# Using models to improve our understanding of Antarctic krill and their ecological role in the Southern Ocean

REPORT of the online Integrating Climate and Ecosystem Dynamics of the Southern Ocean (ICED) workshop, 17-20 May 2021

---


**<u>Organizing committee:</u>**
ECRs: Devi Veytia, Alexis Bahl, Zephyr Sylvester, Dominik Bahlburg
Along with Eugene Murphy, Stuart Corney, Eileen Hofmann, Bettina Meyer, Nadine Johnston, Sally Thorpe, Cassandra Brooks

**<u>Supporting ECRs:</u>**
Tracey Dornan, Andréa Mesquita, Cecilia Liszka, Mauricio González Díaz, Akeem Olaniyu, Nicole Hellessey, Katherine Hudson, Onur Karakus, Sara Labrousse, Denise O'Sullivan, Elisa Seyboth and Svenja Halfter

**Summary:**
The Integrating Climate and Ecosystem Dynamics in the Southern Ocean program (ICED) provides a framework for research by identifying key science priorities and delivering targeted research and activities to understand the interactions between climate and ecosystem dynamics, their links to the Earth System, and generate scenarios and projections of the impacts of future change to support conservation and management. Over the coming decades major shifts in Southern Ocean ecosystems are expected in response to multiple stressors including climate-driven change and harvesting, with consequences for marine ecosystems and societies around the world. Understanding and predicting the response of Southern Ocean ecosystems is crucial for conservation and sustainable management. This report summarizes the ICED-sponsored workshop, 17-20 May 2021, focussed on improving our modelling of Antarctic krill (hereafter krill) which is a keystone species in Southern Ocean food webs and the subject of an international fishery. The workshop also aimed to provide Early Career Researchers (ECRs) with opportunities to network and highlight their work, as part of ICED's wider goal of including ECRs in ICED activities to foster career development and shape the future of ICED research. This was also timely in providing opportunities for this cohort of researchers that have been limited during the COVID-19 pandemic. The workshop included background talks together with three themed sessions focussing on key aspects of krill modelling. Each themed session contained the main components: (1) speed talks presenting ongoing research projects; (2) tutorials on current approaches/best practices on methods for modelling krill; and (3) zoom polls and guided discussions on advancing understanding. Workshop attendees represented a broad cross-section of the international krill modelling community, in addition to researchers focussed on other species, comprising 81 registered participants across all career stages. This report summarises initial findings for research priorities, data requirements, facilitation methods for integrating modelling approaches, and ideas for fostering ECR networks and involvement within the ICED community.

# Table of contents

# 1. Workshop outline

This workshop was a targeted research activity to improve understanding of circumpolar ecosystem structure and function in order to link to the Earth System, to generate scenarios and projections of future change, and to support sustainable governance. As krill are a key species within the Southern Ocean and the subject of an international fishery, modelling their behaviour, population dynamics, ecological processes and environmental drivers, as well as developing future projections, will facilitate ecosystem-based management of the krill fishery. This requires consideration from the perspectives of different modelling fields, and working to advance capabilities within each. These advancements will come from addressing key knowledge gaps, including understanding of how krill population dynamics and their ecological roles connect across scales from individuals to populations, as well as in cycling energy and nutrients from phytoplankton to top predators to the deep ocean. Improving our representation of these mechanisms requires improvements in the data and process studies that underpin these models, as well as the representation of the Southern Ocean physical and biological processes within the Earth System Models that are used to provide both current climate and future projections. There is impetus for a workshop to provide community-driven input into the future directions of krill modelling research, as well as engage the next-generation of researchers in this field. In light of how the COVID-19 pandemic and travel restrictions have interrupted conventional avenues for ECRs to attend face-to-face conferences and workshops. This workshop also aimed to provide opportunities for ECR career development, to make important contacts within the research community, to further develop skills in science communication, and to feature their research amongst their peers and the wider community.

The workshop aimed to:

1. outline a clear set of priority research needs for the development of models of krill and the wider ecosystem and to help inform decision-making for conservation and management;
2. develop insights into integrating modelling approaches; and
3. foster connections between ECRs and established researchers.

These aims were accomplished over 4 days of 2 hour sessions, organized across the following themes:
May 17, Introduction and context of krill modelling in the Southern Ocean
May 18, Theme 1: Modelling krill from individuals to populations: linking across scales
May 19, Theme 2: Environmental drivers of krill population dynamics and distribution
May 20, Theme 3: Ecosystem impacts of changes in krill populations, and implications for conservation and management and conclusions

These themes were selected to encompass the main areas for krill modelling research, which have cohesive data requirements, methods, knowledge gaps and aims. Each theme was structured into three sections:

1. Tutorials: 20 minute presentations provided participants with an overview of a topic relevant to the theme, including methodological and analytical approaches.

2. Speed talks: 5 minute presentations provided concise syntheses of a researcher's current work. These allowed the community to exchange ideas on current research, assess what work is being undertaken in this field.
3. Discussion: Based on the tutorial and speed talks, the discussion sessions facilitated the exchange of ideas to identify research priorities, data requirements and approaches for addressing research challenges. These sessions were structured into two parts:
    a. Zoom polling. Zoom polls were predetermined multiple or single choice questionnaires that were completed by the participants live during each online session. Questions relating to each theme were posed to the participants at the beginning of each discussion session. Results can be found in the "Polling results" sub-sections for each theme.
    b. Chaired discussion. These discussions were more malleable depending on the interests and priorities of the participants. It was left to the co-chairs' discretion to stimulate discussion either based on a topic of interest that had already emerged from the presentations from that theme, or from a list of pre-determined open-ended discussion questions. Participants were invited to respond verbally or in the chat, and the participation of ECRs was particularly encouraged.

A full schedule can be found in Appendix A, a list of registered participants in Appendix B, and the participant demographics in Appendix C.

# 2. Theme summaries

## 2.a Background

The first day comprised a series of background talks designed to give context for framing our research questions and key priorities in modelling Antarctic krill. These included an introduction to the workshop aims and objectives, an overview of the Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) program, and a summary of outcomes from the recent SCAR Krill Action Group (SKAG) meeting held in April 2021, and the current state of krill modelling science including Southern Ocean data availability, CCAMLR's use of modelling in management, and a review of current Southern Ocean ecosystem modelling from the perspectives of the workshop themes.

Dr. Eugene Murphy linked scientific challenges of understanding the structure and functioning of Southern Ocean ecosystems, the impacts of climate change, role in biogeochemical cycles and provision of scientific advice for conservation and management - central to addressing these challenges is improved understanding of the biology and ecology of Antarctic krill. Dr. Murphy emphasized the spatial and temporal variability of krill distribution and abundance and the importance of considering scales of physical, biogeochemical and biological poceesses and their interactions in developing analyses and models of krill. The modelling studies presented in the workshop will cover models that consider processes over a very wide range of scales including studies of behaviour and physiology, regional population dynamics and connectivity, food web interactions and future projections of distribution and abundance.

Dr. Bettina Meyer provided an overview of the outcomes of the SKAG workshop on ‘Evaluating change within the krill-based food web and developing solutions for the future sampling of krill’, held in April 2021, in order to provide context of the research priorities for the broader krill research community. Along with identifying research priorities, the 2021 workshop identified possible sampling methods to support the research process. The SKAG workshop outcomes highlight the broader research community's overall desire to improve the generation of scientific data that can be effectively utilized in Southern Ocean management.

Centralizing the focus of the workshop on what is currently being done and what is possible for the krill modelling community, the final three talks of the day covered data availability, the use of data to support management, and the state of ecosystem modelling. The key principles of data standardization, and generation of polar and global datasets were discussed by Dr. Anton van de Putte in the context of the key data principles. The talk also provided examples of all the current major databases relevant for the krill modelling community as well as advice on how to access data (Appendix D).

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is a multi-national body responsible for management of the Southern Ocean ecosystem. Under the CCAMLR Convention, management is based on a mandated precautionary, ecosystem-based approach—including managing for environmental change, and based on the best available science (Box 1). Science continuously feeds into the decision making process through CCAMLR’s Scientific Committee and Working Groups. Dr. So Kawaguchi presented a detailed overview of how krill are currently managed by CCAMLR, how data are incorporated into management decisions, and the challenges facing the scientific community charged with providing scientific advice to the decision makers. Dr. Kawaguchi identified key questions for models to answer that would best feed into management. These questions included: 1) What are the appropriate scales for management? 2) What would an ecosystem model for management look like? 3) How often do management approaches need to be updated? 4) Based on environmental drivers for krill distribution and future changes, what areas need special attention? 5) What are the likely scenarios and how to prepare?

**Box 1. CCAMLR**

The historical unmitigated harvesting of whales and seals in the Southern Ocean resulted in their unsustainable use and the subsequent collapse of many populations. In the 1970s, the fishing industry began to take a renewed interest in the Southern Ocean through the harvest of Antarctic krill. This raised concern alongside the previous history of resource exploitation, as krill were already recognized for their role as an important prey source in Southern Ocean food webs.

This concern provided the impetus for the Antarctic Treaty parties, along with input from the Scientific Committee on Antarctic Research, to form a management body to oversee the sustainable management of the krill fishery. The Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention) was subsequently adopted as an international treaty in 1980 to establish conservation measures and other harvesting activity decisions impacting Antarctic marine resources (for a map of the CAMLR area, see http://gis.ccamlr.org). The Commission (CCAMLR) was subsequently established in 1982 as the decision-making body to carry out the provisions of the CAMLR Convention including to formulate, adopt, and revise conservation measures based on the best scientific evidence available (Article VII of CAMLR). CCAMLR adopted an innovative approach to resource management, which considered not only the continued availability of the resource for the fishery, but also for the maintenance of its role within the wider ecosystem (Article II of CAMLR). This approach is known as ecosystem based management (EBM).

Advice based on the best available science is a key component that supports the EBM and conservation of Antarctic marine life. This responsibility is held by the Scientific Committee (SC-CAMLR). SC-CAMLR achieves its mandate by running data collection programs to feed into their recommendations, which include fisheries monitoring, scientific observers on fishing vessels and ecosystem monitoring. Specialized working groups, such as the Working Group on Ecosystem Monitoring and Management (WG-EMM) also play a role in formulating advice on key areas. In the context of the krill fishery, models that represent krill, their population dynamics, distribution and abundance, environmental drivers and ecosystem functions are valuable for assessing current and future impacts of the fishery and potential risks. An example includes the Generalized Yield Model (GYM) which is actively used by CCAMLR to inform decision making by generating projections of krill populations under various scenarios. Therefore the content and outcomes of this workshop directly support the objectives of SC-CAMLR.

*More information on CCAMLR can be found on their website: https://www.ccamlr.org/*

For each theme of the workshop, Dr. Eileen Hoffman provided participants with an overview of what is known, what is needed, and where future research can go. Theme 1 covered modelling krill from individuals to populations and linking across scales. Regarding individual krill, we are currently able to model controls on egg descent/larval ascent and post-larval growth relatively well. However, we need extended experiments on mechanistic physiological responses under different environments. When considering krill swarms, krill models have different parameterizations for swarm initiation. To improve these models we need experimental observations on behavioural ecology as well as new technologies and observations (e.g. remote sensing). Lastly, models of krill populations and the food web are in need of experimental observations of the role of krill within the food web.

The second theme focused on environmental drivers of krill population dynamics and distribution. There are currently summaries of large datasets that allow us to explore krill habitat distribution and related environmental parameters. Coupling these statistical relationships with gridded environmental datasets allows habitat quality to be predicted. Models have subsequently identified regions of plausible krill habitat that have sparse sampling coverage of krill data. Within these spaces, coincident distributional and environmental data would improve our ability to evaluatemodel predictions.

In regards to the final theme, ecosystem impacts of changes in krill populations, and implications for conservation and management, the most significant question for addressing this theme is how we take projections and incorporate food web interactions (e.g. phytoplankton assemblages).

In general, the opening day highlighted that future research should focus on improving our understanding of trophic links and biogeochemical cycling within the Southern Ocean food web. Other key research challenges included human impacts, impact and attribution and adaptation pathways (ie alternate energy pathways, what happens in years when krill are not important). New approaches to address these areas could include data (e.g. ‘omics branches of biology that include genomics, proteomics, metabolomics, metagenomics and transcriptomics), new technologies (autonomous underwater vehicles; AUVs), and model ensembles. Future research should also consider  what observations are needed to advance our models and what kinds of data are needed to get mechanistic understanding rather than empirical relationships. One possible framework that could advance the krill modelling community would be a Coupled Model Intercomparison Project (CMIP)-style framework for krill models with community-based scenarios that would allow models to  be compared across systems.

### 2.a.i Polling results

Of the ~75 participants in attendance at the workshop on the first day, the majority of people joined the meeting from Europe (33% of participants), followed closely by North America (25%) and Australia/New Zealand (21%), as well as South America (13%), Africa (4%) and Asia (4%) (Figure C.1). Early career researchers (<7 years of experience) were the most highly represented career stage at the workshop (64% of participants). Mid-career researchers (7-20 years of experience) made up 27% of participants while 9% of participants were in the expert stage of their careers (>20 years of experience) (Figure C.2).

