

Environmental and ecosystem drivers of catch efficiency within Australia's subantarctic Patagonian Toothfish fisheries

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Abbreviations / Glossary

| AAIW | Antarctic Intermediate Water is a water mass with salinities ranging |
|--------------------------|---|
| | from 34.25-34.4 psu |
| ACC | Antarctic Circumpolar Current |
| Antarctic sea ice tongue | Seasonally variable sea ice tongue that forms from the advection of ice |
| | from the south rather than by in situ thermodynamic ice formation in |
| | the East Antarctic around ~ 80°E |
| Fawn Trough | Gap in the Kerguelen Plateau between 55°S and 57°S |
| HIMI | Heard Island and McDonald Islands |
| Lower mesopelagic zone | Pelagic waters between 400 – 1000 m |
| MBES | Multibeam Echosounder |
| MI | Macquarie Island |
| Mesopelagic zone | Pelagic waters between 200 – 1000 m |
| Micronekton | A grouping of free-swimming fish, crustaceans, squid, and jellyfish |
| | between 2 – 20 cm in length that reside in the mesopelagic zone. |
| SAMW | Subantarctic Mode Water |
| SBES | Single Beam Echosounder |
| SIO | Southern Indian Ocean |
| SWP | Southwest Pacific |
| WW | Winter Water layer is a remnant of the previous winter's mixed layer, |
| | and is formed seasonally by deep convection |
| WWS | Warm Water Saturation is the percentage of a water mass, by volume, |
| | that exceeds some temperature threshold. |
| WWSA | Warm Water Saturation anomaly, is WWS with the seasonal mean |
| | removed |
| UCDW | Upper Circumpolar deep water in this study is defined as a deep-water |
| | mass with a potential density of between 27.6-27.8 kg/m ³ |

Executive Summary

This report explores how regional scale variation in biophysical habitats may influence Patagonian toothfish catchability and condition. We use BRAN2020, a 0.1 degree vertically resolved global ocean circulation model, a novel bioacoustic dataset - collected by the fishing vessels during normal operations over a 10-year period, and the latest spatiotemporal modelling techniques to explore how the biophysical conditions over the fishing grounds may influence fishing success and fish condition historically. If relationships can be established, models could be used to predict fishing success and fish condition into the future. These are products that may assist with improving the fisheries triple bottom line.

Background

The Southern Indian Ocean and SW Pacific sectors of the Southern Ocean, support some of the world's largest toothfish fisheries. Recently Australian toothfish fisheries in the Heard Island and McDonald Islands (HIMI) and Macquarie Island (MI) regions have experienced a decline and increase in variability in catch rates respectively. One explanation is that changes to the species biophysical environment may be influencing the availability or the catch efficiency of the fleet. Due to their isolation, the long-term sustainability of these fisheries is dependent on the interaction between large scale oceanography, ecosystem productivity and adaptive fisheries management practices.

Aims

The overarching aims of this project are to; Characterise historical oceanographic conditions over fishing grounds in the HIMI and MI regions; Characterise variability in toothfish foraging habitats using 741 and 250 days of bioacoustic data at HIMI and MI respectively. Use state-of-the-art spatiotemporal modelling techniques to explore relationships between biophysical conditions and toothfish catch rates and physical condition.

Key findings

In the HIMI and MI regions the Antarctic Circumpolar Current (ACC) is comprised of four distinct water masses and three associated biogeographical provinces that are separated by dynamic frontal regions, whose position is determined by gaps in regional topography. In the HIMI region we report that circulation over the fishing grounds was relatively weak, with the high flow observed in the Fawn Trough (FT) to the south of the HIMI grounds. The dominant water mass over the HIMI grounds is UCDW between 200 - 2000m. UCDW in this region experiences considerable seasonal and interannual variability with bottom temperatures that vary around 2°C, towards the lower end of thermal preference for toothfish. There are years when bottom temperatures were significantly colder than average (e.g., 2009, 2010, 2011, and 2015), and years that bottom temperatures were warmer than average (e.g., 2017, 2019 and 2020).

In the MI region we report that circulation and physical conditions are highly dynamic, due to the location of the subantarctic front located in the ridge gap to the north of Macquarie Island. The dominant water masses over the MI fishing grounds between 300 - 1200m is AAIW with UCDW found deeper than 1200m. The annually averaged salinity gradients between AAIW and UCDW, indicate that there are years when AAIW has broader influence over the grounds than normal (e.g., 2005-2010) and years when UCDW shoals (2011, 2012, 2019 and 2020). The subantarctic front is located in the ridge gap

to the north of MI, separating the SAMW from AAIW between the surface and 600m. In 2017 there appears to be greater influence of SAMW over the core fishing grounds between.

The community composition and biomass of toothfish prey fields varied between regions. MI had a higher net biomass of micronekton per unit area compared to HIMI. Overall, micronekton biomass at MI was mostly from fish while at HIMI micronekton biomass was more evenly spread across all acoustic/functional categories. In both regions squid had the lowest biomass. Interestingly in waters to the south of HIMI, the gelatinous organisms were the dominant acoustic/functional group. Regional differences in the backscatter, biomass, and community composition of micronekton correspond to regional differences water masses and biogeographical provinces.

For the environmental and ecological variables only, bottom temperature produced significant relationship with catch and effort data at HIMI. The effect was strong – and positive so that increases/decreases in bottom temperature were very clearly linked to increases/decreases in the probability of obtaining a suitably high CPUE for a set at a lag of 6 months but possibly up to 1 year. Stochastic spatial variations in catch rate success-per-set are around 6-7 times greater at HIMI than at MI. The major difference in terms of oceanography and acoustic covariates is the significant strong effect of bottom temperature estimated in HIMI, relative to the not-quite-significant effect estimated for MI. In both cases the backscatter was not significant but was apparently stronger at MI relative to HIMI. Its insignificance is not to be interpreted as its lack of potential impact but probably more a result of the patchy nature of the historical data and its apparent covariance with the bottom temperature.

At both HIMI and MI, toothfish condition increased over time, similar to the overall increase in average bottom temperature at both locations. Where they contrast most obviously is the average values – fish condition is consistently higher at MI than at HIMI which is consistent with a higher average water temperature and micronekton biomass at MI relative to HIMI. There is also no apparent spatial variation at MI, whereas at HIMI in the West we see a rapid drop in condition from 2014 to 2015; in the East this drop occurs from 2015 to 2016. We hypothesise that this lag by one year seems very consistent with the large drop in water column temperature in the West in 2014 and the East in 2015.

Implications for relevant stakeholders

We report that seasonal and interannual variability in biophysical conditions over the fishing grounds at both HIMI and MI have a considerable effect on toothfish catch rates and condition. Understanding how short term seasonal and longer-term ecosystem forecasting may be used for operational and management planning in the future is recommended. One item that needs to be considered by management and stakeholders is to envisage what the potential adoption of these methods might resemble and how that might interact with the current management framework.

Recommendations

The impact of this work would be enhanced though short-term research priorities identified at AFMA Climate adaptation workshops for the HIMI and MI toothfish fisheries:

- i) Identify the drivers of oceanographic variability at HIMI and MI.
- ii) Increase observations of biophysical habitats to obtain reliable forecasts in the future.
- iii) Investigate the how seasonal forecasting may assist with operational planning.
- iv) Consider how longer term (years +) change in biophysical conditions over the grounds may affect the sustainability of the fishery.

Keywords

Patagonian Toothfish, catchability, fish condition, Antarctic Circumpolar Current, deep scattering layers, thermal tolerance, Southern Ocean ecosystems

Introduction

Background

Patagonian toothfish (*Dissostichus eleginoides*), here after referred to as toothfish, subpopulations of the SIO and SWP support many high value fisheries. In the SIO the Kerguelen Plateau supports two of the world's largest toothfish fisheries, managed by French and Australian authorities. Recently the Australian fishery at HIMI, experienced a decline in catch rates that were not related to stock decline. While at Australia's other toothfish fishery, MI, catch rates have become increasingly variable. One explanation is that changes to the species biophysical environment may be influencing the availability or the catch efficiency of the fleet. Due to their isolation, the long-term sustainability of these fisheries is dependent on the interaction between large scale oceanography, ecosystem productivity and adaptive fisheries management practices. This study aims to explore historical relationships between regional scale oceanography, biophysical habitats and toothfish catchability.

Habitat preferences of toothfish

Subantarctic continental shelfs and ridges support isolated subpopulations of toothfish; a large, longlived species, that have a thermal preference of water temperatures between 2- 11 °C (Collins et al., 2010). They are a bottom dwelling, non-migratory fish that undertake an ontogenetic migration down the continental slope into deeper waters as they grow (Arkhipkin & Laptikhovsky, 2010; Brown et al., 2013; Welsford et al., 2011). Movement, diet, and fisheries catch records report that adults and sub-adults are resident in depths between 500 - 2500m on the Kerguelen Plateau (Duhamel, 1981a; Welsford et al., 2011; Williams & Lamb, 2002)., with depths between 600-1200m thought to be an optimal ecological niche that contains abundant resources with reduced competition (Péron et al., 2016).

