to decrease (*medium confidence*).	Bracegirdle et (2008) and Cavanagh et al. (2017) have predicted reductions in sea ice area of >30%. CMIP models do not accurately reproduce current sea ice, as such a mechanistic understanding of ice dynamics and its response to drivers such as winds, should be used to develop projections. Currently, the best method for generating plausible circumpolar sea ice scenarios is to use a weighted selection of CMIP5 models based on their ability to reproduce past conditions. Past trends show that the seasonal duration and summer extent of sea ice is decreasing	
PCS4	Sea ice	On the basis of PCS3, the influence of sea ice is expected to be reduced in the Scotia Sea and east around the South Sandwich Islands and in Area 48.6. The duration and concentration of winter pack ice in subareas 48.1, 48.2 and 48.5 are expected to reduce but the dynamics are uncertain	As above	
PCS5	Sea ice	The SAM will maintain a largely positive phase and this is *likely* to drive the decrease in seasonal duration and summer extent of sea ice (*medium confidence*)		

PCS6	Sea ice	CMIP5 models do not accurately reproduce current sea ice extent and timing. This suggests that the current generation of CMIP5 models are not yet accurately representing all processes that control sea ice timing and extent. As such, confidence in the projections of future spatial and temporal variation provided by CMIP5 models is low. In order to improve our confidence in projections the development of high-resolution regional models, forced by the global scale CMIP5 models, that can more accurately simulate the mechanistic processes that drive sea ice concentration and extent is needed	Area 48 is an atmospherically highly variable region, which is strongly influenced by the position of the Amundsen Sea Low (ASL, Turner et al. 2013). The intensity and position of the ASL is crucial to determining ocean and sea ice variation to the west and east of the Antarctic Peninsula. There is *low confidence* that the ASL will continue deepening due to the complex relative importance of tropical variability, ozone depletion and greenhouse gas emissions forcing. This uncertainty in the future trend of the ASL reduces our certainty in future regional sea ice cover in Area 48	
PCS7	Sea ice	Confidence in projections of sea ice for the specific regions of CCAMLR subareas 48.1 and 48.2 is higher than compared to projections in other Antarctic sectors. There is *high confidence* that summer sea ice extent and seasonal duration will decrease in subareas 48.1 and 48.2. In contrast, confidence in projected sea ice change for subarea 48.5 is lower than for other regions		
PCS8	Sea ice	Current CMIP5 models indicate that signals of change in sea ice will not be distinguishable from model variability until after ~2050		
PCS9	Sea surface temperature (SST)	Consistent warming of all Southern Ocean water masses concentrated mostly in the upper ocean, of between 1-3°C for moderate to strong warming scenarios (RCP 6 and 8.5). This includes up to 3°C on the northern boundary of the ACC. Elsewhere generally more moderate. In regions where sea ice formation remains the change in SST is expected to be small	There has been a general trend of increased SST north of the Polar Front (PF), and zero or negative trend over the Pacific sector north of the PF and most regions south of the PF. Cooling south of PF thought to be largely due to vertical circulation bringing water to the surface, combined with cooling and freshening effect of enhanced sea ice melt export. Shelf and bottom waters are predicted to become warmer and more saline (due to projected reduction in production of cold fresh bottom water due to increased surface stratification)	Sallee et al 2013a; Sallee et al 2013b; Meijers 2014; Armour et al 2016; see WS-SR-13-2018 for further detail
PCS10	Sea surface temperature	SST will increase south of the PF by 2050 (*medium confidence*). There is *high confidence* that subsurface water temperature will increase by 2050. By 2100 SST across the Southern Ocean will increase at the surface by 1-2°C (under RCP8.5) and will increase (but by less than 1-2°C) at the depths of the circumpolar deep water current, CDW (*high confidence*). Increases in SST under RCP4.5 are *likely* to be less than under RCP8.5. There is *high confidence* that the magnitude of SST change will exhibit a north-south gradient, with greater warming in the north and less in the south	SST in Area 48 is highly variable and has shown marked interannual and decadal variability in the past. Current CMIP5 models indicate that signals of change in SST will not be distinguishable from model variability until after ~2050	
PCS11	Sea surface temperature	The spatial structure of the above projected changes in SST (both horizontally and vertically) is *likely* to be consistent with already observed changes, except in the region south of the PF where observed weak cooling is projected to switch to warming at some point before 2050	The observed weak cooling of SST south of the PF is projected to switch to warming at some point before 2050 as the impact of upwelling of warm circumpolar deep water becomes apparent	

PCS12	Ocean circulation	All water-masses warm. Mode and intermediate water masses freshen. Bottom waters increase in salinity (*unlikely*). Spin up and southward shift of sub-tropical gyres along with southward shift of northern extent of the Antarctic Circumpolar Current (ACC). Mean position of ACC core will not shift. Vertical circulation continues to change, this may increase upper cell overturning by up to 20%. Formation and export of bottom water to continue to decrease	No change to interior density structure of the ACC, or its transport, has been detected. Similarly, no significant trend in mean latitude of the main jets and fronts of the ACC has been detected. Significant interannual variability in ACC frontal strength and position. Interannual variability in ACC frontal strength and position has only weak (or no) correlation with the dominant wind forcing patterns. Predictions of ACC strength vary e.g. predicted to weaken or strengthen by up to 15% across models. Model resolution is too coarse to get fronts in the correct location	Böning et al. 2008; Meijers et al. 2011; Meijers et al. 2012; Downes and Hogg 2013; Lenton et al. 2013; Sallee et al. 2013a; Meijers 2014; Shao et al. 2015; see WS-SR-13-2018 for further detail
PCS13	Ocean circulation	Based on CMIP5 projections there is *high confidence* that the position of the ACC core will not shift out to 2100. This implies no change in the position of the PF	There is *high confidence* that no statistically significant shift in the mean latitude of the PF has been observed	
PCS14	Ocean circulation	There is *low confidence* in projections of any change in the strength of the ACC or subpolar gyres by 2100, however, there is *high confidence* that the eddy activity is *likely* to increase north of the PF		
PCS15	Ocean circulation	There is *low confidence* in projections of any change in horizontal large-scale circulation and gyres of the ACC		
PCS16	Ocean circulation	There is *medium confidence* that upwelling of deep water will increase by 2100		
PCS17	Ocean circulation	Warming and freshening due to upwelling of circumpolar deep water (CDW) along the western Antarctic Peninsula is expected to continue in association with a more positive SAM		
PCS18	Ocean stratification	There is *medium confidence* that stratification will increase in Area 48 by 2100		
PCS19	Mixed layer depth (MLD)	Strong increase in stratification will lead to shallowing of mixed layer (mean of 40m, and regionally up to 150m). This will *likely* lead to reduction in nutrient circulation and supply to upper layers	There is evidence of reduced winter MLDs, although with considerable regional variability. In CMIP5 models, MLD is consistently too shallow, too light and shifted equatorward. This is particularly evident in the summer	Bopp et al. 2013; Sallee et al. 2013b; Schmidtko et al. 2014; Hauck et al. 2015; see WS-SR-13-2018 for further detail
PCS20	Mixed layer depth	There is *medium confidence* that SO average MLD will shoal by 2050 and *high confidence* that it will shoal by 2100, with a circumpolar average shoaling of ~40m	MLD is driven by combination of winds and changes in buoyancy. At present, no change has been observed in MLD. CMIP models project a shallowing of the MLD, however, these models at present have a shallow bias. The models also have a warm temperature bias	
PCS21	Mixed layer depth	MLD will be spatially variable. More shallowing is expected in winter (when MLD is deeper). Shoaling over subareas 48.1 and 48.2 is expected to be smaller than the mean trend. There is *very low confidence* in projections of MLD in Area 48.5 due to uncertainty in dynamics of the Weddell Gyre	MLD is currently spatially variable and projections are likely to reflect this complexity	

