Ecologically sustainable development of the fishery for Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island: Population parameters, population assessment and ecological interactions

Editors: Xi He and Dianne M. Furlani

Author listing (Affiliation and Chapter number)

Catherine Bulman	CSIRO	Ch.15
Robert Campbell	CSIRO	Ch.13
Andrew Constable	AAD	Ch.1, 10, 13, 14, 18
Dianne Furlani	CSIRO	Ch.7
Anne Gaskett	CSIRO	Ch.15
Simon Goldsworthy	CSIRO	Ch.7, 15, 17
Xi He	CSIRO	Ch.1, 7, 9, 13, 14, 15, 17, 18
Bill Hearn	CSIRO	Ch.13
John van den Hoff	AAD	Ch.15
Rudy Kloser	CSIRO	Ch.7, 8, 9
Tony Koslow	CSIRO	Ch.7, 8
Sakari Kuikka	CSIRO	Ch.14
Tim Lamb	AAD	Ch.6, 7, 8, 9, 10
Mark Lewis	CSIRO	Ch.7, 8, 9, 15, 17
William de la Mare	AAD	Ch.1, 3, 4, 5, 13
Sandy Morrison	CAF	Ch.10
Thomas Moore	CSIRO	Ch.7
Peter Nichols	CSIRO	Ch.16
Steve Rintoul	CSIRO	Ch.7
Graham Robertson	AAD	Ch.12
Tim Ryan	CSIRO	Ch.8
Keith Sainsbury	CSIRO	Ch.1, 3, 4, 5, 18
Tony Smith	CSIRO	Ch.13, 14
Geoff Tuck	CSIRO	Ch.10, 13, 14, 17
Bob Ward	CSIRO	Ch.11
Barbara Wienecke	AAD	Ch.12
Esme van Wijk	AAD	Ch.12
Alan Williams	CSIRO	Ch.9
Dick Williams	AAD	Ch.6, 7, 8, 9, 10, 11, 12, 13, 15, 17
Gareth Wilson	CSIRO	Ch.16
Jock Young	CSIRO	Ch.15

AAD	Australian Antarctic Division
CAF	Central Ageing Facility, Marine and Freshwater Research Institute
CSIRO	Commonwealth Scientific and Industrial Research Organisation

1. Non-technical summary

97/122   **Ecologically sustainable development of the fishery for Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island:** *Population parameters, population assessment and ecological interactions*

Principal Investigators: Drs. X. He[1], A. Constable[2], K. Sainsbury[1] and W. de la Mare[2]
[1]CSIRO Marine Research
GPO Box 1538
Hobart Tasmania 7001

[2]Australian Antarctic Division
Channel Highway
Kingston, Tasmania 7050

Objectives:

1. Determine the key population parameters (age validation, growth, age at maturity, mortality of fished cohorts, and population structure after age validation), distribution, movements and relative abundance of the Patagonian toothfish around Macquarie Island.

2. Assess the usefulness of DNA micro-satellite markers for determining stock structure.

3. Assess the biological and physical oceanographic effects on catch rates, toothfish availability, and interactions between the fishery and non-target species.

4. Assess the magnitude and composition of the fishery bycatch, and identify the food chain linkages between the fishery, the toothfish, and the main bird and mammal species.

5. Develop population models for the Patagonian toothfish fishery and provide strategies for developing and managing the fishery.

Non-technical summary

Outcomes achieved

The study provided and tested a framework for managing a developmental fishery where very limited knowledge of fish biology and environment existed. The study engaged the fishing industry in data collection and monitoring from the commencement of the fishery. In particular, it applied the principle of management strategy evaluation (MSE), and ecosystem-based management, in addition to traditional stock assessment. The results achieved through the multi-disciplinary research approach, and close multi-organisation collaborations, revealed that there are few concerns about bycatch and ecological impacts of fishing on marine mammals and seabirds around the island. The first ever survey of the biological oceanography around Macquarie Island was conducted, along with data collections and analysis on age, growth, and diets, on toothfish and major marine predators. These results were directly fed to the management process through the MSE and the ecosystem-based evaluation. The framework provided by this study should be readily adapted by other fisheries where there are needs for dealing with uncertainties in stock assessment and ecosystem impacts.

Fisheries Pty. Ltd. The active participation and support from the fishing industry have been invaluable. Without them, the project would not have been successful. The overall objective of this study was to understand population and fishery biology of Patagonian toothfish (*Dissostichus eleginoides* Smitt, hereafter termed toothfish), and its interactions with other ecologically important species, and to provide scientific advice for ecologically sustainable development of the fishery. The proposed objectives were achieved through a multi-disciplinary research approach and close multi-organisation collaborations.

Specifically, the key population parameters, distribution, movements and relative abundance (Objective 1) were determined using combined methods of otolith ageing, tagging, and analysis of fishery catch data. A pilot genetic study of toothfish stock structure (Objective 2) was developed using DNA microsatellite loci. A first ever survey on biological oceanography was conducted by the RV Southern Surveyor. Along with satellite data on sea surface temperature and ocean colour, toothfish catch rates, their availability, and their interactions with non-target species (Objective 3) were assessed. The fishery bycatch and trophic interactions between the fishery, toothfish, and main marine predators (Objective 4) were assessed from the commercial fishery data, dietary data, and consumption estimates of main predators. Stock assessment models for the toothfish fishery were developed and were fed into the framework of management strategy evaluation to assist the fishery management (Objective 5). Detailed achievements for each objective are described in the following sections of this summary.

Macquarie Island is a small Sub-Antarctic island situated approximately 1,500 km south east of Tasmania. The island and surrounding systems support a variety of protected seabird and seal populations. A developmental fishery for toothfish commenced near the island in 1994. The fishery is managed by the Australian Fisheries Management Authority (AFMA). To date, only one fishing vessel, *Austral Leader,* is licensed to fish on the commonwealth waters around the island. Since 1994, approximately 3,060 tonnes of toothfish have been harvested.

The island is a part of the Macquarie Ridge, and has a relatively small "shelf" area. The major oceanographic influence on Macquarie Island is the eastward flowing Antarctic Circumpolar Current. The Sub-Antarctic Front passes through a gap in the Macquarie Ridge about 60 nautical miles north of Macquarie Island. The Antarctic Polar Front crosses the Macquarie Ridge to the south of Macquarie Island. Satellite data on sea surface temperature and ocean colour, retrieved and compiled by the CSIRO Marine Research, indicate that the mean sea surface temperature is around 6.6˚C in summer and varies by about 3˚C over the course of a year. Available ocean colour data from 1997 shows marked annual differences in primary production around the island.

A research voyage aboard the *FRV Southern Surveyor* was conducted by the CSIRO Marine Research and the Australian Antarctic Division in January 1999. It was the first ever research survey on biological oceanography around the island. In addition to biological oceanography surveys at six stations, which represent the main biological and physical oceanographic features around the island, extensive acoustic and trawl surveys of toothfish were also conducted. Although the voyage was a one-time snapshot survey, it suggests that the biomass of midwater fishes, which are a principal food source for toothfish, seabirds and seals, is greater near the island than in the offshore areas. Biomass of zooplankton, which is prey for midwater fishes, was greater west of the island than to the north.

The acoustic and trawl surveys used the deep water multi-frequency and towed body aboard *Southern Surveyor* in conjunction with a demersal trawl aboard the *Austral Leader*, and showed low to moderate catches of toothfish but relatively high catches of species with gas filled swim bladders, namely morids and whiptails. As toothfish do not have a gas filled swimbladder their acoustic reflectance is expected to be significantly less than the gas-bladdered species. During the broad acoustic survey, no acoustic mark identified with the single frequency acoustic system could be definitely and uniquely attributed to toothfish. However, the data show that where

suitable concentrations of toothfish exist, multi-frequency methods can be used to separate them from associated species with swimbladders. The survey suggested that present acoustic methods would be of limited use for estimating toothfish abundance with the low densities of toothfish observed during the survey. The survey also confirmed that the multi-frequency system was very effective in detecting and identifying targets in the water column, including small targets without swimbladders.

Collection of toothfish biological data (including length, weight, sex and maturity stage) and otoliths, from commercial fishing operations and research programs conducted from the fishing vessel, were made by AFMA observers and co-ordinated by Australian Antarctic Division. Toothfish can grow to over 2m in length with longevity of 35-50 years and relatively low natural mortality (<0.2 per year). The age of toothfish at maturity is likely to be in the order of 12-15 years, with males maturing at a younger age than females. However, toothfish caught at Macquarie Island are generally immature or in the resting stage of gonad development, which provides no information on behavior and/or seasons of toothfish spawning.

The toothfish fishery started in November 1994 and has continued each year until the present. All fishing has taken place in the spring and summer between the months of October and March, except during 2000, when a fishing voyage was undertaken in June. During the first two seasons the Aurora Trough ground was established and catches and CPUE increased as knowledge of the grounds and fishing techniques improved. A second fishing ground in Colgate Valley and Grand Canyon (Northern Valleys fishing ground) was discovered in the 1996/97 season. Since then, both fishing grounds have been targeted. From the 1998/99 fishing season, Aurora Trough has been closed to fishing, and the Northern Valleys ground has produced very few fish.

Bycatch of fish and invertebrates and contacts between seabirds and seals and fishing gear have been systematically recorded since 1997. Bycatch of fish and invertebrates averaged 8.5% of total catch in all hauls (5.1% fish and 3.4% invertebrates), and was relatively low in the established fishing grounds of Aurora Trough (2.2%) and Northern Valleys (12.0%) as compared to the exploratory hauls in other locations (52.9%). In both fishing grounds, percentage bycatch has risen from the 1998/99 season onwards, coincident with a decline in toothfish catches. The vast majority of fish bycatch is of common and widespread species and is not considered a threat to their populations either locally or globally. While some invertebrate types may be vulnerable to fishing operations, these are predominantly found outside the established fishing grounds where fishing effort is low.

To assist fishery stock assessment and monitor toothfish movement, a tagging program has been undertaken by Australian Antarctic Division since the start of the 1995/96 season, with a target of tagging about 1,000 fish per year. A total of 5,123 tagged toothfish have been released since then with an overall average of 10.8% being recaptured. Only two tagged fish have moved between the Aurora Trough and the Northern Valleys fishing grounds. Such low exchange rates of tagged toothfish between the two fishing grounds, which are only about 40 nautical miles apart, suggest high localisation of toothfish. Other movements of toothfish have been over distances of less than 10 nautical miles.

A pilot genetic study of toothfish stock structure developed, and then used five DNA microsatellite loci. Results from two loci suggested that toothfish from the two fishing grounds might be different stocks while results from the other three loci did not demonstrate different stocks. A combined analysis across all five loci indicated stock differentiation. As the genetic study was only performed on small numbers of both fish and loci, these results must be regarded as preliminary. A more comprehensive genetic study, which is now a separate project, is using many more fish samples and some extra loci. It will provide more definitive conclusions concerning the stock structure of toothfish.

A Total Allowable Catch (TAC) for the fishery was first introduced in the 1996/97 fishing season. The setting of TAC for the 1996/97 fishing season was based on the catches of the first two fishing seasons and the tagging experiment in the 1995/96 fishing season. The setting of TAC's after the 1996/97 fishing season was then based on results from the stock assessment models. For the Aurora Trough region, TAC's were 750 and 200 tonnes for the 1996/97 and 1997/98 fishing seasons, respectively, and were zero after the 1997/98 fishing season (but with a 40 tonne research TAC for continuing tagging experiment and monitoring). For the Northern Valleys region, TAC's were 1000, 1500, 600, and 540 tonnes for each fishing season from 1996/97 to 1999/2000, respectively. However, the TAC's for the last two fishing seasons (1998/99 and 1999/2000) were allowed to increase within the fishing season if the catch rates exceeded a specified amount.

Stock assessment for the fishery used data from fishery catches, tag-recapture experiments, and biological information collected from the fishery. The assessment models include dynamics of tagged and untagged fish, daily releases, catches and recaptures, natural mortality, and annual net recruitment. Key assumptions in the models, including mixing rates between tagged and untagged fish, natural mortality rates, estimated daily catches, and availability of toothfish in the fishing grounds, were intensively tested during the assessment processes. The stock assessment models provide estimates of the historical abundance of toothfish accessible to the fishery. This measure is known as the *available* abundance (we also refer to this as *fishable* abundance). The available abundance is that abundance which can be fished by the gear of the vessel *and* is available to the gear. This is quite distinct from *total* abundance and *spawning* stock abundance that may be substantially more extensive than available abundance both spatially and in total magnitude. The available abundance is a proportion of the total abundance of the population.

Depending on model assumptions, point estimates of pre-tagging available numbers of fish were between 0.5 and 1 million fish in Aurora Trough, and between 4 and 10 million fish in the Northern Valleys region. For Aurora Trough, the estimated current available number of fish is 50% to 60% of the estimated pre-tagging available number of fish, and between 30% and 40% in terms of available biomass. For the Northern Valleys region, the models indicated a substantial decline in available abundance. The estimated current available number of fish is 11% to 14% of the estimated pre-tagging number of fish, and between 6% and 8% in terms of available biomass. However, the estimated decline in available abundance is much greater than can be explained by the fishery catches, even in the absence of recruitment. In addition, while catches were large in the first season in the Northern Valleys, only 3 tagged fish were recaptured, leading to estimates of pre-tagging available abundance that were very imprecise. Dynamic spatial behaviour could account for these large changes in available abundance. Hypotheses being explored to explain the dynamics include (i) that the population is composed of a small resident population, but that most fish are part of a broader transient population, and (ii) that the fish have remained in the area but their availability fluctuates greatly over space and time (due to dispersion in the water column, moving to untrawlable ground or escaping detection). This uncertainty indicates that an understanding of the fishes' behaviour and its movement may be important. Uncertainties also surround its reproductive biology, growth, natural mortality and the relationship between available abundance and total abundance. The challenge for management is to adopt management strategies that recognise these uncertainties, and yet are capable of achieving the management objectives of sustainable fishery development.

Management objectives for this fishery were discussed at a workshop attended by managers, industry and scientific representatives in April 2000. Management goals included both conservation and utilisation objectives. Management strategies for the fishery have been discussed at various sub-Antarctic fisheries assessment group (SAFAG) meetings. A management strategy is a set of pre-agreed rules for selecting management actions, designed to achieve specified management objectives. The components of a management strategy are a sampling program, a stock assessment and a TAC setting rule. A stock assessment uses data from the sampling program to estimate the stock's status, which can then be used in the TAC

setting process. The method used to evaluate the performance of alternative management strategies under various resource assumptions that encompass the system's uncertainties is called Management Strategy Evaluation (MSE). It is important to emphasize that MSE neither attempts to find an 'optimal' strategy, nor predict exact future catch or population biomass. Rather, MSE is designed to explicitly outline the trade-offs inherent in managing stocks with potentially competing objectives.

The basic method for evaluating performance uses repeated stochastic simulations (Monte Carlo simulation). The method involves the simulation of the fishery from its beginning to a pre-determined future year (2050 in this instance). An 'operating model' is used to simulate the 'true' dynamics of the toothfish population and the fishery. Once a set of assumptions about the dynamics of the resource (a scenario) and a management strategy have been chosen for evaluation, the biology and fishery dynamics are simulated over historical and future years. Each projected year, the management strategy prescribes the form of annual assessment, the sampling effort, and the annual catch limit. The annual catch limit may be a function of the assessed current or past status of the stock, but may also be unrelated to current knowledge of the stock (e.g. if no TAC is set). A range of performance statistics is produced for each simulation and management strategy/scenario combination. The performance statistics are combined over all simulations and tabulated to provide a summary of the performance of the particular management strategy for a given scenario. These summaries provide a means of comparing the performance of each management strategy across many scenarios.

Three underlying resource scenarios are considered when evaluating the management strategies. These are *(i)* a single stock model, *(ii)* a single stock model with periods of zero recruitment, and *(iii)* a two stocks model. The first resource model assumes that the harvested population is reproductively isolated from external sources of immigration. The second resource model is similar to the first except that the population occasionally experiences recruitment failure occurring over a number of consecutive years. This resource model has been included to model the apparent poor observed recruitment of young fish in this fishery. The third resource model assumes that an external transient population of toothfish exists that occasionally moves into the region occupied by a resident population. The first two models are believed to represent the situation occurring in Aurora Trough, whereas the third model attempts to account for the dramatic estimated changes in fishable abundance in the Northern Valleys region. Clearly these resource models vary considerably in their assumptions and one of the aims of management strategy evaluation is to provide management strategies that are robust (in terms of performance) across all resource models and other key uncertainties.

Management strategies considered include feedback management strategies that take data from the sampling program and perform an annual stock assessment to estimates the current status of the stock (the available biomass). A fraction of the estimated available biomass is then assigned as the TAC for that management year. A fixed TAC management strategy is also considered, where a fraction of the estimated pre-fishing available biomass is used as the TAC for all projected years. Both having no TAC, so economics alone constrain the fishery, and no catch, to consider population recovery, are also explored. Some management strategies also include the ability to increase the quota if catch conditions are favourable.

The initial results from an evaluation of various management strategies for the Macquarie Island toothfish fishery appear to suggest that fishing operations have a smaller impact on the resource than one might expect. However, this result is conditional on several key factors. These are that (a) selection applies to a narrow range of ages, (b) spawning fish contribute to local recruitment only, (c) economic constraints lead operators to cease fishing and depart the region in poor catch conditions, (d) effort is limited, and (e) assessment estimates of key biological parameters are reasonable. If any of these factors are false, then results show that the impact on the stock can be substantial.

An evaluation of management strategies showed that a range of policies, with appropriately chosen parameters, can satisfy sustainability criteria and maintain catch levels under most of the scenarios considered. Some management strategies considered can dramatically impact the stock even when effort is limited to the current levels in the fishery. The inability to catch the full TAC appears to be the controlling factor in the current fishery indicating that the current rules for establishing TAC's need to be refined so that they are an effective management tool should they ever be reached routinely.

The development of the management strategy evaluation software now provides a flexible tool to evaluate management strategies when applied to complex dynamical resource models for situations similar to Macquarie Island.

There remain several areas of uncertainty to be explored and improvements can be made within the model structure, dynamics (biological and fishery) and management models. For example, key components of the model rely upon measures of catch rates in order to trigger either management responses or operational responses. As such, the modelling of catch rates is critical and should be considered carefully in future work. The models of toothfish population dynamics also require some consideration, as some management strategies are sensitive to resource model assumptions (noting however that an ideal management strategy should be robust to resource model choice). The software developed provides the opportunity to expand the resource hypotheses and management alternatives in a relatively expedient manner. For example models that consider alternative gears (e.g. longlining), effort regimes (e.g. extended seasons, multiple vessels) and resource hypotheses (e.g. MPAs, metapopulations) could be explored.

Ecological interactions between toothfish, its prey species, seals, and seabirds, were studied using combined diet analysis and consumption models. These analyses were developed from conceptual models proposed by a workshop on predator-prey-fisheries interactions at Macquarie Island in 1997. The Workshop recommended that for ecologically sustainable development of the fishery it is essential to understand the ecological interactions between the fishery, the toothfish population and marine predators, such as seabirds and seals. Diet analysis for these species includes examination of the gut contents and fatty acid analysis of muscle, and comparison of food composition. Consumption models estimate food consumption of these species from estimated population biomass, diet composition, respiration and reproductive costs, and resident time. Examination of gut contents from midwater fishes show that they feed mostly on zooplankton. Toothfish however feed on a broad range of foods, including fish, squid and zooplankton (58%, 32% and 10% in biomass, respectively), suggesting that toothfish are opportunistic predators. Fatty acid analysis of toothfish muscles also indicates fish and squid are the main foods for toothfish. Both gut content and fatty acid analyses show that diet compositions were different for toothfish between the two fishing grounds and between years.

Diet compositions for toothfish are different from those of seals and seabirds, which are considered to be potential competitors of toothfish. Of the total foods consumed by the main marine predators within the Macquarie Island Economic Exclusive Zone, penguins consume most foods by weight (88%), followed by toothfish (8%), seals (3%), and other seabirds (<1%). Data from available literature also indicate that toothfish are not food sources for seabirds and seals. These results suggest insignificant ecological interactions, in terms of food consumption, between toothfish, seabirds, and seals.

Keywords: Macquarie Island, Patagonian toothfish, *Dissostichus eleginoides* , ecologically sustainable development, developmental fishery, management strategy evaluation, ecological interactions, bycatch, acoustic assessment, midwater fish community, biological oceanography, food web.