Regional oceanography

Southern Ocean (SO) circulation is dominated by the eastward flowing Antarctic Circumpolar Current (ACC). The ACC has four distinct water masses and three associated biogeographical provinces in the HIMI and MI regions that are separated by strong fronts, being the polar and subantarctic fronts respectively. In regions where the eastward flow encounters the Kerguelen Plateau and Macquarie Ridge, the ACC divides into several jets, with fronts collocated with gaps in topography (Marshall & Speer, 2012; Rosso et al., 2015). In the HIMI region the divergence of the ACC into three jets results in increased mixing (Tamsitt et al., 2017) and significant nutrient enrichment of the surrounding waters (Schallenberg et al., 2019). The ACC flows around the north of Kerguelen Plateau, with strong, deep currents; through the Fawn Trough - on the southern edge of the HIMI fishing grounds - with a strong, narrow jet; and farther south, through Princess Elisabeth Trough, as a broad, weak, baroclinic current (Bestley et al., 2020; McCartney & Donohue, 2007). The water mass that overlies the Kerguelen Plateau in the HIMI region is mostly Upper Circumpolar Deep Water (UCDW, Martinson et al., 2008; Schmidtko et al., 2014), a relatively warm fresh layer that originates in the North Atlantic Ocean and is transformed off the Antarctic coast as it impinges on the continent and entrains shelf water and sea ice melt (Tamsitt et al., 2017, 2021). A secondary feature of the circulation in the HIMI region, is flow from the SE associated with the Antarctic Sea ice tongue (Rintoul et al., 2008). This

cold fresh water originates from flow of the ACC through the Princess Elisabeth Trough that converges with the westward flowing Antarctic Slope current, which results in a northward deflection of net transport, that reaches the eastern edge of the HIMI region.

In the Macquarie Island region, the AAC is a strong, deep, eastward flow that is littered with meanders and eddies. As the ACC approaches the Macquarie Ridge, the ACC breaks into several jets, with flow through ridge gaps to the north and south of Macquarie Island (Rintoul et al., 2014). As a result, the ocean currents over the fishing grounds are strong and variable. The subantarctic front is located in the ridge gap to the north of MI, separating the SAMW from AAIW. The dominant water masses over the MI fishing grounds between 300 - 1200m is AAIW with UCDW found deeper than 1200m. Here we aim to characterise the variability in regional oceanography using a vertically resolved global ocean circulation model.

Pelagic habitats of toothfish

An archival tagging experiment by Williams and Lamb (2002) in the HIMI region successfully demonstrated that toothfish can be caught, tagged and recaptured and that they do undertake regular vertical movements into the water column. Thirty-nine toothfish fish between 717 – 815 mm in length were tagged and released in depths that ranged between 450 – 620 m. Seven of these fish were recaptured between 27 - 59 days later. Overall, fish were found to inhabit water temperatures 2.2 - 2.3 °C, displayed low horizontal movements (min 2.85 km, max 14.6 km) and alternated between inactive periods where they rested on/near to the seafloor and active periods when they moved into the water column, to presumably forage, returning to pre-departure depths some hours after lift-off. Five of the seven fish moved between 20 – 100 m off the bottom at regular intervals, with one fish moving > 200 m into the water column.

In French waters of the Kerguelen plateau, Duhamel (1981) analysed the stomach content of 1514 toothfish (748 empty), finding that the main constituents of their diet were myctophids (27%), icefish (25.4 %), Unidentifiable fish (partially digested) (23%), Crustaceans (5%), and squid (1%). Gelatinous Cnidarians or salps were not recorded as a prey item for toothfish in this region. However, they accounted for 23.5% and 14.3% of prey in Grey rockcod and marbled rockcod respectively. Of the identifiable prey for toothfish, *"micronekton"* accounted for 33% of the diet. Micronekton is a grouping of free-swimming fish, crustaceans, squid, and jellyfish between 2 – 20 cm in length that reside in the mesopelagic zone (200-1000 m).

At Macquarie Island, Goldsworthy et al. (2002) sampled the stomach content of 1423 toothfish (961 empty), caught between 500 – 1290 m, that ranged in size between 310 – 1490 mm. The main constituents of toothfish diet in this region were: Fish (65%), cephalopods (35%) and crustaceans (32%). Of the identifiable prey "*micronekton*" accounted for 73.1% (Bathylagidae 14.4%; Myctophidae 10%; cephalopods 20.6%, Prawn-like crustacea 28.1%). In the MI region Gelatinous cnidarians or salps were not recorded as a prey item for toothfish.

Foodweb studies in the SO have identified two major energy pathways, *Krill and Copepod*, that support the production of higher trophic levels (Hill et al., 2012; McCormack et al., 2020; Subramaniam et al., 2020). In regions where large cell diatoms dominate primary production "krill foodwebs" prevail. In regions where small cell phytoplankton drive primary production, "copepod

foodwebs" emerge, as observed in the HIMI and MI regions. In these regions micronekton communities are a key mid-trophic link between primary producers/consumers and higher trophic levels. SO Micronekton communities display broad circumpolar distributions, with abundance and size varying between biogeographical provinces of the ACC (Hulley & Duhamel, 2011). Generally, the population structure of most mesopelagic fish species in the SO comply with Bergmann's rule, with larger fish observed in colder waters at higher latitudes, and recruitment constrained to waters north of the Polar Front (Saunders et al., 2017; Saunders & Tarling, 2018). Crustaceans commonly occur in high abundance along the shelf break and upper slope particularly in regions that experience episodic upwelling. Despite their ecological importance, large knowledge gaps remain around the distribution and ecology for SO cephalopods and gelatinous communities, as they are underrepresented in traditional net sampling programs. Echosounders are commonly used to study micronekton communities as they form deep scattering layers (DSL) in the mesopelagic zone between 200 - 1000m (Kloser et al., 2009; Proud et al., 2018). Here we aim to characterise the variability in toothfish pelagic habitats using historic bioacoustic data collected over the fishing grounds by the toothfish vessels that participate in the IMOS Bioacoustic Ships of Opportunity Program (BASOOP) in the HIMI and MI regions.

Demersal habitats of toothfish

Deep-water demersal fishes are crucial in continental shelf and slope ecosystems and have economic significance in many countries. Their distribution and abundance are influenced by various factors such as oceanography and benthic habitat (Bartholomä, 2006). Benthic habitat refers to the ecological community and physical environment (e.g., bathymetry and slope) that exists on or near the seabed. Seabed structure and composition, along with habitat arrangement, affect ecological value, including biodiversity and fishery production. Well-established fish-habitat associations enable habitat to serve as a proxy for predicting fish distribution and abundance (Anderson et al., 2009).

Benthic habitats can be determined using acoustic methods that are validated or "ground-truthed" through physical sampling or visual verification (Anderson et al., 2007). Among the best available acoustic technologies are calibrated multibeam echosounders (MBES), which offer high-quality, high-resolution (~200 m @ 1000 m depth) data. Due to their wide beam angles (~ 100°) they can map large areas of the seabed quickly. However, conducting dedicated MBES surveys aboard large offshore research vessels is expensive, limiting the availability of this data in some regions. MBES surveys conducted by Australian and New Zealand research vessels in the HIMI and MI regions provided important bathymetric data in this study.

Single beam echosounders (SBES) offer an additional (supplementary) source of information for informing benthic habitats at HIMI and MI, specifically bathymetry and slope. In this study we analysed the SBES acoustic data collected by the fishing industry in the HIMI and MI regions. We learned early on in the process that habitat type (e.g. soft or hard bottom) could not be derived from the available SBES data. This was mostly because of the depths in the regions (500-1500 m), which make accurate interpretation of seabed backscatter difficult, in addition to a lack of ground-truth data. Instead, we focused our efforts on producing a high quality SBES dataset that could be used to supplement the bathymetric and slope maps generated from the MBES data.

Catch histories

The aim of the catch analysis is to integrate summaries of the oceanographic, bioacoustic and bathymetric data products with statistical analyses of the operational catch and effort data for both fisheries and explore predictive models for the catch-per-unit-effort (CPUE) and fish condition for both fisheries. Traditional fisheries analyses of catch and effort data relates mostly to the derivation of relative abundance indices for use in stock assessments and other related analyses (Maunder & Punt, 2004). The focus in this project is, in essence, the opposite of what those types of analyses are trying to do: our focus is to implicitly model the abundance signal in these data but, more importantly, to explore how the various system drivers influence catch efficiency. In addition to operational catch analyses, we were interested to explore historical variation in fish condition given condition indices are a potential bellwether variable of change in target species driven by exogenous environmental forcing and a key economic performance factor.

Need

The HIMI and MI toothfish fisheries have experienced considerable changes to catch rates in recent years, that are not stock related. There is strong interest from industry and managers in determining the extent to which biophysical drivers influence these trends. This proposal will address this by quantifying the relationships between fishery specific environmental, ecological, and economic variables using state-of-the-art spatiotemporal modelling techniques. The analysis will identify relationships between key variables under a variety of environmental conditions, and if successful these variables will be used to produce probabilistic maps of catchability to enhance the efficiency of this quota-managed fishery.