PCS22	Mixed layer depth	There is *high confidence* that the surface ocean will continue freshening within the MLD. There is *high confidence* that the surface ocean will continue to freshen within the MLD in areas away from the sea ice	Present day trends show that the surface ocean is fresher within the MLD	
PCS23	pH	There is *high confidence* that pH (and PCO_2 throughout the water column) is *likely* to decrease in direct proportion to rising atmospheric CO_2 concentrations. The largest decrease will be seen in the upper ocean. Most of the Southern Ocean will start to be seasonally under-saturated (with respect to aragonite) by around 2030 and fully under-saturated by 2100 (Bopp et al. 2013). A strong south-north gradient in the progression of aragonite under-saturation from 2030 onwards in *very likely*	Earth System Models (ESMs) capture the large-scale characteristics of ocean acidification in the Southern Ocean, but do not exhibit well the observed regional (zonal) variability, which remains a key challenge. Likewise projecting how ocean acidification will change and how this may impact the Southern Ocean remains an important ongoing challenge, as the ESMs used to project future changes are limited in terms of their dynamic and biological complexity. At present, most ESMs are coarse-resolution and therefore cannot explicitly resolve key dynamical features such as mesoscale eddies, nor capture well observed variability (see Bellerby WS-SR-11-2018 for further details)	
PCS24	Extreme (high impact) climate-related events	Changes in the frequency and magnitude of extreme (or high impact) climate-related events (e.g. upwelling events, very high air or sea temperatures events, or rapid loss of sea ice, intense storms that can collapse ice shelves or destroy habitat) may occur across Area 48	Global models do a poor job at simulating climate-related extreme events that can lead to high impacts on ecosystems (see Cavanagh et al. 2017, Supplementary Table), as such projections of change in the frequency and likelihood of these events are uncertain. High-resolution models, forced by the global models, are required to better answer questions regarding the impacts of extreme events	

* = Unless otherwise stated, the scenarios relate to Southern Ocean-scale changes. In general, there is lower confidence in oceanographic statements in areas closer to the continent

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Table 4. Projections of ecological change in the Southern Ocean (based on the physical and chemical scenarios in Table 3). Refer to https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf and Appendix IV for guidance on IPCC calibrated language where used

Statement ID	Statement category	Projection	Associated information
EP1	Primary production	Increases in primary production are indicated by the end 2100 for the region south of 50°S. It is *likely* there will be changes in phytoplankton community structure but there is *low confidence* in what those changes will be	Plankton biomass estimates and primary production projections (in current CMIP5 models) are poorly determined, largely because of the lack of long-term observations. Drivers of primary production include temperature, light, nutrients, ocean chemistry and top-down control (zooplankton grazing). Changes in sea ice, ocean temperatures and MLD and zooplankton grazing will therefore have an important influence on primary production in Area 48
EP2	Krill (distribution)	A general southward shift of favourable krill habitat is expected as a result of warming of the surface ocean	
EP3	Krill (distribution)	Over the next 5- 10 yrs the effects of change on the distributional range of krill are unlikely to be detectable (*high confidence*). By 2050 minor shifts in krill production at the northern range edge may be detectable (*low confidence*). By 2100 significant wide spread range contraction will occur under RCP8.5, however, no effects will be detectable under RCP2.6 (*medium confidence*)	
EP4	Krill (recruitment)	Sea temperatures in excess of 5°C are unsuitable for larval survival and adult krill growth (*high confidence*)	Other species of krill exhibit the ability to adapt to different thermal conditions. The adaptive capacity of *Euphausia superba* to such change is uncertain
EP5	Krill (recruitment)	A decline in sea ice is *likely* to result in less refugia for larvae from predators and affect survival (*medium confidence*). Changes in sea ice distribution and movements may also result in a change in krill recruitment locations (*medium confidence*)	Sea ice is important (but not essential) for larval survival to recruitment as it is a habitat for larvae during winter and provides refuge from predators (*high confidence*). The spring bloom occurs as sea ice retreats through stratification (*high confidence*). The spring bloom also boosts egg production, and provides food for larvae to enhance transition into juveniles (*high confidence*). Krill larvae are also strongly associated with sea ice and are transported with the sea ice as it moves (*high confidence*)
EP6	Krill (recruitment)	Over the next 5-10 yrs changes in krill recruitment will be within the range of natural variability (*high confidence*). Under RCP8.5 environmental conditions may be sufficient to affect recruitment by 2050 (*low confidence).* Under RCP8.5 environmental changes are *likely* to be sufficient to influence recruitment (with regional differences) by 2100 (*low confidence*)	Projections of large-scale change in sea ice dynamics and temperature (and other environmental variables) over the longer term (30-70 yrs) imply increasing risk to krill recruitment. Over the near-term it is unlikely that these projected changes will result in changes to recruitment that are discernible from current variability. Krill recruitment is dependent on the interaction of multiple physical and biological processes. Key physical drivers include sea ice, temperature, transport, and water column structure. Key biological process include primary production, food availability (quality and quantity) and predation. Recruitment to South Georgia depends mainly on advection from further south. At the WAP and NAP sea ice dynamics is important