2. Acknowledgements

3. Background

Keith Sainsbury and William de la Mare

The Patagonian toothfish (*Dissostichus eleginoides*) is the focus of a number of fisheries in Sub-Antarctic waters, primarily based on bottom-set longlining. A trawl fishery has recently developed for this fish in Australian Commonwealth waters around Macquarie Island. The fish has a high landed value and the catch in 1995 was over 1,000 tonnes. A precautionary Total Allowable Catch (TAC) of 1,000 tonnes was imposed for the following fishing season, but a high degree of uncertainly remains in relation to key fishery management issues including the appropriate magnitude of the TAC and the environmental effects of fishing. Only one vessel, the 85 metre freezer trawler, *Austral Leader*, has been licensed to fish the Macquarie Island area since the commencement of the fishery.

In the early periods the fishery was mainly fished in 600-900m depth in a small area to the west of the island. The fishery then expanded to the areas north of the island. However, little is known of the extent of the resources in other areas of the Macquarie Ridge, of which Macquarie Island is a part. Since the fishery began in November 1994, the Australian Antarctic Division (AAD) has monitored catch and effort, and collected data and samples on the biology of the toothfish, such as length and weight, sex and maturity, stomach contents, and scales and otoliths. Fish and invertebrate bycatch have also been monitored.

From the results of conventional counting of "annual rings" on otoliths and scales, toothfish are believed to live about 25 years. However, ageing of the species has not been validated and age/length curves are linear, suggesting that the age of old fish is underestimated. There are now several well-known instances (e.g. orange roughy, the deep water oreos, *Sebasters* spp.) where deep water species turned out to be far longer-lived than initial, unvalidated, estimates indicated. Recently, maximum ages for southern bluefin tuna have been validated at 40+ years rather than the 20 years initially indicated.

It is not know whether the Macquarie Island stock is a separate stock, or is part of a large Sub-Antarctic population. The species is found on sea-mounts and submarine ridges throughout the Sub-Antarctic zone. All of these places are separated by wide expanses of abyssal ocean, but the amount of linkage via pelagic larval drift, or by migration, is unknown. This project includes a pilot study aimed at developing DNA microsatellite markers for the toothfish, so that the genetic status of the Macquarie Island stock can be properly determined.

It is also critical that the distribution of the toothfish around Macquarie Island be fully assessed in order to determine sustainable yield. The fishery is presently concentrated in a relatively small area (~12 n miles in extent) just west of Macquarie Island. However, there are grounds of suitable depths spread along the Macquarie Ridge, which have yet to be explored in detail. Detecting its presence, however, is not straight forward. The toothfish, like the orange roughy, does not have a gas-filled swim bladder, so it presents a relatively poor acoustic target for a fish of its size. The fishers report not being able to use acoustics to target toothfish on the bottom or midwater, and even large catches (~50 tonnes) are not associated with acoustic targets. However, in its 1996 survey of orange roughy, CSIRO trialed a multi-frequency acoustic system which proved capable of distinguishing between layers of 'feed' fish and orange roughy. It is expected that the same technique would be successful on toothfish.

Recent surveys in the area by the commercial fishing vessel *Austral Leader* have highlighted the variable nature of catches over the same fishing ground. There is some evidence that oceanographic conditions, either directly or mediated through feed availability, may be an

important determinant of catch success. However, oceanographic conditions in the Macquarie Island region have not been studied on spatial or temporal scales sufficient to determine any linkage.

The ecological impact of this developing fishery is also an important issue. Macquarie Island is a breeding site for several species of seabirds and mammals, and it has been identified as being of fish conservation value. Potentially there are both direct effects, through the removal of additional species as bycatch, and indirect effects, which may be mediated through food chain interactions. Information on the biological oceanography of the region is limited, and data on trophodynamic relationships of fishes, mammals and seabirds in this region are patchy. For example, toothfish are an important component of the diet of sperm whales and may also be important in the diet of elephant seals. These interactions, and others, between fish, mammals and seabirds, needs to be better understood to allow for their proper incorporation in fishery and conservation management of the region.

4. Need

Keith Sainsbury and William de la Mare

The Patagonian toothfish fishery is expanding worldwide and may play a pivotal role in the development of an Australian fishing industry in the Southern Ocean. The recommended Total Allowable Catch (TAC) for toothfish in other Southern Ocean regions was revised upwards by the 1996 CCAMLR Scientific Committee. For example, in the CCAMLAR area 58.5.2 (primarily the AFZ around Heard and MacDonald Islands) a TAC of 3800 metric tonnes of toothfish was set. As a result, considerable national and international interest in the fishery is expected.

Given the conservation value of Macquarie Island, it is expected that operation of the fishery will be closely scrutinised – the scrutiny is already clear at the national (MACs, SAGs, AFMA, DPIE and conservation groups) level. Development of the Macquarie Island fishery provides a great opportunity as a demonstration project to illustrate that fishery development can be achieved while protecting conservation values – a demonstration of Ecologically Sustainable Development (ESD) in action. Furthermore, much of what will be learnt will also be relevant to the emerging Hear Island toothfish fishery.

To date little research has been done to establish the basic biological parameters of the toothfish necessary to develop sound management policies. As recognised by both the Macquarie Island Fish Stock Assessment Group and the Sub-Antarctic Ecosystem Assessment Group, there is a real need to develop a comprehensive program of research which not only addresses basic biological parameters such as age and stock structure, but also examines the distribution and abundance of this species, so that effective management of the fishery can proceed. As the Macquarie Island area is likely to be sensitive to possible ecosystem changes brought about by a developing fishery, there is also need to understand where toothfish 'fit into' the broader offshore Macquarie Island ecosystem, and likely ecosystem effects.

5. Objectives

Keith Sainsbury and William de la Mare

1. Determine the key population parameters (age validation, growth, age of maturity, mortality of fished cohorts, and population structure after age validation), distribution, movements and relative abundance of the Patagonian toothfish around Macquarie Island.

2. Assess the usefulness of DNA micro-satellite markers for determining stock structure.

3. Assess the biological and physical oceanographic effects on catch rates, toothfish availability, and interactions between the fishery and non-target species.

4. Assess the magnitude and composition of the fishery bycatch, and identify the food chain linkages between the fishery, the toothfish, the main bird and mammal species.

5. Develop population models for the Patagonian toothfish fishery and provide strategies for developing and managing the fishery.

6. History of the toothfish fishery

Dick Williams and Tim Lamb

Summary
The Macquarie Island toothfish fishery started in November 1994 and has continued each year until the present. With the exception that one fishing voyage was taken in July 2000, all fishing has taken place in the spring and summer, between October and March. During the first two seasons the Aurora Trough ground was established and catches and CPUE increased as knowledge of the grounds and fishing techniques improved. A second set of grounds in Colgate Valley and Grand Canyon (the Northern Valleys) were discovered in the 1996/97 season and high catches and CPUE were obtained for a short period on large aggregations of toothfish, particularly in Grand Canyon. These large aggregations have not reappeared since then and fishing continued with lower catches and CPUE in the known grounds, including Beer Garden in a deeper part of the same submarine valley as Grand Canyon. Since the start of the 1998/99 fishing season catches and CPUE in all grounds have dramatically declined. Despite extensive prospecting over the whole of the Macquarie Ridge within the AFZ, no other fishing grounds have been discovered. About 1,000 fish per year have been tagged since the start of the 1995/96 season, and 11.5% have been recaptured. Only two tagged fish have moved between the Aurora Trough area and the Northern Valleys area; apart from these, other movements have been less than 10 nautical miles. Assessments based on recovery rate of tagged fish and CPUE have led to progressive reductions in TAC for Aurora Trough, from 750 tonnes in the 1996/97 season to 200 tonnes in 1997/98 and since 1 January 1999 this ground has been closed to fishing apart from an annual 40 tonne allowance for research.

History of activities
Due to the 'Commercial - in Confidence' nature of some aspects of the fishery data, catch figures have not been provided for individual trawls, or for individual voyages or seasons. Catch data has generally been provided as CPUE, or area totals.

1994/95 season
The Macquarie Island fishery started in the 1994/95 season. *Austral Leader*, an 85m factory stern trawler owned and registered in Australia, made three voyages to the Macquarie Ridge to assess the fishable stocks. Only toothfish was discovered in commercially interesting quantities.

During Voyage 1 (V1) in November/December 1994, various parts of the Macquarie Ridge within the AFZ were explored. Much of the ground was found to be untrawlable, but nine sites between 53°50'S (north of the island) and 56°23'S (near the southern extremity of the ridge) were trawled. None of these sites produced any worthwhile quantity of fish. Early in the voyage, a trawlable track which produced some toothfish was found to the west of the island in 600-1,000m depth and about 12 nautical miles long, just outside the three mile limit of the Tasmanian State Waters. Fifty trawls were eventually made in this area, named Aurora Trough, producing 87 tonnes of fish.

Voyage 2 (V2) immediately followed Voyage 1 in January/February 1995 and concentrated exclusively on Aurora Trough. Improvements were made to the fishing gear early in the voyage and, during the 198 trawls, details of where the fish were to be found along the trawl track began to emerge. A way was found to extend the trawl track slightly to the north, where a lot of the catch seemed to be taken. There was a very high variation in CPUE, with at least two peaks, 5-10 times the baseline level, which were not correlated with the slight northward extension of the trawl track. This was the first voyage with an observer on board to collect biological data. This allowed us to observe that the CPUE peaks appeared to coincide with a change in feeding

pattern of the fish, as well as changes in water temperature at the bottom from 2.5^{o}C to 3.2^{o}C. This voyage involved 198 trawls.

Catches of other organisms including fish, squid, crustaceans and other invertebrates were very small, collectively accounting for less than 20kg per haul (see Chapter 12 for details). The potential for damage to the seabed and its fauna appeared to be slight as a result of the rigging of the gear and the nature of the bottom. Close attention was paid to the interaction of seabirds and mammals with the vessel and fishing gear. None were caught in the net or injured on the rigging, despite an average of over 250 birds being close to the vessel during fishing operations. Most bird activity occurred during discharge of factory waste, but the distribution of this waste and the configuration of the trawl warps kept the birds out of the danger zone.

A third voyage was made to the island in March 1995, but failed to reproduce the catch rates of the previous voyage. Voyage 3 again concentrated on the Aurora Trough ground but, in 46 trawls, only managed to catch very limited amounts of toothfish. Nine of these trawls investigated areas to the north or south of the usual track, but catch rates were not significantly different from the normal track. Further investigations were made to find fishing grounds in other parts of the Macquarie Ridge. Eight trawls were made at the northern end of the Macquarie Ridge, near to the boundary with the NZ EEZ and five in other part of the Ridge close to the island (four in an area later to become the Grand Canyon/Beer Garden fishing ground), but very little of any species was caught.

1995/96 season
The vessel returned to Macquarie Island in late December 1995. Voyage 4 lasted from late December to mid-February and again concentrated on Aurora Trough except for one unsuccessful trawl at the northern end of the ridge. The first 30 trawls followed the well-established track and produced catches per unit effort equivalent to the baseline values on Voyage 2. Starting at about haul 30, a new trawl track was developed at the northern end of the original track, and slightly further to the west, which started to give good catches. This part of the trawl ground has been dubbed the *Golden Track*. It had been noticed on V2 that most fish seem to be caught at the northern end of the track, and this extension further north was probably only delayed by the need to find trawlable ground. Some large catches were made in this area, and apparent CPUE increased further when, after about haul 42, the southern end of the original track was omitted and trawling concentrated entirely on the *Golden Track*, thus decreasing the swept area. Even if the average area swept in V2 (0.40403 km^2 per haul) is used in the CPUE calculation for V4 (where the average area swept was in fact 0.2268 km^2 per haul, reflecting the shorter trawl track), the average CPUE for V4 is about 2.5 times that of V2, indicating that there was a real increase in the fish abundance and/or catchability.

Although *Golden Track* was a very small extension/alteration of the normal trawl track, its effect on CPUE was remarkable. The mean catch/haul and CPUE for hauls 2-31, before *Golden Track* was developed, were 345kg and 720 kg/km² respectively, whereas for hauls 48-168, when the fishery was concentrated almost exclusively on *Golden Track*, the catch/haul and CPUE were 5807 kg and 44520 kg/km².

Voyage 4 was actually completed in two halves, with a break of 12 days between hauls 61 and 62 when the vessel returned to New Zealand for repairs. The last haul in phase 1 (haul 61) was exceptionally large (30 tonnes), but after the break catch rates remained high for a further 12 days at least.

Exploratory trawling during Voyage 4 was limited to 3 trawls; two on the ridge north of the island and one in the far north near the boundary with the New Zealand EEZ.

Following the success of Voyage 4, *Austral Leader* spent part of the following voyage (Voyage 5, 1 to 29 March 1996) at Macquarie Island, the other part being devoted to exploring Zone 6 of the New Zealand EEZ. In a similar pattern to the previous year, this March voyage following a successful January/February voyage was not very productive. From 116 hauls along the standard track, toothfish were caught at a mean catch per haul of 1147 kg and a mean CPUE of 5654 kg/km². It was clear that *Golden Track* was not producing much fish, and many of the hauls reverted to the long original track, in some cases in addition to *Golden Track*. This is reflected in the mean swept area being intermediate between those of V2 and V4 at 0.32 km². Some areas were explored immediately to the north of *Golden Track*, but without any greater success. Some trawls were also made at the far northern and southern ends of Macquarie Ridge, but again did not catch any toothfish.

On both voyages this season an AFMA observer was present who, among other things, collected information on each haul, data on the biology of toothfish and monitored by-catch. A program of tagging toothfish was initiated on Voyage 4 in an attempt to estimate the population size and to investigate the extent of movement of the fish. This proved to be very successful, and has continued to the present. In 1995/96 most tags were placed in Aurora Trough.

1996/97 season
For this season, a TAC of 1,000 tonnes of toothfish was set for the entire fishing zone, with no more than 750 tonnes to be taken from Aurora Trough. It was originally planned to commence this season earlier than usual in order to investigate fishing conditions at a different time of the year, but exploration and fishing did not start until late December 1996. Fishing on Voyage 6 started in Aurora Trough with good catch rates, although they were less than half those experienced during the original fishing on Golden Track on Voyage 4 at approximately the same time of year in the previous season.

In early January a concentration of fish was found in Colgate Valley, which had been prospected during the previous season. The catch rate was about the same as that for Aurora Trough for the first week, but did not hold up after that, and during the second week of January fishing again concentrated in Aurora Trough. Catch rates remained low in Colgate Valley for the rest of the season although only a little sporadic fishing occurred.

During the second week of January another new ground was discovered in Grand Canyon, a relatively large valley a few miles from Colgate Valley. A large and dense concentration of toothfish was found in one part of this valley; this was the first time that toothfish was observed to produce a mark on the echo sounder. Shots on this mark were only of a few minutes' duration in order to prevent catches from exceeding processing capacity, and CPUE was very high, at times approaching 1,000 tonnes per km^2. Between the discovery of the Grand Canyon ground and the end of Voyage 6 on 23 January, fishing effort was divided between Grand Canyon and Aurora Trough. Good catches were made in both locations, and while CPUE halved in Grand Canyon and about doubled in Aurora Trough it was still about 5 times higher in Grand Canyon than Aurora Trough.

Voyage 7 returned to the fishery on 12 February, but the fish had all but disappeared from Colgate Valley and Grand Canyon. Only a small amount of effort was expended in these locations, for very small catches. Aurora Trough, however, continued to provide good catch rates, similar to those in the early part of the season. After completing 60 shots, the vessel left the fishery on 23 February.

During this season, two observers were present on each voyage. One observer on Voyage 6 was a specialist ornithologist, required to make a detailed study of the interactions of birds with the ship and to recommend an observing procedure. On voyage 7 and all subsequent voyages, one observer had primary responsibility for bird/seal observations, and one for fish observations.

From the start of the 1996/97 season one of the permit conditions was zero discharge of waste and offal in an attempt to minimise the attractiveness of the vessel to birds, and hence the likelihood of bird death or injury.

Tagging of toothfish continued this season, with about 500 tags placed in Aurora Trough and another approximately 500 placed in Colgate Valley and Grand Canyon combined.

1997/98 season
In the light of the preliminary results from the tagging program, a specific TAC of 200 tonnes was set for Aurora Trough, with the balance of the total TAC of 1500 tonnes to be taken anywhere in the Macquarie AFZ. *Austral Leader* started fishing early in this season, with the first haul of Voyage 11 occurring on 10 October (Voyages 8-10 took place at Heard Island earlier in 1997). Initial activity was in Colgate Valley and Grand Canyon, but catches were low and attention shifted to continuing to explore for new grounds on the northern part of the ridge and outside the Macquarie AFZ. When the vessel returned on 18 October attention was mainly focused on Aurora Trough for the remainder of the month, where CPUE was similar to that experienced in the previous season. Five exploratory hauls were made in locations outside the known fishing grounds.

From 29 October to 10 November the vessel was fishing outside the Macquarie AFZ, and on its return to Macquarie Island it concentrated almost exclusively on Aurora Trough until it left for a port call on 14 November. Catches and CPUE were substantially less than during early October and were approaching the low levels experienced during the first (1994/95) season.

Voyage 12 returned to the fishery on 30 November and, after completing 7 hauls in the Colgate Valley/Grand Canyon area and two in Aurora Trough without much success, the vessel spent 3 days prospecting on the ridge to the south of Macquarie Island where 11 hauls were made, producing very small catches. Between 6 December and 15 January fishing was concentrated in Grand Canyon, with occasional excursions to Colgate Valley or for prospecting for new grounds, and a total of 226 hauls were made. The first few days in Grand Canyon produced modest catches interspersed with the occasional large one, but after 11 December catches were consistently very poor. This situation persisted until 22 December when a new ground (Beer Garden) was found in a different part of Grand Canyon, deeper than the original ground, from which moderate catches, of the order of 1 tonne per haul, were taken consistently. Between 25 December and 2 January catches improved to the order of several tonnes per haul, but by 4 January had reverted to about ½ tonne per haul. Fishing continued to concentrate almost exclusively on Beer Garden, with catch rates of about ½ tonne per haul persisting until 15 January, when the vessel moved to Aurora Trough. Here catches were poor to moderate, in the range ½ to 5 tonnes per haul, and after 19 January the vessel alternated between the known grounds, looking for good catches but without much success. The vessel left the fishing grounds on 22 January.

Voyage 13 returned to the fishing grounds on 6 February, but after completing 18 hauls covering all established grounds with, at best, modest results, left the fishery on 10 February.

The tagging program continued, with approximately 500 tags being placed each in Aurora Trough and Colgate Valley/Grand Canyon/Beer Garden (hereafter referred to collectively as the Northern Valleys). This season was remarkable for the high number of tag recaptures in all fishing grounds, both of fish tagged in the current season and those tagged in previous seasons.

1998/99 season
By mid-1998 most of the Aurora Trough TAC of 200 tonnes had thus been taken, but the catch from the other areas was well below the available limit. As no new analysis was available at that time it was decided to extend the current management arrangements until 31 December to

allow time for analysis to be completed and to bring the Macquarie season more into line with that established by CCAMLR for Heard Island. This meant that very little TAC was available in Aurora Trough before the end of 1998. Later, conditions for the fishery starting on 1 January 1999 were established. These included the closure of the Aurora Trough area except for an allowance of 40 tonnes for monitoring of the population and maintenance of the tagging program and a TAC of 600 tonnes for all other areas within the AFZ.

Voyage 17 started fishing on 13 October 1998 and concentrated on the Northern Valleys area and in prospecting for new grounds. New grounds investigated included those on the far north and far south parts of the Macquarie Ridge and many places between Aurora Trough and the Northern Valleys. Most hauls in these places produced, at best, only a few kilograms of toothfish, with the exception of four shots near Aurora Trough that produced ½ to 1 tonne of toothfish. Twenty-four shots on the established grounds in the Northern Valleys produced only a few tens of kilograms of toothfish each. After completing a total of 72 hauls, *Austral Leader* left the fishery on 24 November.