Objectives

- 1. Develop a high-resolution oceanographic tool to characterise historical oceanographic conditions over the Kerguelen Plateau and Macquarie Ridge regions, utilising data from available resources.
- 2. Characterise variability in toothfish foraging habitats using historic bioacoustic data collected on-ground by the toothfish vessels that participate in the IMOS BASOOP in the Kerguelen Plateau and Macquarie Ridge regions.
- 3. Investigate how historic bioacoustic data collected on-ground by the toothfish vessels that participate in the IMOS BASOOP can be used for seabed habitat classification in the Kerguelen Plateau and Macquarie Ridge regions.
- 4. Combine environmental, ecological, and economic covariates and catch histories to characterise variations in catchability.

Method



Figure 1: Map of the region surrounding Kerguelen Plateau, showing bottom topography (colour), various subdomains (blue boxes; labelled East, West, South, and Far South), and a section between the HIMI region and the Antarctic continent (red line) referred to in this study. The light grey lines denote the boundaries of the Australian EEZ and the French EEZ (to the north). The key topographic features are labelled.



Figure 2: Map of the region surrounding Macquarie Island, showing bottom topography (colour), and a section along the Macquarie Ridge (red line) referred to in this study. The light grey lines denote the boundaries of the Australian EEZ. The key topographic features are labelled.

Oceanography

To characterise regional scale variation in oceanography in the HIMI and MI regions, we use data from version 2020 of the Blue ReANalysis (BRAN2020), a 1/10°-resolution, data-assimilating global ocean model. Observations assimilated include sea-level anomaly (SLA) from satellite altimetry, and in situ temperature and salinity from programs that include Argo. BRAN2020 provides gridded estimates of ocean temperature, salinity, velocity and sea-level, on a near-global 1/10°-resolution horizontal grid, with sub-surface fields at 51 vertical levels between the surface and seafloor (with higher resolution nearer the surface).

At HIMI the analysis of the historical oceanographic conditions in over the fishing grounds and waters to the south and far south (Figure 1) is performed by calculating the following: Time series of annually area-averaged bottom temperature between 400 and 2000 m; The percentage of area warmer than 2°C, 1.8°C, and 1.4°C; Temperature on different potential density surfaces of Upper Circumpolar Deepwater (UCDW); A vertical section along ridge to define properties of ACC in the HIMI region, no-tably winter water, UCDW, and the strength of the zonal current through the Fawn trough; Average depth and thickness of UCD. And finally, the Warm Water Saturation which is the percentage of water, by volume, between sigma-27.6 and sigma-27.8 in each region that is warmer than 1.8°C, to explore seasonal and interannual variability in UCDW.

At Macquarie Island (Figure 2), an analysis of historical oceanographic conditions around MI is performed by calculating the following: Regional mean kinetic energy with average velocities at 155 m depth, longitudinal sections of time-mean; density, eastward velocity, temperature and salinity over the Macquarie Ridge and at RIDGE-3°, RIDGE-2°, RIDGE-1° and RIDGE+1°, RIDGE+2°; Annual-averaged temperature and salinity over the Macquarie Ridge for years 2005-2020; Timeseries of time averaged near-bottom (a) potential temperature, (b) salinity, and (c) potential density between 2005-2020 over the Macquarie Ridge.

Toothfish pelagic habitats

A total of 2,576 days of raw bioacoustic data collected by fishing vessels over the HIMI and MI fishing grounds between 2010 and 2020 were analysed to characterise regional scale variation in toothfish prey fields. All bioacoustic data were collected by Simard EK60, EK70 and EK80 single frequency splitbeam 38 kHz echosounders, installed on commercial fishing vessels. Echosounders were calibrated annually (Demer et al., 2015), post processed to remove acoustic artifacts (Haris et al., 2021; Ryan et al., 2015) and raw data was corrected for amplifier nonlinearity biases (De Robertis et al., 2019).

After post processing, approximately 741 and 250 days of QA/QC watercolumn acoustic data were suitable for analysis at HIMI and MI respectively. Hourly along-track integrations of the lower-mesopelagic zone (400 – 1000 m) backscatter (s_A nautical area scattering coefficient, m² nmi⁻²), were averaged at statistically significant time intervals within 0.3-degree grids at HIMI and 0.2-degree grids at MI. Note that data collection only occurred within designated fishing seasons, March – November at HIMI and April – August at MI, so not all quarters/seasons are represented. Generalised Additive

Models (GAMs) were used to test for relationships between mesopelagic backscatter and a suite of environmental variables (quarter, year, lower mesopelagic temperature, salinity, oxygen and net primary production) in time and space in both the HIMI and MI regions.

Mesopelagic micronekton community composition. Three historic midwater trawl surveys in the MI, HIMI and BANZARE bank regions were used to provide snapshot of micronekton communities in each region. Each survey characterised the micronekton community between the surface and 1000 m, using a depth stratified IYGPT Pelagic trawl fitted with multiple opening and closing nets fitted with 10 mm mesh codends (MIDOC). The specific depth horizons that were sampled varied between surveys. For this analysis we incorporated all samples collected in the mesopelagic zone between 200 - 1000 m. Given the high diversity of the micronekton community in each region, species were assigned to one of five acoustic groups based on morphology/acoustic properties: Crustaceans, Gelatinous, Fish with gas-filled swimbladders, fish without gas-filled swimbladders and Squid. The most numerically abundant species within each group were prioritised for Target Strength modelling and the numerical abundance of species within each group were used to estimate the proportion of backscatter (*s*_A) to a group.

Target strength estimates for dominant species groups, were generated using model organisms from samples collected on the <u>SOLACE</u> voyage onboard the RV Investigator between 4th December 2020 and 16th January 2021. We characterise length/weight relationships of dominant species and then imaged individuals with a computerised tomography (CT) scanner and the data was processed to yield either a three-dimensional surface mesh (Figure 3) or a three-dimensional voxel dataset (for euphausiid species) of the body of each specimen. Internal voids, such as the gas-filled swimbladder were included where present. Literature target strength (TS) and weight values were obtained for the gelatinous and squid categories.

Estimates of specimen density and sound speed were derived from the CT scan data, calibrated by scanning objects of known density. The density and sound speed of the gas in any detected swimbladders was that of air at the pressure and temperature of the surrounding seawater. Seawater density and sound speed was set to the average values around HIMI over depths of 400-1000 m.

The target strength (*TS, dB re 1 m*²) of each organism was estimated using either a coupled boundary element method model (C-BEM, (Gonzalez et al., 2020)) or, for the euphausiid species, a phase-tracking distorted wave Born approximation model (PT-DWBA, (Jones et al., 2009)). The C-BEM model simulated the scattering of sound from the body and the enclosed swimbladder. The PT-DWBA model simulated the scattering from a voxel-based dataset where each voxel was assigned a sound speed and density pair based on the organism body properties.

The TS was estimated at tilt angles of head-on through to tail-on at acoustic frequencies of 18, 38, 70, and 120 kHz. The tilt-averaged TS, <TS>, was derived from the convolution of the TS with a tilt angle distribution with mean of 0° and standard deviation of 25° (nominal values in the absence of species-specific tilt distributions). For each species or species group a length-to-<TS> relationship of the form $<TS> = a \ 10 \ log_{10} \ l - b$, was estimated by linear regression, where a is the fitted slope, *l* the length and b the fitted intercept.



Figure 3. Model mesh obtained from a 62 mm long Lampanyctus australis. The yellow mesh is the body, and the grey mesh is the swimbladder.

Partitioning of acoustic backscatter. Gridded quarterly estimates of echo-integrated 38 kHz echosounder data (s_A , *NASC* $m^2 nmi^{-2}$) around HIMI and MI were used to estimate regional biomass estimates for acoustic/functional groups mentioned above. Partitioning followed existing methodology (Dornan et al., 2022) where the proportion of s_A in a grid cell attributed to species i, P_i , is given by:

$$P_i = \frac{N_i \sigma_{bs_i}}{\sum_{i=1}^n N_i \sigma_{bs_i}},$$

where N_i is the relative abundance of species group i, σ_{bs_i} (m²) the backscattering cross-section of species group i ($\sigma_{bs_i} = 10^{TS_i/10}$), and n the number of species groups. The abundance of species group i is then given by:

$$\rho_{a_i} = \frac{s_A \cdot P_i}{4\pi \cdot 1852^2 \cdot \sigma_{bs_i}},$$

where ρ_{a_i} has units of individuals per square metre of the ocean surface. Species group biomass is obtained by multiplying ρ_{a_i} by species group mean weight and total biomass by summing the grid cell species group biomass estimates over the entire area.

Toothfish demersal habitats

In this project we generated seafloor data products (bathymetry and slope) for the HIMI and MI regions by combining (1) cleaned and sound velocity corrected historic SBES data, (2) MBES data collected by CSIRO, Australia and the National Institute of Water and Atmospheric Research (NIWA), New Zealand (NZ), and from data available through the General Bathymetric Chart of the Oceans (GEBCO, <u>www.gebco.net</u>). Below we provide a detailed description of the data and methods used to generate the seafloor products at HIMI and MI.

The Macquarie Island bathymetry coverage was created using the NZ Regional Bathymetry Compilation 2016 (250m) - NIWA, (Mitchell et al., 2012), MBES datasets available from RV Investigator and RV Tangaroa from voyages in2020_v06 and tan2021_v01 and on ground SBES data collected by the fishing industry. The specific processing steps for the different datasets are given below.