			for overwinter survival and advective loss of larval stages affects the magnitude of recruitment
EP7	Krill (recruitment)	Feeding and excretion rates of krill are *likely* to increase with increasing CO_2 conditions across the SO (*high confidence*). Energy will be diverted away from egg production due to higher cost of living (*high confidence*). High CO_2 is also *likely* to lead to developmental defects in krill embryos (*high confidence*). Parts of Southern Ocean may become unsuitable for embryo development and hatching by 2100 under RPC 8.5 (*high confidence*)	Feeding and excretion increases in krill under high CO_2 conditions (*high confidence*)
EP8	Krill (growth)	Over the next 5-10 yrs the effects of increased ocean temperatures on adult growth is unlikely to be distinguishable from natural variability (*high confidence*). By 2050, and under RCP8.5, a minor decrease in growth rate at South Georgia may be detectable (*low confidence*). By 2100 a significant change in growth affecting most areas except the Weddell Sea will occur under RCP8.5 but there will be no detectable effects under RCP2.6 (*medium confidence*)	Krill growth is influenced by both food availability (which is linked to NPP and the composition of the phytoplankton community) and temperature: both of which are projected to change substantially across the SO over the longer term (i.e. the next 30-70 yrs). The parabolic relationship between sea temperature and krill growth means that in some areas, increased temperatures could produce more efficient growth and in other areas, near the temperature maximum for krill, growth rates are likely to decline. The areas of declining growth are likely to be widespread throughout subareas 48.1 to 48.3 under strong warming (e.g. RCP 8.5) and is likely to negatively affect krill production at the northern margins of their range. The effects of temperature may be modified by interactions with primary production, sea ice etc. There is *high uncertainty* regarding the magnitude of future changes to NPP and even more uncertainty about future phytoplankton community structure under warming scenarios. The consequence of krill adaptation to changing environmental conditions are unknown. It is precautionary to assume that adaptation is not possible in the near future
EP9	Krill (mortality)	Over the next 5-10 yrs the effects of change on mortality is *unlikely* to be detectable (*high confidence*). By 2050 whale predation is expected to increase, with regional differences but the effects on krill mortality are uncertain. By 2100 further increase in whale predation is expected. The effects on krill mortality are uncertain (*high confidence*). Cumulative stresses under RCP8.5 are *likely* to increase mortality (*low confidence*)	Mortality may increase in warming scenarios due to a variety of stresses, including the direct effects of temperature near the temperature maximum for krill, changes in sea ice, and potentially increases in pathogens, parasites, disease and UV exposure. Mortality rates may vary spatially depending on changes to the biological community. The recovery of predator populations, especially whales, could also be an important factor (see whale recovery below). The direction, magnitude and spatial variability of future changes to mortality is uncertain
EP10	Krill (general)	Temperature will increase stresses for krill in the north. These will impact physiology, energetics and hence growth, development and recruitment. Stresses will have different effects on different life stages	These changes may be ameliorated by changes in primary production (as per EP8)
EP11	Krill (seasonality and phenology)	Changes in seasonality will affect the phenology and timing or a range of food web interaction processes. A mismatch between the timing of sea ice advance and retreat, the timing, magnitude and composition of the spring phytoplankton bloom and krill phenology, is *likely* to have	Seasonality affects the phenology and timing or a range of food web interaction processes. The spring bloom occurs as sea ice retreats through stratification (*high confidence*). The spring bloom boosts krill

		substantial impacts on krill abundance and population dynamics. These relationships are also *likely* to be heterogeneous in space and time within subareas of Area 48	egg production, and also provides food for krill larvae to enhance transition into juveniles (*high confidence*)
EP12	Krill (multiple drivers)	Synergistic effects are *likely* between temperature and ocean acidification and these will have different effects on different life stages of krill	
EP13	Krill (food availability)	A shallower mixed layer may lead to lower nutrient supply, less primary production and lower food availability for krill (*medium confidence*)	Increased stratification may lead to eggs sinking to a different depth. This may result in reduced development rate if eggs are stuck in an inappropriate habitat or increased development rates if temperature increases overall. It may also may result in more rapid ascent into the mixed layer and access to food, and changes in predation pressure
EP14	Krill (food availability)	Changes in the magnitude of primary production, phytoplankton community composition and the winter availability of phytoplankton will affect food availability for krill	Food availability is crucial for understanding the responses of krill to climate change. Changes in the quality, quantity and availability of food may be an important driver of krill population dynamics. There is little understanding of the diet of adult krill populations that are not ice associated during the winter
EP15	Ecosystem (general)	Major ecological changes in response to climate change may occur in the next 30 years, but will be difficult to distinguish from natural variability seen in current ecological models	
EP16	Ecosystem (general)	Not all potential future changes will be negative. Many species are likely to have a reasonable level of resilience and adaptive capacity because these ecosystems naturally exhibit high variability	As ranges shift southwards, populations of more polar species will increase in the south. In more northern regions, biodiversity may increase as a result of increased survival of sub-Antarctic species. Benthic connections are also important for krill, and with enhanced productivity, these communities, and hence benthic-pelagic interactions may increase
EP17	Ecosystem (whale recovery)	With increasing abundance of krill-feeding whales locally (particularly humpback whales) there may be potential for more competition for krill, which may influence the local carrying capacity of krill-obligate colonies in the WAP. Increased competition among different krill predators may also cause declines in some other predator populations. This will be the natural consequence of the recovery of whale populations. The effects of whale recovery are *likely* to occur on similar decadal time scales to the effects of climate change	In Area 48.1 humpback whales are thought to have been steadily increasing in the past three decades as they recover from exploitation. Fin whales are also present in increasing numbers towards the north and northwest of the Peninsula. Humpback whales are locally feeding on Antarctic krill while fin whales are thought to be feeding on a mixture of Antarctic krill and *Thysanoessa macrura*
EP18	Ecosystem (food webs)	Southward contraction in krill habitat may result in increased spatial and temporal competition and other interactions between krill predators (*medium confidence*). There will be different responses from predators depending upon their association with sea ice (*medium confidence*)	There have been substantial changes in the numbers and species composition of penguin across colonies in the WAP (*high confidence*). Ice dependant penguins (Adélies) have declined and gentoos (ice avoiding) have increased (*high confidence*)
EP19	Ecosystem (food webs)	Energy flows through the system may shift if higher trophic level krill predator species (e.g. gentoo penguins, elephant seals) continue shift in range towards higher latitude waters. There are *likely* to	Colony based predators can respond in an amplified fashion to subtle shifts in local krill and ice distribution and abundance because they are