Voyage 18 arrived at the fishing grounds on 9 December 1998 and continued a similar pattern of alternating testing of the established grounds at the Northern Valleys with prospecting for new grounds over a wide area of the Macquarie Ridge, many of which were in similar areas to those on Voyage 17. The balance of the TAC in Aurora Trough was taken before 31 December. Apart from a few shots in Aurora Trough, where 1 to 3 tonnes per shot were taken, most shots in both established and new areas produced only a few tens of kilograms. Following this there was a concentration of effort in the Northern Valleys for 16 days, when the best period of fishing was experienced with most shots producing about ½ tonne and some between 1 and 5 tonnes of toothfish. Between 14 and 19 January 1999 *Austral Leader* was working in conjunction with *Southern Surveyor* as part of the research program funded by FRDC. *Southern Surveyor* was using acoustic techniques to try to assess distribution and abundance of toothfish in Aurora Trough, Northern Valleys and other areas outside the main fishing grounds while *Austral Leader* trawled in areas of acoustic targets to ascertain the identity of the fish responsible for the marks (see Chapter 7). Following this, *Austral Leader* alternated between the Aurora Trough and the Northern Valleys areas, utilising part of the 40 tonne allowance in Aurora Trough by making daily shots to complete the tagging program and monitor for changes in CPUE. The vessel left the Macquarie Island area on 31 January, making two shots on the northern part of the Macquarie Ridge before leaving the AFZ. Despite making a total of 162 shots, the overall catch of Toothfish was very low, indicating that no new influx of fish had appeared in the Northern Valleys or elsewhere.

The tagging program continued this season with 602 tags placed in Aurora Trough, 306 in the Northern Valleys and 43 in new grounds. A total of 61 tagged fish were recaptured during the season.

1999/2000 season
The low catch rates in the established fishing grounds in the previous two seasons, combined with stock assessments based on analysis of tagging data and CPUE, indicated that for Aurora Trough there had been no significant recruitment of fish to the area and that the population available to the fishery remained close to the target level of reduction. The area thus remained closed to commercial fishing although the 40 tonne allowance for continuation of the tagging program and monitoring of CPUE was retained. In the Northern Valleys there had equally been no sign in the previous season of the return of the large aggregations of fish seen in the 1996/97 season, and a TAC of 510 tonnes was set for all areas outside Aurora Trough.

Voyage 22 of *Austral Leader* arrived at the fishing grounds on 3 January 2000. Conditions were very similar to the previous season with low catch rates experienced in the established fishing grounds. The vessel therefore adopted a similar fishing strategy, with series of 4 – 8 hauls taken

in the Northern Valleys interspersed with exploration of other areas ranging from the far north of the Macquarie Ridge to the banks to the far south of the Island, but mainly involving tracks in the central region of the Macquarie Ridge between and around Aurora Trough and the Northern Valleys. Aurora Trough was fished periodically in accordance with the research program.

A total of 84 hauls were undertaken. Most hauls produced from zero to less than 100kg of toothfish, with only two hauls in Aurora Trough and one in Beer Garden producing more than 1 tonne. A further 6 hauls in Aurora Trough and one in Beer Garden produced catches of between 100 kg and 1 tonne of toothfish.

During Voyage 22, 470 tags were placed in Aurora Trough, 303 in Northern Valleys, 87 in Caroline Trough and 25 in other locations. A total of 6 tagged fish were recaptured, all in Aurora Trough.

Exploration for new grounds
Macquarie Ridge is the product of the collision of two crustal plates and as a result is a long, narrow, steep-sided, basalt ridge, and boulder-covered ground or pinnacles are widespread. Consequently it is only possible to trawl in a relatively few locations. Since the beginning of the fishery there has been consistent exploration to establish the distribution of toothfish over the Ridge and to discover new fishing grounds in order to avoid concentrating effort in a few locations. Table 6.1 illustrates this by listing the number of hauls made in established fishing grounds and those exploratory trawls in new areas. The number of exploratory trawls is not a complete guide to the amount of effort expended on exploration, however, as much time has been spent on searching for possible fishing grounds using acoustic methods; only when trawlable ground was discovered that appeared to be suitable toothfish habitat was trawling attempted. The Ridge system from about 51^oS to about 58^oS has been explored extensively, but the far north and far south areas appear to contain few or no toothfish. Only the central part of the Ridge in the vicinity of Macquarie Island, between about 53° 30'S and 55° 30'S appears to contain significant amounts of toothfish, and all known fishing grounds are in this sector.

Toothfish tagging
A program of tagging toothfish was instituted at the beginning of the second fishing season in December 1995 and has continued to the present. The aims of this program were:
- To investigate the movements of toothfish in order to assess the effect of fishing on surrounding areas and the likelihood of refuge areas existing
- From the recapture rate, provide an assessment of the size of population affected by the fishery

The second aim was particularly important because the rough terrain precluded a trawl survey that could have provided a fishery-independent estimate of biomass.

Although toothfish are trawled from depths of more than 400m, tagging was straightforward because the fish lack swim-bladders and reach the surface in good condition. Lively fish were selected from the pounds and placed in a holding tank of circulating seawater, and a length range of fish was chosen that approximated the length range in the catch. At the beginning of the program fish were tagged with a single TIRIS radio frequency identification transponder (Texas Instruments) implanted in the dorsal midline just behind the head and a single, numbered T-bar tag (Hallprint: Adelaide) inserted into the fin ray supports of the second dorsal fin on the left side of the fish. From the beginning of the 1997/98 season, two dart tags were inserted into each fish in order to improve detection of recaptured fish and to give data on tag loss rate. Fish were replaced in the holding tank for about 30 minutes after tagging to check on vital signs and then released through a scupper in the factory.

This technique allowed two independent methods of detection of recaptured fish; by a TIRIS detector placed on the factory processing line immediately after the fish are taken from the pounds, and by the factory processing crew or observers seeing the dart tags. The TIRIS detector was fitted with a warning light that flashed when a transponder was detected to warn the crew to look out for a tagged fish. Comparison of detection events by these two methods enables the detection rate of each method to be calculated.

About 1,000 fish have been tagged in most seasons. Initially these were all placed in Aurora Trough, but since the development of the Northern Valleys grounds, about 500 fish have been tagged annually there, and 500 in Aurora Trough. In addition, fish have been tagged outside the established fishing grounds whenever the opportunity has arisen.

Tagging has been successful judging by the recapture rate (526 recaptures from 4,564 releases) and the time at liberty (98 fish were at liberty for more than 365 days before recapture, and the longest time at liberty of a recaptured fish to date is 1,119 days). Twelve fish have been recaptured a second time after having been re-released after their first recapture. Table 6.2 summarises the movements of tagged fish between fishing grounds. It is remarkable that over a period of 4½ years and with 526 fish recaptured, there have been only two instances of exchange of fish between Aurora Trough and the Northern Valleys, even though these locations are only 40 n miles apart on the same section of ridge. It is surprising that such a large and apparently active predatory fish does not appear to range further. This inference from tagging data corroborates the preliminary results of DNA analysis (see Chapter 10), that suggest the Aurora Trough and Northern Valleys fish are genetically different. The three instances of movements of fish between "other" grounds and the established fishing grounds (Table 6.2) all involve small distances, less than 8.5 n miles. Within the Northern Valleys area there is considerable interchange of fish. This is not surprising as all three locations are within 10 n miles of each other and Grand Canyon and Beer Garden are situated within the same submarine valley.

Summary of activities
Details of catch and catch per effort in the various grounds by voyage and by season are given in Tables 6.3 and 6.4. The catch history and results of tagging and DNA analysis all suggest that the sector of the Macquarie Ridge adjacent to the island is the only area where trawlable aggregations of toothfish occur. Within this sector there appear to be two self-contained populations of toothfish; one in Aurora Trough and the other in the Northern Valleys area. Outside these areas to the north and south exploratory fishing has shown that only small amounts of toothfish occur.

The history of the fishery can be divided into four phases:
- Initial exploration and development of the Aurora Trough fishery with high catches in the second season (November 1994- March 1996)
- Discovery of the Colgate Valley and Grand Canyon grounds and fishing on temporary large aggregations of toothfish (December 1996 – January 1997)
- Middle period of continued fishing in known grounds (including Beer Garden, adjacent to Grand Canyon) but without the very high catches of the early phase; continued exploration failed to find further new grounds; catch limits placed on Aurora Trough as a result of early assessments (February 1997 – February 1998)
- Dramatic decline in catches and CPUE in the Northern Valleys grounds; Aurora Trough catches restricted further or prohibited except for research purposes; no new grounds discovered despite further intensive exploration (October 1998 – present)

There appears to be a transitory population of toothfish as well as a more resident one. This is particularly the case in Grand Canyon where, in January 1997, acoustic survey and catch results were used to estimate that a large aggregation contained about 30,000 tonnes of fish. This

aggregation was not seen again, but because only 370 tonnes was fished from it, its disappearance cannot be a result of fishing. A similar situation occurred in Aurora Trough in January 1996. Since these events the fishery appears to have been taking principally the resident stock, with little or no recruitment being evident (see Chapter 13).

Acknowledgements

Table 6.1 Distribution of fishing effort and number of hauls in each fishing ground by voyage.

Voyage	Season	Aurora Trough	Colgate Valley	Grand Canyon	Beer Garden	New/other	Total
1	1994/95	50				9	59
2	1994/95	198					198
3	1994/95	37				22	59
4	1995/96	165				3	168
5	1995/96	116				8	124
6	1996/97	100	37	28			165
7	1996/97	43	8	8		1	60
11	1997/98	54	26	5		9	94
12	1997/98	41	26	76	133	24	300
13	1997/98	6	3	3	6		18
17	1998/99	9	9	8	7	39	72
18	1998/99	41	13	7	60	41	162
22	1999/00	23	8	6	12	35	84

Table 6.2 Summary of movements of tagged toothfish between fishing grounds around Macquarie Island. Tags from all fishing seasons were combined in this table. Number tagged includes re-releases.

Release location	Number tagged	Number recaptured in				
		Aurora Trough	Colgate Valley	Grand Canyon	Beer Garden	Other
Aurora Trough	2746	369	1			1
Colgate Valley	591	1	20	6	48	
Grand Canyon	514		1	11	53	
Beer Garden	449				13	
Other	264	1			1	

Table 6.3 Summary of toothfish CPUE by voyage and fishing ground around Macquarie Island (CPUE in kg/km^2).

Voyage	Dates		Aurora Trough	Colgate Valley	Grand Canyon	Beer Garden	Other grounds
	Start	End	CPUE	CPUE	CPUE	CPUE	CPUE
1	15/11/94	4/12/94	4316				<1
2	1/1/95	12/2/95	3981				
3	6/3/95	19/3/95	497				833
4	23/12/95	15/2/96	64142				293
5	1/3/96	29/3/96	5654				1181
6	23/12/96	24/1/97	26102	25902	543061		
7	12/2/97	23/2/97	17852	3206	466		<1
11	10/10/97	14/11/97	16134	5821	669		146
12	1/12/97	22/1/98	8649	581	31822	18102	295
13	6/2/98	10/2/98	7041	429	1261	1655	
17	14/10/98	24/11/98	7067	154	419	307	281
18	9/12/98	31/1/99	10434	171	265	3287	1018
22	3/1/00	10/2/00	2285	42	175	745	105

HISTORY OF THE TOOTHFISH FISHERY

Table 6.4 Summary of toothfish CPUE and quota by fishing season and fishing grounds around Macquarie Island (quotas in tonnes and CPUE in kg/km^2). Quotas have been set as a total quota for the whole area within which is a subsidiary quota for Aurora Trough. For example in the 1996/97 season the overall quota was 1,000t, of which no more than 750t could be taken in Aurora Trough.

Season	Dates		Aurora Trough		Colgate Valley	Grand Canyon	Beer Garden	Other grounds	Total Quota
Fishing	Start	End	CPUE	Quota	CPUE	CPUE	CPUE	CPUE	
1994/95	15/11/94	19/3/95	3599	N/A				555	N/A
1995/96	23/12/95	29/3/96	39997	N/A				939	N/A
1996/97	23/12/96	23/2/97	23621	750	21867	422485		<1	1000
1997/98	10/10/97	10/2/98	12406	200	2945	29216	17392	252	1500
1998/99	14/10/98	31/1/99	9852		164	347	2976	649	
1999/00	3/1/00	10/2/00	2285		42	175	745	105	
Administrative									
1999	1/1/99	31/12/99	12578	40	271	<1	4342	1572	600
2000	1/1/00	present	2285	40	42	175	745	105	510

7. Physical and biological oceanography

Simon Goldsworthy, Xi He, Dianne Furlani, Thomas Moore, Steve Rintoul, Tony Koslow, Rudy Kloser, Dick Williams, Mark Lewis, and Tim Lamb

Summary
This chapter describes the regional physical and biological oceanography around Macquarie Island, and attempts to identify the major oceanographic factors that underpin biological activity in the region. Oceanographic data used were obtained from remote sensing (SST, ocean colour, altimeter) and CTD and zooplankton trawl stations undertaken during the RV *Southern Surveyor* (SS0199) voyage to Macquarie Island between 10 January and 4 February 1999. The major oceanographic influence on Macquarie Island is the eastward flowing Antarctic Circumpolar Current (ACC), the main flow of which is associated with the Subantarctic Front (SAF), which passes through a gap in the Macquarie Ridge just north of Macquarie Island. A weaker jet, part of the ACC, is associated with the Antarctic Polar Front (APF) that crosses the Macquarie Ridge to the south of Macquarie Island. Macquarie Island thus lies in the oceanographic region between the SAF and the APF known as the polar frontal zone (PFZ). The PFZ is characterised by mixing and poorly defined water masses. CTD and hydrology data from the region are indicative of this. Zooplankton biomass in the region was dominated by copepods and amphipods, with greatest biomass occurring in stations west of the island. The zooplankton assemblages in the two fishing grounds were significantly different. Remote sensing data indicate that sea surface temperatures (SST) around the island vary by about 3°C over the course of a year, but that mean summer SSTs in the vicinity of the island have varied by about 2°C over the past 20 years, with some years warmer or colder than the mean SST (6.64°C). Such variation may be driven in part by the oceanographic and climatic phenomenon called the Antarctic Circumpolar Wave (ACW), although longer, 7-10 cycles in SST also contribute. For example, SSTs at Macquarie Island were warmer in the 1980s than in the 1990s. Although there is evidence that variability in SST has biological consequences in other parts of the Southern Ocean and around Macquarie Island, no relationships were detected between SSTs in the fishing grounds and variation in toothfish CPUE. Three years of ocean colour (surface chlorophyll a concentration) data for the region show marked annual differences in the extent of primary production in the vicinity of Macquarie Island. Although the record is very short, the ocean colour data suggest that cooler SSTs are associated with increased primary productivity.

Introduction
The major aims of this part of the study were to describe the regional physical and biological oceanography around Macquarie Island, in order to examine the major oceanographic factors that may underpin biological activity in the region. The oceanographic data described here were obtained from remote sensing (SST, ocean colour, altimeter) and a survey undertaken by the RV *Southern Surveyor* (SS0199) around Macquarie Island between 10 January and 4 February 1999. This survey obtained oceanographic data from six stations around Macquarie Island, including data on conductivity, temperature and depth (CTD), nutrients and plankton.

Methods
Research voyage oceanography
A broad-scale survey of waters in the vicinity of Macquarie Island and the Macquarie Ridge (between 53° and 56° 17' S latitude, and 158° 30' and 159° 25' E longitude) (Figure 7.1), was undertaken by the RV *Southern Surveyor* between 10 January and 4 February 1999. Six stations were investigated: Macquarie Ridge Gap (RG), Colgate Valley (CV), Aurora Trough (AT), Deep West (DW), East Macquarie (EM) and Southern Ridge (SR) (Figure 7.1, Table 7.1).

CTD casts were undertaken to define the general oceanography in the area at the time of the voyage. In addition to conductivity and temperature, fluorescence and dissolved oxygen were

measured continuously for each cast, and water samples were taken at representative depths for nutrient analysis. Water samples were analysed for phosphate, silicate and nitrate concentrations using standard methods described in Marine Labs Report No, 166.

Zooplankton samples where collected from four areas of the survey site, covering the region north and west of Macquarie Island (Figure 7.1, Table 7.1). Using a 70cm diameter bongo net with a 500 μm mesh, tows were made obliquely through the water column between the surface and 200 m depth during daylight hours. Standard tow duration was 20 minutes. Samples were retained separately from the port and starboard cod-ends, and preserved in 10% formalin.

In the laboratory, individual samples were drained, and total wet weights recorded. For each sample, a sub-sample of known wet weight was sorted, and the zooplankton identified and counted. Ten major groupings were apparent (Table 7.2). Individual wet weights where obtained for organisms from each of the 10 groupings. Within each sample, total biomass for each grouping was then calculated, multiplying up individual numbers, individual weight, and sub-sample proportions.

Broad-scale oceanography
A range of remote sensing products was used to investigate the regional oceanography around Macquarie Island.

- CAC (Reynolds) monthly 1º x 1º grid, optimally interpolated SST analysis was used to generate monthly images of average SST in the Macquarie Island EEZ from 1995 to 1999.
- CAC (Reynolds) weekly, 1º x 1º grid, optimally interpolated SST analysis for November 1981 to May 1998 was used to investigate seasonal and annual variation in SST around Macquarie Island.
- 9 x 9 km Pathfinder SST images were produced for December, January and February over two consecutive years (1997/98, 1998/99). Data for 1999/00 were unavailable.
- Monthly 9 x 9 km SeaWIFS ocean colour images were generated for the Macquarie Island EEZ between December and February over three consecutive years (1997/98 – 1999/00) to examine seasonal and annual variability in primary production (chlorophyll a concentration).
- 10 day, 0.25º x 0.25º sea-height anomaly data were used to examine annual changes in the summer (December – February) position of the Subantarctic Front (SAF) and the Antarctic Polar Front (APF) near Macquarie Island. The sea-level anomaly product combined data from the TOPEX/POSEIDEN and ERS-1 and ERS-2 satellite altimeters. A mean sea –level field was added to the 10-day maps of sea level anomaly. The SAF and APF were defined as having a mean sea-height range between 140-170 cm and 90-110 cm, respectively.

These data were extracted using Matlab into text files, converted to Excel files and then imported in MapInfo™. Data were interpolated (triangular irregular network interpolation with 5th order polynomial) and plotted using VerticalMapper™.

Results and discussion
Regional and local oceanography
Macquarie Island is predominantly influenced by waters associated with the eastward flowing Antarctic Circumpolar Current (ACC). The main fronts associated with this current are the SAF and the APF, with the bulk of eastward flow associated with the SAF (Rintoul *et al.* 1997). Both these fronts flow in a south-eastward direction in the region of Macquarie Island following deviation further west from the South-East Indian Ridge (Rintoul and Bullister 1999). The main flow of the SAF passes just north of Macquarie Island where it passes through a gap in the Macquarie Ridge (about 3,000 m deep), 100-140 km north of the Island (Figure 7.2). The main flow of the APF passes through a broad band between 100-500 km south of the island (Figure 7.2). Both the SAF and APF are characterised by steeply sloping isotherms (Rintoul and Bullister 1999).

There are five main water masses in the Southern Ocean in the region of Macquarie Island. South of the PF, this includes (from the surface to the sea-floor) Antarctic Surface Water (AASW), Circumpolar Deep Water (CDW), and Antarctic Bottom Water (AABW) (Figure 7.3). The fourth water mass, Subantarctic Mode Water (SAMW) is formed north of the ACC by deep (>500 m) winter convection (Figure 7.3). The fifth water mass, Antarctic Intermediate Water (AAIW), is also found north of the ACC. AASW is the cold, relatively fresh highly oxygenated waters found south of the APF. CDW consists of an upper (UCDW) and lower (LCDW) layer. The UCDW originates from deep water in the Indian and Pacific Oceans where it spreads into the Southern Ocean, and is characterised by a nutrient maximum and oxygen minimum layer (Callahan 1972). LCDW is North Atlantic Deep Water that enters the Southern Ocean through the South Atlantic Ocean and is characterised by a salinity maximum (Callahan 1972, Rintoul and Bullister 1999). AABW consists of a thin layer of fresh, cold, highly oxygenated water that originates from the sea surface off the Antarctic coast, where it sinks off the continental shelf (Rintoul and Bullister 1999). SAMW is characterised as having vertically uniform temperature, high oxygen concentration and relatively low density (Rintoul and Bullister 1999). AAIW is characterised by a prominent salinity minimum between 1,000-1500 m north of the SAF (Rintoul and Bullister 1999).