In order to better understand the research challenges and needs of the krill modelling communities, participants were asked polling questions. First they were asked what they thought were the top two challenges for modelling in Antarctic krill research. The majority of participants agreed that controls on krill population dynamics, distribution, and abundance as well as the impacts of climate change were the top challenges facing the krill modelling community (Figure 2.3). Next, participants were asked to indicate which sampling approaches from the year-round operating fishery (already available and emerging) were most applicable to their modelling work  (Figure 2.4).

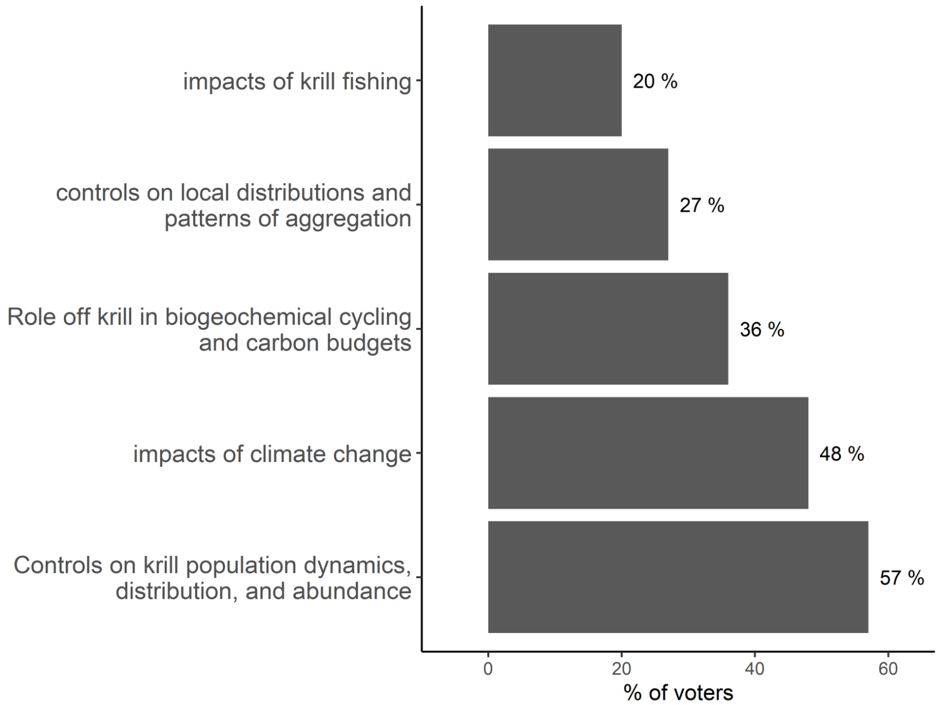


**Figure 2.3 Polling results from the question: "What are the key challenges for modelling in Antarctic krill research? (select 2 options)".**

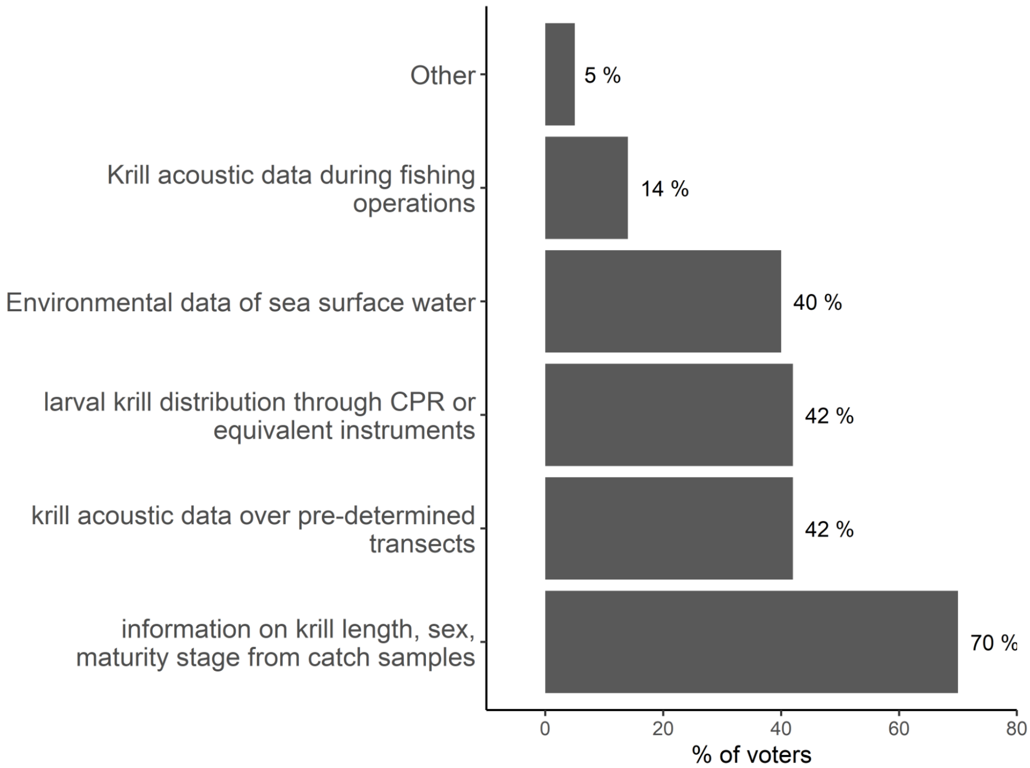


**Figure 2.4 Polling results from the question: "What sampling approaches from the year-round operating fishery (already available and emerging) are most applicable to innovating your modelling work?"**

## 2.b Theme 1: Modelling krill from individuals to populations: linking across scales

The second day of the workshop addressed Theme 1. The day began with two tutorials:

1. Choosing a model for representing Antarctic krill
By Andrew Constable.

This tutorial insightfully challenged the common quote by George Box that "all models are bad, but some are useful", which has become a proverb for the modelling community, instead shifting the focus to understanding what makes a model good. A definition for a good model was proposed as "one that is structurally and logically defensible, does not constrain emergent properties, and results in those properties satisfactorily approximating reality". This presentation then laid out the framework for building a good model within this new paradigm, using a fully-dynamic krill model developed by the presenter as a case study. The presentation also discussed how models such as this may be useful for exploring the effects of different scenarios for management purposes.

Next steps for improving the parameterisations of these models included getting a better understanding of trade-offs and priorities between growth and reproduction, feeding, energetics of physiological condition and movement, energetics of larvae and juveniles, and limits to moult increase-decrease under different temperature regimes. Field studies with co-located samples of krill physiological condition, demographics and environment over the seasonal cycle were also identified as important for model validation.

2. Modelling krill across scales
By George Watters.

This presentation was framed around the research question of using modelling across scales to inform management when the scales of krill management and fishing are mismatched. This question also dealt with krill flux as a mechanism that modulates the supply of krill to the fishery and predators. Within this scope, the presentation addressed the following aims:

1. To provide background on a cutting edge approach in the field. Here management strategy evaluation (MSE) was described
2. Provide a case study of how the approach can be innovatively applied. Here the overall structure and mechanics of an MSE for the krill fishery in CCAMLR area 48.1 was described. The biological model component for krill biomass involved coupled ordinary differential equations that included parameters for krill flux with randomized initial conditions.
3. Explore how these approaches can be used to make inferences about different performance metrics and management strategies. This included scenario building and model fitting.
4. Future improvements for the case study model. These included parallelizing computations, reparameterization of links between local and remote inputs

and recruitment, using circulation to constrain fluxes between biomass pools and fitting to time series of biomass estimates.

Speed talks comprised modelling projects directed towards representing Antarctic krill population processes across scales, from individual-based models (IBMs) through to fully-dynamic population models.

### 2.b.i Polling results

Zoom polling was carried out to find out the workshop participants' views on research priorities, challenges and data requirements in relation to Theme 1.  Participants could give multiple responses to the survey questions and, as such, the poll results in the following figures give the percentage of voters that selected an option, rather than the percentage of total votes and hence do not sum to 100%. Overall, polling identified uncertainty in krill population connectivity, and regional-scale dynamics and distribution as research priorities.

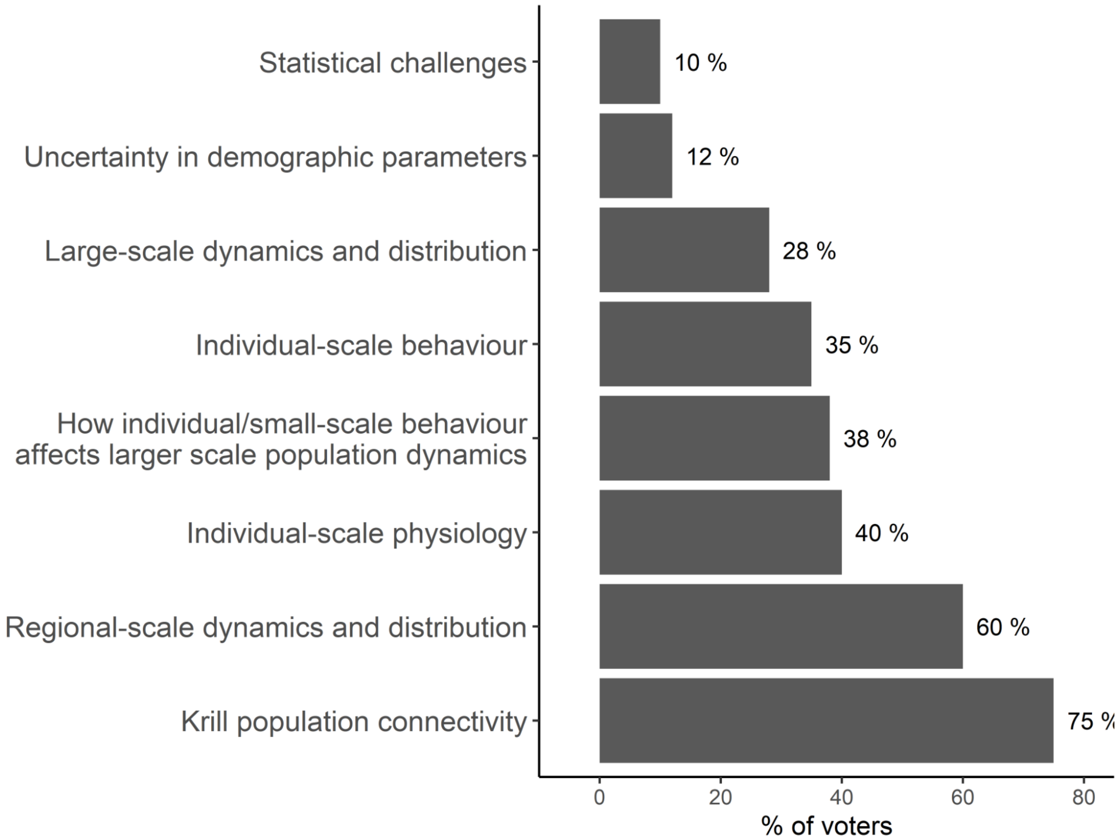


**Figure 2.5 Polling results from the question: "What are the priorities for improving models of the life cycle and circumpolar scale distribution and abundance of Antarctic krill?"**

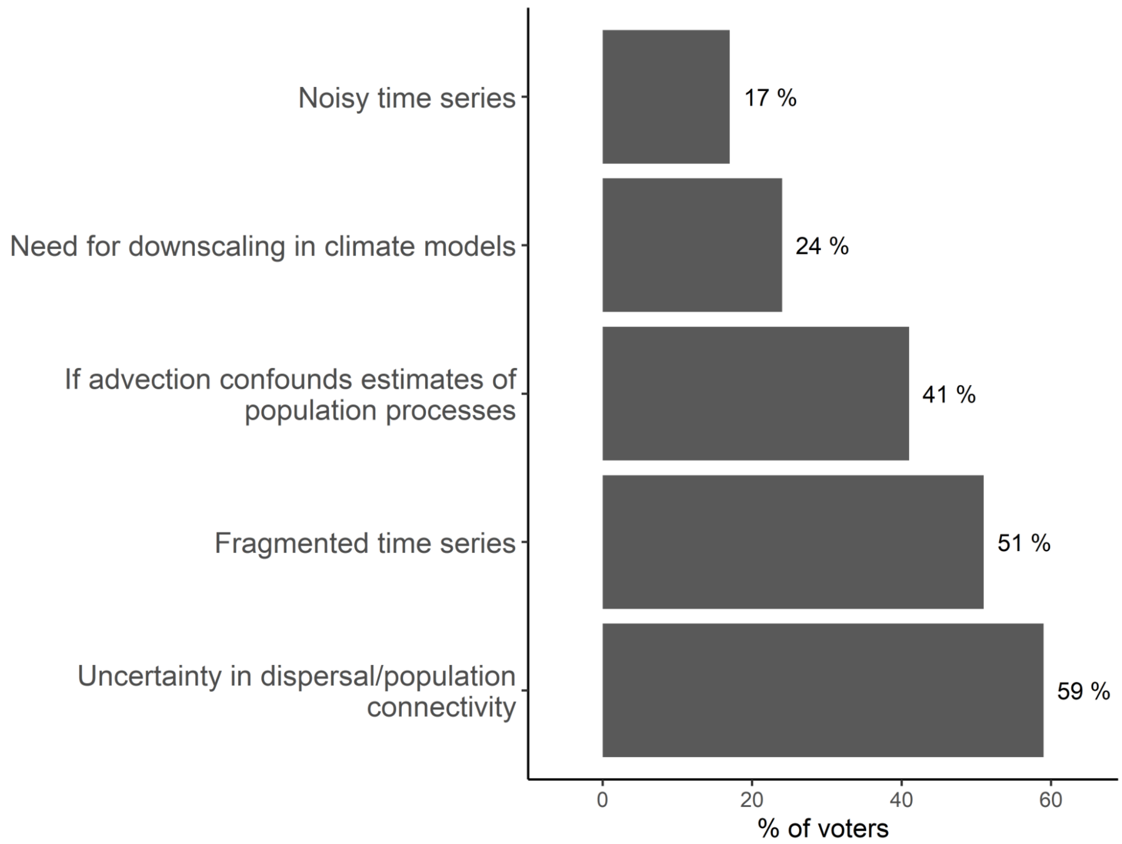


**Figure 2.6 Polling results from the question: "What are the biggest challenges to modelling krill at regional scales?"**