		be substantial changes in the numbers and species composition of penguin colonies across the WAP- for example, Adélie penguins are *likely* to increase in more southern regions as these become more favourable habitats	seasonally restricted to these areas during the breeding season. Some predators, such as Adélie and chinstrap penguins (that have been widely recorded in Areas 48.1 and 48.2) are krill obligate predators. Others, such as gentoo penguins and Weddell seals, are more generalist, and are increasing in these areas. The causes of these shifts are widely debated. Adélie and chinstrap colony declines are likely to have been mediated by reductions in survival, since breeding success has not declined, suggesting availability of food locally has not reduced. These two species also forage very widely outside of the breeding season and so may be impacted by factors distant from the colony. In contrast, tracking of gentoo penguins and Weddell seals suggests that they forage locally through the winter
EP20	Ecosystem (food webs)	Shifts in dominant energy pathways away from krill are increasingly *likely* under strong climate change (i.e RCP 8.5). This has implications for the transfer efficiency of energy to higher predators, which might have spatially variable effects on these populations	Copepods or salps may increase in relative abundance compared to krill in more northern regions. Salp based systems may not support large numbers of higher trophic level predators. Mesopelagic fish (e.g. myctophids) may increase in response to changes in MLD and SST. Mesopelagic fish based energy pathways are more likely to be important in areas where krill abundance declines
EP21	Ecosystem (food webs)	Increased sea temperatures may increase interactions and competition between salps and krill (*medium confidence*). Southward movement of fronts may increase interactions and competition between salps and krill (*low confidence*). Salp and krill co-occurrence will increase in regions such as the tip of the AP (*high confidence*), associated with increased temperature and the decrease in distance between fronts in this location (*low confidence*)	
EP22	Ecosystem (Invasive species)	Northern areas of the Scotia arc, such as around South Georgia, may experience more incursions of sub-Antarctic zooplankton and fish. Species that are currently observed infrequently in SO waters following warm water intrusions may be observed more frequently and become invasive	Understanding the environmental constraints of non-native species and their likelihood of becoming invasive is limited. The potential for invasion of larger fish species requires attention
EP23	Ecosystem (Invasive species)	Non-native species may be introduced into Area 48 via tourist, fishing, research or other vessels and become invasive	
EP24	Fishery	Changes in sea ice dynamics may allow new areas within Area 48 to become accessible for fishing, including the WAP region (Subarea 48.3). This may also lead to changes in shipping arrangements and ports to better access fishery areas	
EP25	Fishery	A decline in winter sea ice is *likely* to result in krill fisheries exploring newly exposed areas or remaining longer in established grounds in subareas 48.1 and 48.2 that are currently seasonally closed by sea ice (*high confidence*).	The krill fishery prefers krill without a gut full of phytoplankton and high lipid content (*high confidence*) and therefore typically catches its preferred krill during winter (*high confidence*). Sea ice is currently a constraint on when the fishery targets krill in subareas 48.1 and 48. during winter (*high confidence*)

EP26	Fishery	Major future changes in the krill fishery are likely to be driven by global issues external to the SO, including conservation decision making, socio-economic drivers and geopolitics	

AP = Antarctic Peninsula, CMIP = Coupled Model Intercomparison Project, MLD = mixed layer depth, NAP = northern Antarctic Peninsula, NPP = net primary production, SST = sea surface temperature, SO = Southern Ocean, WAP = western Antarctic Peninsula

Table 5. Priorities for developing quantitative projections of krill populations in Area 48: improvement of physical and chemical scenarios

Priority areas for improvement	Steps
Physical and chemical projections *Standard set of projections:* Develop a standard set of projections of physical and chemical drivers for the Southern Ocean and Area 48 under different emissions scenarios	- Develop a standard set of physical and chemical projections that can be used as a consistent basis for developing a priority set of physical and chemical scenarios (see below) and spatially and temporally inter-comparable ecological projections - In step with each new IPCC Assessment Report, review and refine this standard set of physical and chemical projections as new information regarding probable anthropogenic emissions pathways and greater understanding of Southern Ocean physical processes becomes available
High resolution physical and biogeochemical models for downscaling to ecological processes: Improve physical and biogeochemical models so that they better resolve physical and chemical processes at finer scales than current global models N.B. See Table 3 (associated information and references therein) for examples of inadequacies of CMIP(5) models in predicting SO processes	- Develop high resolution (space, time) regional physical and chemical models that better resolve local and regional SO processes at a scale suitable for the biology/ecology of the system (including for sea ice, ice sheet/shelf melt, ACC, MLD, coastal circulation, westerly wind jets, pH and phytoplankton*). Ideally these high-resolution models should be forced from boundary conditions provided by CMIP(5) models so that the regional models are consistent with projections provided by global models - Use these high resolution models (and other appropriate CMIP and non-CMIP models) to generate regional projections of change in the physical and chemical environments. Maintain dialogue with WCRP and IPCC colleagues in future CMIP Phases and Assessment Rounds to improve the production of global (and possibly higher resolution regional) models that adequately resolve SO processes that are key to interpreting and projecting ecological change. This is feasible for the CMIP7/AR7 process
Sea ice models: Improve sea ice models so they resolve key sea ice processes and habitats	- CMIP models cannot reliably capture sea ice processes and habitat characteristics that are important for interpreting variations in krill and ice obligate predator dynamics, such as ice type (snow vs ice, sea ice vs ice shelf) and physical structure (e.g. thickness, ridges and raft structures), timing of advance and retreat, or retention and connectivity of ocean circulation under the ice. Additionally, few model groups have archived all of the available sea ice diagnostics. Until CMIP models reliably achieve this, the development of high spatial resolution sea ice models that better resolve local and regional processes is required. Good examples include the 1.5-3km Regional Ocean Modelling System (ROMS) model of the Ross Sea/Antarctic Peninsula Dinniman and Klinck (2004) and the West Antarctic Peninsula model of Piñones et al. (2011) - Increase resolution and performance of sea ice models in future CMIP experiments so that they can resolve sea ice processes and habitats, such as through CliC's endorsed diagnostic Model Intercomparison Project for CMIP6: Sea Ice Model Intercomparison Project, SIMIP (see http://www.climate-cryosphere.org/activities/targeted/simip), which should address some of these sea ice issues
Model accessibility: Make physical and chemical models and projections openly accessible to the community as and when they are developed	- Engage with relevant organisations who have developed protocols for storage and use of projection data and models - Set up common protocols for storage and use of physical and chemical projections, data and models. Establish a platform for cataloguing and sharing model outputs to improve access
Collaboration with FISH-MIP: Learn lessons from FISH-MIP regarding their use of physical and chemical projections from CMIP models and provide feedback	- Liaise with FISH-MIP's global and regional coordinators to initiate these collaborations

