Darwin Plus Project:
Evaluating climate change risks to Patagonian and Antarctic toothfish

First workshop report:15th June 2023, British Antarctic Survey, Cambridge, UK.

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Background

Climate change is altering ecosystems and fisheries yet is mostly absent from fisheries management policy and implementation. The effects of climate change on high value toothfish caught in Southern Ocean longline fisheries are largely unknown. This Darwin Plus funded project will synthesise environmental, biological and fishery information to undertake a risk assessment of climate-driven change to toothfish in South Georgia and the South Sandwich Islands (SGSSI), contributing to conservation priorities for the region, including enhancing existing management of fisheries and the Marine Protected Area.

The project was launched in June 2023 at a workshop attended by the project team, partners, and stakeholders. This report presents a summary of the workshop.

Workshop Aim

This workshop brought the project team, partners, and stakeholders together at the start of the project to discuss the objectives and identify available information and sources for relevant environmental (e.g., temperature, climate indices), biological (e.g., toothfish distribution, life history parameters, physiology) and fishery (e.g., timing, location and management measures) data, to underpin the risk assessment.

Workshop Outputs

- Workshop report
- Project webpage
- Plans for knowledgebase
- Information paper for CCAMLR

Workshop Participants

Participants comprised the British Antarctic Survey (BAS) project team, project partners (Centre for Environment, Fisheries and Aquaculture Science (Cefas) and the Government of South Georgia and the South Sandwich Islands (GSGSSI)), and stakeholder representatives.

Name	Organisation	Role in Project
Mark Belchier	GSGSSI	Partner
Otis Brunner	BAS	Postdoctoral Research Assistant
Rachel Cavanagh	BAS	Project Lead
Martin Collins	BAS	Co-Investigator (Toothfish management)
Deborah Davidson	Argos Froyanes	Stakeholder
Tim Earl	Cefas	Partner
Susie Grant	BAS	SGSSI MPA
Sue Gregory	GSGSSI	Partner
Simeon Hill	BAS	Co-Investigator (Foodweb, fisheries)
Phil Hollyman	BAS	Co-Investigator (Toothfish fisheries)
Oli Hogg	Cefas	Partner
Katie Longo	Marine Stewardship Council	Stakeholder
Jess Marsh	Cefas	Partner
Helen Peat	Polar Data Centre (BAS)	Data management
Lisa Readdy	Cefas	Partner
Ainsley Riley	Cefas	Partner
Marta Soeffker	Cefas	Partner
Matt Spencer	WWF	Stakeholder
Peter Thomson	Argos Froyanes	Stakeholder
Sally Thorpe	BAS	Co-Investigator (Oceanographer, biophysical modeller)
Claire Waluda	BAS	Co-Investigator (Ecologist)
Mari Whitelaw	Polar Data Centre (BAS)	Data management

Workshop Agenda

The format of the workshop was a short talk on each topic followed by discussion.

Introduction (Rachel Cavanagh) Presentation on project objectives, deliverables, and timeline, followed by brief introduction of stakeholders and their interest in the project and SGSSI region
Toothfish overview (Mark Belchier, Tim Earl, Jess Marsh) Presentation followed by discussion to include toothfish fishery, stock assessment and management - where we are now and how this project will help
Modelling (Jen Freer) Recorded presentation followed by discussion including species distribution models, niche modelling and climate change; relevant oceanography models, modelling; projections
Break
Data/information (Otis Brunner, Mari Whitelaw) Presentation followed by discussion on data/information required (including environment, climate, toothfish distribution and life history, fishery) and sources
Final discussion and wrap-up

The rapporteurs were Otis Brunner, Rachel Cavanagh, Sally Thorpe and Claire Waluda. The minutes taken, as well as additional information from the presentations, are summarised in this report.

Introduction: Rachel Cavanagh, BAS, Project Leader

Rachel welcomed all participants, particularly Otis Brunner, who started in his post at BAS as the Postdoctoral Research Assistant on this project two days prior to this workshop.

A summary of the project was presented based on the proposal available online at https://www.darwininitiative.org.uk/project/DPLUS189/. The overall impact of this project will be that potential risks of climate-driven change to toothfish in SGSSI are better understood and made available to inform ecosystem-based fisheries management in the region. The ultimate outcome will be that the evaluation of the risks that climate change poses for toothfish in SGSSI informs ecosystem-based fishery management such that it can incorporate measures to reduce these risks.