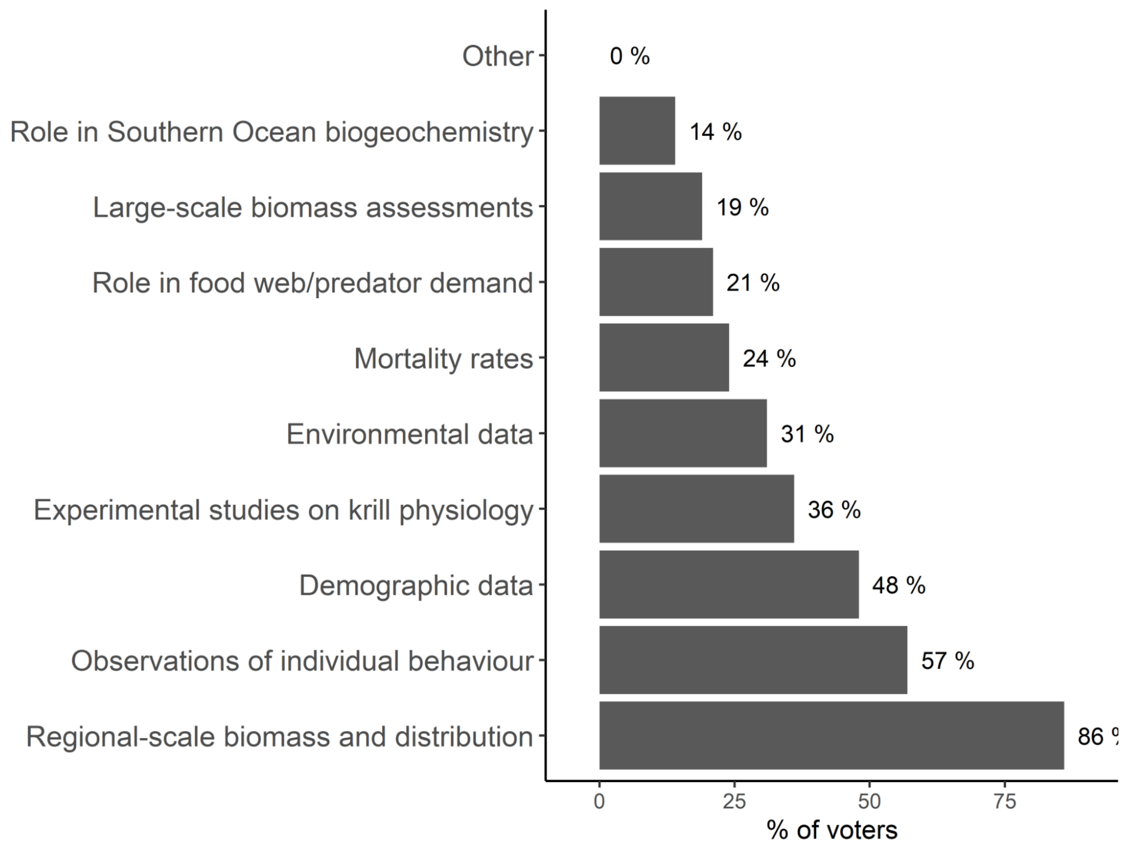

**Figure 2.7 Polling results from the question: "What are the main data (observational and process studies) requirements to improve these research priorities and challenges?"**

## 2.b.ii Discussion summary

The discussion focussed on identifying further research priorities and their concomitant data requirements. Emerging modelling approaches for making inferences on krill population dynamics from highly variable existing data were also discussed.

The research priorities that were identified reflected key knowledge gaps in modelling krill across scales:

- Individual scale: process studies aiming to quantify the direct links between environmental conditions and biological processes, e.g. growth and survival, were highlighted as important. These studies would need to resolve variability in environmental conditions, such as food availability and quality, over longer spatiotemporal scales. This would include seasonal coverage over interannual timescales, as well as sampling over larger areas that comprise different regions and habitats, such as within sea ice and open ocean.
- Intermediate scale: better understanding of swarm energetics and the interaction with circulation was identified as important for understanding the health of krill in swarms, and parameterizing the transport of krill within regions.
- Larger scale: scaling up regionally-focused food web models incorporating krill to larger-scales was identified as an important challenge. Regional food web models that are developed independently from un-coordinated science programs may not be comparable due to different structures, yet standardized models may be comparable but might all be similarly wrong.

To improve our understanding of these priorities for modelling krill across scales, key data requirements were identified.

Data requirements largely reflected a need to better parametrize variability in individual physiology and energetics and movement across seasonal and larger spatial scales. From an energetics perspective, the data requirements were broad. These included:

- Energetics of individuals within swarms
- Energetics of trade-offs between growth and reproduction
- Energetics of larvae. Larval and juvenile energetics in particular pose logistical challenges as such measurements need to be carried out *in-situ* on ships or stations.

For improved model evaluation, the importance of co-located samples was also stressed. Such a regime would include:

- Samples of krill physiological state and demographics (e.g. weight, instantaneous growth rate, body length, condition and reproductive stage). Emphasis was placed on the need for a measure of weight. Since weight and growth are unrelated in krill, a measure of weight would be useful to understand feeding success.
- Environment (e.g. food concentration, water temperature, local krill densities). It was agreed that seasonal variability in all measurements would need to be resolved in future sampling strategies.

Future directions for modelling applications to support emerging sampling methods and data were also discussed. To direct future sampling strategies, modelling approaches such as management strategy evaluation could be used to assess the performance of different data types and sampling programs to maximize units of sampling effort. To support emerging data, modelling approaches to make inferences from highly variable existing data were also discussed. Promising methods included comparative approaches, partitioning error and integrating modelling. In general, the importance of informed parameter selection, rather than model parsimony was discussed, alongside the need for increased emphasis on model development, testing and validation stages.

## 2.c Theme 2: Environmental drivers of krill population dynamics and distribution

Theme 2 comprised modelling projects ranging from best practice in the application of different types of environmental data as inputs into krill models, to simulating krill population dynamics and inferring distribution from environmental predictors. The day began with the following two tutorials:

<u>1. Using gridded environmental information</u>
By Stuart Corney, David Green, Denisse Fierros Arcos and Devi Veyia

This tutorial aimed to provide the participants with:

- An understanding of the role of gridded environmental data in research
- A list of considerations helpful for selecting a product, and determining the appropriate product(s) for the research question
- A workflow for improving the reliability of information by assessing strengths and limitations of gridded data

The application of these concepts in model selection and evaluation was demonstrated through a case study taken from Veytia et al. (2020, *Nature Climate Change*).

<u>2. Approaches for Ecosystem Modelling: Ecopath</u>
by Alexis Bahl and Simeon Hill

This tutorial aimed to provide the audience with:

- An introduction to Ecopath with Ecosim (EwE) accompanied by a demonstration of the use of mass balance in a constructed and hypothetical ecosystem model representing South Georgia
- An understanding of network analysis and the indicators extractable from the EwE food web outputs
- A list of uncertainties, best practices, and reference guides for balancing EwE models
- An overview of studies using EwE to increase an understanding of Antarctic krill

Speed talks comprised modelling projects focused on dynamic processes for determining environmental drivers on krill distribution, recruitment, and spawning.

### 2.c.i Polling results

Overall, for improving models of krill response to current and future environmental drivers, polling identified a need for better understanding of the functional relationships between the environment and krill population dynamics, and how these relationships will respond to future change. Particular emphasis was placed on sea ice as an overwintering habitat, as well as regional-scale biomass and distribution.

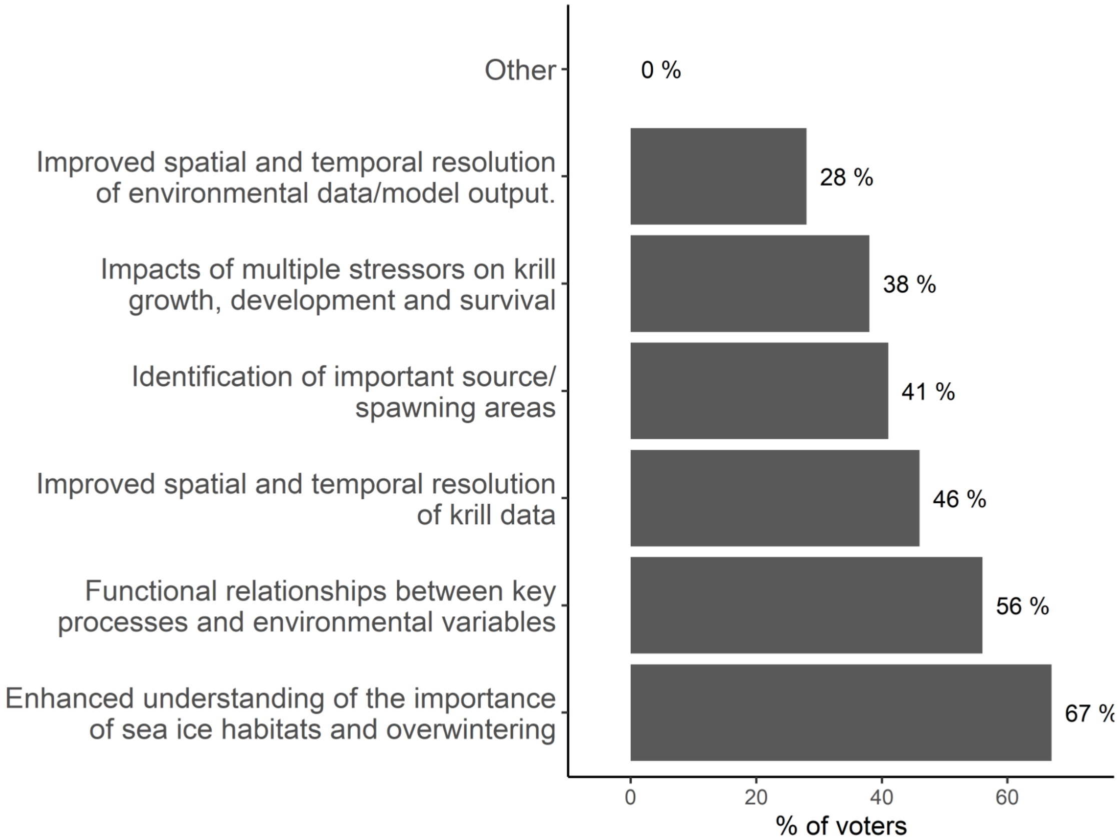


**Figure 2.8 Polling results from the question: "What are the priorities for improving models of the environmental drivers of krill population dynamics and distribution? (select 3)"**