Extreme (or high-impact) climate-related events: Develop projections of change in frequency and magnitude of extreme climate-related events for the Southern Ocean and Area 48	- Initiate a research focus of the occurrence and ecological impacts of extreme climate-related events in the SO and Area 48 - Analyse climate model projections to assess past extreme events and use these as a basis for developing projections of extreme climate-related events using the high resolution models developed above
Data/observation/fieldwork *Classification of sea ice habitats:* Develop a classification of sea ice habitats that are important to under-ice or above ice associated communities (i.e. krill, plankton and ice obligate marine mammals and seabirds) in Area 48 and monitor their distribution and change	- Work with MEASO and SOOS to enhance observations of sea ice characteristics - Improve knowledge of ice characteristics that define sea ice habitats to develop a classification system, e.g. ice type -snow vs ice, sea ice vs ice shelf, physical structures- surface ridges and rafts, melt pools, thickness, age, timing of advance and retreat, and underlying water-column properties - Undertake a synoptic classification of past sea ice habitat in Area 48 (via sea ice modelling as above) to determine whether the observed sea ice loss in Area 48 represents a loss of ecologically important habitat for under-ice or above ice associated communities - Fieldwork campaigns (particularly during transition periods of winter-spring and autumn-winter) to improve understanding of the sea ice environments and their influence on distribution and association of krill, plankton and ice obligate marine mammals and seabirds and the seasonal variability of their use. Campaigns over successive seasons to examine how changes in sea ice dynamics (including advance and retreat, concentration and extent) affects the structure and functioning of associated fauna. NB. ICED is currently developing plans for a multi-disciplinary international collaborative field study to examine the role of sea ice in SO ecosystems.
Model environmental variables: Assess the suite of environmental variables in current models to ensure they capture key environmental characteristics of Area 48 required for developing scenarios (and ecological models related to krill)	- Identify the environmental variables that need to be derived from the CMIP and high resolution projections of physical and chemical drivers for developing physical and chemical scenarios (and ecological models) - Conduct a methodical assessment of model output against a range of observations. Many environmental variables are calculated in CMIP models runs. However, many are not extracted and archived due to storage constraints or uncertainty owing to a lack of observations to compare them against. -Request for the full suite of ecologically relevant variables to be stored in the CMIP and other projections. Continually review and revise this suite based on improvements to mechanistic understanding and model development as well as improved understanding of the ecology of the system. Work with WCRP, IPCC and CliC colleagues (as above) to ensure these required set of variables are updated and incorporated into future CMIP Phases and Assessment Rounds
In situ measurements of environmental variables: Improve measurements of *in situ* physical and chemical variables to increase precision accuracy, spatial and temporal coverage, for ground-truthing remotely sensed data and evaluating models	- Collaborate with MEASO and SOOS (and their regional working groups) to identify variables that require improved measurement and to expand the number of variables that are currently measured - In collaboration with MEASO and SOOS, improve *in situ* measurements of priority variables including sea ice, polynyas, SST, ocean circulation, pH (particularly ACC, gyres, eddies, and upwelling of deep water), stratification and MLD, SAM, and ASL. Encourage technological advances to allow *in situ* measurements of ocean pH (i.e. with small rugged sensors as opposed to current spectrophotometric techniques), and sea ice type and thickness (current altimeters cannot distinguish between snow and ice and do not accurately measure thickness). Develop assessments of the skill of models to represent ecologically-relevant variables

Mechanistic understanding: Increased mechanistic understanding of key dynamical processes, complex ocean-atmosphere-ice-feedbacks and the interactions between multiple climate processes is needed to decrease uncertainty in physical and chemical projections	- Compile a list of processes and feedbacks that require further elucidation/development. These include for example, links between atmospheric forcings and complex ocean circulation, such as winds and sea ice trends, sea ice and sea surface temperature in Area 48, and coastal circulation, the impact of future ice sheet and ice shelf melt on surface waters - Undertake observational programs to improve our understanding of the key processes identified in previous column, for example, MIZ voyages to understand impact of waves on sea ice formation/break-up in MIZ. Develop regional models incorporating improved mechanistic understanding of key dynamical processes. Incorporate understanding into future CMIP Phases and Assessment Rounds and physical and chemical projections by working with WCRP and IPCC colleagues (as above)
Physical and chemical scenarios *Priority scenarios of key drivers:* Develop a robust set of scenarios of key physical and chemical drivers of krill dynamics	- Based on an assessment of the physical and chemical projections (above) develop priority scenarios of key drivers including summer, winter and regional sea ice concentration and extent, SST, movement of water masses, winds, MLD and pH - Iteratively update and agree this set of priority scenarios based on improvements to physical and chemical projections

* = ecological driver, ACC = Antarctic Circumpolar Current, ASL= Amundsen Sea Low, CliC = Climate and Cryosphere project CMIP = Coupled Model Intercomparison Project, FISH-MIP = Fisheries and Marine Ecosystem Model Intercomparison Project, IPCC = Intergovernmental Panel on Climate Change, MIZ = marginal ice zone, MEASO = Marine Ecosystem Assessment of the Southern Ocean, MLD = mixed layer depth, SAM = Southern Annular Mode, SO = Southern Ocean, SOOS = Southern Ocean Observing System, SST = sea surface temperature, WCRP = World Climate Research Programme

References

Dinniman MS and Klinck, JM (2004). A model study of circulation and cross-shelf exchange on the west Antarctic Peninsula continental shelf. Deep Sea Research Part II: Topical Studies in Oceanography. 51 (17-19)

Piñones A, Hofmann EE, Dinneman, MS and Klinck, JM (2011). Lagrangian simulation of transport pathways and residence times along the western Antarctic Peninsula. Deep Sea Research Part II: Topical Studies in Oceanography. 58 (13-16)

Table 6. Priorities for developing quantitative projections of krill populations in Area 48: improvement of krill and other ecological models

Priority areas for improvement	Steps
Krill (and other ecological) models	
Krill Yield Model and Risk Assessment models: Use scenarios to inform recruitment, growth and mortality parameters of these models	- Qualitative scenarios could be applied now - Quantitative scenarios could be applied once developed and iteratively refined
Krill population dynamics models: Develop a strategic approach to improve krill life cycle, recruitment and growth models. This will enable exploration of the impacts of spatial and temporal variations of key physical, chemical and ecological drivers on krill	- Develop a strategic approach to move from the current suite of models focussed on limited time scales and processes to a set of models equipped to address priority questions at appropriate scales - Develop a krill population dynamics model for Area 48. See Table 1 for the types of models that could be used to inform this
Food web models: Develop food web models to explore the spatial and temporal variability in the role of krill as a link between lower trophic levels, mesopelagic species and higher trophic level predators	- This is already outlined as a future priority research area by ICED
High spatial resolution ecosystem models: Develop high resolution coupled biological-physical models of Area 48 ecosystems. This will enable exploration of the impacts of spatial and temporal variations of key physical, chemical and ecological drivers on ecosystem structure and functioning. These can also provide a basis for quantitative assessment of alternative spatial management strategies in key areas of change	- Develop high spatio-temporal resolution biological-physical ecosystem models that incorporate high resolution physical and chemical models outlined in Table 5
Collaboration with FISH-MIP: Learn lessons from FISH-MIP regarding their approaches to coupling CMIP projections with ecological models to generate quantitative fisheries projections	- Liaise with FISH-MIP's global and regional coordinators to initiate these collaborations
Data/observation/fieldwork	
Krill recruitment	- Improve understanding of recruitment processes, their regional variations and key drivers, particularly: • Winter processes • Northwestern Weddell Sea, Bransfield Strait and South Orkney regions (as the krill and ecosystem processes in these areas influence wider AP and Scotia Sea processes) • Relationships between krill recruitment and sea ice, particularly in the northern Antarctic Peninsula region
Krill growth	- Improve understanding of krill growth, regional variations and key drivers, particularly: • Regional variations of growth in first year krill. This will require a calibration exercise and improved ageing techniques (a potential future workshop focus); • Continued monitoring of krill production (size and growth rates) to detect any negative trends, particularly in northern margins of their range. This will ensure that CCAMLR implement modifications to management in a timely manner if required •
Krill mortality	- Improve understanding of krill mortality, regional variations, and key drivers