Macquarie Island is situated between the SAF and the PF, a region termed the polar frontal zone (PFZ) (Figure 7.2 and 7.3). Within this zone there is much mixing and water masses are poorly defined. CTD and hydrology data for the six stations are presented in Figures 7.4 – 7.7. Temperature at the surface was warmest in the northern stations (Ridge Gap and Colgate Valley) and coldest in the southern most station (South Ridge) (Figure 7.4). Surprisingly the coldest water was recorded in the northernmost station (Ridge Gap) where the water temperature dropped below 2° C between 180-400 m. A common definition for the position of the APF is the northernmost extent of the temperature minimum, with temperatures less than 2° C near 200 m (Botnikov 1963). This would suggest the occurrence of APF water in the Ridge Gap at the time of the survey, and altimeter data from the time of the survey shows the occurrence of APF water just west of the Macquarie Ridge north of the Island at this time (see below). This suggests that the oceanography at the time of the voyage was anomalous, with unusually cold water at depth in the north near the SAF.

Salinity increased with depth at all stations, which is expected for waters south of the SAF (Figure 7.5). Salinity data from all stations are also consistent with the definition of waters south of the SAF by Orsi *et al*. (1995), where salinity is less than 34.2 psu at depths <300 m. The steep gradients of increasing density with depth in near surface waters at all six stations are also consistent with waters south of the SAF (Rintoul and Bullister 1999, Rintoul and Trull submitted, Parslow *et al*. submitted) (Figure 7.6). Nutrient data from all stations indicating surface silicate levels between 5-10 μM/l, surface nitrate levels between 20-25 μM/l, and surface phosphate levels of around 1.4 μM/l are also typical of PFZ waters (Rintoul and Bullister 1999, Rintoul and Trull submitted, Parslow *et al*. submitted) (Figure 7.7).

Zooplankton
Histograms of the relative biomass of the ten categories of zooplankton sampled at each station are presented in Figure 7.9. The most abundant categories were 'Copepod 1', 'Copepod 2', 'Chaetognath', and 'Amphipod 1 large' (Figure 7.8), with the lowest biomass in the 'Euphausiid' and 'Ostracod' categories. Within each category, relative biomass was found to differ markedly among the four stations. The highest biomass samples were obtained from the Aurora Trough, with Deep West, Colgate Valley and Ridge Gap samples containing similar biomass (Table 7.1). The higher biomass in Aurora Trough samples was associated with a large biomass contribution from copepod 2, which occurred at comparatively low biomass in all other station (Figure 7.8). Copepod 1 and gastropods accounted for a greater proportion of the biomass in the northern station samples, while amphipod 1 and chaetognaths accounted for more biomass in southern station samples (Figure 7.8).

A Bray-Curtis cluster dendrogram provided an index of dissimilarity between the individual samples at each station (Figure 7.9). It identified three main grouping, one associated with 5 of the 6 Deep West stations, a second containing 3 of the 4 Aurora Trough stations, and a third contain all bar one of the Ridge Gap and Colgate Valley stations. Two additional groupings, one containing a single Ridge Gap station and a second containing a Deep West and Aurora Trough station were also identified in the Bray-Curtis analysis (Figure 7.9). As with the dissimilarity analysis, multidimensional scaling also identified that the two stations along the Macquarie Ridge, Colgate Valley and the Ridge Gap were more similar, compared with the inshore (Aurora Trough) and offshore (Deep West) stations to the west of the island (Figure 7.10).

Remote sensing (SST, ocean colour and sea height)
Within the PFZ around Macquarie Island, average mean monthly sea-surface temperatures (SSTs) varied by about 3˚C over the course of a year between 1981 and 2000, with average maxima occurring in February (7.1˚C) and minima occurring in September (4.1˚C) (Figure 7.11). Within this range significant seasonal and annual variability is apparent over the past 20 years (Figures 7.12 and 7.13). Mean summer SST in the vicinity of the island has varied by about 2˚C over the past 20 years, with some years warmer or colder than mean SST (6.64˚C)(Figure 7.13). The cause of such variability may be partly attributed to the oceanographic and climatic phenomenon called the Antarctic Circumpolar Wave (ACW), described by White and Peterson (1996). The ACW is manifest by an eastward propagation of oceanographic and atmospheric variables including SST, seal-level pressure, meridional wind stress and sea-ice extent that propagates around the Antarctic continent in about 8-10 years. At any one point, the ACW signal appears and repeats itself every 4-5 years (Christoph *et al*. 1998, White and Peterson 1996). The main axis of the ACW is roughly centred on 55˚ S and it is most energetic between 150˚E and 100˚W (eastern South Pacific Ocean) (Christoph *et al*. 1998). SST anomalies are thought to be advected intact by the ACC (Christoph *et al*. 1998, White and Peterson 1996).

However, the mean summer SST record for Macquarie Island, does not show great support for a 4-5 year cycle, although the main ACW events reported along the Astrolabe XBT line just west of Macquarie Island in 1984/85 and 1988/89, and weaker events in 1992/93 and 1997 (Sokolov and Rintoul submitted) were all years of above average SST in the vicinity of Macquarie Island (Figure 7.13). In addition to ACW events, there are also longer 7-10 cycles in SST in the Southern Ocean, and this is perhaps supported in the Macquarie Island SST records that show that SSTs in the 1980s were typically warmer than those during the 1990s, however, the time series is really to short to establish if this cycle is typical for the Macquarie Island region.

Warm episodic SST anomalies in the Southern Ocean have been shown to correlate with the breeding performance of seals and seabirds (Croxall 1992, Chastel *et al*. 1993, Boyd 1993, Guinet *et al*. 1994, 1998). These studies have shown that warm SST events prior to or during the breeding season can depress the body condition and breeding performance of seals and seabirds. These studies suggest that during warm SST events, prey distributions may change such that they are less available to predators, and/or that prey population levels are reduced under such conditions (Guinet *et al*. 1998). At Macquarie Island, a ten year record of fecundity in the fur seal population there (Goldsworthy unpublished data) indicates that warm SSTs around the island during autumn months are significantly correlated with low fecundity rates in the following breeding season (Figure 7.14). Autumn SSTs may be important to the subsequent breeding performance of fur seals because this is the most energetically demanding part of the lactation period of Antarctic fur seals (*Arctocephalus gazella*), and the period when active gestation commences (after a four-month delayed implantation period). As such, oceanographic influences that affect the food supply and hence body condition of animals at this time appear to be playing an important role in determining the annual breeding performance of fur seals.

It is possible that such SST anomalies could also effect the recruitment strength of toothfish, as a recent investigation of a commercially fished squid (*Illex argentinus*) in the southwest Atlantic

has shown a strong negative relationship between SSTs in the northern Patagonian Shelf during the hatching period (June and July) and catches of squid in the following fishing season (Waluda *et al*. 1999). The authors suggest that the SST anomalies were associated with the ACW, and that by predicting cold-water events in the hatching grounds, they would be able to predict recruitment strength of *I. argentinus* in the southwest Atlantic. However, cross-correlations between three years (1996-98) of toothfish recruitment data from the Aurora Trough, with mean monthly SST data between 1989 and 1996 produced no significant correlations. Further, there are no apparent correlations between SST and CPUE in either the Aurora Trough of Colgate Valley fishing grounds, although there is an indication in the Aurora Trough that CPUE tends to be greatest when SSTs <4° and >6° C (Figure 7.15).

Monthly average SST in the Macquarie Island Region throughout the first five years of the toothfish fishery (1994-1999), are presented in Figures 7.16a-e. These figures corroborate the summer trend data (Figure 7.13), and indicate that 1995 had cool summer and winter SSTs, that the 1996/97 summer had warm SSTs, that the 1997/98 summer had cooler SSTs and that the 1998/99 summer had warmer SSTs. Higher resolution (9 x 9 km) SST data are available for the summer months of 1997/98 and 1998/99 (Figure 7.14). Comparisons of monthly averages for these two summers (December, January, February), clearly show warmer water masses around Macquarie Island in the 1998/99 summer. Average summer SST (December – February) from two seasons (1997/98 and 1998/99), and ocean colour and sea-height (December – February) data for the last three seasons (1997/98 – 1999/00) periods in the Macquarie Island region are presented in Figures 7.18 – 7.21. These indicate major contrasts in the extent of primary production in the vicinity of Macquarie Island, with extensive production to the north of the island in the 1997/98, an absence of any significant local production in the 1998/99 summer, and broad homogeneous production around the island in the 1999/00 summer, with a concentration of production west of the island (Figure 7.19). Interestingly, the pattern of both the extent and spatial distribution of primary production around Macquarie Island varied greatly over these three years (Figure 7.19).

The two summers with heightened local production were also summers characterised by lower than average mean SSTs (Figure 7.12 and 7.18). There is some variation in the position and extent of the SAF and APF over the three seasons (Figures 7.20 and 7.21), however, the relationship between the location and intensity of the frontal systems to Macquarie Island, with SST and primary production is unclear. At least in the three seasons examined here there appears to be a relationship between local SST and the extent of primary production in the vicinity of the island, with greatest primary production in summers with cooler SSTs. As nitrate and phosphate levels appear to be high enough not to be limiting primary production in summer, silicate levels that are typically low across the PFZ during summer months could limit the extent of primary production, especially that of diatoms. It is possible that higher silicate levels typically present in colder waters may enable greater primary production in the region around Macquarie Island, during seasons with colder SSTs, assuming that cold SSTs are due to cold silicate rich southern waters shifting north.

References

Botnikov, V. N. (1963). Geophysical position of the Antarctic convergence zone in the Pacific Ocean. Soviet Antarctic Information Bulletin 4: 324-327.

Boyd, I. L. (1993). Tooth growth in male Antarctic fur seals (*Arctocephalus gazella*) from South Georgia: an indicator of long term growth history. Journal of Zoology, London. 229: 177-190.

Callahan, J. E. (1972). The structure and circulation of Deep Water in the Antarctic. Deep-Sea Research 19: 563-575.

Chastel, O., Weimerskirch, H. and Jouventin, P. (1993). High annual variability in reproductive success and survival of an Antarctic seabird, the snow petrel *Pagodroma nivea*. Oecologica 94: 278-285.

Christoph, M., Barnett, T. P. and Roeckner, E. (1998). The Antarctic circumpolar wave in a coupled ocean-atmosphere GCM. Journal of Climate 11: 1659-1672.

Croxall, J.P. (1992). Southern Ocean environmental changes: effects on seabirds, seal and whale populations. Philosophical Transactions of the Royal Society London, B 338: 319-328.

Guinet, C., Chastel, O., Koudil, M., Durbec, J-P. and Jouventin, P. (1998). Effects of warm sea-surface temperature anomalies on the blue petrel at the Kerguelen Islands. Proceedings of the Royal Society, London B. 265: 1001-1006.

Guinet, C., Jouventin, P. and Georges, J-Y. (1994). Long term population changes of fur seals *Arctocephalus gazella* and *Arctocephalus tropicalis* on subantarctic (Crozet) and subtropical (Amsterdam) islands and their possible relationship to El Niño Southern Oscillation. Antarctic Science 6: 473-478.

Orsi, A. H., Whitworth III, T. W. and Nowlin, W. D. (1995). On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Research I 42: 642-673.

Parslow, J. S., Boyd, P., Rintoul, S. R. and Griffiths, F. B. (submitted). A subsurface chlorophyll maximum in the Polar Frontal Zone south of Australia: seasonal evolution and implications for phytoplankton – light – nutrient interactions. Journal of Geophysical Research.

Rintoul, S. R. and Bullister, J. L. (1999). A late winter hydrographic section from Tasmania to Antarctica. Deep-Sea Research I 46: 1417-1454.

Rintoul, S. R., Donguy, J. R. and Roemmich, D. (1997). Seasonal evolution of upper ocean thermal structure between Tasmania and Antarctica. Deep Sea Research I 44: 1185-1202.

Rintoul, S. R. and Trull, T. W. (submitted). Seasonal evolution of mixed layers in the Subantarctic Zone south of Australia. Journal of Geophysical Research.

Sokolov, S. and Rintoul, S. R. (submitted). The subsurface structure of Southern Ocean surface temperature anomalies. Geophysical Research Letters.

Waluda, C. M., Trathan, P. N. and Rodhouse, P. G. (1999). Influence of oceanographic variability on recruitment in the *Illex argentinus* (Cephalopoda: Ommastrephidae) fishery in the South Atlantic. Marine Ecology Progress Series. 183: 159-167.

White, W. B. and Peterson, R. G. (1996). An Antarctic circumpolar wave in the surface pressure, wind, temperature and sea-ice extent. Nature 380: 699-702.

Table 7.1 The numbers of CTD casts and Bongo net (zooplankton) trawls undertaken at each of the six stations surveyed at Macquarie Island during SS0199, together with site codes and zooplankton mean biomes values, and standard deviations (*S.D.*).

Station Name (Station Code)	CTD No. of CTDs (CTD No)	Bongo Net Samples Collected	Bongo Net Samples Analysed	Bongo Net Sample Codes	Plankton Mean Biomes (*S.D.*)
Ridge Gap (RG)	2 (10,11)	7	6	RG1-RG6	25.77 (10.17)
Colgate Valley (CV)	1 (9)	5	4	CV1-CV4	33.39 (11.31)
Aurora Trough (AT)	1 (1)	9	4	AT1-AT4	52.95 (26.63)
Deep West (DW)	3 (3-5)	6	6	DW1-DW6	32.12 (12.70)
East Macquarie (EM)	1 (8)	0	0		
Southern Ridge (SR)	1 (2)	0	0		

Table 7.2 Ten zooplankton groups used in the analysis of Bongo net samples taken from four survey stations around Macquarie Island during SS01/99. Average size and wet weights for each group are also presented.