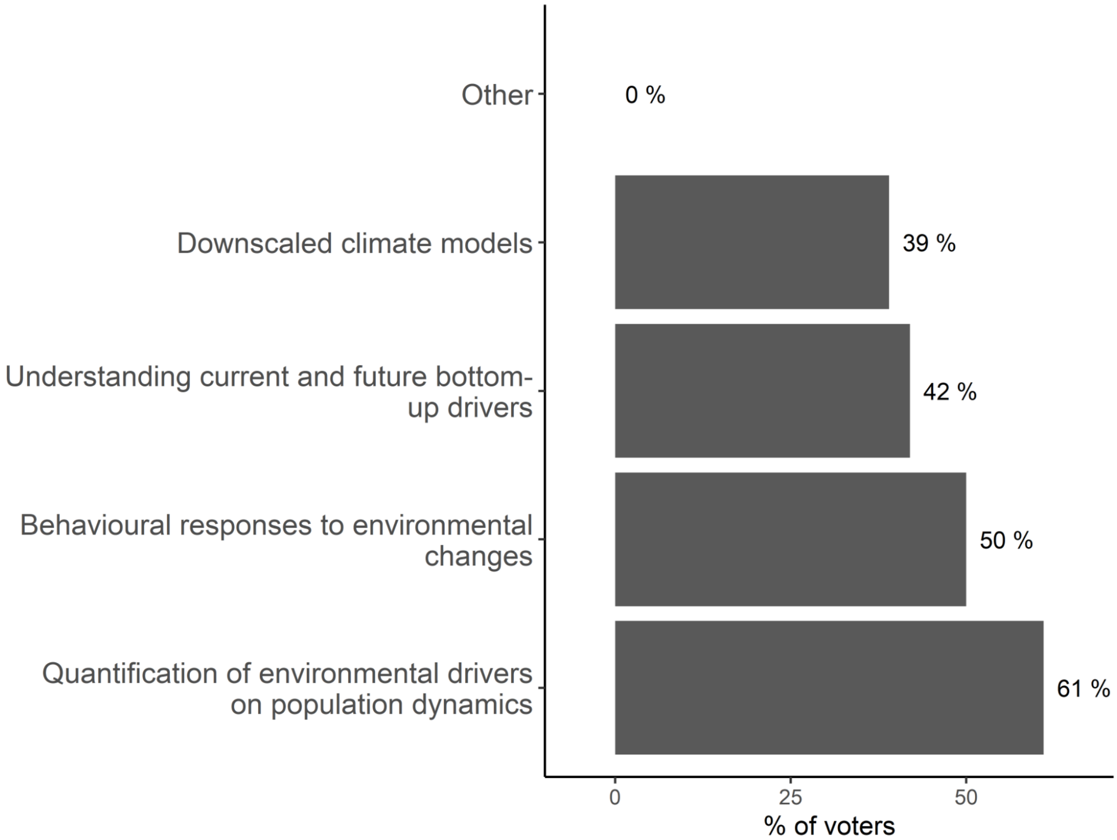


**Figure 2.9 Polling results from the question: "What are the next steps/biggest knowledge gaps for predicting climate change impacts on krill (select 2)"**

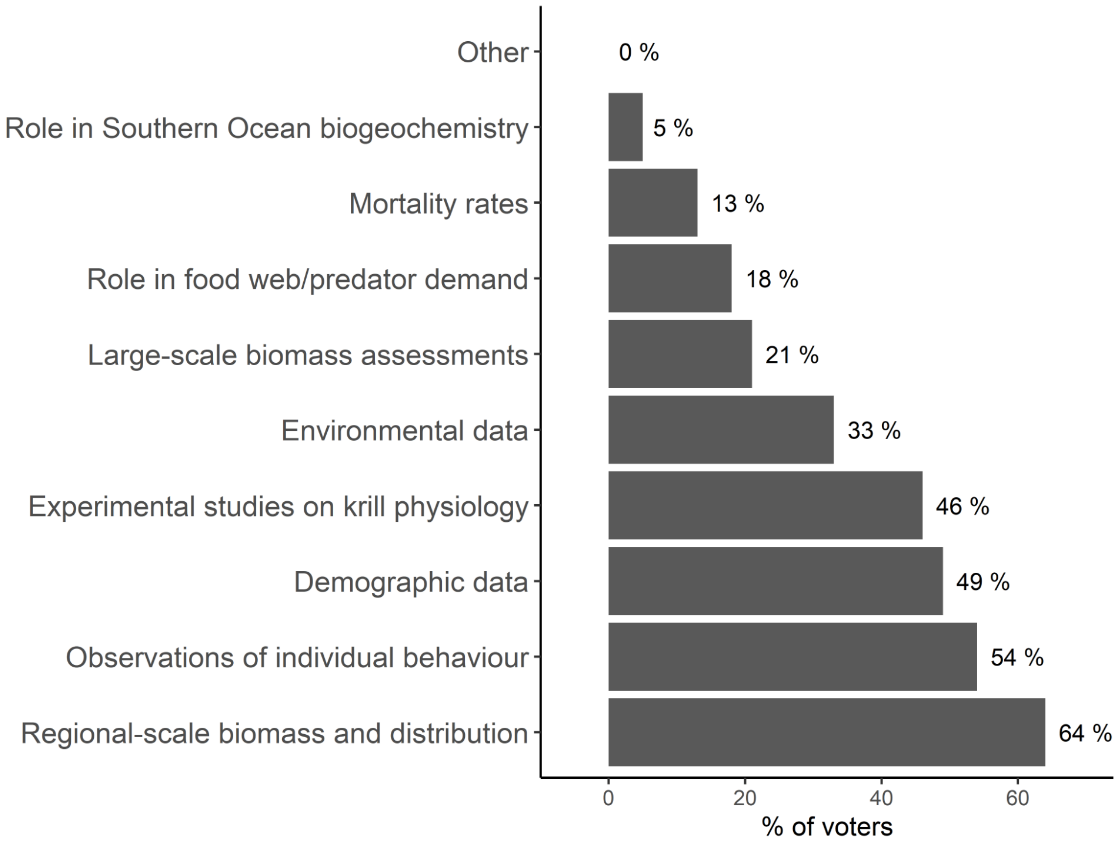

**Figure 2.10 Polling results from the question: "What are the main data (observational and process studies) requirements to improve these research priorities and challenges?"**

## 2.c.ii Discussion summary

The research priorities discussed expressed a need for better understanding in both the mechanisms underpinning krill responses to environmental drivers, as well as better confidence in projections of environmental drivers. These research priorities included:

- The survival of larval krill over winter. This is likely highly sensitive to environmental variability, however the environmental drivers that influence larval krill body condition and mortality are largely unknown.
- Additional knowledge of larval and egg stages to improve population and life history models. For example, many models of krill early life stages commonly assume that if an egg hits the seafloor before hatching it dies. The hypothesized mechanism for this includes the predation by benthic organisms and physical damage. Considerable interest and discussion was generated over an apparent absence of *in-situ* observations to support this common assumption.
- A need for earth system model (ESM) outputs that are better parameterized for the Southern Ocean was expressed. ESMs still struggle to represent Southern Ocean physics such as circulation patterns, vertical structure and sea ice. These biases subsequently affect biogeochemical and plankton dynamics when the physical and biogeochemical models are coupled. Developing regional coupled physical-biogeochemical models specifically for areas of the Southern Ocean was discussed as a possible way forward. A better representation of regional Southern Ocean physics in these models would therefore provide more realistic underpinning for biological models to improve capacity to predict impacts of environmental change

The data requirements from Theme 1 expressing needs for sampling to resolve seasonal and regional dynamics were echoed. Sampling during winter, which is a key research priority for this theme, is sparse. There are regions where good temporal sampling coverage exists (e.g. US AMLR, Palmer LTER and South Shetlands), however these are limited in space (and often time). Many habitats that are hypothesized as important for krill lack similar coverage (e.g. deep sea and ice-covered areas in Weddell Sea). Therefore year-round measurements of egg and larval krill development and mortality across a range of habitats are required to infer responses to environmental drivers.

Opportunities do exist to fulfill these requirements.

- Moorings, gliders and within-sea ice acoustic drifters may help improve coverage in temporal and regional variability.
- The multi-national fleet of new or soon-to-be purchased icebreaking research vessels presents another opportunity to lead a coordinated effort to sample during sparsely sampled regions and seasons.
- Collaboration with the fishing industry to use their vessels as platforms to collect data is also promising.
- Lastly, existing study areas, such as those developed by CCAMLR in the 1980's may provide the framework for future co-ordinated long term programs.

Future directions for modelling within this theme were also discussed. It was noted that a range of modelling approaches have been developed for other species and ecosystems that may be useful for krill and Southern Ocean ecosystems.  For example, coupled modelling for sub-Arctic ecosystems may provide a useful framework for similar work in the Southern Ocean.  Developing a community end-to-end modelling effort could also provide a useful focus for future work.

## 2.d  Theme 3: Ecosystem impacts of changes in krill dynamics and populations, and implications for conservation and management

Theme 3 comprised a diverse range of model detection methods for analyzing both the impact of a changing ecosystem on management, and the impact of conservation and management efforts on ecosystem structure. The session started off with one tutorial presentation:

1. Application for Krill Modelling to CCAMLR: The Generalised Yield Model
By Dale Maschette

This tutorial aimed to provide the audience with:

- An introduction to the Generalised R Yield Model (GRYM), a type of Generalised Yield Model implemented in R at the request of CCAMLR
- An overview of GRYM's capabilities and uses for CCAMLR, most notably its toolkit of functions used to build projection models to conduct fish assessments, was explained
- An explanation of the inputs required for the model and the outputs generated
- A list of needs for the modelling community

Speed talks followed the tutorial and comprised projects including diverse approaches to modelling krill behavioural traits to further understand the present and future state of krill and its interactions within Southern Ocean ecosystems.

### 2.d.i  Polling results

The following polling results identified the biggest sources of uncertainties for predicting the impacts of a changing Southern Ocean on krill biomass, as well as the model developments and data requirements necessary to target the largest uncertainties. The greatest uncertainties decided upon resided mainly amongst ecologically-focused processes rather than physical or biogeochemical processes. This is further reinforced by the high percentage of voters who defined ecosystem-level approaches as the best model resource for informing the development of management strategies. Regional-scale biomass and distribution data are therefore required to fulfill these efforts.

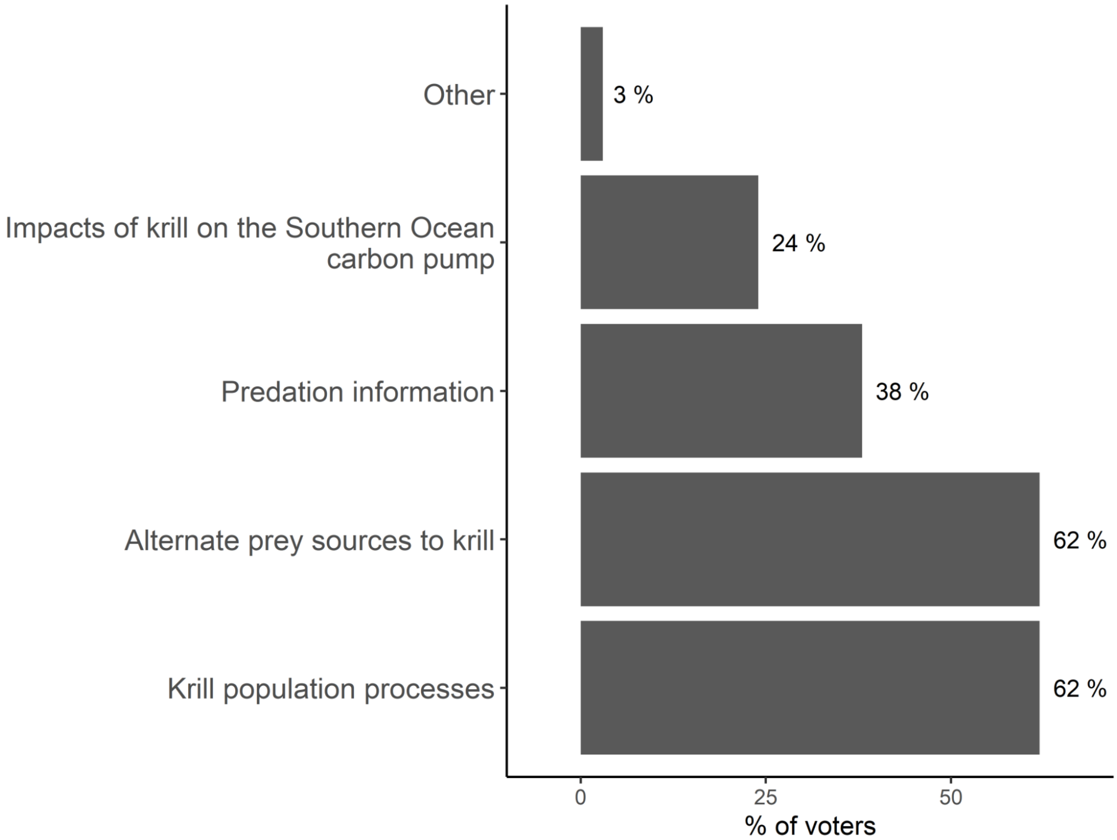


**Figure 2.11 Polling results from the question: "What are the biggest sources of uncertainty (either in krill modelling or in wider interactions) surrounding predicting the impacts of a change in krill biomass on the Southern Ocean ecosystem? (select 2)"**