In this study we only considered the 38 kHz SBES data collected at a 2.048 ms pulse duration and 2000 W transmit power in our analysis. All data was calibrated following the standard procedures

described in (Demer et al., 2015). A non-linear correction was then applied to all the data based on the method described by (De Robertis et al., 2019). Motion corrections were only available for a small number of the datasets analysed in this study and therefore motion correction could not be applied consistently. To maximise the amount of data available for seabed detection (depth) motion correction was not applied to any of the datasets. To minimise the effects of motion on seabed detection special care was taken to exclude all regions where the data appeared compromised. We applied a serious of noise filters following Haris et al. (2021). Soundings were then manually edited using a combination of Single Beam Editor and Subset Editor in CARIS HIPS&SIPS 11.4.12. Cleaned data were re-exported to CSV format so that sound velocity secondary corrections could be made. The corrected depths were between 5 and 35 m shallower than the measured depth for both the HIMI and MI regions.

XYZ Point data from the NZ Regional Bathymetry Compilation, Macquarie Island Bathymetry 210m CUBE surface, and cleaned SBES soundings (as above) were re-gridded using QPS DMagic software v7.8.3 using a weighted moving average with a weight diameter of 9 at a resolution of 210 m using the Coordinate Reference System FP_WGS_84_Mercator_41 (EPSG 3994). Slope was calculated from the bathymetry geotiff in CARIS HIPS & SIPS 11.4.12 by converting to *csar format and adding a Slope Band. A final XYZS (X, Y, Z, Slope) file was exported from Caris to *.txt format. Data were exported in WGS84 latitude longitude coordinates in decimal degrees with a precision of 4.

The HIMI bathymetry coverage was created using geotiff data layers produced from RV *Investigator* MBES voyages (in2016_v01 and in2020_v01). RV *Investigator* data was combined with GEBCO background data, and historic SBES data collected by the fishing industry. All data were clipped to a HIMI region bounding box. Each multibeam geotiff was loaded into Fledermaus 7.8.3. Each surface was re-exported to *.xyz format to be used in QPS DMagic.

GEBCO background data geotiff gebco_2022_n-45.0_s-62.0_w54.0_e95.0.tif was downloaded from <u>https://download.gebco.net</u>. GEBCO data was resampled to 200m (World Mercator WGS84) in ArcGIS (Resample tool) using a Cubic resampling technique (gebco_himi_resample_200m_WM.tif).

Compiled Kerguelen Plateau bathymetry at ~100m resolution (Beaman, 2023)) was downloaded from https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/147703 [26 April 2023]. Distinct differences between the SBES data and certain areas of the Kerguelen_Plateau_2022_100m_MSL_cog.tif dataset was observed. Due to these differences, a section of the Kerguelen_Plateau_2022_100m_MSL_cog.tif was excluded from the compilation. A section between a bounding box of coordinates [78.5 -52.63, 77.45 53.2] was removed from the Kerguelen_Plateau_2022_100m_MSL_cog.tif using ArcMap. The remaining data were re-projected to World Mercator and loaded into Fledermaus.

The HIMI SBES data followed the same processing steps described above for MI. XYZ Point data from each of the above datasets were re-gridded using QPS DMagic software v7.8.3 using a weighted moving average with a weight diameter of 9 at a resolution of 200 m using the Coordinate Reference System FP_WGS_84_World Mercator (EPSG 3395). Slope was calculated from the bathymetry geotiff in CARIS HIPS & SIPS 11.4.12 by converting to *csar format and adding a Slope Band. A final XYZS file was exported from Caris to *.txt format. Data were exported in WGS84 latitude longitude coordinates in decimal degrees with a precision of 4. Band 1 (depth) is the depth value with a

precision of 1. Slope is in degrees with a precision of 1. The file includes a header, is comma delimited and the Z convention is down as positive.

Catch and effort modelling at HIMI and MI

Traditional models of catch and effort data have been based using initially the GLM paradigm (Maunder & Punt, 2004), moving into the more flexible GAM framework, and more recently fully spatiotemporally resolved models that can accommodate potentially complex covariance structures. The INLA package is a popular example using the GMRF statistical paradigm to encompass both the GLM and GAM model options. Given the complicated spatial structure in the fisheries we are working with, especially the Macquarie Island toothfish fishery, we constructed custom-designed models in the Template Model Builder (TMB) statistical modelling framework that can explore the full functionality of the INLA package, but could also be modified to allow for the specific model features we need for our purposes.

For both the HIMI and MI fisheries we explored two general classes of models:

- 1. Spatiotemporal GLMM for the expected mean catch of toothfish in terms of a linear predictor of fixed categorical and continuous effects and random spatial effects.
- 2. Spatiotemporal binomial GLMM for the probability of the catch rate exceeding a minimum threshold level in terms of a linear predictor of fixed categorical and continuous effects and random spatial effects.

The fixed effect parts of the model are very standard GLM elements that can be explored using standard model selection criteria. The random spatial terms had an assumed *a priori* covariance structure which was parameterised using the Matern covariance function (Lindgren & Rue, 2015). This general covariance function is prevalent in spatiotemporal analyses of this kind (Lindgren & Rue, 2015) and allows us to define a suitably flexible Gaussian Process (GP) for the spatial terms whereby parameters control the magnitude of the spatial terms, the covariance between spatial locations, and the smoothness of the random spatial field. A fully spatiotemporal structure was also explored whereby the random spatial effects are also permitted to change over time in a covariant (autoregressive) manner.

These models we employ are reasonably large (hundreds of parameters when including the spatial terms) but their general function can be summarised as follows:

- The fixed effects accommodate the key operational (vessel, effort) and abundance/availability related (quarter, year) effects.
- The fixed effects also include the key continuous data products derived in the project (e.g. bottom temperature, salinity, acoustic back-scatter). It is these variables that would be of utility when considering a predictive forecasting focussed version of the model.
- The random effects deal with the innately stochastic variations in catch efficiency in space (and possibly time) whereby the scale of the covariance therein is actively estimated. In

simple terms: we assume that "closer" spatial cells are more likely to have the same magnitude and size of effect than "distant" spatial cells, and we estimate the strength of that relationship directly.

The random spatial (and temporal) effects obviously significantly increase the complexity of the models. However, they do not just deal with fine-scale covariant variation in catch efficiency, they play a number of key roles:

- 1. By dealing with the random variations in catch efficiency at a fine scale we can include the fine scale oceanographic and acoustic data and be more confident that we are likely to detect effects at this scale as we have attempted to remove the random portion of the compound signal we get in the data.
- 2. The parameters of the random effects in particular the parameter that dictates the scale at which the covariance between the spatial cells decays to a specific level are both interpretable and useful. For example, the key parameter in our models is the distance at which the covariance between spatial cells has decreased to 10% of what it would be for adjacent cells. This provides us with a spatial scale below which any predictions we make are going to become increasingly influenced by the inherently random spatial variations in catch efficiency.

The initial suite of model covariates, for both classes of general model explored, were: effort, year, quarter, vessel, spatial cell, bottom temperature, salinity, net primary production, oxygen, and acoustic back-scatter. For the expected catch models the log-transformed effort data are used as an offset; for the binomial CPUE threshold models effort is actually used as a continuous covariate. For both fisheries, space is discretised into equally sized longitudinal and latitudinal cells – for HIMI the spacing is 0.25 of a degree, and for MI it is 0.1 of a degree. Focussing only on cells that have been fished at least once this resulted in 321 cells in HIMI and 97 in MI. For both fisheries, each of these cells is ascribed a unique (but spatially correlated) random effect in all the models. For all the classes of model we incrementally include the covariates one-by-one starting from the intercept parameter to the random effects and their covariance parameters. At each stage we use the likelihood ratio test to assess the significance (or otherwise) of including the covariate. If these incremental inclusions in model complexity are not judged to be significant at the p = 0.05 significance threshold, that covariate is not included. The general class of models explored are basically the same, but there are specific modifications made for each fishery, so each fishery's results are taken in turn. While we fully explored the expected catch models, that showed very similar overall parameter trends and values to the CPUE threshold models, we do not outline those results explicitly in this report. After initial feedback with stakeholders it was decided to put the major focus on the probabilistic CPUE threshold models - not only do they focus on a feature of more interest and potential utility to the stakeholders but it also affords more flexibility as we can apply any CPUE threshold the stakeholders wish to explore. This aligns with the project goals of developing a fully probabilistic modelling framework for the catch and effort data that both integrate the oceanographic and acoustic data and give us the ability to provide commercially applicable predictions to industry.

Fish condition modelling at HIMI and MI

Fish condition, as defined hereafter in terms of a fish or group of fishes' deviation from the average weight-at-length relationship, is both a potential bellwether variable of change driven by exogenous environmental forcing and a key economic performance factor. Over the whole period of the fisheries there are over 900,000 HIMI and 100,000 MI accurately measured weight-length paired observations.

For both fisheries we estimated a base-line overall weight-at-length relationship: $w = al^b$. To explore fish condition, we then estimate annual and/or spatially specific *b* parameters for both fisheries and, hereafter, interpret any deviations from the overall average *b* parameter as the relative change in condition of the fish at that particular disaggregation level.