Phylum	Grouping	Size (mm)	Average wet weight (gm)
Mollusca	Gastropod	<2	0.00054
Arthropoda	Copepod 1/Calanoid	3-5	0.00066
Arthropoda	Copepod 2/Cyclopoid	6-8	0.01214
Arthropoda	Ostracoda	<2	0.00040
Arthropoda	Euphausiacea	<10	0.00105
Arthropoda	Amphipod 1(Hyperiid small)	2-3	0.00129
Arthropoda	Amphipod 1(Hyperiid large)	~16	0.09547
Arthropoda	Amphipod 2(Phrosinid small)	2-4	0.00109
Arthropoda	Amphipod 2(Phrosinid large)	~9	0.05000
Chaetognatha	Chaetognath	10-15	0.00272
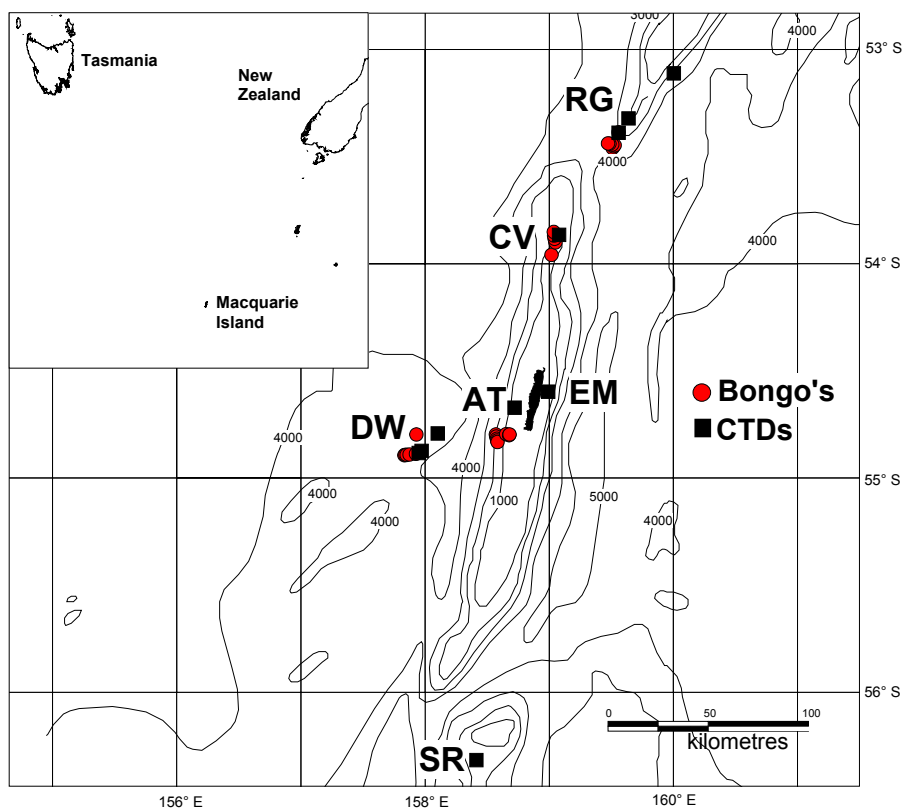
Figure 7.1 Map of Macquarie Island showing local bathymetry, the location of CTD casts, bongo net tows, and the six station locations investigated during the RV Southern Surveyor voyage SS0199. See Table 7.1 for station codes.
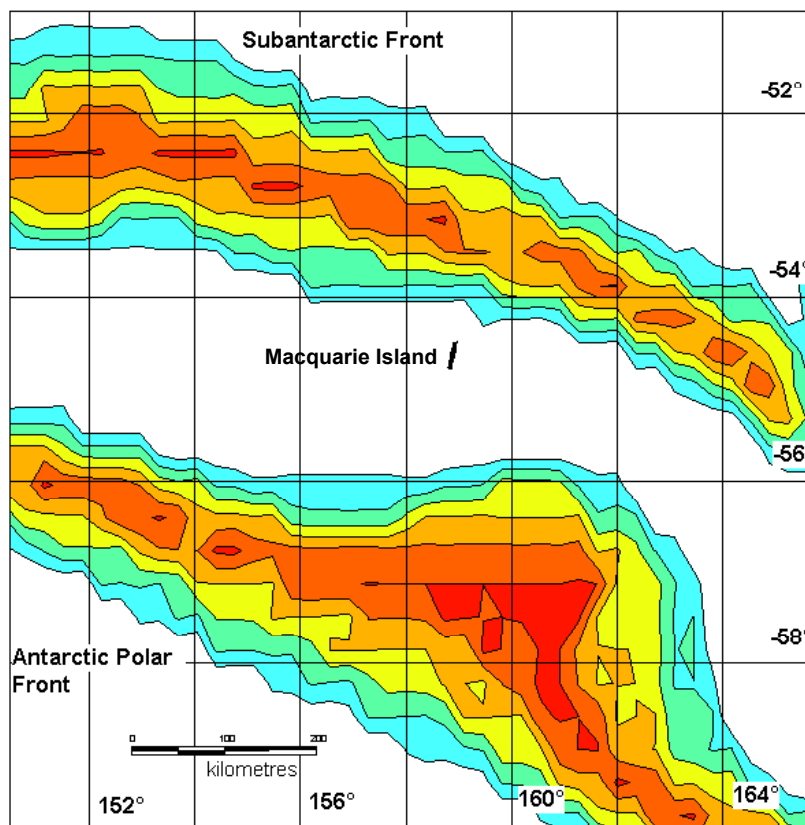
Figure 7.2 Average position of the Subantarctic Front and Antarctic Polar Front in relation to Macquarie Island. The colour gradient represents the range of mean sea heights associated with the SAF (140-170 cm) and APF (90-110 cm).
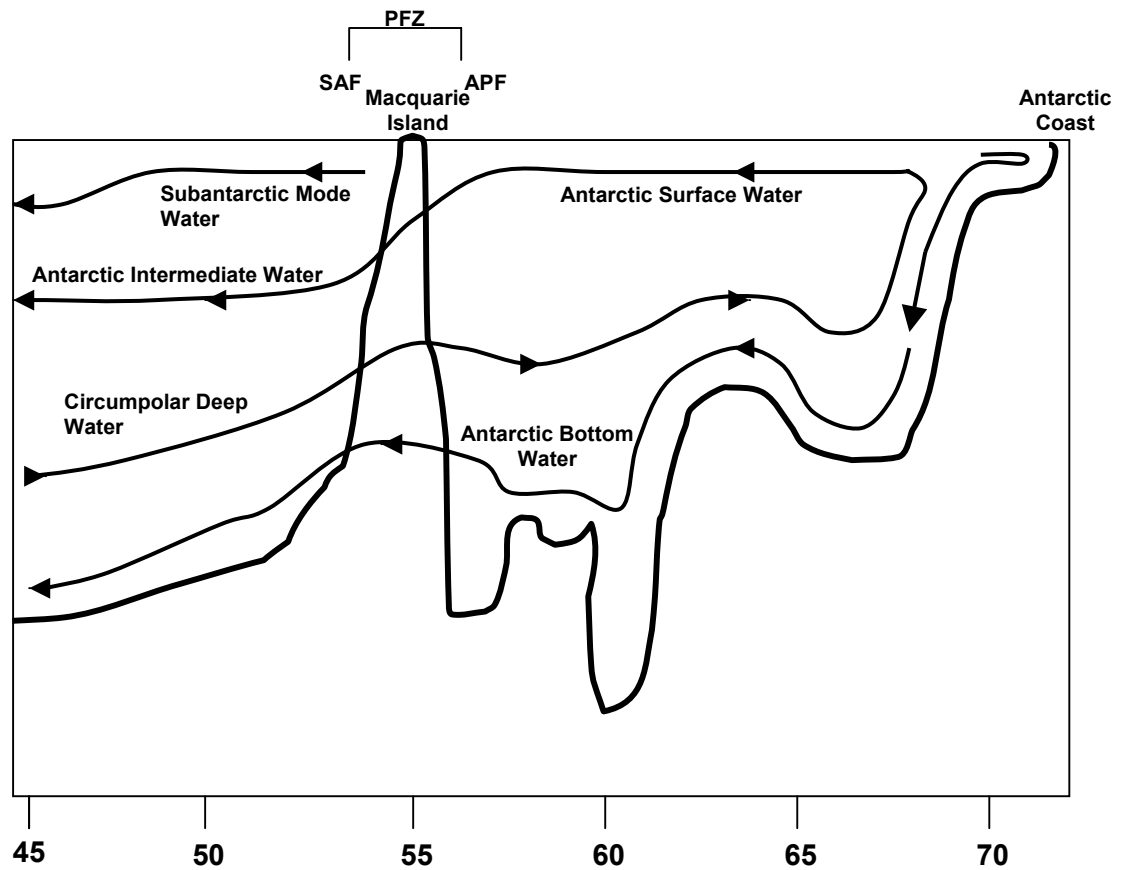
Figure 7.3 A schematic view of the major water masses along a north south plane centred on Macquarie Island (160º E)
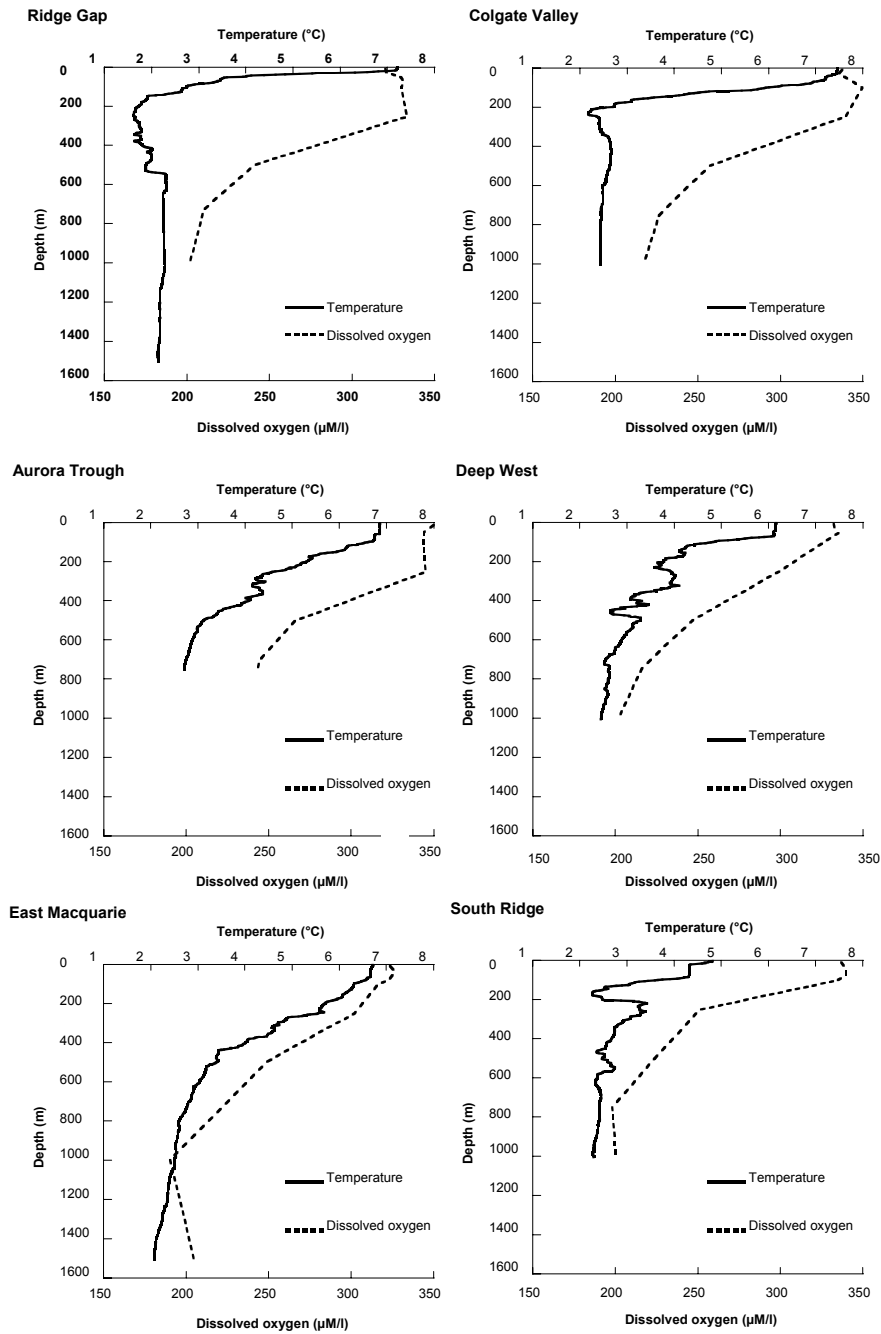
Figure 7.4 Temperature and dissolved oxygen at depth across the six main stations around Macquarie Island.
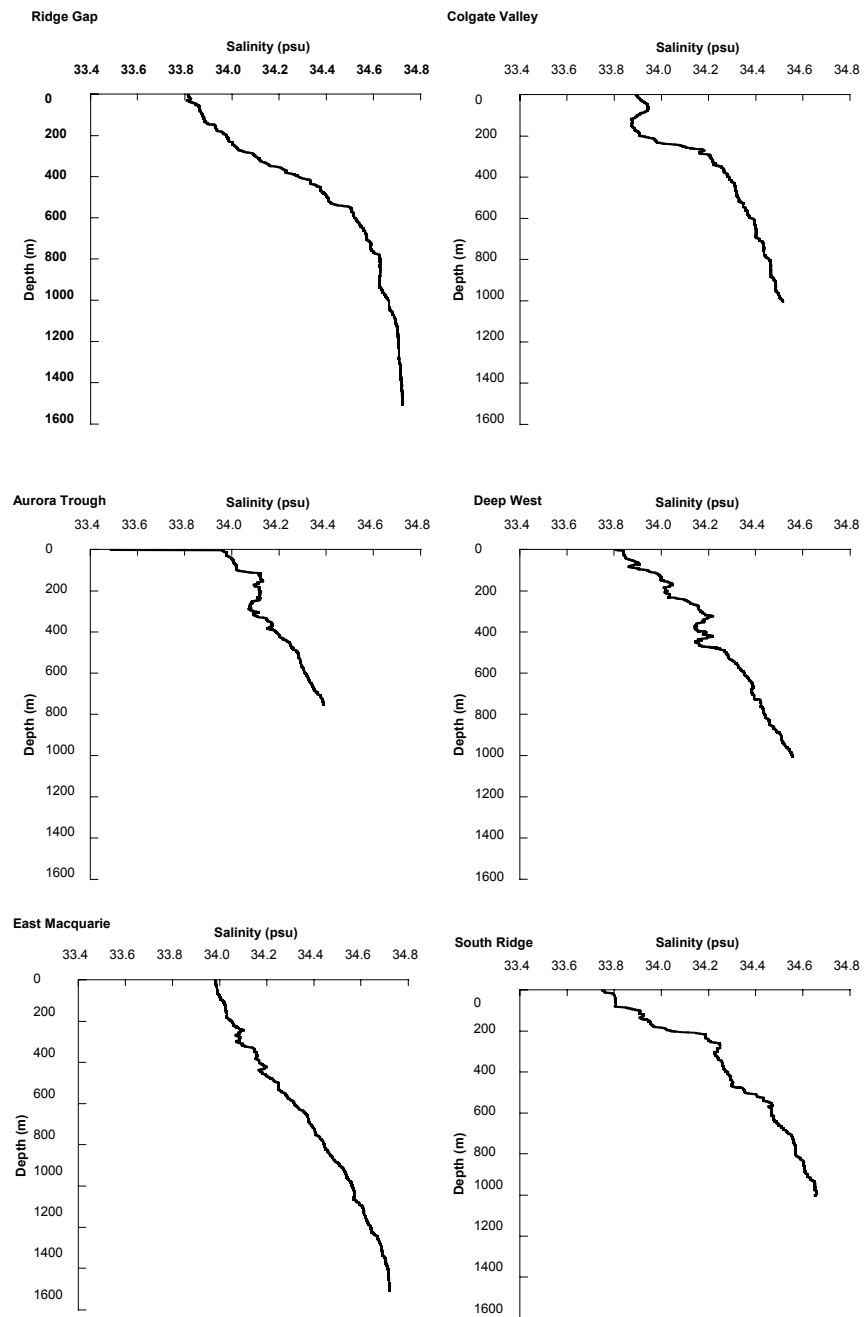
Figure 7.5 Salinity at depth across the six main survey stations around Macquarie Island.
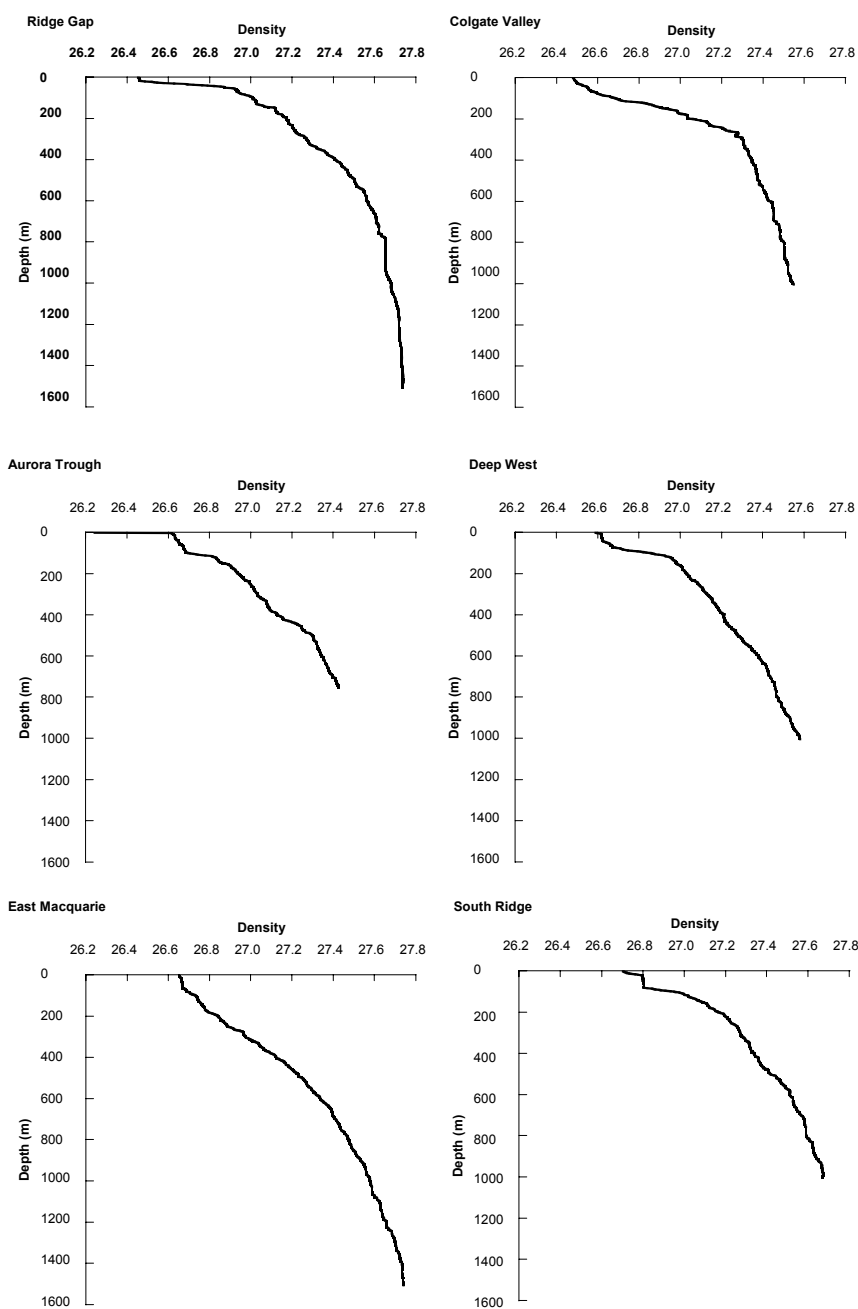
Figure 7.6 Density at depth across the six main survey stations around Macquarie Island.
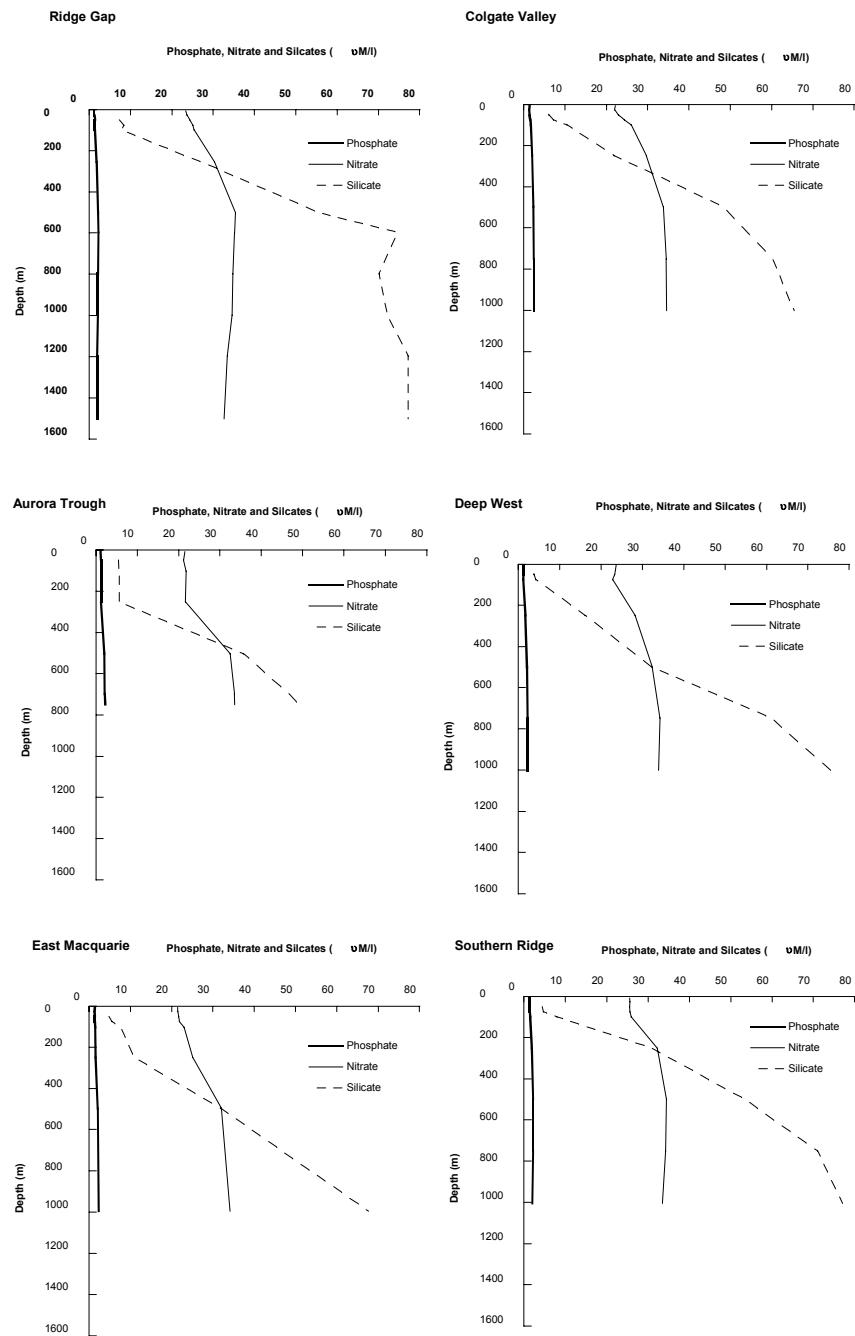
Figure 7.7 Phosphate, Nitrate and silicate levels at depth across the six main survey stations around Macquarie Island.
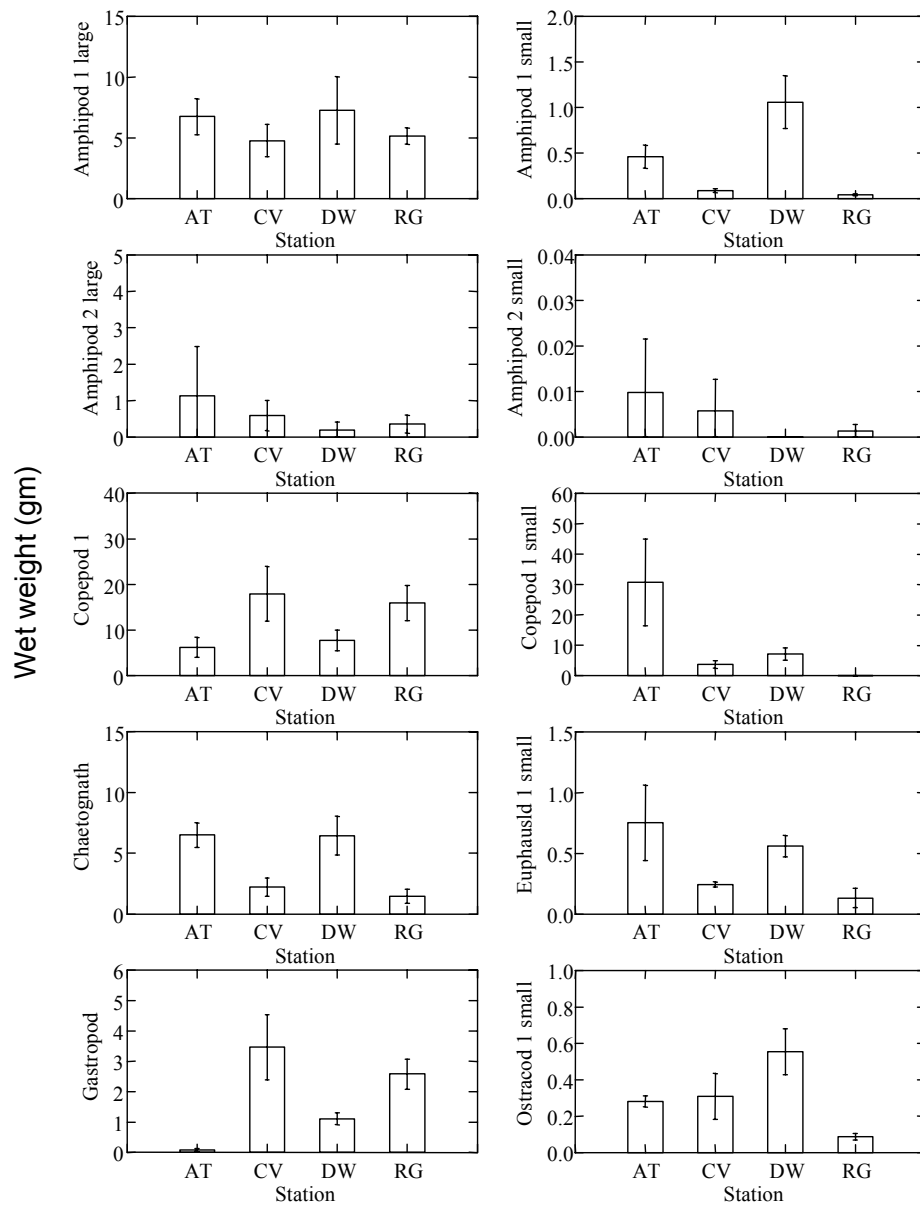
Figure 7.8 Bar chart plots for four stations showing wet weights (gm) and standard error for each of ten zooplankton groups. See Table 7.1 for station codes.
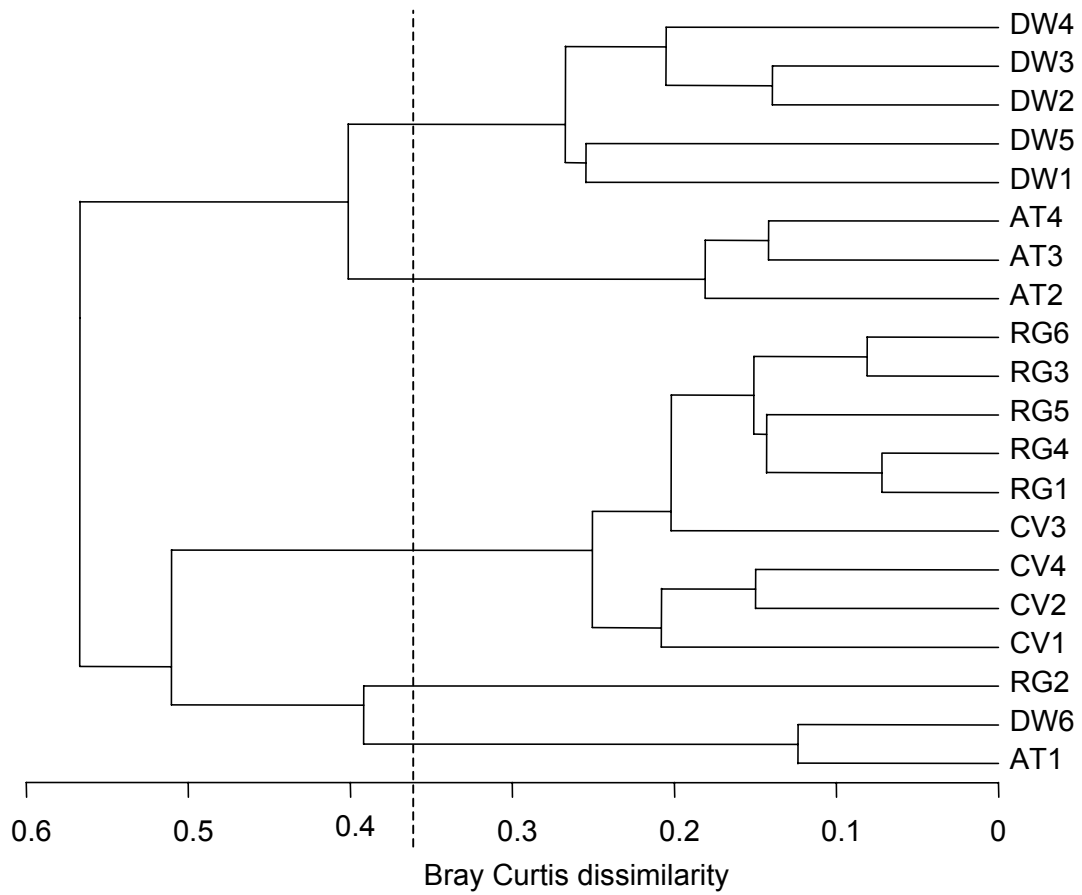
Figure 7.9 Cluster dendrogram based on Bray-Curtis dissimilarity for 20 zooplankton samples from near Macquarie Island. Sample codes are listed in Table 7.1. Samples are separated by vertical dashed line into 5 significant clusters, identified at the significant level of dissimilarity of 0.359.