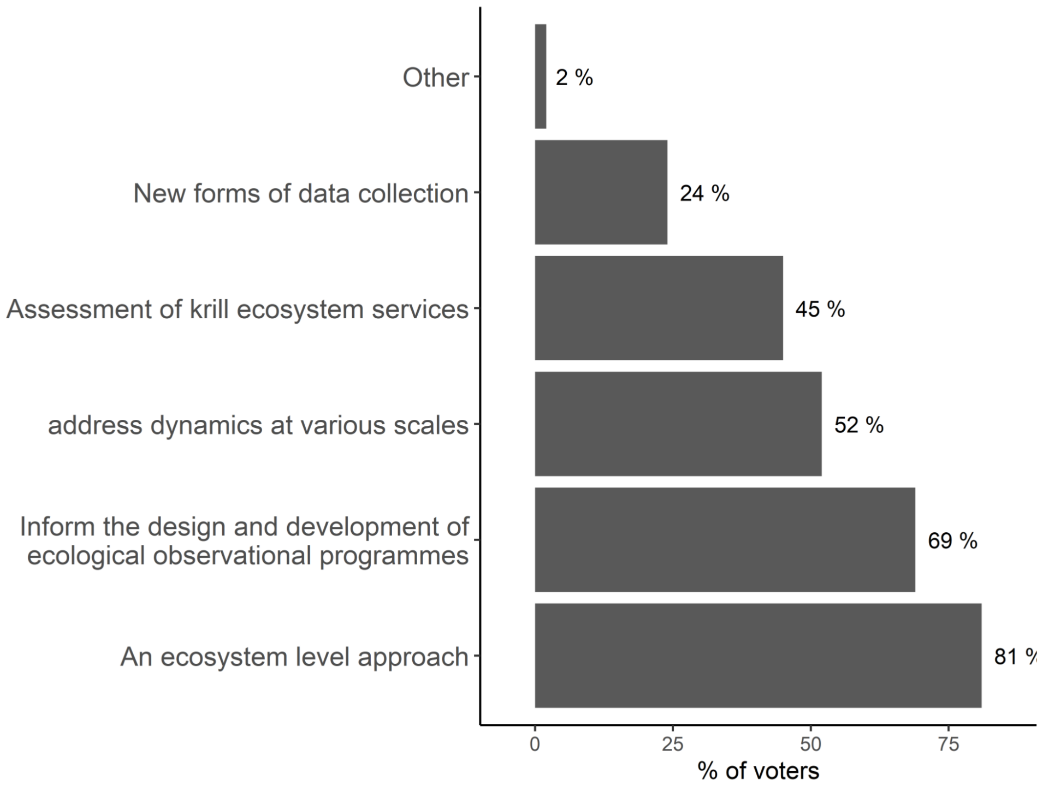


**Figure 2.12 Polling results from the question: “How can models be used to inform the development of management strategies (select 3)”**

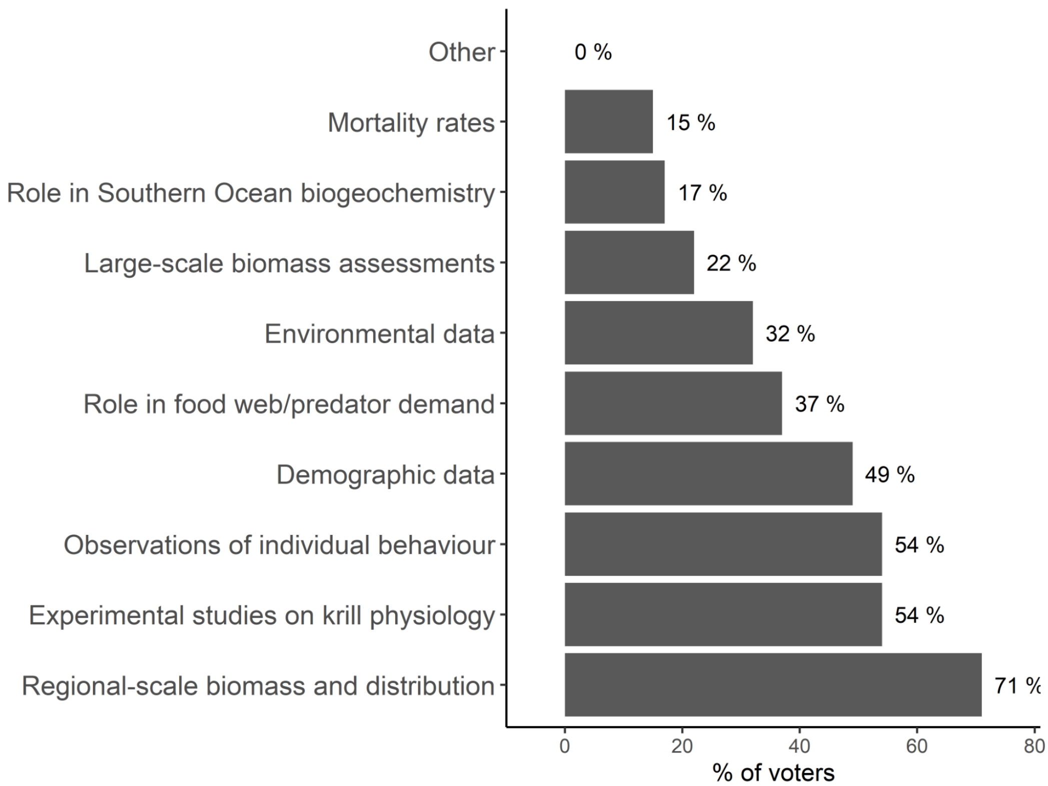


**Figure 2.13 Polling results from the question: “What are the main data (observational and process studies) requirements to improve these research priorities and challenges?”**

## 2.d.ii Discussion summary

Theme 3 discussion focused on the model developments that would be required to inform ecosystem monitoring and management decision making. This would facilitate improved conservation. Knowledge gaps in this area were identified, which focused on uncertainties in krill population connectivity and predicting climate change impacts on krill-centered ecosystems. Given CCAMLR's pivotal role in Southern Ocean management procedures, both past and future, the discussion naturally accounted for its needs as a focal point.

Discussion was initiated around approaches for developing krill flux modelling as a strategy to inform management procedures. It was mentioned that, in 1994, CCAMLR hosted a workshop (SC-CAMLR, 1994) titled, "Evaluating Krill Flux Factors" to develop such approaches. The decided-upon methods from the CCAMLR workshop included regular stock assessments in statistically-significant regions for collecting estimates of large-scale movements of krill from one sub area to another. The relevance of these methods were considered when the following areas of model development were discussed as high-priority topics:

- Krill flux/population connectivity: This was identified as an important source of uncertainty. Lagrangian particle tracking model studies have increased our understanding of such movements, including within CCAMLR Area 48.
- Biomass flows: The conservation and management of Antarctic marine resources requires bounding and a deeper understanding of biomass flows, otherwise defined as the magnitude of energy required to support the next trophic level. Inferences from likely food web structure scenarios are useful in detecting biomass flow response times (i.e. short-term response in months/seasons or long-term response over years). When considering more mobile krill predators that travel in and out of a modelled region, such as whales, compared to more stationary, localised species, biomass flows become a very important component in modelling a region's krill population through time and space.
- Spawning areas: The detection of successful spawning locations (and how variable they are) is also valuable for complimenting work on krill flux, specifically for larval krill.

It was noted that new sampling technologies, such as autonomous underwater vehicles and moorings, can improve the knowledge of krill flux. These platforms could provide data to estimate krill distribution and abundance through the food web, as well as estimate food web biomass flows.

An improved estimation of krill flux has broad applications and relevance for understanding population dynamics and connectivity. Including krill movement in regional stock assessment models is necessary to accurately account for mortality vs. recruitment in an area. Furthermore, these data alongside Lagrangian models can be used to estimate the inflow, or flux, of krill required to replenish a region's local stock. This information therefore becomes extremely valuable for investigating questions such as, 1) after krill is intensively fished in an area, do individuals return to that area? And 2) if they do return, how long does it take? Understanding this large scale movement of krill is needed to drive the advancement of regional scale stock assessment models used by CCAMLR.

Predicting the impacts of climate change on krill-centered ecosystems requires an improved knowledge of the following key knowledge gaps:

- Sea ice reliance: Krill reliance on sea-ice under projected changes in volume, extent and timing in advance and retreat, and its impact on krill larvae was unanimously agreed upon as a major gap. This requires an understanding of how selective krill are with their food, whether the composition of primary producers will change, and alternative food sources and how these influence energy and nutrient flows within the system.
- Krill diet alternatives: Accounting for winter and autumn diets of krill and other Southern Ocean species and projecting changes remains difficult when winter data are severely lacking. Studies applying genetics, fatty acids and stable isotope methodologies were found to be promising in accounting for krill diet. The complexity of these needs prompted a comment on performing krill and salp group perspective comparisons from a behaviour point of view to investigate future scenarios. This approach would improve an understanding of the behavioural traits of krill competitors, of which end-to-end models are currently being applied. Improving an understanding of krill predation pressure would also benefit small-scale management of krill fisheries.

The number of Lagrangian studies presented during Theme 3, and in earlier workshop sessions, prompted a comment on model integration as a necessity for formulating likely scenarios and applying methods in different regions.This would allow researchers to compare results from different areas and so simplify evaluation studies. This was exemplified through presentations stating that model ensembles, and the intercomparison of models, is not only useful in understanding areas of uncertainties in model projections but is also valuable in developing a consistent message for decision makers. Model integration is defined and discussed in more detail in section 3c of the Conclusions.

# 3. Conclusions

Through this workshop, the Antarctic krill modelling community has identified priorities for modelling krill populations at a range of scales, coupling these processes to environmental drivers, and finally, predicting the impacts of variability in krill on the wider circumpolar ecosystem. The following sections include a research priority roadmap, data requirements, model integration approaches, and ECR involvement. Data requirements and modelling integration approaches were consistently discussed throughout the workshop as overwhelming priorities. Thus, the following two stand-alone sections are included to document these needs in further detail.

## 3.a Developing a research priority roadmap

By assessing the research priorities across themes, a roadmap for future research could be synthesized in consultation with the community. The workshop highlighted a series of key priorities (summarised below) that can inform the development of the roadmap.

To improve our representation of the life cycle and distribution of krill (Theme 1), research priorities include:

- addressing uncertainty in krill population connectivity;
- swarm energetics and interaction with circulation; and
- standardization methods for comparing differences in model structure between regional models for larger-scale inferences.

Models of krill population processes can then be coupled to environmental drivers to simulate population dynamics in response to environmental variability (Theme 2). To parameterize this coupling, future research is needed in:

- quantifying functional relationships between the environment (especially sea ice habitat) and biological processes, in particular larval mortality over winter;
- experimental studies to underpin projections of how these functional relationships may respond to future environmental change; and
- ESM biogeochemical outputs that are better parameterized using Southern Ocean regional variability.

The importance of these conclusions can then be assessed within an ecosystem context to better inform conservation and management practices (Theme 3).These assessments would be improved by an increased understanding in:

- alternate energy pathways within the food web;
- krill flux and its impact on biomass flows;
- the ecological role of krill competitors; and
- krill reliance on sea ice in a changing climate

Modelling approaches can also be used to inform the design of ecological observation programmes for management, and thus facilitate an ecosystem-level management approach.

## 3.b Data requirements

Poll results for the data requirements that feed into the theme-specific research priorities demonstrate that having a regional-scale resolution of biomass, distribution and demographic data is important, but that conclusions drawn from these data also need to be underpinned by observations of individual behaviour and physiology. In addition, an improved understanding of the role of krill in the food web, as well as predator demand, is needed for an understanding of their role in the ecosystem (Table 3.1). Overall, we see that the data requirements identified by each theme to support their research priorities were broadly similar.

**Table 3.1. Summary of data requirements poll results for each theme.** Numbers within columns refer to the percentage of voters.

| | Theme 1 | Theme 2 | Theme 3 |
|---|---|---|---|
| Demographic data | 48 | 49 | 49 |
| Regional-scale biomass and distribution | 86 | 64 | 71 |
| Large-scale biomass assessments | 19 | 21 | 22 |

| | | | |
|---|---|---|---|
| Experimental studies on krill physiology | 36 | 46 | 54 |
| Observations of individual behaviour | 57 | 54 | 54 |
| Environmental data | 31 | 33 | 32 |
| Mortality rates | 24 | 13 | 15 |
| Role in Southern Ocean biogeochemistry | 14 | 5 | 17 |
| Role in food web/predator demand | 21 | 18 | 37 |
| Other | 0 | 0 | 0 |

This consistency in requirements indicates that sampling programs could potentially be designed to simultaneously address the research challenges identified. The community stressed the importance of the need for sampling strategies that:

A. Had sufficient temporal coverage to resolve seasonal variability, especially through the Austral winter
B. Had sufficient spatial coverage to resolve regional variability
C. Sampled known and hypothesized key habitats and to continue existing timeseries (Figure 3.1)
D. Were useful for model evaluation, by sampling habitats that models predict to be important for krill but currently have sparse sampling coverage. Examples include the Bellingshausen/Amundsen Seas, Weddell Sea, Prydz Bay and Ross Sea (Figure 3.2)

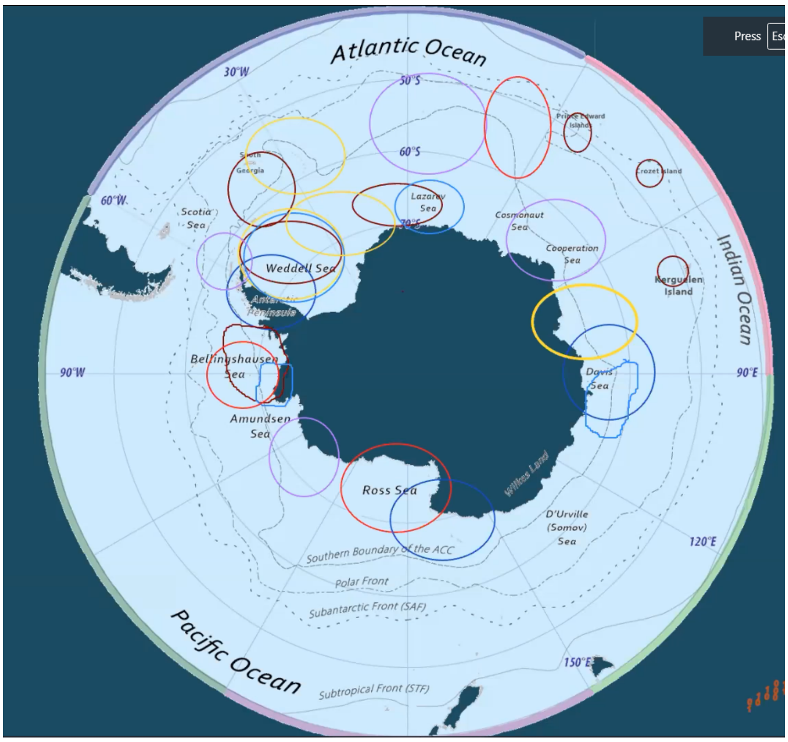


**Figure 3.1 Regions identified by participants in response to the question: "Where should we target sampling? Which regions are important for krill?"** In this exercise, a map was placed on

the screen and all participants were invited to use the annotate tool to indicate regions in response to the question prompt.