	- Increased krill mortality rates will negatively affect the precautionary yield. Spatial differences will require adjustments to the spatial allocation of catches. CCAMLR should evaluate whether its management approach is robust to potential changes in mortality. Improving understanding and estimation of mortality, and improving estimates and monitoring of krill consumption by predators are laudable goals
Impacts of seasonality on krill phenology	- Improve understanding of the temporal synchrony between krill phenology and sea ice advance and retreat, and the timing, magnitude and composition of the spring phytoplankton bloom. This could be achieved by modelling these processes and conducting more observations of growth and development of krill during winter
Impacts of multiple drivers on krill	- Improve understanding of the (synergistic) impacts of multiple stressors (particularly temperature, ocean acidification and oxygen) on different life stages krill. This should include effects on physiological rate processes as well as epibionts, parasites and pathogens - Examine the resilience and adaptive capacity of krill to stressors
Whale recovery and impacts on krill	- Improve understanding of the recovery of whale populations via collaborations with IWC colleagues - The potential effect of whale recovery on local krill abundance could be investigated using inferred humpback whale trend data from subarea 48.1. The whale data could be used to infer changes in local krill consumption and calculate the relative reduction in biomass, and estimate the relative effect on the local carrying capacities of krill-obligate species
Relationship between krill and sea ice	- Improve understanding of the correlation between the krill life cycle and sea ice dynamics, their regional variations, and the mechanisms involved. This should include an understanding of krill survival in ice free areas and the resilience and adaptive capacity of krill to sea ice loss - As per Table 5, conduct fieldwork campaigns (particularly during transition periods of winter-spring and autumn-winter) to improve understanding of the sea ice environments and their influence on distribution and association of krill, plankton and ice obligate marine mammals and seabirds and the seasonal variability of their use. Campaigns over successive seasons to examine how changes in sea ice dynamics (including advance and retreat, concentration and extent) affects the structure and functioning of associated fauna. NB. ICED is currently developing plans for a multi-disciplinary international collaborative field study to examine the role of sea ice in SO ecosystems
Impacts of food availability for krill	- Improve understanding of food availability, regional variations, and key drivers - Conduct diet studies, particularly of post larval krill populations during the winter months in areas where they are not associated with sea ice. Couple these with *in situ* measurements of primary production and community composition, together with appropriate regional biogeochemical models that include specific plankton functional types and the key processes that affect them (e.g. nutrient supply, the iron cycle, ocean acidification, and sea ice processes)
Changes in food webs	- Improve understanding of the response of other species within the food webs of Area 48 to change. This will facilitate projections of how krill populations will affect, and be affected by wider ecosystem changes. - CEMP remains a valuable resource for monitoring changes in food webs - Where possible CCAMLR should leverage CEMP, the fishery and other research/monitoring efforts to increase understanding of the dynamics and feeding relationships of salps, mesopelagic fish and higher trophic level predators

Winter/transition period processes	- Improve general understanding of ecosystem dynamics and processes during winter and transition periods (winter-spring and autumn-winter)
Invasive species	- Improve understanding of the environmental constraints of non-native species and their likelihood of becoming invasive - Monitor the occurrence of non-native species (particularly larger fish species) and their possible mode of entry (e.g. via frontal systems or vessels)
Observation and monitoring	- Improve observation and monitoring to enable the distinction between ecosystem responses to climate change and the natural variability of the system - Use existing resources and also collaborate with MEASO and SOOS to develop a systematic approach to the development of observation and monitoring

CEMP = CCAMLR Ecosystem Monitoring Programme, FISH-MIP = Fisheries and Marine Ecosystem Model Intercomparison Project, MEASO = marine ecosystem assessment of the Southern Ocean, SOOS = Southern Ocean Observing System

Table 7. Potential ICED-CCAMLR collaborations to support development of quantitative ecological projections

Collaborations	Details
CMIP and IPCC	- Maintain dialogue and collaborations with physical and chemical modellers involved in CMIP and IPCC to encourage development and refinement of models, outputs, and projections in future CMIP Phases and IPCC Assessment Rounds that are suitable for generating physical and chemical scenarios and ecological projections
FISH-MIP	- Liaise with FISH-MIP to learn lessons (and provide feedback) regarding their approaches to generating quantitative ecological projections
IWC	- Collaborate with the IWC to obtain information on the recovery of whale populations
Further ICED-CCAMLR Projections Workshops	- Follow on workshops to refine assessments and development of quantitative projections as krill and ecosystem models and physical and chemical models are improved (based on advances in understanding of processes, mechanisms, and CMIP model development at the global and regional scale) - The frequency of these workshops should allow adequate time for scientific progress and to be considered within SC-CAMLR's 5 yr planning process. A second ICED-CCAMLR Projections Workshop could potentially be held alongside the SCAR Open Science Conference, Tasmania, Australia, 2020
WG-EMM	- Ongoing participation of ICED in WG-EMM to inform WG-EMM of progress and solicit feedback
Other CCAMLR Working Groups	- Participation of ICED in other relevant CCAMLR Working Groups and Workshops where appropriate
CCAMLR's draft Climate Change Response Work Programme (CCRWP)	- ICED to continue to provide input to the draft CCRWP as appropriate and contribute to the programme once finalised
SCAR Specialist and Action Groups	- Collaborate with relevant SCAR groups, including the new SCAR Krill Action Group (SKAG), and the SCAR Southern Ocean Acidification Group
MEASO and SOOS	- Continue collaborations with MEASO and SOOS to support observation and monitoring
ICED Task Teams	- Involvement of CCAMLR in ICED's planned Task Teams (which will coordinate the delivery of ICED in the coming years), for example to develop krill projections within a potential 'scenarios and projections' task team
ICED workshops and conference sessions	- Involvement of CCAMLR in future ICED workshops, such as the forthcoming ICED and MEASO Southern Ocean session at the IMBeR Open Science Conference, Brest, France, 2019. This will include CCAMLR and a range of stakeholders and is aimed at considering ways to improve research on understanding and projecting changes in SO ecosystems relevant to conservation and management strategies
List of references evidencing change	- Compile and update a list of references documenting evidence of ecosystem change in the Southern Ocean attributable to natural and climate-related change
Science papers	- ICED-CCAMLR scientific peer-reviewed paper that summarises rationale and outputs, and opinions generated in this workshop with policy makers (i.e. resource managers and the IPCC) as key focal audiences