Results and Discussion

Oceanographic variability around HIMI

BRAN2020 data indicates that the near-bottom conditions within the HIMI region, vary around an average temperature of 2°C (Figure 4a). We find that the percentage area of the plateau with bottom temperatures warmer than 2°C fell from 60% in early-2014 to 10% in 2015 (Figure 4b).



Figure 4: Time series of (a) area-averaged bottom temperature in the Australian EEZ in the HIMI where the bottom depth is between 400 and 2000 m. The percentage of area warmer than 2°C, 1.8°C, and 1.4°C is recorded in panel (b), along with the percentage of area of area classified as UCDW, with potential density within the range of sigma-27.6 to sigma-27.8. The vertical dashed lines denote the start/end of each year and the tick-marks along the x-axis denote the centre of each year.

It is speculated that the anomalously-cold conditions experienced in the HIMI region in 2015 originated off Antarctica (Figure 5 c,d). The time-series presented in Figure 5 show the mean temperatures for different regions that are denoted in Figure 1. The time-series in Figure 5c, show that to the south of the HIMI region, there was an injection of Antarctic Surface water, evident in the three blue "dips" between 2013 and 2015 on the 27.6 potential density surface. It is hypothesised that the cold water to the south could be carried northward from higher latitudes into the HIMI region with flow associated with the Antarctic Sea Ice tongue. However, flow through the Fawn Trough (FT) may impede flow associated with the Antarctic Sea-Ice tongue displayed at 56°S in Figure 6b. The region occupied by the Antarctic Sea Ice tongue is evident in the shallow, northward extension of waters of 27.7 kg/m³ - the red "tongue, south of HIMI – in Figure 7a.



Figure 5: Temperature on different potential density surfaces, averaged in regions: (a) East, (b) West, (c) South, and (d) Far South, defined in Figure 1.

Figure 6: Mean (a) potential density, (b) zonal current (yellow-red is eastward), (c) temperature (note that temperatures below

0.1°C are off the colour-scale chosen here), and (d) salinity along a section between the HIMI region and the Antarctic continent (denoted in Figure 1) for the period 1994-2019 in BRAN2020. The bold contours denote the mean isopycnal depths for sigma-27.7 (solid bold) and sigma-27.6 and sigma-27.8 (dashed bold).







The variability in annual bottom temperature over the HIMI fishing ground is quantified in Figure 8, showing maps of near-bottom temperature for every year between 2010 and 2021. In some years, the bottom temperatures over the HIMI region are cold – often dipping below the threshold of 2°C, which is relevant to toothfish. This includes 2014, and 2015, when the CPUE was declining (Figure 25). Other years, the bottom temperatures are much warmer – and more favourable to toothfish (e.g., 2017, 2019, 2020). Also evident in Figure 8, is the significant spatial variability of near-bottom conditions over the Kerguelen Plateau.



Figure 8: Maps of annual-mean near-bottom temperature (averaged over the bottom 200 m) for areas where the bottom depth is between 400 and 2000 m in the HIMI region. The percentages reported in each panel are the % area within the Australian EEZ, between 400 m and 2000 m depth, with average bottom temperatures exceeding 1.8° and 2.0°C. The magenta contour is the 1500 m isobath, and the bold black line denotes the border of the Australian EEZ.

Quantifying the variability in UCDW at HIMI

To quantify the temporal variability of UCDW in the HIMI region we estimate the volume and temperature of this water mass through time in the eastern and western regions. This is presented in Figure 9, showing a metric that we call Warm Water Saturation (WWS). WWS is the percentage of a water mass, by volume, that exceeds some temperature threshold. This metric is intended to quantify the volume of water that represents favourable conditions for toothfish. The WWS, shown in Figure 9a, has a clear seasonal cycle, with lower percentages every winter (i.e., colder UCDW in winter), and the eastern region has a consistently lower percentage than the west. To isolate the interannual variability from seasonal variability, the WWS anomaly (WWSA), Figure 9b, is produced by removing a mean seasonal cycle from the total WWS. We find that the WWSA in both the eastern

and western parts of the HIMI region reduce significantly in 2014 and 2015. We interpret this to mean that during that period, the volume of unfavourable habitat expands into the water column.



Figure 9: Time series of (a) warm water saturation and warm water saturation anomaly (showing anomalies from the mean seasonal cycle), where the WWS is the percentage of water (by volume) between sigma-27.6 and sigma-27.8 that is warmer than 1.8°C. Time series are shown for the East and West regions, denoted in Figure 1.

Discussion of HIMI results

Overall, we observe considerable seasonal and interannual variability and a warming of UCDW in the HIMI region. The annually averaged bottom temperatures indicate that there are years that are colder than normal (e.g., 2010, 2011, and 2015), and years that are warmer than normal (e.g., 2016, 2019) and years that that display "hot spots" (e.g. 2017).

A detailed analysis of the processes that drive observed variation in UCDW and bottom temperatures is beyond the scope of this study, however we consider two scenarios that may account for the cold conditions observed in 2015 when CPUE started to drop, these are:

- 1. Antarctic Surface Water in the region to the south of HIMI is entrained into the ocean interior along isopycnal surfaces, modifying the properties of UCDW in the HIMI region.
- 2. The deep zonal (eastward flow) current through the Fawn Trough (FT) may vary in its location, strength and/or depth in response to larger scale oceanographic processes (van Wijk et al., 2010). Flow through the FT is referred to as the southern Polar Front and separates warmer, fresher UCDW to the north, from colder salty LCDW (to the south). When the deep component of polar front varies latitudinally, weakens and/or shoals, then a greater quantity of LCDW could be transported into the HIMI fishing grounds.

Oceanographic variability around Macquarie Island

Analysis of the circulation around Macquarie Island is performed using (BRAN2020). The circulation around Macquarie Island is dominated by the Antarctic Circumpolar Current (AAC). In this region the ACC is a strong, deep, eastward flow that is littered with meanders and eddies. As the ACC approaches the Macquarie Island Ridge, the ACC breaks into several branches, with strong flow to the north, south, and through the channels of the ridge (Figure 10). As a result, the ocean currents are strong and variable.





The water properties over the Macquarie Ridge in the MI region are dominated by Antarctic Intermediate Water (AAIW) and upper circumpolar deepwater (UCDW). These water masses are evident in Figure 11 - Figure 14. The fresh tongue of AAIW extends from the ocean surface at around 55°S to the ocean interior at 1000 m depth to the north. Both AAIW and UCDW intersect with the seafloor over the ridge. The section of time-averaged properties is presented in Figure 11, shows UCDW intersecting with the seafloor over the Macquarie Ridge at depths ranging from around 1200 m and below. It also shows AAIW intersecting with the seafloor over the ridge above that depth. The time-averaged zonal (eastward flowing) velocities show that the strongest jet, associated with the ACC over the ridge, flows through the channel at ~ 53°S Figure 11b.

Analysis of the properties and velocities to the east and west of the Ridge (Figure 12) paints a picture of the ACC being organised into three branches to the west – before it encounters the ridge – with all three jets relatively weak and broad. The central jet of the ACC flows immediately over the ridge, with strong eastward velocities that extend to the seafloor. To the east, after the ACC flows past the ridge, the ACC jets combine to form a strong, broad, and deep jet. At each of the sections shown in Figure 12, the slope of the density contours changes from west to east, with isopycnals (density



contours) steepening to the east, as the ACC jets strengthen (the relationship between the slope of isopycnals and velocity is well understood – relating to geostrophic flow).

Figure 11: Time-mean potential density(top, a), zonal velocity (b), temperature (c), and salinity (bottom, d) from BRAN2020, along the orange section denoted in Figure 10. The bold-black contours in panel (a) and (b) denote the 27.7 kg/m³ isopycnal – nominally denoting the middle of the band of UCDW, which is banned above and below by the 27.6 and 27.8 kg/m³ isopycnals, denoted by the black-dashed contours.



Figure 12: Time-mean potential density, zonal velocity, temperature, and salinity (top-bottom) from BRAN2020 for sections parallel to the section denoted in Figure 10. "RIDGE-3° means the section that is parallel to the section in Figure 10, but displayed 3° to the west. The bold-solid density contour for density (in the top panels) is 27.7 kg/m³, denoting the core of UCDW, and the bold-based lines above and below are 27.6 and 27.8 kg/m³ respectively, denoting the nominal upper and lower extent of UCDW. The bold contour in the temperature panel denotes the 2°C isotherm. Positive velocities ate eastward.

To better understand the interannual variability of properties over the ridge, we present the annualaverage temperature (Figure 13) and salinity (Figure 14) along a section over the ridge (Figure 2). We find that the variability in salinity (Figure 15), and particularly the penetration of AAIW may be more important. Moreover, we wonder whether the salinity gradients between AAIW and UCDW over the fishing grounds may provide conditions that are highly variable and may contribute to the variability in catchability of toothfish in this region.