Key project outputs:

1. Knowledge base of relevant environmental biological and fishery information for both species of toothfish created, providing the basis for understanding toothfish sensitivity to environmental parameters.
2. Ecological risk assessments of the effects of climate change on toothfish.
3. Climate change evaluation framework for toothfish fishery management

Additional items discussed in this workshop were the sources of relevant information; modelling approaches, e.g. including reference points for change, incorporating uncertainty, and the potential for modelling distinct life-stages separately to better understand the effects of climate change.

Beyond this workshop there will be regular meetings with the team, partners and stakeholders and progress reports will be shared. **The project will link with existing collaborators** researching toothfish and/or climate impacts in other regions and circumpolar:

- Matt Pinkerton – New Zealand (NIWA)

- Erica Carlig – Italy (CNR)
- Cassandra Brooks – USA (CU Boulder)
- Jilda Alicia Caccavo – France (IPSL)
- Rebecca Konijnenberg – Germany (AWI)

Focusing on toothfish, and on SGSSI, our framework will also inform toothfish management in areas outside SGSSI, providing an example of best practice for integrating climate change into fishery management.

Toothfish Overview Part 1: Mark Belchier, GSGSSI, Project Partner

This presentation introduced the two species of toothfish *Dissostichus eleginoides* (Patagonian toothfish) and *Dissostichus mawsoni* (Antarctic toothfish). A brief overview was presented as an introduction to the ecology and life history traits of *D. mawsoni* and *D. eleginoides* including their population structures based on otolith analyses, and their relative distribution from the Antarctic shelf (*D. mawsoni*) to low latitudes on continental shelf west of South America (*D. eleginoides*) (Figure 1). At the South Sandwich Islands, the thermal structure of the water masses linked to the regional ocean circulation leads to separation of the habitat of *D. mawsoni* in the south from *D. eleginoides* in the north, with some overlap in the more central areas of the island arc. Research into a potentially distinct subspecies of *D. eleginoides* around the Falkland Islands has recently been published (Arkhipkin et al., 2022).