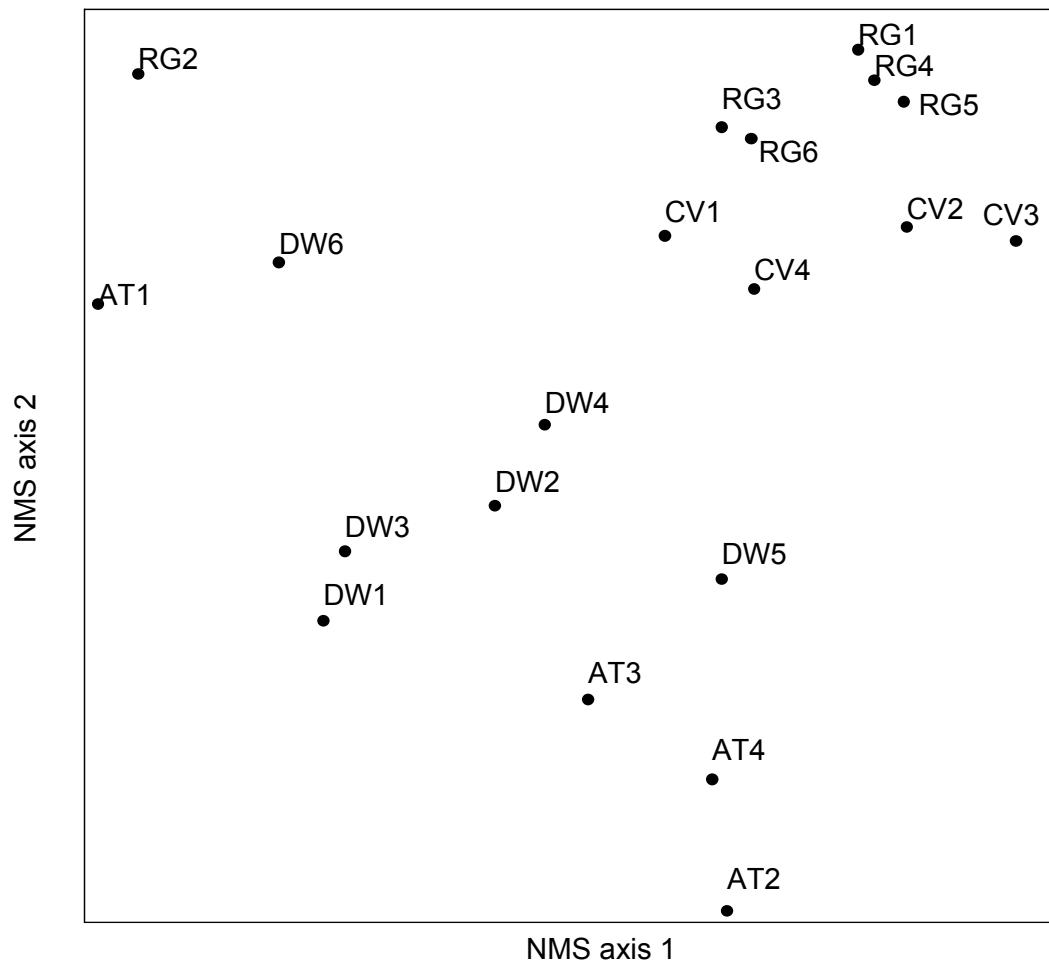
Figure 7.10 Non-parametric multidimensional scaling (NMS) plot of 20 zooplankton samples, from near Macquarie Island. Sample codes are listed in Table 7.1. This two-dimension solution has a reasonable low stress value of 0.0738. Bray-Curtis dissimilarity was used in the NMS.
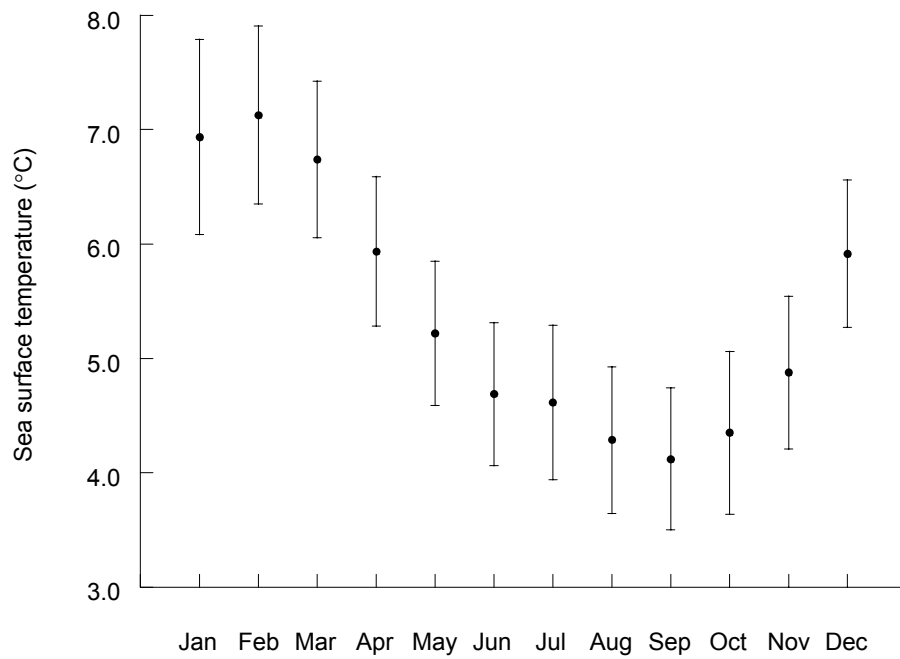
Figure 7.11 Means and standard deviations of monthly sea surface temperature within a 1 x 1 degree region around Macquarie Island. Means and standard deviations are computed from available records from 1981-2000.
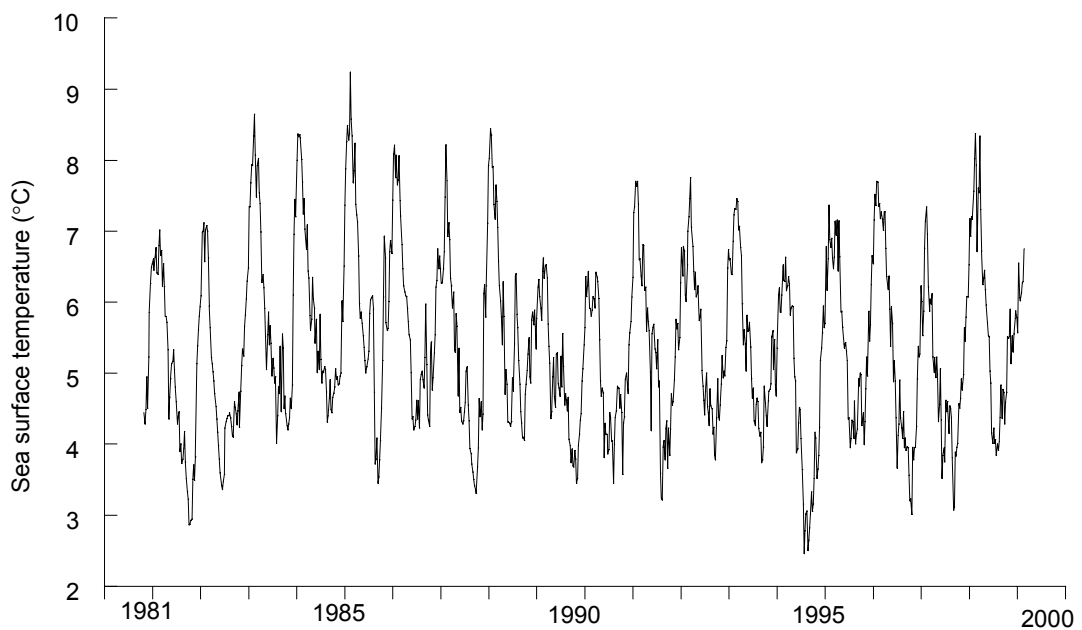
Figure 7.12 Weekly averages sea surface temperature within the 1° x 1° degree square centred on 54.5° S, 158.5° E, around Macquarie Island between 1981 and 2000.
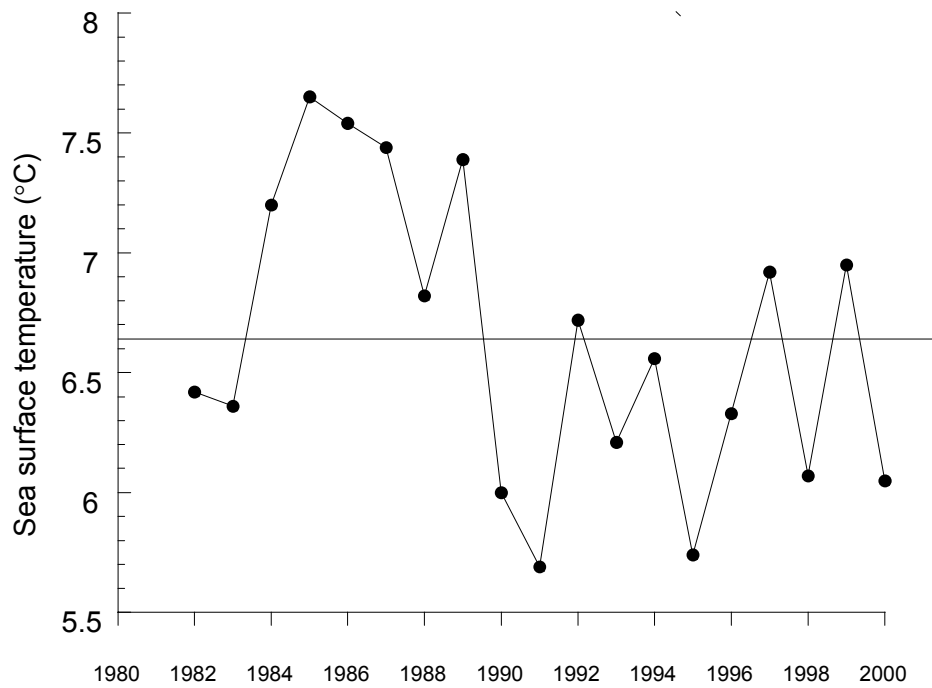
Figure 7.13 Mean summer (December – February) sea surface temperature within the 1° x 1° degree square centred on 54.5° S, 158.5° E, around Macquarie Island between 1981 and 2000. The horizontal line represents the average sea surface temperature of 6.64°C.
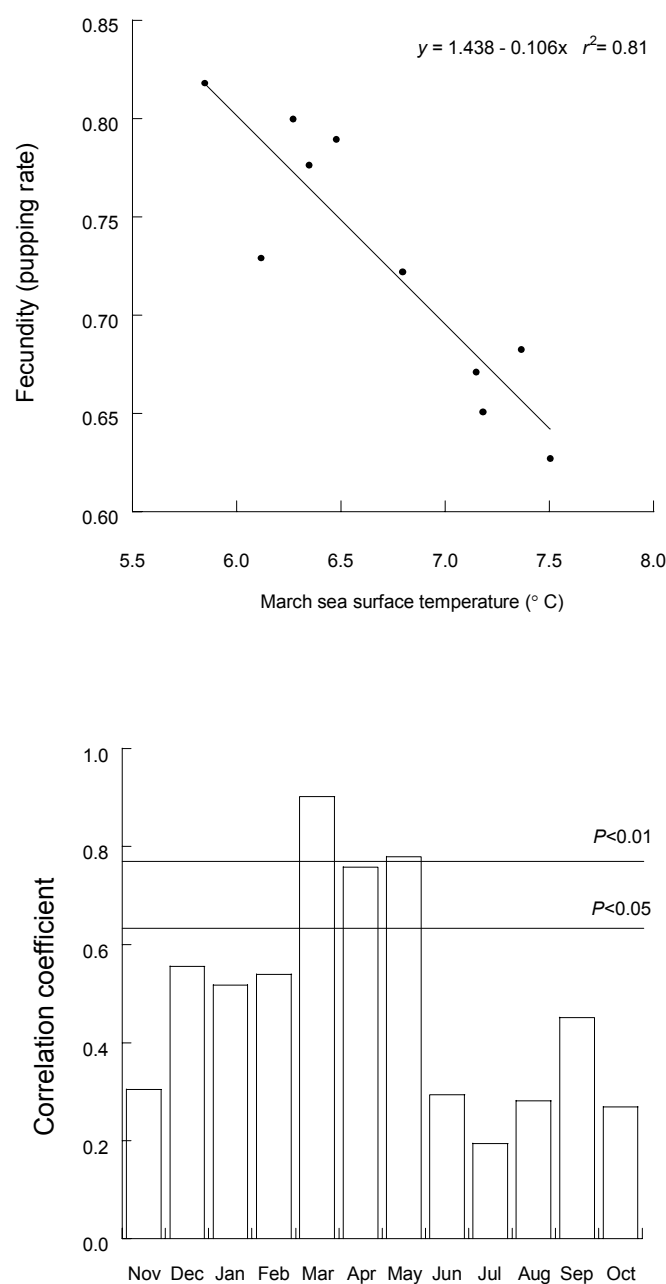
Figure 7.14 Relationship between the mean sea surface temperature in the 1° x 1° region around Macquarie Island in March (above) and the mean fecundity (pupping rate) of females fur seals breeding in the following breeding season (November-December). The lower figure plots the correlation coefficient of the relationship between mean monthly sea surface temperature prior to the breeding season and subsequent fecundity, indicating the relationship is only significant for sea surface temperature during the autumn months.
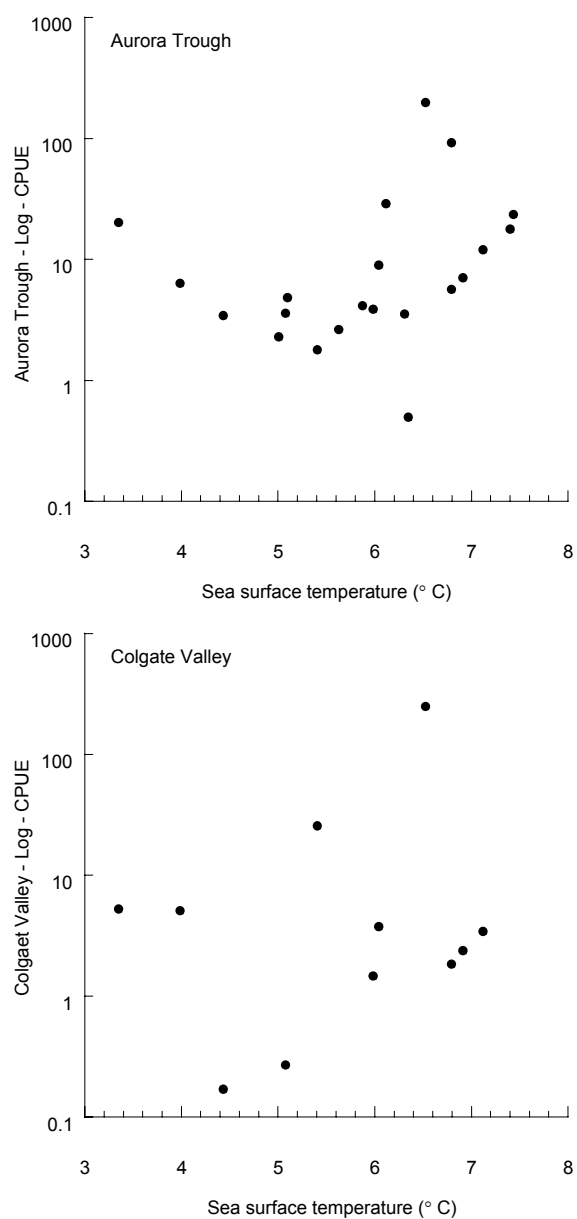
Figure 7.15 Relationship between the mean sea surface temperature in the 1° x 1° region around Macquarie Island and log-CPUE in Aurora Trough and Colgate Valley.
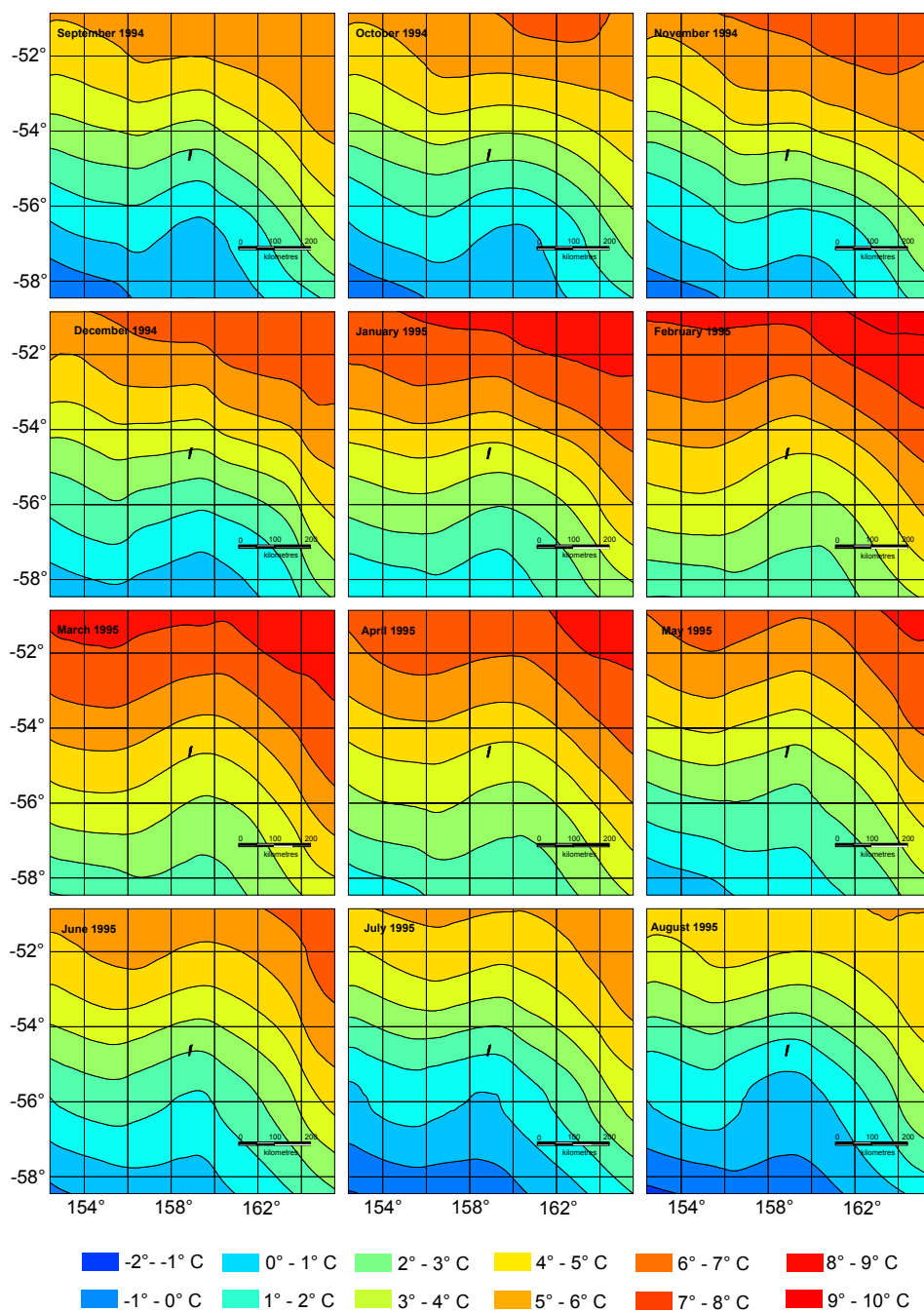
Figure 7.16a Monthly average sea surface temperature images (1° resolution) for the Macquarie Island EEZ September – August 1994-1995.
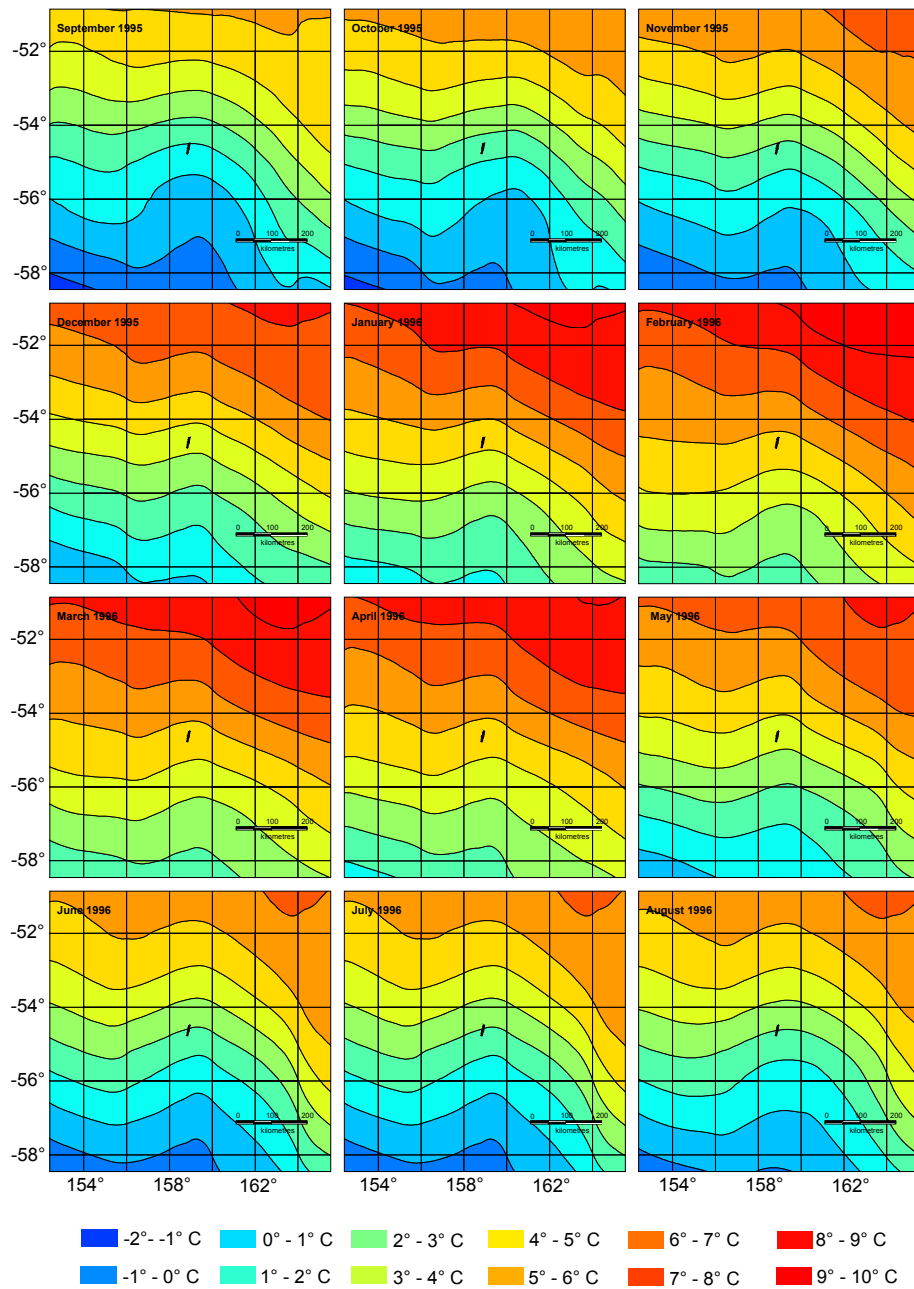
Figure 7.16b Monthly average sea surface temperature images (1° resolution) for the Macquarie Island EEZ September – August 1995-1996.