Regarding the salinity variability – it looks like there are two or three periods with distinct characteristics (Figure 15):

- 2005-2010 appears to have fresher and colder UCDW and highly variable AAIW;
- 2011-2012 has salty UCDW (note the predominance of red and dark red in the lower-left of each panel), indicating that waters saltier than 34.6 psu have penetrated onto the ridge; and deep penetration of AAIW (the green contours) that extends right over the ridge and extend to the north;
- 2017-2019 shows conditions similar to 2011-2012, again with salty UCDW and broad penetration of AAIW.

Discussion of MI results

In the depth-range that toothfish are fished at MI, the mean temperature always seems to be warmer than 2°C (Figure 15). This indicates that the sensitivity of toothfish to water temperatures colder than 2°C is likely to be less of an issue around Macquarie Island. We speculate that in the presence of highly variable currents, and the mixing of AASW, AAIW and UCDW over the ridge may play influence the availability/catchability of toothfish. This warrants further investigation.



Figure 13: Latitude vs depth sections, for the section denoted in Figure 10, of annual-averaged temperature over the ridge near Macquarie Island for years 2005-2020 (as labelled in each panel).



Figure 14: Latitude vs depth sections, for the section denoted in Figure 10, of annual-averaged salinity over the ridge near Macquarie Island for years 2005-2020 (as labelled in each panel). The tongue of fresh water, between 34.25-34.4 psu (green colours) denotes Antarctic Intermediate Water (AAIW), and the deeper, salty water (denoted by the red and dark-red regions nominally denotes UCDW.



Figure 15: Time series of near-bottom (a) potential temperature, (b) salinity, and (c) potential density over the Macquarie Ridge from BRAN2020 (averaged over the bottom 200 m). The topography of the region is shown in panel (d), with the regions used to construct these estimates of properties at the seafloor highlighted in blue. Macquarie Island is in red. The grey contours show topography.

Toothfish pelagic habitats

Spatiotemporal variation in regional backscatter. At both HIMI and MI a lack of spatiotemporal representative data prevented a comprehensive comparison of mesopelagic backscatter between 2010 and 2020 (Figure 16 and Figure 17). At times when we do have sufficient data to enable comparisons through time, e.g. 2016 and 2020 at HIMI, regional backscatter displayed significant seasonal and interannual variability, with backscatter increasing from quarter 1 - 3. In 2016 and 2017, backscatter was stronger in the west compared to the east. Between 2018 – 2020 backscatter is more spatially consistent across the HIMI region with marginally higher backscatter observed in the west compared to the east (Figure 16).

Significant spatiotemporal relationships exist between backscatter and mesopelagic temperature and salinity at HIMI. The effect was positive with salinity so that increases/decreases in mesopelagic salinity were linked to increases/decreases in the backscatter intensity. The opposite trend was observed for temperature, so that increases in mesopelagic temperature were linked to decreases in the backscatter intensity. We speculate that this trend is largely due to an intrusion of anomalously warm water in 2017, in the eastern HIMI region that resulted in low backscatter (Figure 5).



Figure 16. Quarterly estimates of mean mesopelagic backscatter, between 400 – 1000m, over the HIMI fishing grounds between 2011 and 2020. Grey lines are 500, 1000 m and 2000 m contour lines. Numbers in lower left corner of each panel indicate the number of hours of data available for a respective quarter.

At MI, backscatter was spatially consistent along the ridge, within any one quarter, but did vary significantly between quarters and years (Figure 17). Backscatter was found to decrease from quarter 2 to quarter 3 and generally increase along the Macquarie Ridge between 2011 and 2020, except in 2017 when backscatter was anomalously low.

Significant spatiotemporal relationships exist between backscatter and mesopelagic temperature at MI. The effect was positive so that increases/decreases in mesopelagic temperature were linked to increases/decreases in backscatter intensity. The exception to this trend was observed in 2017, where water temperatures were high in the MI region and backscatter was low.



Figure 17. Quarterly estimates of mean mesopelagic backscatter, between 400 – 1000m, over the MI fishing grounds between 2011 and 2020. Grey lines are 500, 1000 m and 2000 m contour line.

Mesopelagic micronekton community composition. The relative proportion of micronekton acoustic/functional groups varies by region (Figure 18). At Macquarie Island we observe a relatively high abundance of fish with gas-filled swimbladders (FGB), fish (F) and crustaceans (Crust). At HIMI crustaceans (Crust) are the most abundant group. Over the BANZARE Bank and deeper waters to the east gelatinous (Gel) and crustaceans (Crust) species dominate communities.



Figure 18. Proportion of the micronekton community by acoustic group per sample by region.

A summary of Target strength estimates for dominant species that form group means is in Appendix 1 (Figure 30, Figure 31), and mean length - <TS> relationship coefficients at 38 kHz in Table 2.

Regional estimates of micronekton biomass indicate that the net biomass is greater at MI than at HIMI per unit area (Figure 19). At MI fish were the main contributors to backscatter, while at HIMI the biomass was more evenly spread across all the categories. In both regions squid had the lowest biomass density. At both HIMI and MI, fish with gas-filled swimbladders had the highest density in both regions (Figure 19). At MI fish without gas-filled swimbladders were the second highest biomass (about 50% lower), while at HIMI crustaceans were the second highest at about 90% of the fish with gas-filled swimbladders.



Figure 19. Quarterly estimates of mean density derived from 38 kHz backscatter for the Macquarie Island region (upper panel) and Heard Island and McDonald Islands region (lower panel). Quarters with no data points occur when no backscatter data are available.

Discussion of pelagic habitat results

Regional differences in backscatter, community composition and biomass of mesopelagic micronekton communities, are consistent with regional differences in water column temperature and biogeographical provinces. Where communities contrast most obviously is the relative abundance/biomass of key functional groups – at MI we observe a greater proportion of fish per unit area when compared to the HIMI, where the biomass was more evenly spread across all the groups. In 2017 at MI and over the eastern region of HIMI we observe an unexpected low backscatter, we speculate that this trend is largely due to the intrusion of anomalously warm and low salinity seawater. We note that the partitioning of backscatter into acoustic/functional groups, is dependent on the relative abundance of organisms taken from a single survey in each region, so spatiotemporal changes to the community composition are not accounted for in this analysis. Secondly, we do not account for temporal variations in group TS, that may result from ontogenetic/life history factors, as data were sourced from a single survey in each region conducted in the Austral summer.

Toothfish demersal habitats

The processing steps described above produced a set of high-resolution seabed data products for both the HIMI and MI regions. These products are available as geotiffs and will be shared along with this report.

- 1.1. MI data products
- (1) Bathymetry (210m resolution): MI_bathy_compilation_210m_WM41.tif
- (2) Slope (210m resolution): MI_bathy_compilation_210m_WM41_SLOPE.tif
- (3) X Y Z Slope *.txt: MI_compilation_210m_wgs84_xyzs.txt

- 1.2. HIMI data products
- (1) Bathymetry (200m resolution): HIMI_bathy_compilation_200m_WM.tif
- (2) Slope (200m resolution): HIMI_bathy_compilation_200m_WM_SLOPE.tif
- (3) X Y Z Slope *.txt: HIMI_compilation_200m_wgs84_xyzs.txt

For inclusion in objective 4 the above seabed data products were resampled to provide mean depth and slope for the HIMI and MI regions according to the below grids (Figure 20).



Figure 20. Gridded bathymetry data for HIMI used as part of objective 4.

Discussion of demersal habitat results

Whilst the seabed data products generated in this study represent the most up to data information available for HIMI and MI they are not without limitations. Combining datasets from various sources, such as SBES, MBES and satellite derived, will result in artefacts due to the differences in resolution and accuracy of each of these systems. These artefacts are particularly notable for the HIMI SBES data, which become visible as raised or depressed track lines where the depths do not exactly match with the background datasets. These areas may result in false slope values and should be noted as one of the limitations of the dataset. Higher density coverage from SBES data would mitigate some of these issues.

Catch and Effort modelling at HIMI and MI

Heard Island and McDonald Islands

We use only longline data from 2012 to 2021 – Figure 21 shows the location of each unique set during these years. All the covariates assigned categorical effects (year, quarter, vessel) were adjudged to be highly significant model inclusions. The effort covariate was significant and positive, though far from being the dominant effect – it merely suggests that there is a positive relationship between increasing effort and obtaining a successful (relative to the CPUE threshold) set. This may seem an obvious directional effect (positive) but there are cases where "effort stacking" actively decreases CPUE as one increases the effort – e.g. in "Olympic" open access fisheries where so many boats set their gear in a certain spatially limited location and everyone's CPUE declines as a result of increasing effort.



Figure 21. HIMI longline set location from 2012 to 2021.

For the oceanographic and acoustic (continuous) covariates, we explored several and a number of different quarterly-multiple time lags – it makes little logical sense that a change could be instantaneous in its impact on the fish and the associated fishery. A two-step model selection process was undertaken for a range of lags (from 3 months to 2 years) we estimated the covariate effect and retained only those that were significant at the 0.05 *p*-value. Of the suite of retained lag-effect pairs the one with the smallest *p*-value (i.e., highest increase in the closeness of the fit to the data) was chosen. Of all the covariates only, bottom temperature produced significant relationships and, amongst the three of those (6, 9 and 12 month lags) the 6 month lag was considered optimal given the model selection criteria. The effect was strong – relative to the suite of other covariates – and positive so that increases/decreases in temperature were very clearly linked to increases/decreases in the probability of obtaining a suitably high CPUE set at a lag of mostly likely 6 months but possibly up to 1 year. In terms of the spatial random effects the estimated variance was 0.81 and the correlation parameter estimate – the distance at which spatial correlation falls to 10% of the

maximum level - was 1.28. This distance is measured in degrees so after about 1-1.5 degrees there is little to no spatial linkage between spatial cells in terms of the stochastic system drivers.