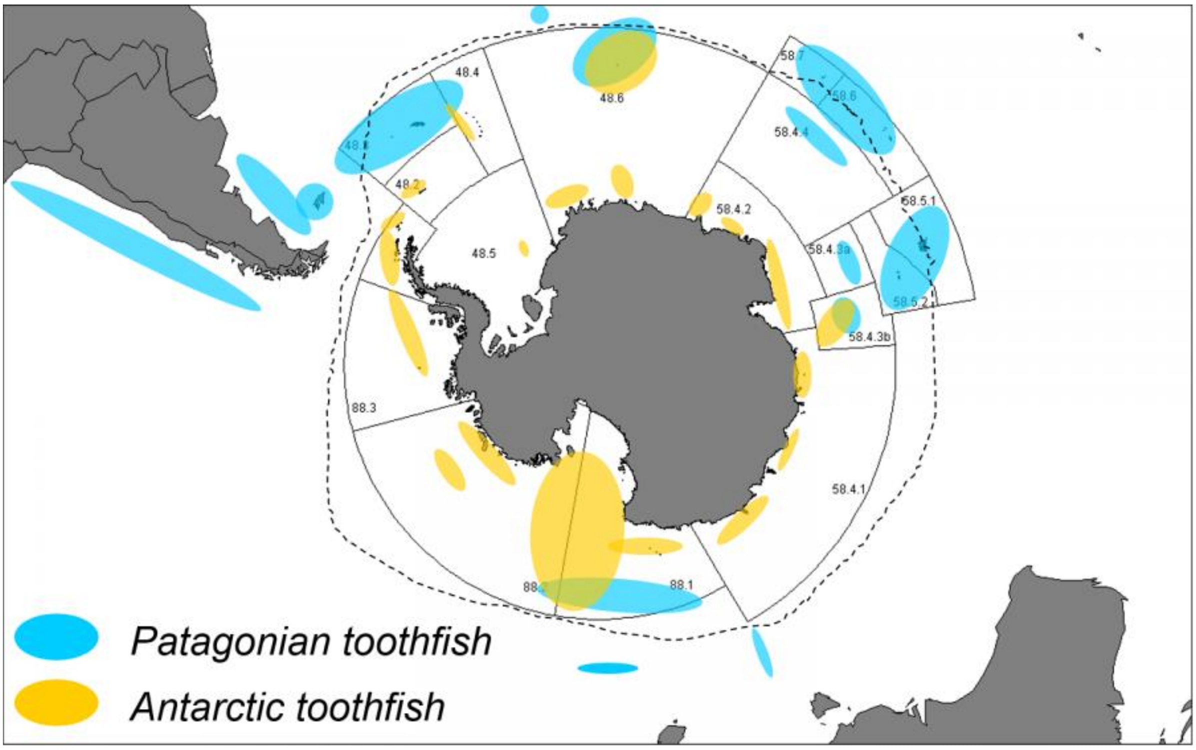

Figure 1: Approximate distributions of Antarctic and Patagonian toothfish in the Southern Ocean, also showing the CCAMLR management areas and the location of the Polar Front (dashed line). Credit: NIWA (https://niwa.co.nz/fisheries/research-projects/antarctic-fisheries-research/the-toothfish)

Both species support a valuable fishery in SGSSI, with the high lipid content meat receiving $30 – $80 per kilo in high end restaurants. Autoline fishing has mostly replaced Spanish line and is responsible for >70% of the fishery in South Georgia. Additional information on fishing practices in SGSSI can be found in the SGSSI Toothfish Fishery Management Plan (Government of South Georgia & the South Sandwich Islands, 2017).

The distinctions between the two *Dissostichus spp.* were outlined. As the two species' morphology is similar, it can be difficult for fishery observers to distinguish between them without additional otolith analysis. Although they fulfil a similar ecological niche, *D. mawsoni* contains a natural antifreeze and is more closely associated with the Antarctic continent (Figure 1). Early life stages of *D. eleginoides* have been sampled by fisheries surveys in the waters of SGSSI and information on their age and diet has been collected. *D. eleginoides* likely spawn at approximately 1000 m depth on the edge of the continental shelf in the austral winter (June – September) (Agnew et al., 1999; Laptikhovsky et al., 2006; Lord et al., 2006; Arana, 2009; reviewed by Collins et al., 2010). Pelagic eggs then drift passively from spawning grounds, until the juveniles hatch and gain the ability to migrate, including to warmer shelf regions around Shag Rocks (Belchier and Collins, 2008; Brigden *et al*., 2017; Bamford et al., unpublished) (Figure 2). A large amount of data related to *D. eleginoides* growth rates was collected by the BAS Groundfish Survey 2000 – 2009, where a cohort was tracked and higher recruitment was associated with colder than average years (Belchier and Collins, 2008). Much less is known of the early life stages of *D. mawsoni* as it is assumed that they remain close to the Antarctic shelf.