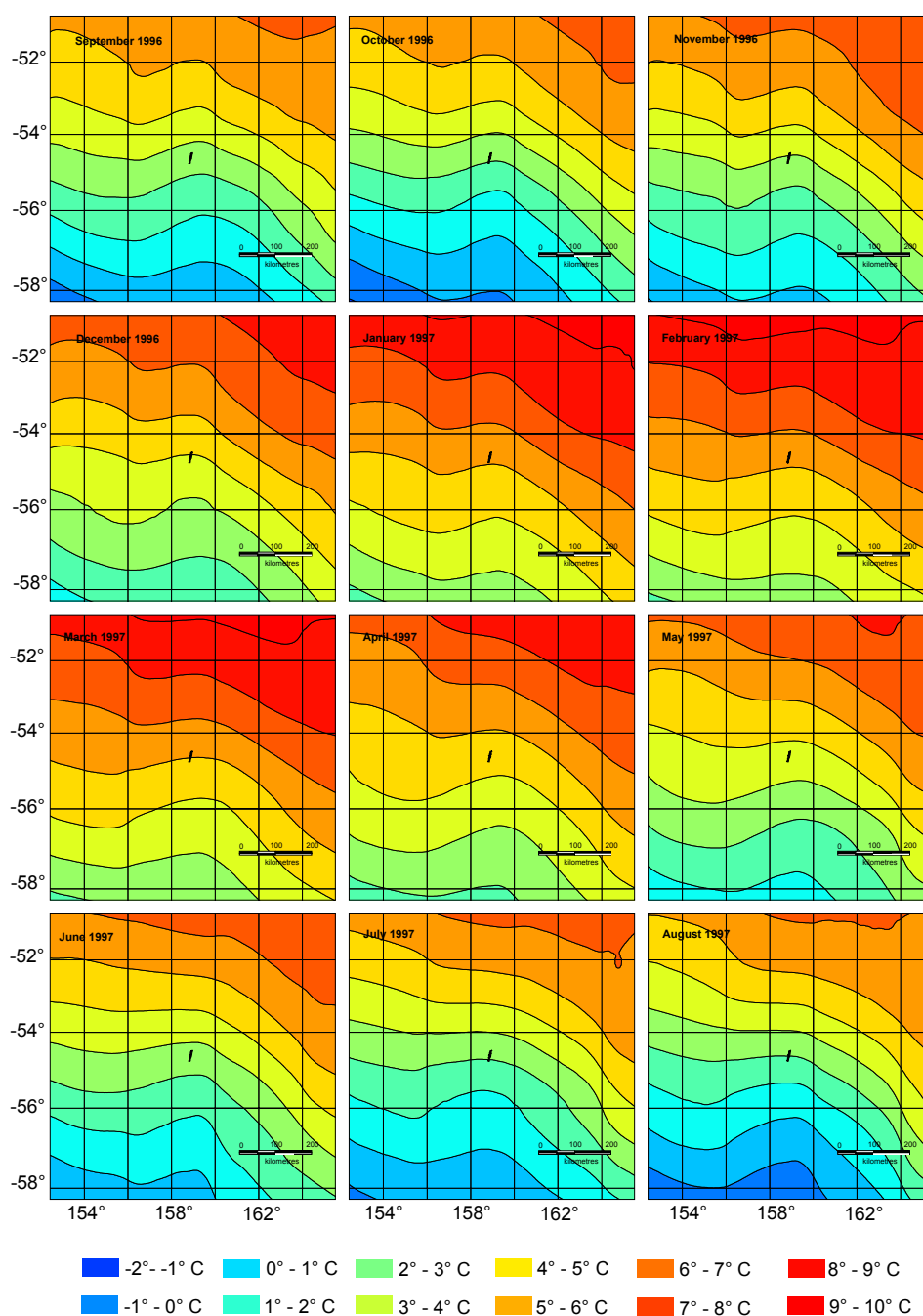
Figure 7.16c Monthly average sea surface temperature images (1° resolution) for the Macquarie Island EEZ September – August 1996-1997.
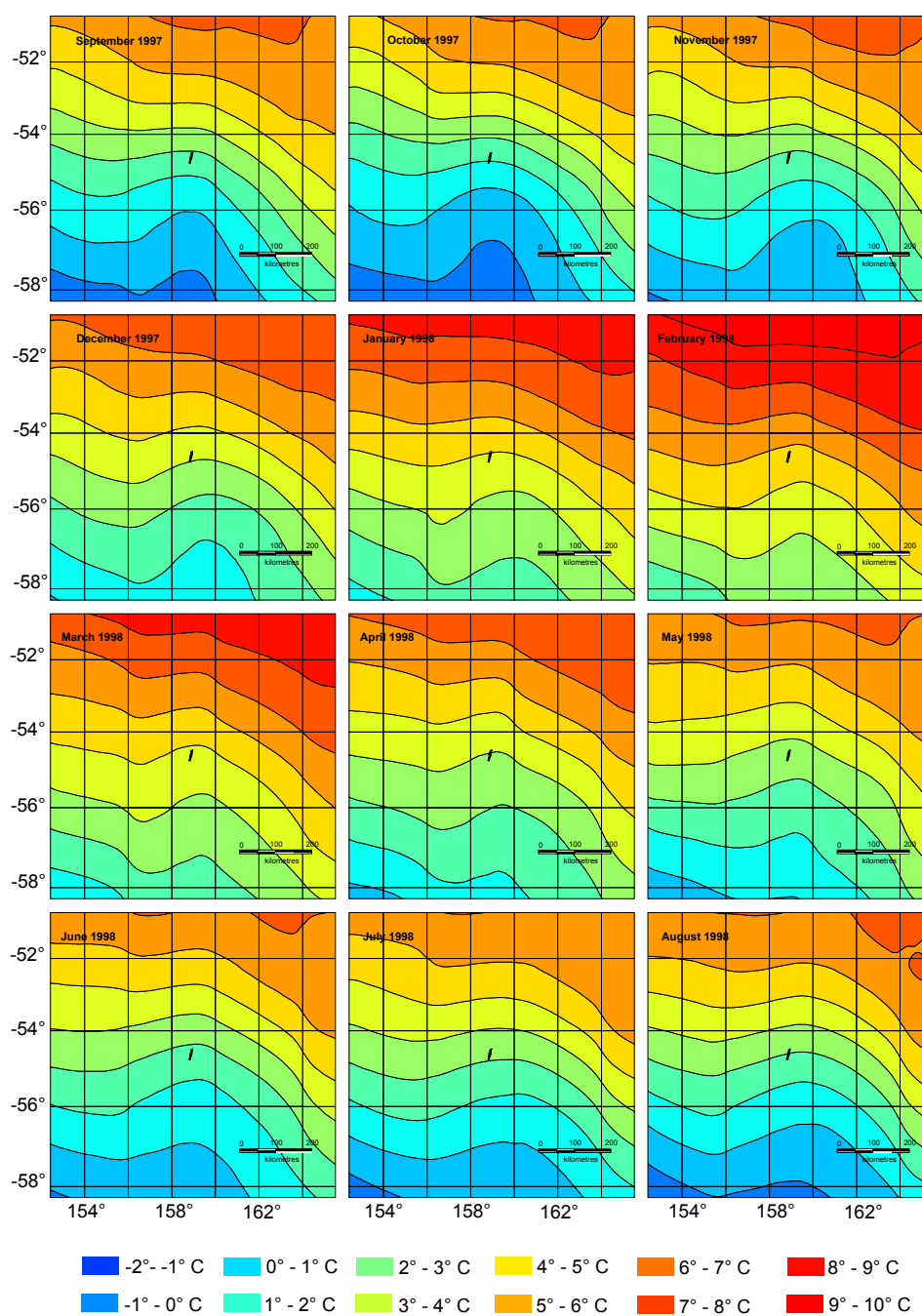
Figure 7.16d Monthly average sea surface temperature images (1° resolution) for the Macquarie Island EEZ September – August 1997-1998.
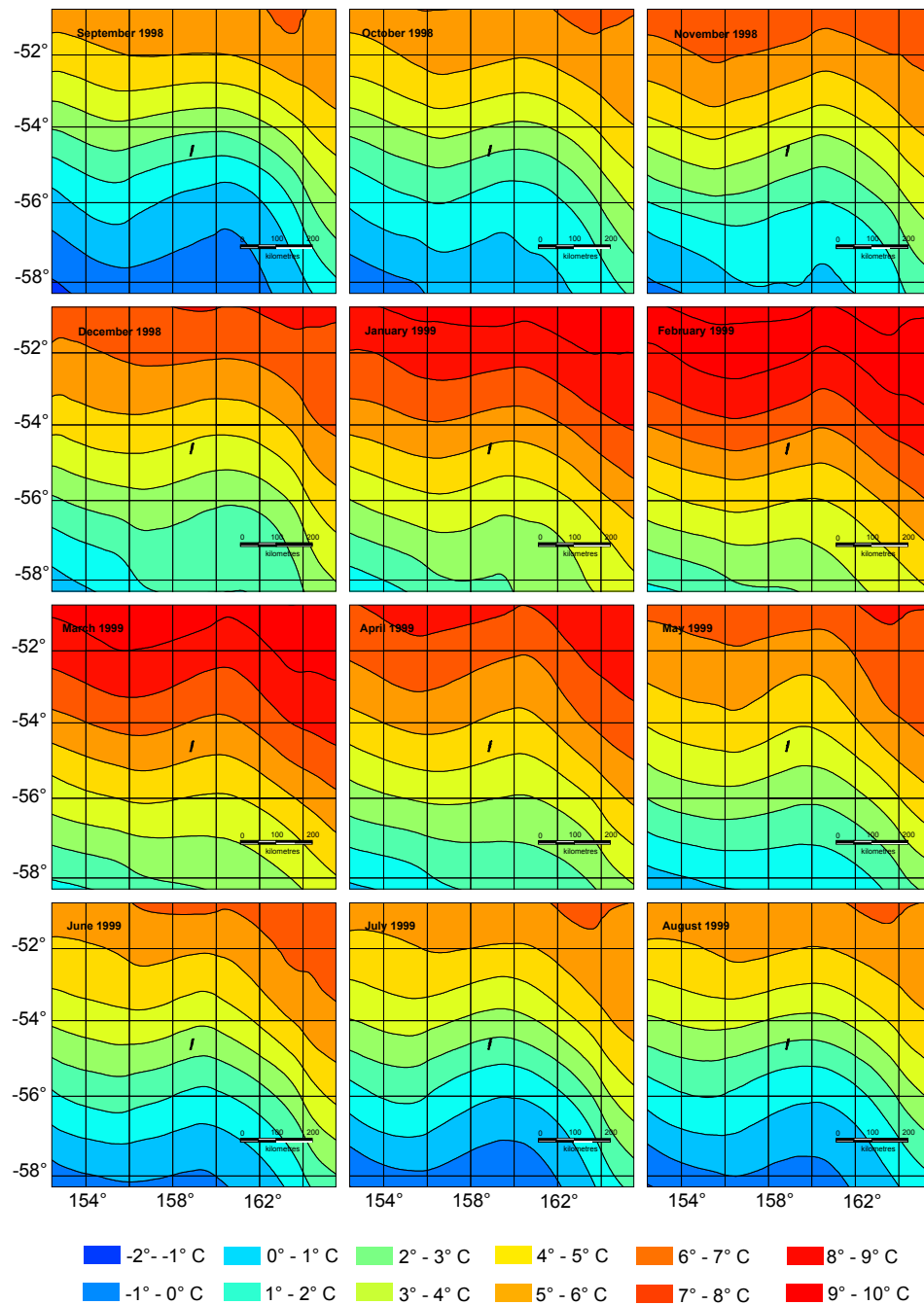
Figure 7.16e Monthly average sea surface temperature images (1° resolution) for the Macquarie Island EEZ September – August 1998-1999.
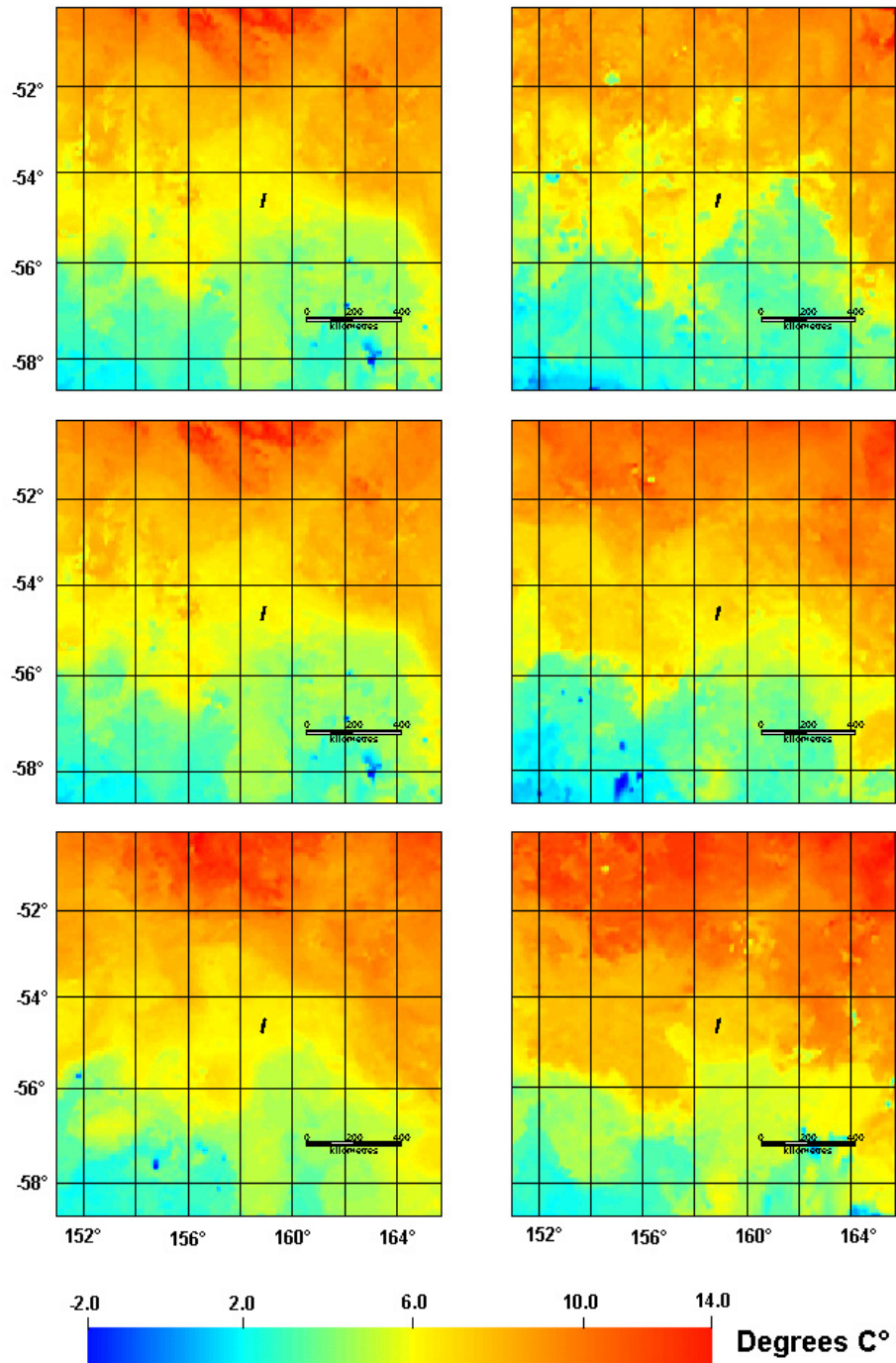
Figure 7.17 Average December, January and February sea surface temperature from 9 x 9 km Pathfinder data from 1997/98 and 1998/99 around Macquarie Island.
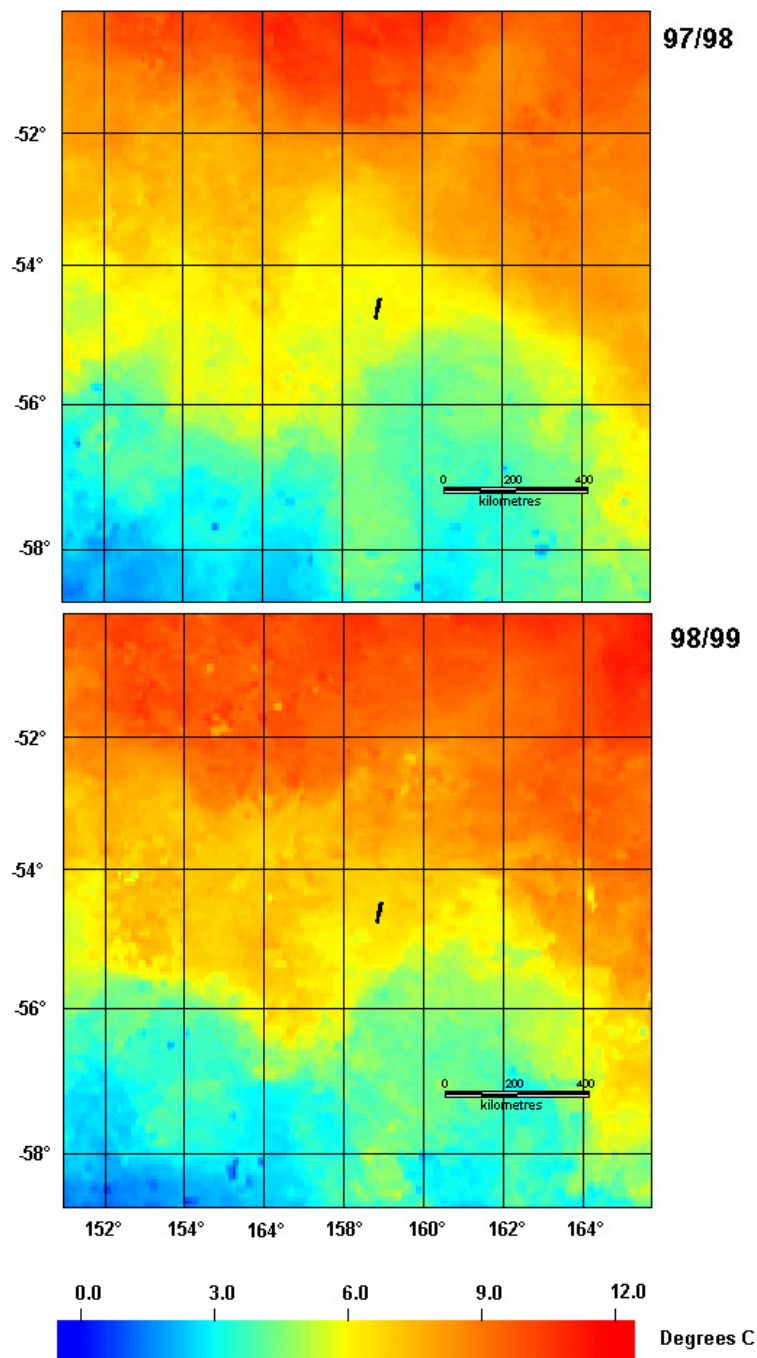
Figure 7.18 Average summer (December – February) sea surface temperature from 9 x 9 km Pathfinder data from 1997/98 and 1998/99 around Macquarie Island.
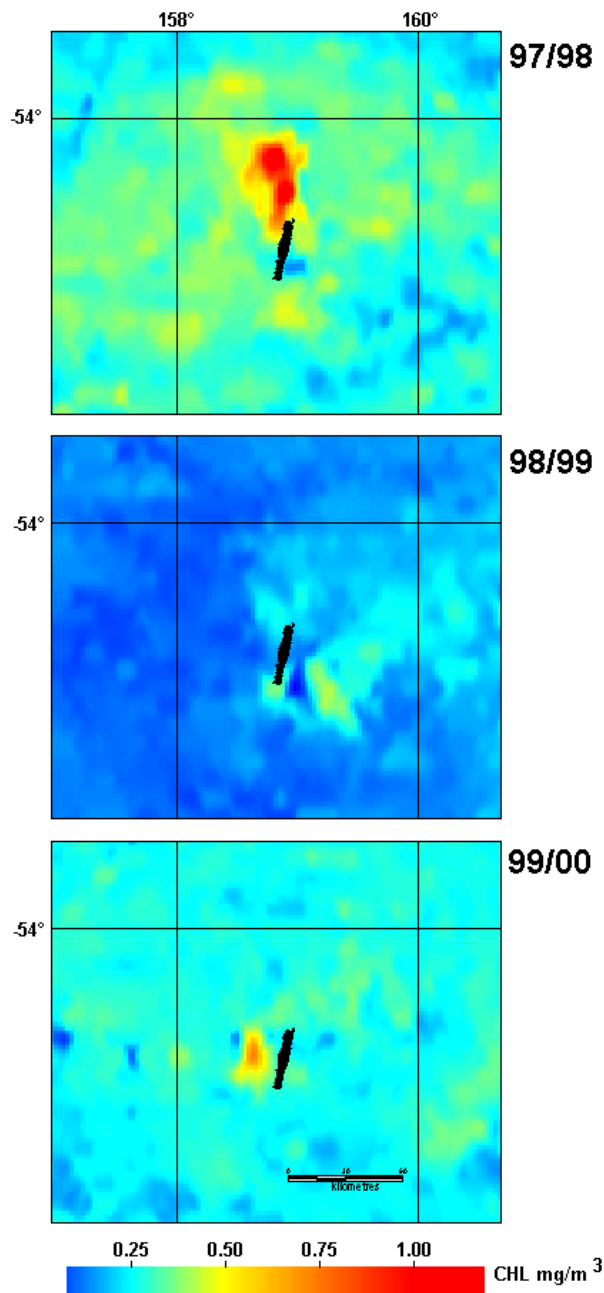
Figure 7.19 Three years average summer (December-February) chlorophyll a concentration around Macquarie Island.
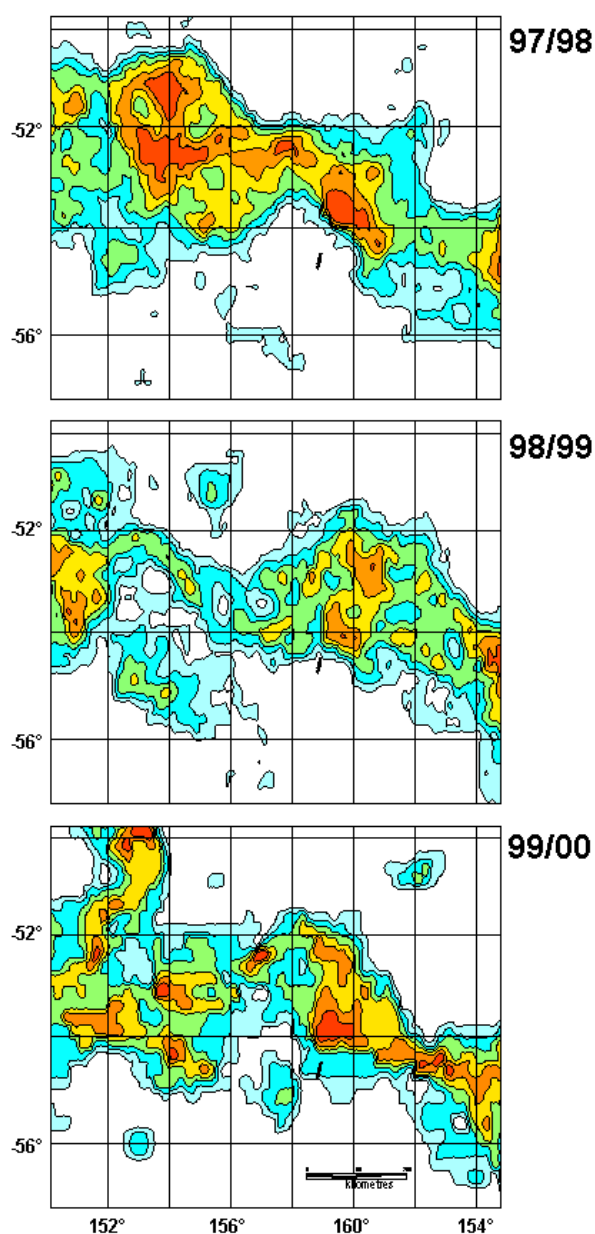
Figure 7.20 Average position of the Subantarctic Front (SAF) in three consecutive summers (December – February) around Macquarie Island. Data for 1997/98 (25 November – 5 March) and 1989/99 (30 November – 10 March) are compiled from 11, ten-day averages, while data for the 1999/00 summer are compiled from 6, ten-day averages (25 November – 14 January). Gradients in colour indicate the spatial frequency of SAF water (eg. red = SAF waters present during all ten day averages, pale blue = SAF water only present during one 10-day average).
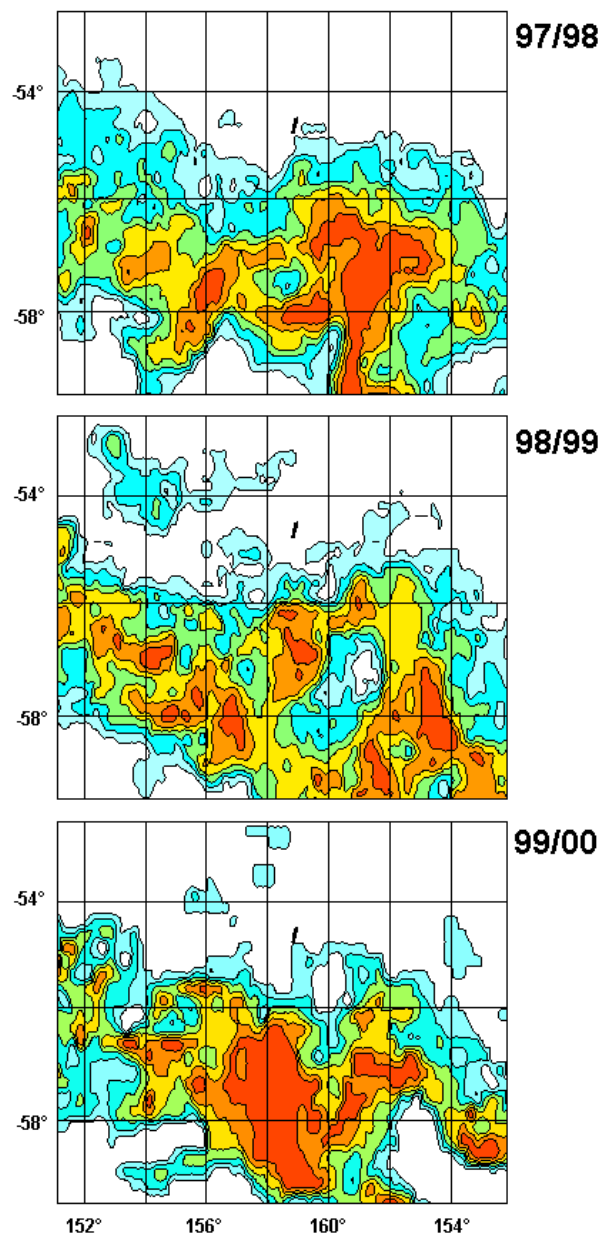
Figure 7.21 Average position of the Antarctic Polar Front in three consecutive summers (December – February) around Macquarie Island. Data for 1997/98 (25 November – 5 March) and 1989/99 (30 November – 10 March) are compiled from 11, ten-day averages, while data for the 1999/00 summer are compiled from 6, ten-day averages (25 November – 14 January). Gradients in colour indicate the spatial frequency of APF water (eg. red = APF waters present during all ten-day averages, pale blue = APF water only present during one 10-day average).