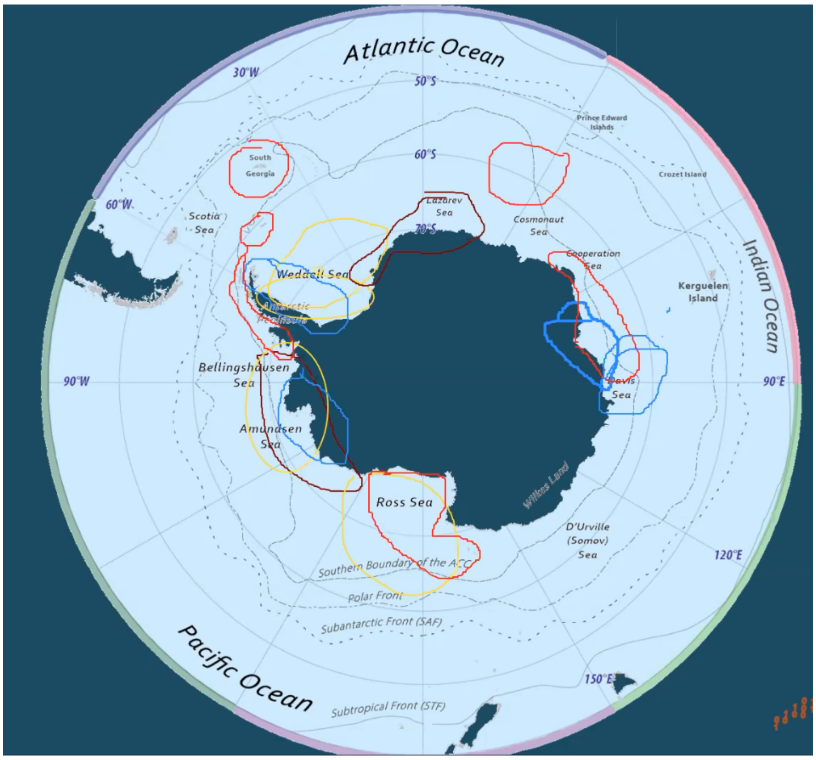


**Figure 3.2 Regions identified by participants in response to the question: "Where do we need data for validation?"** In this exercise, a map was placed on the screen and all participants were invited to use the annotate tool to indicate regions in response to the question prompt.

Overall, the results of these exercises (Figures 3.1 and 3.2) emphasized the requirement for information throughout the Southern Ocean and across the whole distribution of krill. This highlights that sampling and analyses are also required in areas outside of the areas where most sampling has occurred.

## 3.c Integrating modelling approaches

This workshop aimed to develop insights into integrating modelling approaches. This arose from the existence of separate models of different components of the krill life cycle, and the need to integrate them for a whole-of-life cycle krill model. Therefore integration in this context would be defined as model coupling (i.e. two-way feedback between models) or linking (i.e. one-way feedback using outputs from one mode to drive another). As discussion progressed, the community identified that increased model transparency and collaboration, as well as model evaluation, were important first steps towards achieving these goals. It was agreed that, in order to progress, research needs "sharing and engagement with others", as described by a participant.

To capture participant opinion on feasible opportunities for integration and collaboration, as well as achievable five- and ten-year research challenges, three additional polls shown below were conducted following Theme 3 discussion. 68% of participants (Figure 3.3) identified predicting climate change impacts on krill-centered ecosystems as the greatest opportunity for collaboration and integration. Model output from a range of platforms were presented during the workshop. These included:

- Ecosystem models: Atlantis, Ecopath with Ecosim
- Physical models: regional ocean models such as the Regional Ocean modelling System (ROMS) and earth system models (e.g. Community Earth System Model, CESM)
- Krill models: models of krill growth (e.g. the Von Bertalanffy model), energy budgets and moult cycle (e.g. the fully-dynamic model presented by Andrew Constable), krill populations (e.g. the Generalized Yield Model), and predator interactions and environmental drivers (e.g. KRILLPODYM within SEAPODYM).

Each modelling approach covers various aspects of krill-related modelling and has inherent strengths and limitations. Therefore the variety of approaches being applied by the community has an overlapping network of strengths and limitations.

This range of models illustrates an opportunity for model integration that could also facilitate comparative approaches that can be used to test and evaluate models, estimate error, compare model structure, and identify key parameters. One suggestion was to build an open-source repository that would provide a framework for integrating models and/or data (Figure 3.4). While many agreed that such a repository would be useful, others also felt that a repository, in and of itself, would be an insufficient toolbox, as it does not include short cuts, calibration code and other important components needed for model development. Developing a data programming group centered on establishing best coding practices as well as providing training was emphasized several times throughout the workshop as being an extremely beneficial avenue for standardizing modelling methods. This would also support the statistical approach for drawing inference where direct data are lacking, as discussed during day 2, Theme 1, of the workshop. Collaboration via Github, Slack or Basecamp could facilitate the communication required for this collaboration. The statistical language, R, was discussed at different points in the workshop as a commonly used language.

Additional ideas discussed for collaboration include:

- Linking to other Southern Ocean working groups, such as SOOS and SKAG
- Scheduling regular meetings every 6 months with all interested workshop participants
- Creating a specific working group for Southern Ocean ecosystem modelling within ICED
- In addition to setting up a repository/github, coordinate working meetings that would allow for collaboratively coding (e.g. basecamp) existing models in a common language (e.g. R) and publish in journal for open science with an R package
- Designing a roadmap to address data and knowledge gaps that currently exist across disciplines

These results further highlight the need to evaluate and integrate modelling approaches for improving model representation to enhance our understanding of projected climate change impacts on the Southern Ocean ecosystems and in turn, global climate.

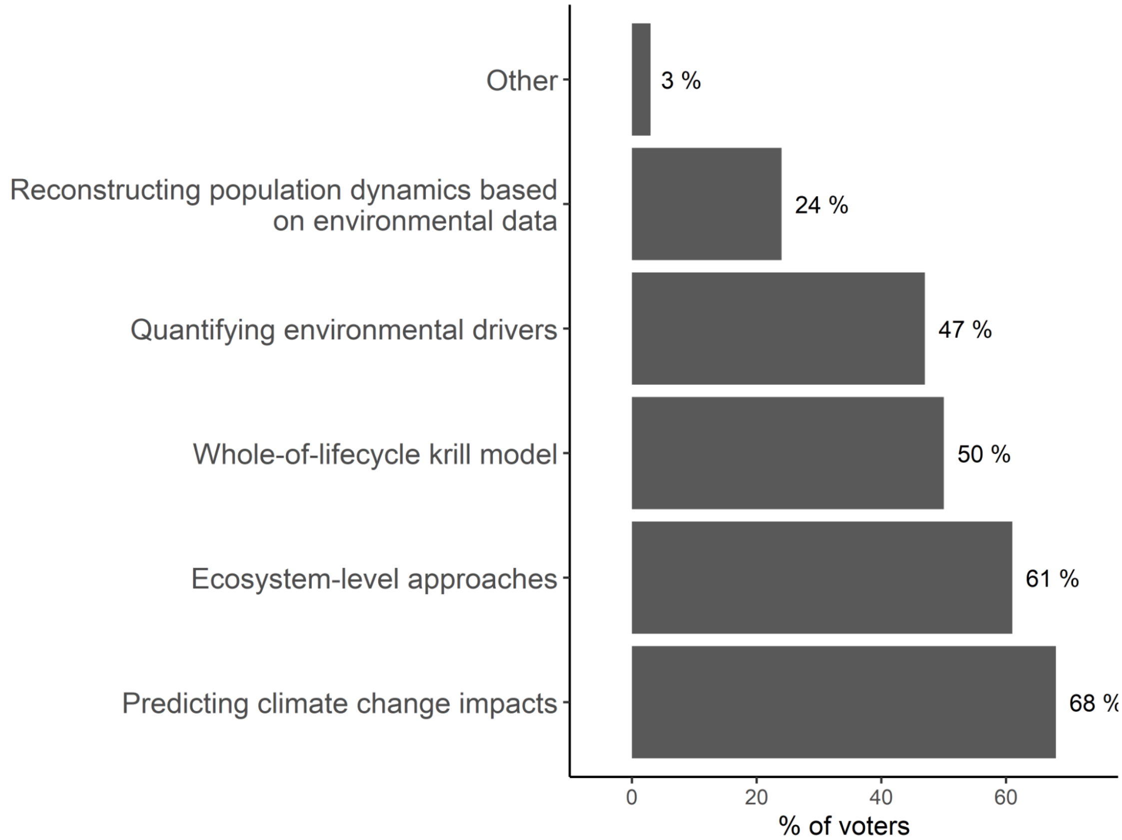


**Figure 3.3 Polling results from the question: "Which research questions present the greatest opportunities for integration/collaboration? (select 3)"**

.

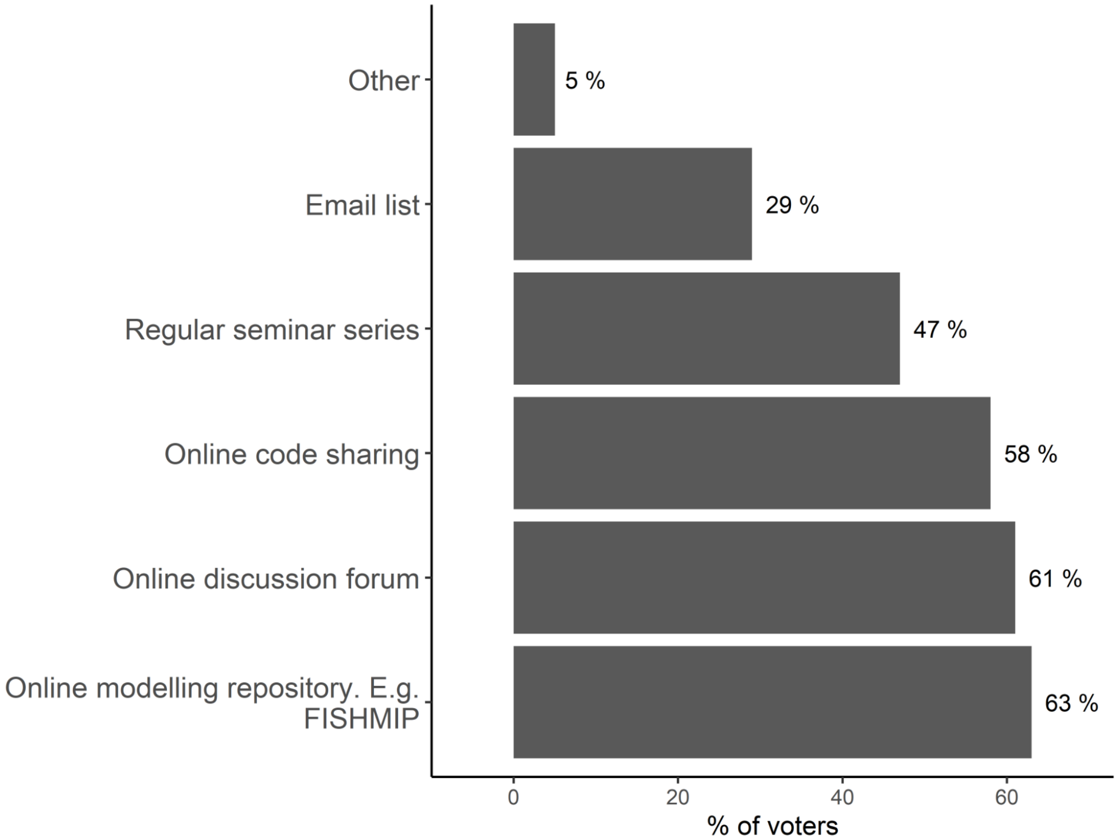


**Figure 3.4 Polling results from the question:"What facilitation methods for integration/collaboration seem most feasible?"**

Lastly, Figure 3.5 presents the results for main research challenges achievable within five- and ten-year timeframes. Short-term challenges, such as improving our understanding of controls on local distributions and patterns of aggregations accounted for 61% of participant opinion. With regard to long-term challenges, 65% of the participants voted for controls on krill population dynamics, distribution and abundance as an achievable research challenge. Particularly relevant is the 54% voting opinion on 'impacts of climate change' being achievable within a ten-year timeframe, while only 25% consider a five-year timeframe to be appropriate. Considering the greatest opportunity for model integration and collaboration was voted as 'predicting climate change impacts' in Figure 3.3, it is clear that this endeavor is timely but will require long-term concerted efforts.