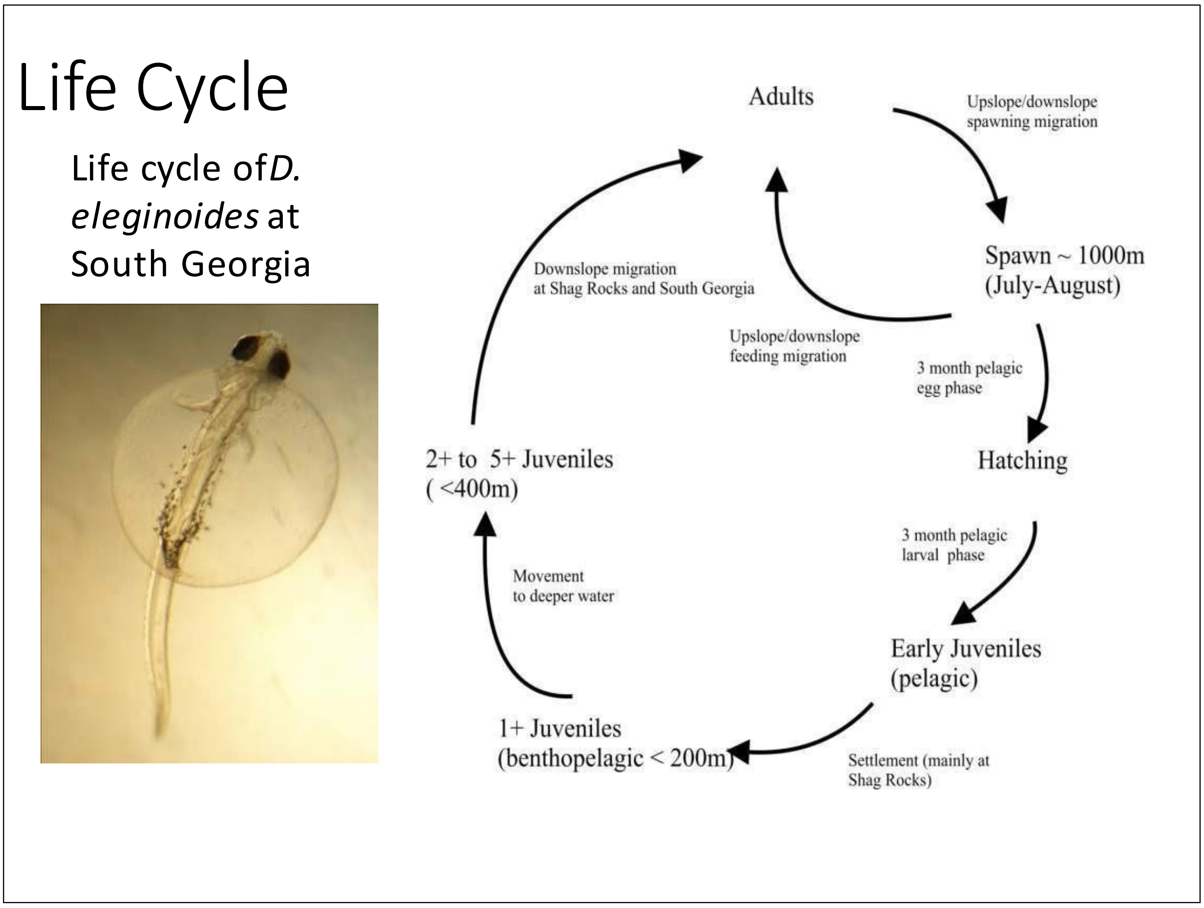

Figure 2: Lifecycle of *D. eleginoides* adapted from Belchier and Collins (2008).

Toothfish Overview Part 2: South Georgia Patagonian toothfish population: stock assessment and biological parameters: Tim Earl and Jess Marsh, Cefas, Project Partner

An overview was presented of the stock assessment methods and biological parameters collected from the fishery. The stock assessment method uses the CASAL (C++ Algorithmic Stock Assessment Laboratory) model and is currently being developed in Casal2 (see Earl et al., 2023 for further details).

CASAL is based on the following data:

- Catch compositions
- Tag recapture rates
- Biennial juvenile surveys
- Standardised Catch Per Unit Effort (CPUE) from fishery

The model assumptions include the following biological parameters, which are assumed to remain constant over the assessment period 1995-present:

- Proportion mature at age
- Average length at age
- Average weight at age
- Natural mortality

Cefas uses CASAL to carry out biannual stock assessments for CCAMLR, including *D. eleginoides* (CCAMLR, 2021). Based on the average recruitment and Coefficient of Variation from 1992 to 2015, Cefas was able to project the spawning stock biomass (SSB) of *D. eleginoides* 35 years into the future and hindcast to 1985. This projection was based on a constant catch rate and does not explicitly consider the effects of climate change. A desired output from these projections of stock status is to determine a catch limit that results in returning the stock to 50% of the 1985 SSB in 35 years, as well as a low risk of depleting the stock (defined as less than 10% probability of going below 20% of the 1985 SSB). However, estimates of the SSB become more variable the further they are projected so there is a need to incorporate this variability into any final recommendation of a catch limit.

Some of the age-based biological parameters in the catch compositions, such as maturity at age and growth parameters, are re-estimated annually, creating a time series of data collected since 1998 with which temporal trends can be investigated (e.g. Marsh and Earl, 2023). Parameters are also estimated as a function of biotic and abiotic variables, such as sex and fishing depths, to capture any influences of toothfish biology as well as the changing fishery dynamics. However, currently, fixed values of the biological parameters (i.e. not sex-specific or varying in time or space) are input into the CASAL assessment model.

From 2023 onwards, the Casal2 assessment method will be used. Casal2 has all the flexibility of CASAL, but allows biological parameters to vary over time (and space) and allows for more model outputs.

Toothfish Overview: Discussion

It was noted that **climate change considerations may be integrated into MSC certification next year**, although there is not a clear timeline as yet. Although some fisheries have integrated climate change considerations into their stock assessment, it has not yet been determined how this can be incorporated into MSC certification. This project may be useful in helping to inform this process.