Summarising the fits to the data is more complicated for Bernoulli/binomial class GLMM models the data in this particular case are 0s and 1s and our prediction is the probability of either of these two possible outcomes. As a result, residual analyses are not particularly revealing. Instead, we use the Butler-Stephens algorithm (Butler & Stephens, 2017) to aggregate the model predictions to a more meaningful level. This algorithm allows us to calculate exactly the probability distribution of a sum of possibly unequal Bernoulli/binomial events. For brevity, we aggregate the model predictions to the annual number of successful (given the threshold CPUE of 0.15 kg/hook) sets to assess the predictive performance of the model. This observed variable is influenced by both the relative probability of success and the number of sets in that given year. Alongside this variable we also employ Bayesian methods to calculate the associated distribution of the annual probability of obtaining a successful set. Figure 22 (a) shows the fits to the annual number of successful sets and Figure 22 (b) shows the associated distribution of the probability of annual success. Figure 23 depicts the full disaggregated probability of success for each spatial cell fished at least once and for each year in the data coverage (2012-2021). In between these two extremes, because of the utility of the Butler-Stephens algorithm, we are able to aggregate to practically any combination of the covariates (year, quarter, effort, fished cells, bottom temperature, vessel or subset of vessels). We can also recondition the model to alternative values of the threshold CPUE so that we have these spatiotemporal probabilistic predictions of success for a range of values and aggregations as is deemed useful by stakeholder groups.



Figure 22. (a, left) Observed (magenta dots) and predicted 95%ile (blue full/dotted lines) number of successful sets-by-year; and (b, right) the posterior distribution of the annual probability of obtaining a successful set.



Figure 23. Base aggregation probability of success for each year and each fished cell for the years 2012 to 2021.

Macquarie Island

As for the HIMI case we explored both classes of model (mean catch and binomial GLMMs) but we focus only on the results from the binomial successful set models (with the same threshold CPUE of 0.15 kg/hook). The same suite of operational and environmental covariates was explored using the same model selection criteria. In contrast to the HIMI example, while the effort, year and quarter covariates were significant in their inclusion the vessel effect was not. There were only two operational vessels with no statistically discernible differences between their performance. To deal with the clear difference between the catch rates on the main grounds and those to the north and east of -53.5 and 159.5 degrees of latitude and longitude, respectively we introduced an overall spatial effect to separate these regions. We explored the same suite of oceanographic and acoustic covariates and time lags as for the HIMI case. In contrast to HIMI the inclusion of bottom temperature did not result in a significant (given the 0.05 threshold) relationship at any explored time lags. It should be noted that the estimated relationship was positive and of a similar magnitude to the HIMI estimate with a similar time lag but did not strictly meet the significance inclusion threshold. It should also be noted that the acoustic backscatter covariate (at a 9–12 month time lag) was very close to being a significant effect at Macquarie Island – stronger than a similar almostsignificant effect estimated at HIMI. As a result, although we do not include the oceanographic and acoustic variables for the MI example there are clear strong hints of their likely role. The lack of significance for temperature is very likely driven by the fact it is warmer at MI and less likely to go below the levels we have hypothesised have a negative impact on toothfish availability. For the acoustic data there is clear contrast over time, but the very patchy nature of the data resulted in the overall covariate effect not being significantly estimated.

As with HIMI, Figure 24(a) and (b) show the observed and predicted number of successful sets for each year and the associated overall annual success probability, respectively at MI. The standard deviation in the spatial random effects was estimated to be 0.58 and the spatial correlation parameter was estimated to be 0.19.



Figure 24: (a, left) Observed (magenta dots) and predicted 95%ile (blue full/dotted lines) number of successful sets-by-year; and (b, right) the posterior distribution of the annual probability of obtaining a successful set.

Comparisons between fisheries

There are a number of comparisons that can be explored between the model predictions for the two fisheries. In terms of average nominal CPUE the current levels are very similar between the two regions – see Figure 25 for a comparison on the annual nominal CPUE for each of the fisheries. However, from Figure 22(b) and Figure 24(b) – and the overall success probabilities of 0.74 at HIMI and 0.6 at MI, respectively, we see that there is clearly more variability in success in Macquarie Island, relative to HIMI. The magnitude of the variability in the spatial random effects is very comparable between the two regions; the spatial correlation parameters are, however, very different. At HIMI the correlation decay parameter estimate was 1.28; at MI the estimate was 0.19. This suggests that the range over which the inherently stochastic spatial variations in catch rate success-per-set are around 6-7 times greater at HIMI than at MI. This presumably reflects both the overall greater size of the apparent population spatial extent at HIMI, but also the difference in the volatility of fishing success (i.e. it is apparently higher at MI). Indeed, this reflects the industry's continued feedback that fishing at HIMI can slowly and consistently (with respect to CPUE) fish across an area, whereas at MI the fishing is far patchier and requires much more movement if good catch rates are to be attained. There is also a clear contrast in the within-year quarterly dynamics: for HIMI we see a clearly continuously increasing effect in successful set probability as we move through quarters 2, 3 and 4. In contrast, fishing success in quarter 3 in MI is less than in quarter 2. The major difference in terms of oceanography and acoustic covariate influences is the significant strong effect estimated in HIMI, relative to the not-quite-significant effect estimated for MI. In both cases the acoustic backscatter effect was not significant but was apparently stronger at MI relative to HIMI. Its



insignificance is not really to be interpreted as its lack of potential impact but probably more a result of the patchy nature of the historical data and its apparent covariance with the bottom temperature.

Figure 25: The HIMI (a, left) and MI (b, right) annual nominal CPUE from 2012 to 2021.

Fish condition modelling at HIMI and MI

Heard Island and McDonald Islands

Figure 26 details the annual condition parameters at HIMI. From 2000 to 2021 timeframe, we see a generally increasing trend in fish condition across the HIMI fishery, that does not appear linked to the transition from trawl to longline fishing and seems concomitant with the overall increasing temperature trend during this period (Figure 5). details the annual and spatially stratified (East-West defined by 73.75 longitude) condition parameters, from what we observe is, in the West we see a rapid drop in condition from 2014 to 2015; in the East this drop occurs from 2015 to 2016. We hypothesise that, lagged by one year, this seems very consistent with the large drop in water column temperature in the West in 2014 and the East in 2015 (Figure 28). The brief but clear drop in the condition parameter in the East in 2020 is, we suspect, a result of the catch of much smaller fish at elevated catch rates in this year only.



Figure 26: The HIMI estimates of fish condition (relative to dotted line overall mean).



Figure 27: The HIMI estimates of fish condition (relative to dotted line overall mean) for the regions East (left) and West (right) of 73.75 degrees longitude.



Figure 28. Quarterly mean water temperature between 400-1000 m, over the HIMI fishing grounds between 2010 and 2020.

Macquarie Island

Figure 29 shows the annual condition parameter estimates for MI, over the whole 1995 to 2021 timeframe, we see a generally increasing trend in fish condition across the MI fishery. As with HIMI, the condition parameter shows an increasing trend with average bottom temperature (Figure 15). There are no obvious spatial differences in condition as there were at HIMI, probably reflecting the smaller extent of the fishery spatial extent. There also appears to be a lagged (by 1 year) relationship between the temporal condition parameter and average bottom temperature over the more recent period (Figure 15).



Figure 29: The MI annual estimates of fish condition (relative to dotted line overall mean).

Comparison between fisheries

Both fisheries display a generally increasing trend in fish condition over time similar to the overall increase in average bottom temperature at both locations. Where they contrast most obviously is the average values – fish condition is consistently higher at MI than at HIMI which is consistent with a higher average water temperatures and micronekton biomass at MI relative to HIMI. There is also no apparent spatial variation at MI, whereas at HIMI there is a very clear East-West contrast in fish condition that persists over time.

Briefly addressing the issue of density-dependent growth, we must separate changes in growth in relation to length-at-age, and growth in terms of weight-at-length. The most comprehensive work on this issue in the fisheries context did show an apparent relationship with growth rate (in terms of *length-at-age*) increasing as biomass decreases (Lorenzen & Enberg, 2001). Two key points on this work: (1) this effect was detectable only in populations that had undergone large changes in biomass (often due to severe over-fishing related depletion); and (2) it was not a change in average fish condition in a given year (weight-at-length) it was long-term changes in growth rate relating to population length-at-age. Returning to the toothfish context, growth in terms of length-at-age is updated every time an assessment is done and neither population in this study has exhibited meaningful trends in population length-at-age. From the assessments of both populations, the fact that both populations are around 50% (HIMI) and 75% (MI) of the unfished spawner biomass makes it highly unlikely that the populations have been depleted nearly enough to be likely to exhibit density-dependent changes even in length-at-age as seen in Lorenzen & Enberg (2001). It seems likely therefore that the estimated changes we see in weight-at-length over time are not being driven by density-dependent changes driven by the 'fish-down to the target' dynamics of both populations.