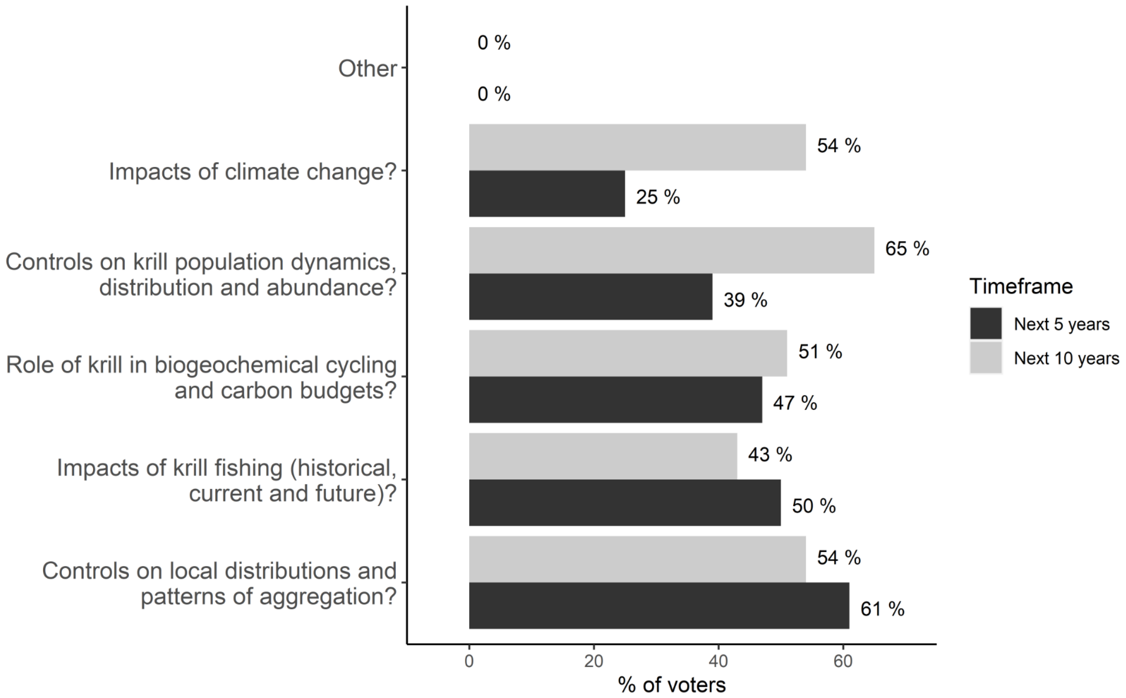


**Figure 3.5 Polling results from the question: "Of the main research challenges below, which are achievable in the next 5 and 10 years?"**

## 3.d. Fostering ECR networks and involvement

ECR workshop participants were polled on their opinions on how to best develop networks and collaboration going forwards from the workshop. The polling results shown below suggest a strong desire for regular ECR meetings, mentor programmes and regular updates via email. It is important to note that the involvement of ECRs in targeted activities throughout the workshop, as well as involvement in broader research challenges of ICED, remains central to the work that is being done. It is a key goal that has been a work in progress over the past few years, and a component of the organization that encourages the participation of ECRs for future work.

### 3.d.i Polling results

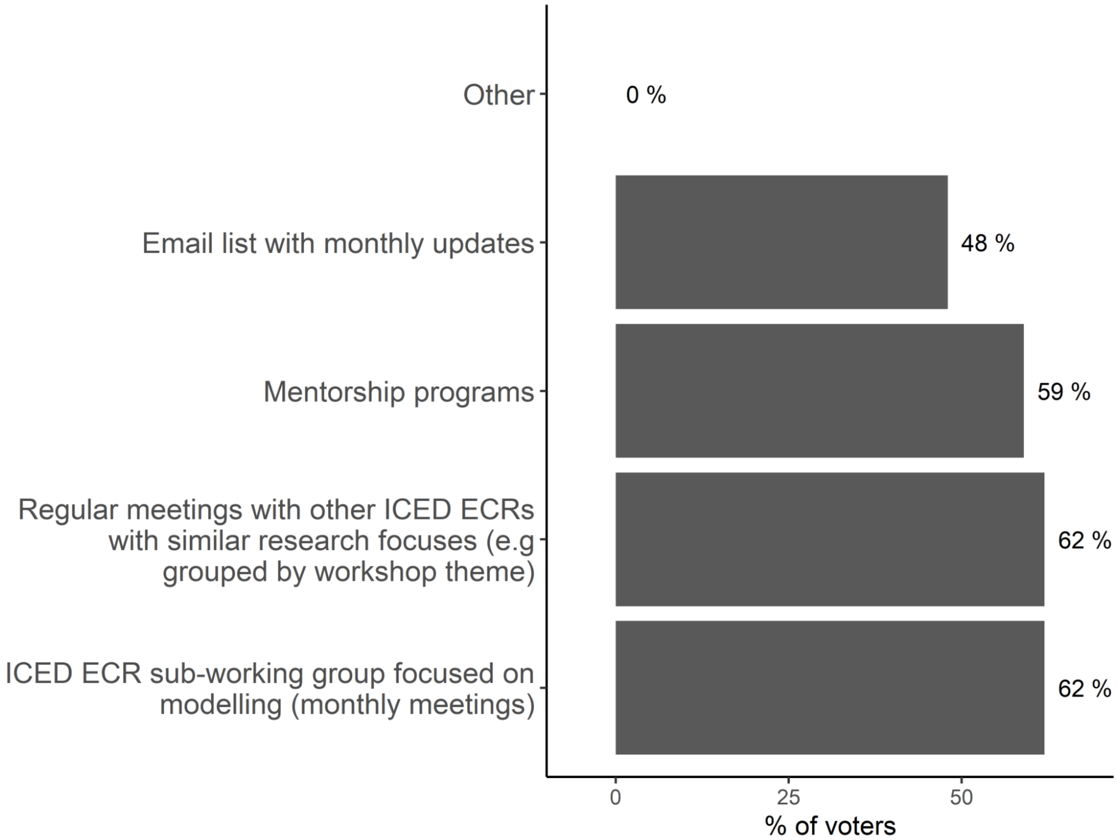


**Figure 3.6 Polling results from the question: "Which modes of ECR development and collaboration would you be most interested in post-workshop? (no limit) (Multiple Choice)"**

### 3.d.ii Discussion summary

One of the biggest successes of the workshop was connecting ECRs with mid and expert level career researchers. Additionally, the polling demonstrates the enthusiasm for increased engagement with the research community and a strong desire for the creation of an ICED ECR sub-working group to focus on modelling along with more regular meetings. This sub-working group would complement the increased involvement of ECRs within broader ICED activities.

# 4. Workshop Outcomes

To build on this workshop a number of community led outcomes are underway or planned, including:

1. A joint ICED-SKAG session proposal was submitted to the 2022 AGU Ocean Sciences Meeting occurring in Honolulu, Hawaii, titled, "The role of Southern Ocean ecology in the Earth system: integrating across scales, disciplines, and methods" for the High Latitude Environments track. The focus of this session is on Southern Ocean earth system modelling issues, representation and integration with biological models. The session has been requested as a hybrid format, in which sessions will occur in Honolulu but will have some form of interactivity with virtual participants.

2. A paper will be submitted to this year's CCAMLR working group on ecosystem monitoring and management (WG-EMM) to communicate the results of the workshop and further strengthen the design and application of krill modelling research to support management

3. Continued engagement of the workshop community including via:
    a. Potential follow-up workshop on identifying key areas needed for sampling for model validation/ground truthing
    b. A range of training workshops in the future to integrate research fields and create a path for collaboration
    c. Bi-annual sessions
    d. Compiling code repositories and encouraging open coding practices within the community

    It is our hope that this continued engagement will facilitate more coordination with future work, as well as collaborative research projects.
4. Development of a more connected network for ECRs and their future involvement within ICED. This could include an ICED sub-working group focused on modelling, including all levels of expertise but led by ECRs. This group would serve as a point of contact for all interested community members, a professional development opportunity for ECRs, and a direct mechanism for integrating ECR involvement within ICED.

# Appendix A: Full workshop schedule

| Day | Section | Presenter/Chair | Presentation title |
|---|---|---|---|
| May 17 - Background | Presentation | Eugene Murphy | Introduction |
| | Presentation | Nadine Johnston | ICED introduction |
| | Presentation | Bettina Meyer | SKAG outcomes |
| | Presentation | Anton Van de Putte | Data availability |
| | Presentation | So Kawaguchi | Modelling for management: CCAMLR objectives and feedback management system |
| | Presentation | Eileen Hofmann | Southern Ocean ecosystem modelling |
| | Discussion | Devi Veytia & Eugene Murphy | Main challenges in krill modelling |
| | ICED breaker | Zephyr Sylvester | Introduction to ICED breaker and how to use Gathertown |
| | ICED breaker | - | Gathertown ICED breaker |
| May 18 - Theme 1: Modelling krill from individuals to populations: linking across scales | Tutorial | Andrew Constable | Choosing a model for representing Antarctic krill |
| | Tutorial | George Watters | Modelling krill across scales |
| | Speed talk | Nicole Hellessey | Krill kinematics in response to physical and chemical stimuli |
| | Speed talk | Bettina Fach | Modeling connectivity vs local retention of Antarctic krill in the |

| | | | |
|---|---|---|---|
| | | | Lazarev Sea |
| | Speed talk | Katherine Hudson | Modeled DVM Increases Retention and Particle Delivery to Penguin Foraging Areas Near Palmer Deep Canyon |
| | Speed talk | Emma Young | Drivers of Antarctic krill distribution in the South Orkney Islands region |
| | Speed talk | Dominik Bahlburg | The overwintering of Antarctic krill in a future Southern Ocean |
| | Speed talk | Haiting Zhang | Fatty acid trophic markers reveal sea ice dynamics structuring (mediating) autumn food availability of Antarctic krill Euphausia Superba in the Bransfield Strait, Antarctic |
| | Speed talk | Simeon Hill | Linking scales in foodweb models |
| | Discussion | Zephyr Sylvester & Sally Thorpe | Discussion on Theme 1 |
| **May 19 - Theme 2: Environmental drivers of krill population dynamics and distribution** | Tutorial | Stuart Corney, David Green, Denisse Fierro Arcos and Devi Veytia | Using gridded environmental information |
| | Tutorial | Alexis Bahl & Simeon Hill | Approaches for ecosystem modelling: Ecopath |
| | Speed talk | Andrea Pinones | Evaluating the role of ocean circulation in the pathways and residence times of the northern Antarctic Peninsula |
| | Speed talk | Devi Veytia | Sea ice drivers of krill recruitment through a lens of krill advection |
| | Speed talk | Denisse Fierro Arcos | Using oceanographic model outputs to understand the impacts of sea ice and ocean dynamics on Southern Ocean ecosystems |
| | Speed talk | Benjamin Merkel | Quantifying circumpolar habitat of two Antarctic keystone species |
| | Speed talk | Kim Bernard | Using Lagrangian simulations to test whether spawning over the WAP shelf can be supported by upward advection |
| | Speed talk | David Green | Simulating Antarctic krill's spatio-temporal dynamics through the adaption of an existing Eulerian model |
| | Speed talk | Cecilia Liszka | Environmental forcing of krill distribution in Area 48: Assessing current status and predicting future trends |
| | Discussion | Devi Veytia & Stuart Corney | Discussion on Theme 2 |
| **May 20 - Theme 3: Ecosystem impacts of changes in krill populations and implications for conservation and management** | Tutorial | Dale Maschette | Application for krill modelling to CCAMLR: The Generalised Yield Model |
| | Speed talk | Aditee Mitra | Krill production under the mixoplankton paradigm |
| | Speed talk | Onur Karakus | Modeling the impact of Antarctic Krill on Carbon Export Production in the Southern Ocean |
| | Speed talk | Andrea Ferriera Cussolim Mesquita | Environmental drivers of fin and humpback whale foraging behavior in the Western and Northern Antarctic Peninsula |
| | Speed talk | Denise O'Sullivan | An ecosystem approach to modelling krill: the Atlantis model in East Antarctica |
| | Speed talk | Zephyr Sylvester & Kristen Krumhardt | Antarctic Marine Predators and Zooplankton Modeling |

| | | | |
|---|---|---|---|
| | Speed talk | Andrew Constable | Applying krill models to management |
| | Discussion | Alexis Bahl & Eileen Hofmann | Discussion on Theme 3 |
| | Closing discussion | Devi Veytia & Eugene Murphy | Closing discussion |