Large iceberg events (e.g., A68 which broke up close to South Georgia in austral summer 2021) were raised as a potentially significant source of environmental variability for toothfish populations in the South Georgia and South Sandwich Islands region. It was pointed out that freshwater inputs would likely have the largest direct impact on toothfish near the surface through cooling and freshening of the surface layer. It was added that, while there is much uncertainty around these stages, eggs and larvae have been found at the surface, so there is the possibility that they could be impacted. Further impacts of A68 on the South Georgia marine ecosystem are being investigated by BAS and other researchers.

The relative Impact of climate change on *D. eleginoides* populations in the Falkland Islands was highlighted as an interesting consideration as they already persist in warmer waters. It was noted that this requires an understanding on whether they are a subspecies (Arkhipkin et al., 2022). More northern fisheries such as the Ecuadorian fishery are likely sourced from early life stages further south.

Observations of *D. eleginoides* development in laboratories was highlighted (e.g., Mujica et al. (2016)) some of which is unpublished. It was mentioned that similar research may have been undertaken by the former Soviet Union (e.g. Yukhov (1982)) during their active fishery. Observations of the development of toothfish eggs/larvae in such laboratory experiments is extremely valuable for modelling the effect of temperature on dispersal.

Modelling: Jen Freer, BAS, Project Team

Fundamental questions in ecology relate to species distributions and their relationship with other species and their environment. This presentation provided an introduction to Species Distribution Models (SDMs), including background on the ecological niche concept, methodological examples from Freer et al. (2019), and considerations when applying to toothfish. A species ecological niche, or the hypervolume that it occupies, will be reflected spatially in their geographic distribution. Being able to map out a species range is vital in the context of a changing environment, especially if that species is commercially or ecologically important.

Predictions are vital components of understanding change and implementing management. Correlative approaches require substantial and appropriate occurrence data on the species as well as numerous suitable environmental parameters at relevant spatial and temporal scales and may include distance metrics (e.g., distance from sea ice is important for Antarctic krill). Occurrence data sources (Table 1) can be accessed via R packages such as 'robis' and 'rgbif', while 'sf' is useful in spatialising such occurrence data.

Selecting environmental parameters must account for a species life history and biology, but may be limited by their spatial or temporal availability, for example, are they included within forecasts of future climate scenarios? Useful sources for environmental variables are listed in Table 1. In terms of climate scenarios, it is important to incorporate uncertainty that arises through disagreements between models. Sea surface temperature (SST) is highly variable between the outputs of the Coupled Model Intercomparison Project (CMIP6) and this variability increases with time from present day. Some sources for climate projection data are listed in Table 1.

Model selection based on an assessment of model performance is very important and insights on this aspect of SDMs are continually being updated through methodological comparisons and assessments in the literature. The performance of SDMs can be evaluated and compared but best practice is usually to use an ensemble of multiple algorithms or to fine-tune the parameterisation of a single algorithm. Some recommended R packages for SDM model selection and parameter tuning are 'sdmTune', 'flexsdm', and 'biomod'.

In terms of applying SDMs to toothfish, it is unlikely that correlative approaches will be appropriate for early life stages, as very little occurrence data has been collected. As higher predators, the commonly used environmental parameter of chlorophyll a concentration may have little direct influence on distribution. On the other hand, sea ice may be of particular importance to *D. mawsoni* but this is another parameter that is extremely uncertain in climate projections.

A useful start for this project will be to compile the literature on best practices in SDMs, perhaps as part of a SDM interest group at BAS.