	- Publication of ICED-Projections workshop summary reports so that they are widely accessible to science and policy makers (e.g. as information summaries on the Antarctic Environments portal)
Dissemination of results to policy makers	- Update the Antarctic Treaty (via SCAR and the CEP) and other relevant policy makers on current and future progress
Dissemination of results to global environmental research programmes	- Update Future Earth, SCOR via IMBeR (of which ICED is a regional programme) on current and future progress

CCAMLR CCRWP = Climate Change Response Work Programme, CEP = Committee for Environmental Protection, CMIP = Coupled Model Intercomparison Project, FISH-MIP = Fisheries and Marine Ecosystem Model Intercomparison Project, IMBeR = Integrated Marine Biosphere project, IPCC = Intergovernmental Panel on Climate Change, SCAR = Scientific Committee on Antarctic Research, IWC = International Whaling Commission, SCOR = Scientific Committee on Oceanic Research, SOOS = Southern Ocean Observing Programme, WG-EMM = CCAMLR's Working Group on Ecosystem Monitoring and Management

Appendix I. Agenda of the ICED Projections Workshop 2018

ICED Projections Workshop Agenda

Developing projections of the future state of Southern Ocean ecosystems:

Incorporating uncertainties associated with climate variability and change in CCAMLR's decision making

CCAMLR Headquarters, Hobart, Tasmania, Australia

5-7 April 2018

Convened by Eugene Murphy, Nadine Johnston, Keith Reid and Stuart Corney

The goal of the ICED Projections Workshop is to bring together experts from across the Southern Ocean scientific community to assess the potential impacts of climate change on the krill-centred ecosystem within Area 48 to provide advice in support of CCAMLR's management of the krill fishery. It is envisaged that this work will serve as a model for projecting the impacts of future change on other species and regions across the Southern Ocean, and form part of a sustained collaboration between ICED and CCAMLR to ensure relevant science can be used effectively in decision-making. The workshop objectives are to:

1. *Assess the potential drivers of change (within three decades and over the 21st century) in the ecosystems in the Scotia Sea and Antarctic Peninsula region of the Southern Ocean (Area 48);*
2. *Assess potential scenarios of these drivers (particularly sea ice change) in Area 48 and the potential impacts on availability of krill to predators and the fishery;*
3. *Examine alternative approaches to modelling and projecting changes in distribution, abundance and biomass of Antarctic krill in Area 48.*

Thursday 5th April

Welcome

09:00 Welcome – Eugene Murphy

09:05 Welcome to Country and Acknowledgement of Country – Stuart Corney

09:10 Opening address – CCAMLR Representative Keith Reid

Part 1. Setting the scene- key presentations

These presentations will outline the workshop goal and objectives and introduce the key issues. They will emphasise what we know about natural and anthropogenic variability and their impacts on physics, chemistry and biology in Area 48.

09:15 Workshop rationale, goal and objectives - Eugene Murphy

09:45 Operation and management of the Antarctic krill fishery in Area 48 - Keith Reid

10:05 Krill biology, life history, and population dynamics in Area 48- Christian Reiss

10:20 Variability and change in sea ice in Area 48 - William Hobbs

10:35 Questions

10:50 Morning tea & Coffee

11:20 Status of physical scenarios of Southern Ocean change - Stuart Corney

11:35 Ecosystem modelling approaches in Area 48- Andrew Constable

11:55 Questions

12:10 Summary of workshop format to address goal and objectives– Nadine Johnston & Eugene Murphy

12:25 Questions

12:30 Lunch

Part 2: Developing scenarios for Area 48 and understanding the potential impacts on krill

The challenge: To develop a strategy for providing CCAMLR with the information it needs to support krill fishery management options in response to future climate change we must first establish the specific requirements of CCAMLR. Part 2 will then focus on considering the major potential (global and regional, natural and anthropogenic) drivers of change in Area 48 by 2050 and 2100, the status of future scenarios of these drivers, and their potential impacts on krill (including their availability to predators and to the fishery). As the ultimate aim is to develop ecosystem models that can project future changes in krill distribution, abundance and biomass over these time frames, we will also assess the status of current krill (and associated) ecology models and consider alternative approaches to coupling them with scenarios of key drivers. These discussions will form the basis for activities in Part 3 and 4.

Plenary Discussion 1: CCAMLR's requirements (chair Watters, rapporteur Watters)

Breakout Group 1a, b & c: Drivers and scenarios (chairs Corney, Meijers, Hobbs, rapporteurs Subramaniam, Trebilco & Hobbs)

Plenary: Summary of Breakout Group 1a, b & c

Afternoon tea & Coffee

Breakout Group 2a, b & c: Impacts on krill (chairs Hill, Kawaguchi, Jackson, rapporteurs Hill, Kawaguchi & Costa)

Plenary: Summary of Breakout Group 2a, b & c

17:30 Adjourn

18:00 ICED-breaker (The Duke of Wellington Hotel)

Friday 6th April

Part 3: Developing initial projections of change in Area 48

The challenge: In order to generate qualitative and quantitative projections of krill populations in Area 48 in response to future climate change by 2050 and 2100, Part 3 will focus on considering a range of future scenarios of key drivers and the likely associated projections of ecological and fishery changes. These initial assessments and statements will form the basis for activities in Part 4.

Plenary: Recap of previous day

Breakout Group 3a, b, c & d: Developing initial projections (chairs Piñones, Welsford, Hill, Jackson, rapporteurs Piñones, Welsford, Hill, Jackson)

Morning tea & coffee

Continue Breakout Groups 3 a, b, c & d

Plenary: Summary of Breakout Group 3a, b, c & d

Lunch

Part 4: Developing projections of change: Recommendations to CCAMLR

The Challenge: To provide CCAMLR with immediate qualitative projections of changes in krill populations in Area 48 in response to future climate change by 2050 and 2100. This session will generate a jointly agreed IPCC-style set of statements (and associated uncertainties) based on the initial statements generated by Breakout Groups 3a, b, c & d. These will cover a range of future scenarios of key drivers and associated projections of ecological and fishery changes. This session will also develop these statements more specifically for CCAMLR.

Plenary Discussion 2: Qualitative projections of change (chair Murphy, rapporteur Johnston)

Afternoon tea & coffee

Plenary: Summary of Plenary Discussion 2

The Challenge: To provide CCAMLR with a Strategy for developing quantitative projections of changes in krill populations in Area 48 in response to future climate change by 2050 and 2100. This session will generate a Strategy that summarises the key short-term (immediately post workshop) and long-term (over the next few years) steps that the ICED community can to take in order to develop quantitative model projections. This will include the scientific steps needed to refine ecological models and scenarios to facilitate their coupling, and the future iterative collaborations between ICED and CCAMLR to support alternative management options, implementation, and management strategy evaluations, as ICED projections are developed, refined and expanded. It will also include mechanisms for an iterative process of projection development in association with the IPCC assessment cycle, as part of a sustained collaboration between ICED and CCAMLR.