Conclusion

The overall aim of this project was to provide the fishing industry and fishery managers with a more contemporary understanding of how biophysical variables may influence toothfish catch rates and condition in the HIMI and MI fisheries. This was achieved through characterising the variation in oceanography and mesopelagic micronekton communities and relating these variables to catch success and fish condition through time. Key messages are:

- Oceanographic conditions at HIMI display significant seasonal and interannual variability.
 Bottom temperatures at HIMI vary around 2°C, which is thought to be towards the lower end of toothfish's thermal tolerance.
- Oceanographic conditions at MI are highly dynamic, with mixing of AAIW, UCDW and SAMW.
- The community composition and biomass of toothfish prey fields differed between regions. With a higher biomass of micronekton observed at MI relative to HIMI and communities responded to regional oceanographic conditions.
- At HIMI increases/decreases in temperature were very clearly linked to increases/decreases in the probability of obtaining a suitably high CPUE set at a lag of mostly likely 6 months but possibly up to 1 year.
- At HIMI the estimate of the spatially resolved correlation decay parameter in catch success was 1.28°; at MI the estimate was 0.19°. This suggests that the range over which the inherently stochastic spatial variations in catch rate success-per-set are around 6-7 times greater at HIMI than at MI.
- At HIMI and MI we report an increasing trend in fish condition over time similar to the overall increase in average bottom temperature at both locations. Where they contrast most obviously is the average values – fish condition is consistently higher at MI than at HIMI which is consistent with a higher average water temperatures and micronekton biomass at MI relative to HIMI.

Implications

The outputs from this project, have general implications for the monitoring and management of deep-water fisheries more broadly. For toothfish it has demonstrated how seasonal and interannual variability in biophysical conditions over the fishing grounds can have a considerable effect on toothfish catch rates and condition. This has been done using state-of-the-art spatiotemporal modelling techniques that have identified key variables that relate to catch success in both the HIMI and MI fishery. These datasets and models may assist with operational planning to reduce catch rate uncertainty in the future.

One item that needs to be considered by management and stakeholders is to envisage what the potential adoption of these methods might resemble and how that might interact with the current management framework. In terms of providing advice on Total Allowable Catch limits (TACs) the current approach is to use integrated stock assessments from which suggested TACs may be calculated according to the CCAMLR harvest control rule. There are additional constraints on how and when operators may fish, but equally a large degree of latitude within those constraints as to where and how vessels fish. This is the point at which the methods would potentially be used to better inform fishing operations. The key feature we see with respect to adoption of these models would be how using them may trade-off with other requirements around key data collection from the fishery. To use mark-recapture information robustly we encourage good spatial release practices and routinely examine spatial recaptures to assess how well mixed they are in the wider untagged population. If the models recommend a substantially different and perhaps more spatially focused fishing strategy this may trade-off negatively with the robust collection of data required to establish sustainability via the stock assessments. We see the SARAG primarily as the place where adoption and the potential tradeoffs and advantages thereof would be explored over time.

Recommendations

On the 1st of May 2023, the project team presented an overview of the results to the AFMA Climate adaptation workshop for the HIMI toothfish fishery. Stakeholders present at the workshop identified several short-term research priorities and longer-term adaptation pathways. The key research priorities relevant to this project were: i) an improved understanding of conditions on the grounds, ii) investigate the how seasonal forecasting may assist with operational planning iii) consider how long term (years +) change in conditions over the grounds may affect the fishery.

These recommendations could be realised through:

- i) Identify the drivers of oceanographic variability at HIMI and MI.
- ii) Increase observations of biophysical habitats to obtain reliable forecasts in the future.
- iii) Investigate the how seasonal forecasting may assist with operational planning:
 - a. assess the suitability of seasonal forecasting products for catch model uptake.
 - b. development of probabilistic catch maps at relevant lead times and test.
- iv) Consider how longer term (years +) change in biophysical conditions over the grounds may affect the sustainability of the fishery:
 - a. Develop a MICE and Size based ecosystem model to assess the way future environmental conditions may impact on toothfish (e.g. population size, ecosystem effects, management scenarios, forecast/hindcast scenarios).

Extension and Adoption

This project has been strongly supported by stakeholders and management at the national level, given it was developed directly with the industry partners.

The outcomes of the project have been presented annually to SARAG and at two AFMA facilitated Fishery Climate Change Adaptation workshops for the HIMI and MI toothfish fisheries. Workshops identified priorities for future research that we envisage will guide a future extension this project.

These outcomes have only been possible due to the support from stakeholders that fund data collection programs at the national level. These being fisheries data collected by AFMA and Industry and Australia Integrated Marine Observing System that funds bioacoustic data collections.

Table 1. Summary of the consultation, extension and adoption at the national level associated with the development and delivery of this FRDC project.

| Year | Event - outcome | Participants |
|------|--|---|
| 2019 | Industry consultation - CSIRO Project proposal discussion | Alistair Hobday, Martin Exel, Mal- colm McNeil |
| 2020 | FRDC Southern Ocean IPA Project proposal accepted and invitation to submit full proposal Full proposal approval | |
| 2021 | SARAG & South MAC Project commenced Project overview presentation <u>Project website</u> Science discussion group meeting # 1 | Rhys Arangio, Martin Exel, Aaron Cameron, Malcolm McNeil, Marty Johnson, Brad Milic, Stuart Corney, Phillippe Zeigler, Brodie Macdonald, Ben Scoulding, Peter Oke, Rich Hil- lary and Ryan Downie |
| | Report on progress #1 ARGO Float deployed at HIMI ARGO Float deployed at MI Argo Australia planning meeting | Peter Oke, Martin Evel |
| 2022 | SARAG & South MAC • Report on progress #2 • Presentation on project progress to SARAG • Report on progress #3 • Science discussion group meeting # 2 | |
| 2023 | SARAG & South MAC Presentation to international science community ICES FAST Project animation complete for communication Science discussion group meeting # 3 | Rhys Arangio, Malcolm McNeil, Marty Johnson, Brad Milic, Noel An- derson, Mike Jackman, Campbell Davies, Alice McDonald, Danait Ghebrezgabhier, Phillippe Zeigler, Ben Scoulding, Peter Oke, Rich Hil- lary and Ryan Downie |
| | Invited to present science to the HIMI toothfish climate change adaptation workshop run by AFMA Invited to present science to the Macquarie Island toothfish climate change adaptation workshop run by AFMA Report on progress #4 Draft Final report to FRDC Southern Ocean IPA Invited to contribute to the development of the HIMI and MI toothfish Climate and Ecosystem status report cards Science Discussion Group #4 | SARAG members, Alice McDonald, Jess Melbourne-Thomas TBA |

Project coverage

If applicable report on any media, industry or government article on the project.

CSIRO, Sustainable Marine Futures, International fisheries website

Project materials developed

If the project creates any products such as books, scientific papers, factsheets, images these should be outlined in this section outline and attach them where possible.

Oke, P. R., Downie, R. A., Rykova, T., Hillary, R., Scoulding, B., (in prep). Cold temperatures over the Kerguelen Plateau drive down Patagonian toothfish catchability. Frontiers in Marine Science.

Macaulay, G. J., Downie, R. A, Scoulding, B., (in prep). Target strength of mesopelagic organisms derived from computed tomography scans. ICES Journal of Marine Science.

Downie, R. A, Macaulay, G. J., Oke, Scoulding, B., Trebilco, R., Hillary, R., Oke, P. R., (in prep). Drivers of mesopelagic deep scattering layers in the Southern Ocean. ICES Journal of Marine Science.

Appendices

Appendix 1

Target strength estimates for dominant species groups



Figure 30. Estimated target strength for a 62 mm long Lampanyctus australis obtained from the BEM model. Positive tilt angles are head up.

Models run were completed on 432 specimens from nine species/species groups. The results from each specimen showed the typical backscattering characteristics from fish – generally higher TS at higher frequencies and lower TS at tilt angles away from the dorsal direction (e.g., Figure 30). The <TS> was generally similar for all species except for *Stomia gracilis*, which was significantly lower for a given length (Figure 31). Length to TS relationships were derived for each species/species group (Table 2) and form the basis for partitioning of acoustic backscatter into biological units.



Figure 31. Tilt-averaged TS estimates for all modelled specimens at 18, 38, 70, and 120 kHz.

Table 2. Length-<TS> relationship coefficients at 38 kHz

| Species | Slope | Intercept |
|--------------------------|-------|-----------|
| Bathylagus spp. | 66.3 | 127.6 |
| Cyclothone spp. | 60.2 | 139 |
| Electrona antarctica | 75.4 | 138.1 |
| Euphausia tricantha | 56.8 | 122.4 |
| Gymnoscopelus braueri | 88.4 | 142.8 |
| Krefftichthys anderssoni | 70.1 | 127.9 |
| Lampanyctus australis | 94.3 | 147 |
| Protomyctophum bolini | 87.6 | 132.6 |
| Stomias gracilis | 117.5 | 204.1 |

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