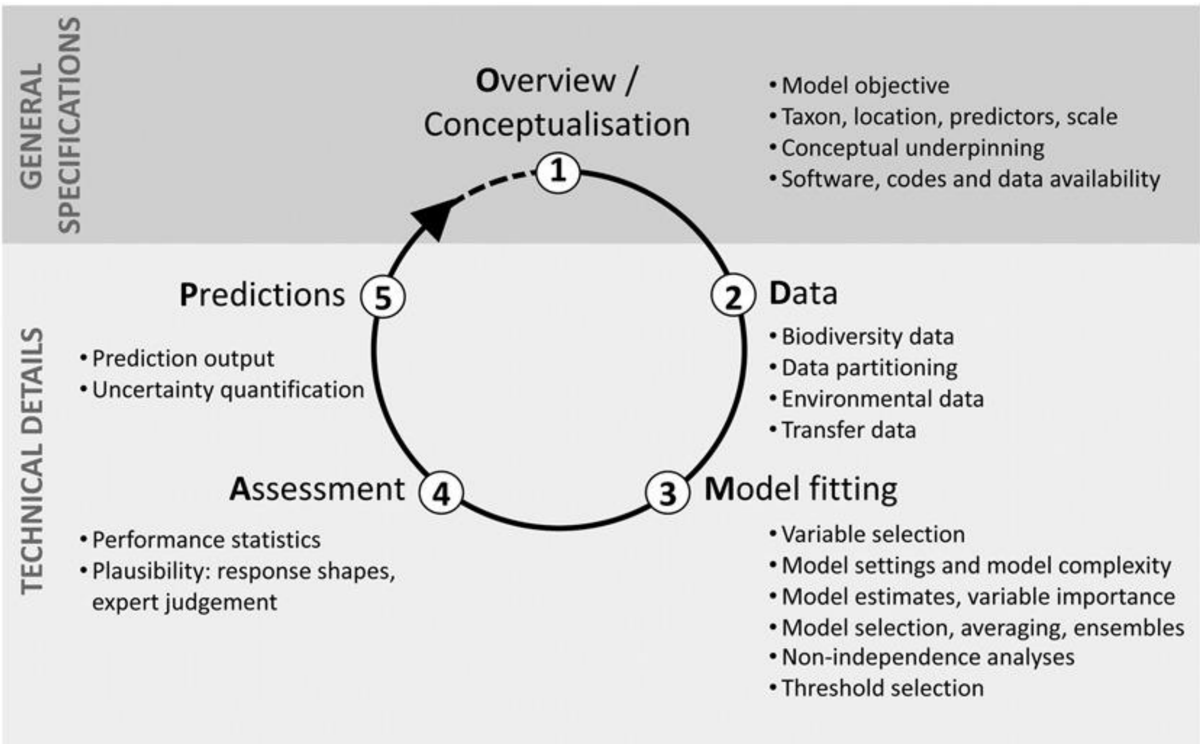

Figure 3: Steps in Species Distribution Modelling (Zurrell *et al.*, 2020).

Modelling: Discussion

For adult toothfish, it was suggested that we do not limit our use of occurrence data to presence only, as we have abundance and biomass in many cases.

Much less is known about **earlier life stages**. It was noted that a common assumption of SDMs is that all life stages have the same niche. Having separate models for distinct life stages would be more relevant. It was further noted that mechanistic rather than correlative models may be particularly relevant for earlier life stages (e.g., temperature dependent growth). The Lagrangian methods employed by Brigden (2019) were highlighted as a useful resource to this project. The local and regional oceanic connectivity in the SGSSI region has recently been investigated (Thorpe and Murphy, 2022). Soeffker et al. (2022) present movement data of *D. eleginoides* between the South Sandwich Islands and South Georgia that show connections between the two regions. The role of sea ice drift and ocean currents in *D. mawsoni* egg dispersal has been modelled for the Ross Sea region (Behrens et al. 2021). It may be important to model the life cycle of *D. eleginoides*, as the connections among life stages is only hypothesised. A qualitative modelling approach could demonstrate how changes in one life stage affects the others.

The discussion also considered potential **indirect impacts of climate change** for example via invasive species or impacts on species with important trophic interactions with toothfish? E.g. warm water intrusions may introduce shark predator species. The possibility of climate change affecting the availability of prey species was discussed, although this was considered unlikely to have a strong effect on the more generalist life stages of toothfish (Roberts et al., 2011). However, juvenile toothfish are less generalist in terms of prey so may be impacted by changes in abundance or timing of prey (trophic mismatch).

Data/information: Mari Whitelaw, BAS/UK Polar Data Centre, Project Team

This presentation served as an introduction and overview of the UK Polar Data Centre (PDC) and how it can support this project. Of particular relevance at this stage is the support that can be provided in the planning stages, including searching for relevant datasets and assisting in compliance with Darwin Plus requirements. There is a wealth of toothfish fishery data accessible from the PDC (subject to approval from GSGSSI) in the form of data from fishing vessels, observer data, tagging data and the annual groundfish survey. The PDC will advise with in-project data management throughout the project. The deliverables for this project include the requirement to archive all the data with the PDC and, where appropriate, make it more widely available.