Plenary Discussion 3: Quantitative projections of change (chair Murphy, rapporteur Johnston)

Plenary: Summary of Plenary Discussion 3

17:30 *Adjourn*

18:00 *Workshop dinner (Willie Smith's Apple Shed, Huon Highway, Grove)*

<u>Saturday 7th April</u>

Part 5: Workshop outputs

Plenary: Recap of previous day

<u>Plenary Discussion 4. Summary of key findings and recommendations to CCAMLR (Chair Murphy, rapporteur Johnston</u>

Morning tea & coffee

<u>Plenary Discussion 5. Workshop outputs and dissemination (Chair Murphy, rapporteur Johnston)</u>

12:00 **Close of meeting and lunch**

Appendix II. Participants of the ICED Projections Workshop 2018

Surname	Name	Country	Institute	Contact
Bindoff	Nathan	Australia	University of Tasmania (UTAS)/Institute for Marine and Antarctic Studies (IMAS)/ Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC)	n.bindoff@utas.edu.au
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Jackson	Jen	UK	BAS	jeck@bas.ac.uk
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Kawaguchi	So	Australia	AAD/ACE CRC	so.kawaguchi@aad.gov.au
Korczak-Abshire	Malgorzata	Poland	Institute of Biochemistry and Biophysics Polish Academy of Sciences/Chair WG-EMM	korczakm@gmail.com
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Nicol	Stephen	Australia	UTAS	steve.nicol@utas.edu.au
Piñones	Andrea	Chile	Universidad Austral de Chile/Centro de Investigacion Dinamica de Ecosistemas Marinos de Atlas Latitudes (Centro IDEAL)	pinones.a@gmail.com
Reid	Keith	Australia	Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)	keith.reid@ccamlr.org
Reiss	Christian	USA	National Oceanic & Atmospheric Administration (NOAA) Fisheries, South West Fisheries Center	christian.reiss@noaa.gov
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Zhu	Guoping	China	Shanghai Ocean University	gpzhu@shou.edu.cn
Additional contributors not in attendance				
Atkinson	Angus	UK	Plymouth Marine Laboratories	aat@pml.ac.uk
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Appendix III. List of summary reports for the ICED Projections Workshop 2018

These summary reports were prepared ahead of the Workshop. They provided background information on past, current and future changes in physical, chemical and biological aspects of Southern Ocean ecosystems within Area 48 to support workshop discussions. Please contact individual authors for documentation.

WS-SR-1-2018. Status of ecosystems in the northern Antarctic Peninsula (Reiss & Watters)

WS-SR-2-2018. Dynamics of krill populations in the Antarctic Peninsula and Scotia Sea (Murphy, Reiss & Hofmann)

WS-SR-3-2018. Changes in zooplankton populations (other than krill) (Johnston, Atkinson & Tarling)

WS-SR-4-2018. Changes in fish populations and fin fisheries (Belchier)

WS-SR-5-2018. Changes in seals and seabirds (Costa & Trathan)

WS-SR-6-2018. Changes in whale populations (Jackson)

WS-SR-7-2018. Alternative Southern Ocean ecosystem models (Trebilco, Melbourne-Thomas, Constable & Murphy)

WS-SR-8-2018. State of Southern Ocean fisheries (Reid)

WS-SR-9-2018. Krill biological influences on krill fishing operations (Nicol & Kawaguchi)

WS-SR-10-2018 Variability and change in sea ice (Hobbs)

WS-SR-11-2018. Potential impacts of ocean acidification on Southern Ocean ecosystems (Bellerby)

WS-SR-12-2018. Potential impacts of ocean acidification on krill (Kawaguchi)

WS-SR-13-2018. Status of scenarios of change for the Southern Ocean (Cavanagh, Corney, Meijers, Hobbs, Lenton, Bracegirdle & Bindoff)

WS-SR-14-2018. Detection of change through biological observation programmes (Constable, Newman, Swart, Schofield, Williams & Bricher)

WS-SR-15-2018. Inclusion of climate change assessments in marine protected area (MPA) development and reviews (Grant, Santos & Capurro)

WS-SR-16-2018. Inclusion of climate change scenarios in current Risk Assessment and Krill Yield models (Constable)

WS-SR-17-2018. Inclusion of climate change scenarios in the FOOSA model (Watters & Hill)

Appendix IV. A guide to the treatment of uncertainty (from Stocker et al. 2013).

Box TS.1 | Treatment of Uncertainty

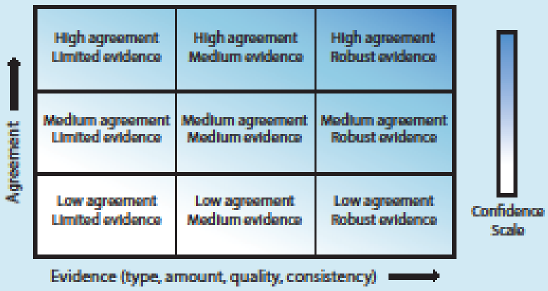
Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, this WGI Technical Summary and the WGI Summary for Policymakers rely on two metrics for communicating the degree of certainty in key findings, which is based on author teams' evaluations of underlying scientific understanding:

- Confidence in the validity of a finding, based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgement) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgement).

The AR5 Guidance Note refines the guidance provided to support the IPCC Third and Fourth Assessment Reports. Direct comparisons between assessment of uncertainties in findings in this Report and those in the AR4 and the SREX are difficult, because of the application of the revised guidance note on uncertainties, as well as the availability of new information, improved scientific understanding, continued analyses of data and models and specific differences in methodologies applied in the assessed studies. For some climate variables, different aspects have been assessed and therefore a direct comparison would be inappropriate.

Each key finding is based on an author team's evaluation of associated evidence and agreement. The confidence metric provides a qualitative synthesis of an author team's judgement about the validity of a finding, as determined through evaluation of evidence and agreement. If uncertainties can be quantified probabilistically, an author team can characterize a finding using the calibrated likelihood language or a more precise presentation of probability. Unless otherwise indicated, high or very high confidence is associated with findings for which an author team has assigned a likelihood term.

The following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. Box TS.1, Figure 1 depicts summary statements for evidence and agreement and their relationship to confidence. There is flexibility in this relationship; for a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement correlate with increasing confidence.



Box TS.1, Figure 1 | A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases toward the top right corner as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high quality. [Figure 1.11]

The following terms have been used to indicate the assessed likelihood, and typeset in italics:

Term*	Likelihood of the outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms (*extremely likely*: 95–100% probability, *more likely than not*: >50–100% probability, and *extremely unlikely*: 0–5% probability) may also be used when appropriate.

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