# Appendix B: List of participants

| **Last name** | **First name** | **Institution / Organization** | **Career stage/Professional position** |
|---|---|---|---|
| Arata | Javier | ARK | Executive Officer |
| Bahl | Alexis | University of British Columbia | ECR |
| Bahlburg | Dominik | TU Dresden, Helmholtz Center for Environmental Research Leipzig | ECR |
| Benkort | Déborah | Helmholtz zentrum HEREON | ECR |
| Bernard | Kim | Oregon State University | Associate Professor |
| Bestley | Sophie | Institute for Marine and Antarctic Studies, University of Tasmania | ARC DECRA Researcher |
| Bhat | Aadil | | |
| Bishop | Jordan | Charles University | ECR |
| Brooks | Cassandra | University of Colorado Boulder | Assistant Professor |
| Cagdas | Bulut | METU | PhD Student |
| Carrasco | Pedro | Helmholtz Institute for Functional Marine Biodiversity (HIFMB) | PhD candidate |
| Chen | Thomas | Academy for Mathematics, Science, and Engineering | ECR |
| Cleary | Alison | University of Agder | affiliated researcher |
| Constable | Andrew | Centre for Marine Socioecology, University of Tasmania | Researcher |
| Corney | Stuart | Institute for Marine and Antarctic Studies | Senior lecturer |
| Dakwa | Farisayi | University of Capetown | Postgraduate student (MSc) University of Cape Town |
| Dornan | Tracey | British Antarctic Survey | ECR |
| Fach | Bettina | Institute of Marine Sciences, Middle East Technical University | Associate Professor |
| Ferreira Cussolim Mesquita | Andrea | Universidade Federal do Rio Grande-FURG | ECR |
| Fierro Arcos | Denisse | University of Tasmania | PhD student |

| | | | |
|---|---|---|---|
| Franco-Santos | Rita | University of Tasmania - Institute for Marine and Antarctic Studies | ECR - research assistant |
| Garcia | Lani | Oregon State University | Undergraduate researcher |
| González Díaz | Mauricio | Old Dominion University | Graduate student |
| Grafsrønningen | Stig | Aker Biomarine | Head of Data Science |
| Green | David | Institute for Marine and Antarctic Studies, University of Tasmania | ECR |
| Halfter | Svenja | Institute for Marine and Antarctic Studies | PhD candidate |
| Hellessey | Nicole | Georgia Institute of Technology | ECR - post doc |
| Hill | Simeon | British Antarctic Survey | Researcher |
| Hofmann | Eileen | Old Dominion University | Professor |
| Hudson | Katherine | University of Delaware | PhD Candidate |
| Johnston | Nadine | British Antarctic Survey | Ecosystems Scientist |
| Karakus | Onur | Alfred Wegener Institute | PhD Candidate |
| Kawaguchi | So | Australian Antarctic Division | Researcher |
| Keith | Patrick | University of Essex | PhD student |
| Kent | Amanda | Oregon State University | Student |
| Krumhardt | Kristen | National Center for Atmospheric Research / UCAR | Researcher |
| Labrousse | Sara | LOCEAN - Sorbonne Université | Postdoctoral researcher |
| Liszka | Cecilia | British Antarctic Survey | ECR |
| Mantha | Gopikrishna | Kuwait Institute for Scientific Research | Associate Research Scientist |
| Martínez | Jaison | Universidad Austral de Chile | Undergraduate student - researcher |
| Maschette | Dale | Australian Antarctic Division | |
| Meiners | Klaus | Institute for Marine and Antarctic Studies/Australian Antarctic Division | Researcher |
| Menze | Sebastian | Norwegian Institute of Marine Research | Post-doc |
| Merkel | Benjamin | Akvaplan niva | post doc |
| Meyer | Bettina | Alfred Wegener Institute | Professor |
| Miranda | Adriana | ICMBio/CMA | Research |
| Mitra | Aditee | Cardiff University | Research Fellow |
| Murphy | Eugene | British Antarctic Survey | Science Leader |
| Nodal | Andrea | Oregon State University | Graduate Student |
| O'Sullivan | Denise | CSIRO | Voluntary Research Fellow |
| Olaniyu | Akeem | University | Researcher |

| | | | |
|---|---|---|---|
| Pakhomov | Evgeny | University of British Columbia | Professor |
| Pietzsch | Bruno Walter | TU Dresden | Researcher |
| Piñones | Andrea | Universidad Austral de Chile | Researcher |
| Raymond | Ben | AAD | researcher |
| Record | Nicholas | Bigelow Laboratory for Ocean Sciences | Senior Research Scientist |
| Reid | Keith | CCAMLR | Science Manager |
| Renner | Angelika | Institute of Marine Research, Norway | Researcher |
| Rombolá | Emilce | Instituto Antártico Argentino | Researcher |
| Ryabov | Alexey | ICBM, University of Oldenburg | researcher |
| Sadighrad | Ehsan | Institute of Marine Sciences, Middle East Technical University | Postdoctoral Researcher |
| Santa Cruz | Francisco | Instituto Antártico Chileno | Researcher |
| Seyboth | Elisa | CPUT (Cape Peninsula University of Technology) | ECR (postdoctoral researcher) |
| Steinke | Kirsten | Oregon State University | Graduate Student |
| Subramaniam | Roshni | Sydney Institute of Marine Science | ECR |
| Sylvester | Zephyr | University of Colorado Boulder | ECR |
| Teschke | Katharina | AWI | researcher |
| Thorpe | Sally | British Antarctic Survey | Researcher |
| Torres-Florez | Juan Pablo | ICMBio/CMA | Researcher |
| Trinh | Rebecca | Lamont-Doherty Earth Observatory Columbia University | PhD candidate |
| Van de Putte | Anton | Royal Belgian Institute for Natural Sciences/ SCAR antarctic Biodiversity Portal | Post doc, project manager |
| Veytia | Devi | University of Tasmania | ECR |
| Watters | George | NOAA | Director |
| Wong | Joel | ETH Zurich | Ph.D Student |
| Wood | Giulia | Oregon State University | Student researcher (honors thesis) |
| Young | Emma | British Antarctic Survey | Senior researcher |
| Zhang | Haiting | Shanghai Ocean University | PhD candidate |

# Appendix C: Participant demographics polling results

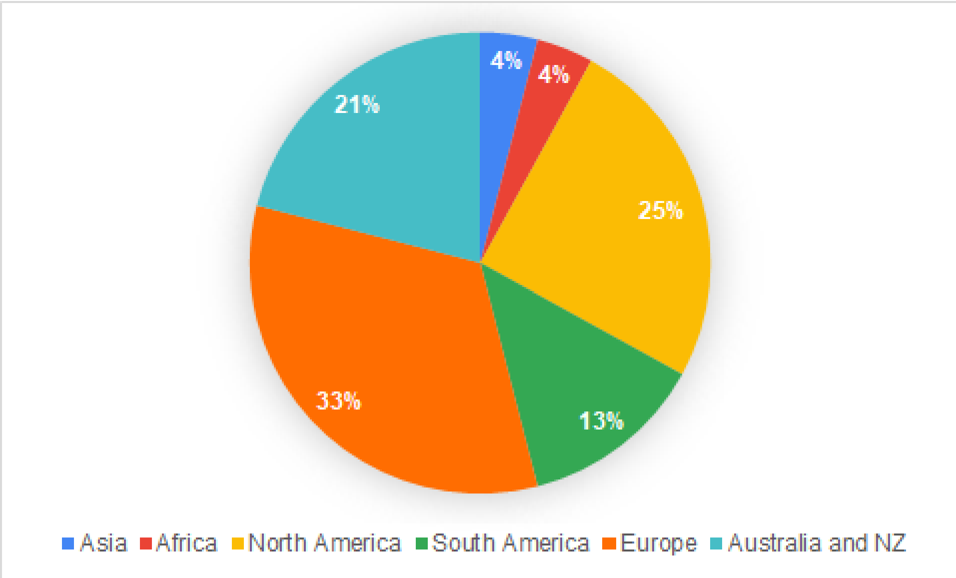


**Figure C.1 Polling results from the question: "Where are you joining us from?"**

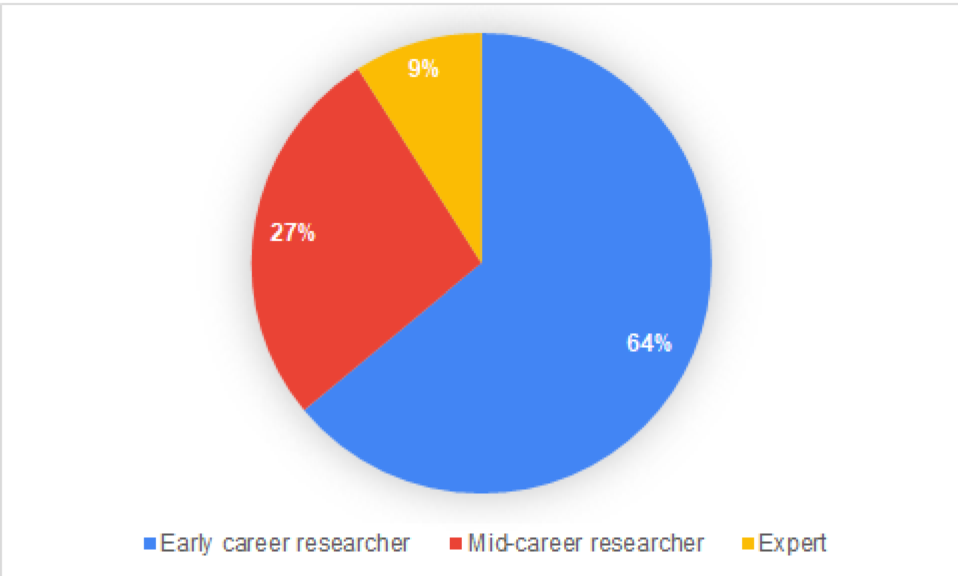


**Figure C.2 Polling results from the question: "What is your career stage?"**

# Appendix D: Relevant Databases for krill modelling

1. The UK Polar Data Centre (UK PDC) coordinates the management of polar data from UK-funded research and supports researchers in complying with national and international data legislation and policy.
    a. Example: Composition of Antarctic Fur Seal diet at Bird Island, South Georgia, from 1989 onwards
2. Antarctic Master Data (AMD) - largest collection of Antarctic data set with >7700 dataset descriptions from 25 countries. It is hosted by the International Directory Network (IDN) of the CEOS-IDN network to minimise duplication of resources and metadata.
3. CCAMLR Data - standardized data for fisheries in the Convention Area, scientific observations on board fishing vessels, research surveys and ecosystem monitoring, and compliance activities and processes.
4. SCAR Antarctic Biodiversity Portal - Biodiversity.aq is an international initiative of the Scientific Committee on Antarctic Research (SCAR).The SCAR Antarctic Biodiversity Portal is the regional thematic node of the Ocean Biogeographic Information System (OBIS, www.obis.org), the Global Biodiversity Information Facility (GBIF, www.gbif.org) and works closely together with the Southern Ocean Observation System (SOOS, www.soos.aq).
    a. SCAR's Expert group on Antarctic Biodiversity Informatics (EG-ABI) - The home for the Antarctic and Southern Ocean biodiversity science community
        i. The SCAR Southern Ocean Diet and Energetics project provides information on diets, energetic content, allometric equations, R packages (Sohungry, solong)
        ii. The SCAR/rOpenSci initiative - A collaboration with the rOpenSci community to improve resources for users of the R software package in Antarctic and Southern Ocean science.
            1. Blueant - a tool to use with the bowerbird package (Bowerbird is an R package for maintaining a local collection of data sets from a range of data providers). Blueant is themed around Antarctic and Southern Ocean data including oceanographic, meteorological, topographic, and other environmental data sets.
5. The Southern Ocean Observing System - (SOOS)
    a. SOOS Map - includes Krillbase, Mooring data, and data from the Continuous Plankton Recorder
6. Southern Ocean Network of Acoustics (SONA) and the Southern Ocean database of Acoustic backscatter (SOBA)
7. The European Marine Observation and Data Network (EMODnet) - long term marine data initiative with the following data portals: Bathymetry, biology, chemistry, coastal mapping, geology, human activities, physics, and seabed habitats
8. World Ocean Atlas (WOA) - a collection of analyzed, quality controlled temperature, salinity, oxygen, phosphate, silicate, and nitrate means based on profile data from the World Ocean Database (WOD). It can be used to create boundary and/or initial conditions for a variety of ocean models, verify numerical simulations of the ocean, and corroborate satellite data.