Data/information: Otis Brunner, BAS, Project PDRA

An overview was presented on the data/information that may be required for this project (including environment, climate, toothfish distribution and life history, fishery) to provide a starting point for discussion. This project will need to integrate various methodologies (Figure 3) that lead to the creation of correlative models like SDMs where data are available and more mechanistic models such as dispersal simulations where data are lacking. The types of data required to create an integrated toothfish ecological model include biological (e.g., toothfish biology and behaviour), environment (e.g., habitat suitability (SDMs)), as well as oceanography and climate.

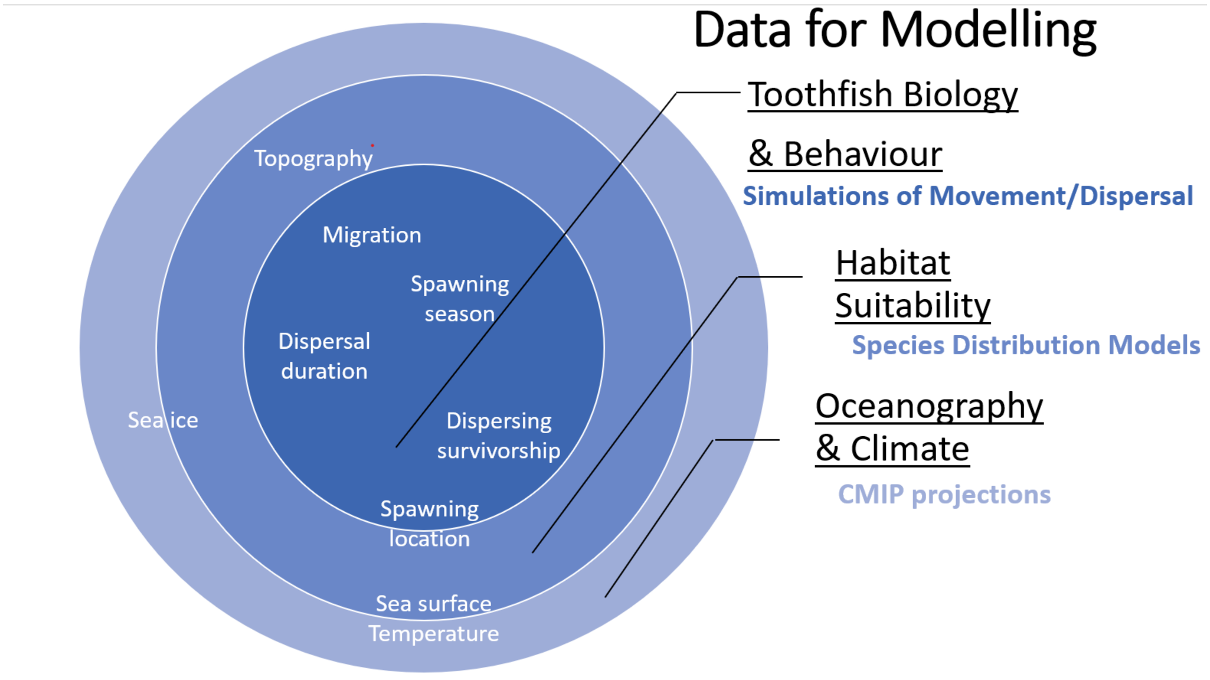

Figure 3: The nested nature of modelling approaches (blue text/circles) and overlap of data inputs (black/white text) required for an integrated model of toothfish response to climate change.

Data/information: Discussion

With numerous approaches and data sources, we considered ways to compartmentalise the different strands and potentially create working groups with a focus on each data type/methodology.

There is currently **data available on toothfish populations** from CCAMLR in the form of their *D. mawsoni* stock assessments and fish growth models. Additional genetic data suggest that *D. mawsoni* is a single stock (Maschette et al., 2019). FishBase was highlighted as a good place to start looking for relevant information. It was noted that juvenile ("sub-adult") *D. eleginoides* have been successfully tagged and found to commonly stay within a relatively small area based on recapture rates (reviewed by Collins *et al*., 2010). It was reiterated that Shag Rocks has been found to be a popular location for juvenile *D. eleginoides*. It was put forward that there are likely oceanographic drivers that lead to the aggregation of juveniles at Shag Rocks, including mesoscale oceanographic features in the circulation that retain biota, and particular environmental conditions (e.g., temperature, salinity) that provide favourable habitat.

There are multiple potential **sources of new data on toothfish populations** that are yet to be explored. It was noted that the Pharos SG could potentially sample the shelf area to collect larval/juvenile *D. eleginoides* near the surface over the shelf area if the appropriate gear could be provided. North (2002) used a multiple RMT8 net (8 m^2, 4.5 mm mesh) or RMT25 net (25 m^2, 5mm mesh) to successfully sample juveniles. It was noted that larval/juvenile toothfish are rarely caught as bycatch in the krill fishery because they mostly operate in the summer, while spawning happens in the winter. The Continuous Plankton Recorder (CPR) has sampled the surface waters around Cumberland Bay and various other areas around Antarctica at the surface and may have inadvertently sampled toothfish eggs/larvae, which have not yet been recorded. It was suggested that it could be worth investigating the CPR samples (silks) in the region via the Sir Alister Hardy Foundation for Ocean Science, Plymouth.

Additional data sources mentioned include FishMIP, which uses CMIP data and looks at the effects on trophic dynamics. It was noted that FishMIP is not particularly well suited to polar regions but the NERC-funded BIOPOLE programme is investigating future productivity rates based on CMIP projections. Resources and guidance for environmental data layers to use in species distribution models can also be found in recent publications (Hogg *et al*., 2016; 2021).

Table 1: Resources available and relevant to this project, as discussed at this workshop

Resource Type	Source	Description
Species Occurrence	GBIF	Global Biodiversity Information Facility has 4,012 and 6,649 georeferenced occurrence points for *D. eleginoides* and *D. mawsoni* respectively
	PDC	UK Polar Data Centre contains occurrence data in the form of fishery records from SGSSI, annual Groundfish Survey and other sources. Contains stock assessment parameters used in CASAL
	OBIS	Ocean Biodiversity Information System has 2,192 and 6,026 occurrence data points for *D. eleginoides* and *D. mawsoni* respectively (most are georeferenced)
	Fisheries	Some data will not be publicly available in the above repositories but can be requested from CCAMLR and GSGSSI etc
	Literature	There are likely occurrence records that have not been uploaded onto any databases yet but can be found in the relevant literature
Environment	Copernicus	The Earth observation component of the European Union's Space programme. Environmental layers are freely available and readily accessible via APIs (Application Program Interfaces)
	GEBCO	The General Bathymetric Chart of the Oceans provides global bathymetric data on a 15-arc second interval grid. The latest version (GEBCO 2023) has incorporated the most recent version of the International Bathymetric Chart of the Southern Ocean (IBCSO, 500 m resolution)
	BioOracle	Provides formatted GIS rasters of biological and environmental data specifically for modelling marine ecosystems
	NOAA	National Oceanographic and Atmospheric Administration (US) contains past present and future oceanographic environmental data
	CEDA	Centre for Environmental Data Analysis holds and makes accessible environmental data from various atmospheric and earth observation projects
	BioPole	This project will collect and model nutrient concentrations and distributions
	PDC	UK Polar Data Centre has high resolution bathymetric data from swath surveys of South Georgia and the South Sandwich Islands

Modelling Methods	PolarRES	Collaborative project to investigate the interacting effects of climate change on the polar regions. Tools and data from this project will be made widely available
	ODMAP	(Overview, Data, Model, Assessment and Prediction) is a standard protocol for reporting species distribution models
	FishMIP	The Fisheries and Marine Ecosystem Model Intercomparison Project combines and compare ecosystem models with inputs from earth system models
Others	FishBase	Repository of metadata and references on various aspects of fish ecology

Next Steps

1. Establish a project webpage to keep partners and stakeholders informed of project progress and increase the visibility of the project.
2. Set up an appropriate online collaboration tool for the project team where topics can be discussed, meetings can be organised and internal material can be shared.
3. Compile literature relevant to the project, including on best practices in SDMs, toothfish-environment relationships, etc.
4. Synthesise data to establish a knowledge base of relevant environmental, biological and fishery information for both species of toothfish.
5. Note any data gaps and, where possible, compile suggestions of means to collect additional data on these, e.g., early life stages of toothfish (i.e., eggs, larvae, and juveniles) are currently under-studied. These could include utilising existing samples (e.g., from Continuous Plankton Recorder surveys) or suggesting complementary sampling as part of current activities in the region (e.g., deploying surface nets from vessels to sample early life stages).
6. Determine candidate analytical and modelling approaches.

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