8. Acoustic assessment of toothfish abundance

Rudy Kloser, Mark Lewis, Tim Ryan, Dick Williams, Tim Lamb and Tony Koslow.

Summary
A trial acoustic and trawl survey for the assessment of toothfish distribution and abundance was carried out around Macquarie Island in January 1999 (SS01/99). The survey using *Southern Surveyor* with the deep water multi-frequency, 12, 38 and 120 kHz, towed body (MUFTI) and a demersal trawl aboard the *Austral Leader* was undertaken along the Macquarie Ridge from 53.5 S to 56.3 S in depths ranging from 300 to 1500 m. Low to moderate catches (mean 108 kg/n.mile to peak 804 kg/n.mile) of toothfish were caught in most trawls as well as significant catches of species with gas filled swim bladders, namely morids and whiptails. As toothfish do not have gas filled swimbladder, their acoustic reflectance is expected to be significantly less than the gas-bladdered species, as is the case with orange roughy. No acoustic mark identified with the single frequency acoustic system during the broad acoustic survey could be definitely and uniquely attributed to toothfish. However, the data shows that if suitable concentrations of toothfish exist (1630 kg/n.mile), multi-frequency methods can be used to separate them from the associated gas-filled swimbladdered species. Our survey suggested that present acoustic methods would be of limited use for estimating toothfish abundance with the low densities of toothfish observed during the survey. Our survey also confirmed that the MUFTI system was very effective in detecting and identifying targets in the water column, including small non-gas bladdered targets (possibly crustaceans) in 700 – 1,000 m depths.

Introduction
The toothfish population around Macquarie Island has been commercially fished since 1994. During this fishing time large aggregations were occasionally observed from the fishing vessel using their echosounders. This suggested that acoustics may be a good tool to estimate the stock size using echo integration techniques, (MacLennan and Simmonds 1992).

Acoustic methods have been successfully used to survey deepwater fishes such as orange roughy at 700 –1100 m depths (Kloser *et al* 1996). Toothfish, like orange roughy, do not have gas bladders and therefore are likely to have much lower target strengths than the associated gas bladder species of similar size. This makes the estimate of abundance using echo integration techniques highly sensitive to species composition (Kloser *et al* 1996). It is therefore imperative to verify the species composition with some accuracy during the acoustic survey. Traditionally pelagic and demersal trawling is used for this purpose but given the unknown herding and avoidance responses of the various fish species encountered in the Southern Ocean, the results can only be used as a guide. The species captured need to be separated into their acoustic groupings and proportions of each group applied to the echo integrated results. Ideally one should remotely identify the species using multiple frequencies. Multiple frequency methods have proven useful in identifying species groups in deep water (Kloser *et al* 1998, 1999). We expected our 12, 38 and 120 kHz frequency system to differentiate the bladderless toothfish from the other gas bladdered species at these depths.

Of less certainty was the ability of our equipment to operate in the conditions of this remote fishing zone where the fishing grounds are rugged and the bathymetry is poorly known. We expected that the poor weather and rough seas would dictate the need to lower or tow our acoustic transducers at depth to improve signal quality (Kloser 1996), although given the unknown bathymetry we were apprehensive that towing equipment may compromise the safety of the survey vessel. This was of particular concern when our towed system needing to be deployed at depths of 200 – 800 m for both echo integration surveys and target strength/species identification studies. For this reason and the need to have an experienced catcher vessel the

survey design incorporated the use of a commercial fishing vessel that had a detailed knowledge of the grounds.

Methods
Survey
The Macquarie Ridge fishing grounds for toothfish from 53.5° S to 56.3° S were surveyed in January 1999 using two vessels. The acoustic surveys were carried out aboard the *Southern Surveyor* using both vessel pole-mounted and deeply towed 38kHz transducers. To support the acoustic survey a fishing vessel, *Austral Leader*, was used to target acoustic marks for information on species composition and species length, weight and swim bladder type. The four dominant fishing regions surveyed were Aurora Trough (AT), Colgate Valley (CV), Hassellborough Ridge (HR), and Bishop and Clark (BC) (Figure 8.1). In each region we carried out acoustic transects that mapped the key fishing trawl lines as supplied by the fishers. The *Austral Leader* targeted acoustic marks as directed by the acoustic vessel as well as conducting tows on known grounds. In between the major grounds we carried out a series of zig-zag transects running from 300 – 1500 m depths. The terrain on the Macquarie Ridge was extremely rugged and official bathymetric charts are of poor quality, to safely navigate in the area better bathymetric charts were needed. We were very fortunate to have been supplied with such charts by Captain Halli Stefansson from the *Austral Leader*. The importance of the bathymetric maps supplied to us can not be overemphasized. Our entire voyage and its safety relied heavily on these maps.

Biological sampling
The trawl net used on the *Austral Leader* was a "Champion Trawl" manufactured by Hampijan (an Icelandic company). The Headline was 38.5 metres, footrope 69.3 meters long with sweeps of 55 metres long. The net has cut-away wings and an 18.3 metre long "Rock-hopper" section in the footrope to handle rough ground with 1800 kg Poly Ice doors on twin warps. The mesh size is 155mm in the wings and the front half of the net with 167mm meshes in the following sections and the cod end. A modification for this survey to retain smaller sized fish was a 40mm (stretch-mesh) net-liner used in the cod-end of the trawl.

The trawl samples were identified to species, where possible, and assigned to acoustic groups based on fish morphology and the presence, absence, relative size and type of swim-bladder (Table 2). The species, numbers, length and weight associated with a trawl were entered into a Microsoft Access database. Fish length data were entered directly into the database via an electronic measuring board. Five acoustic groups were created that captured the dominant morphological and swim bladder characteristics: toothfish (no gas bladder), large fish with closed gas bladders and low oil content, smaller fish with gas bladders and higher oil content, sharks and rays and other non gas bladdered species (Table 2). The trawl catches were grouped by fishing area and acoustic group to give a proportion by numbers of each group and mean length for each region. The sharks and rays group was not included in the analysis as they only occurred in trawl 2 (1@ 1.25 Kg *Simniosus pacificus*).

Acoustic equipment
The acoustic systems used on board the *Southern Surveyor* consisted of a pole mounted 38kHz transducer and a deep towed body housing three frequencies, 12, 38 and 120 kHz. The pole-mounted transducer was lowered 3 m underneath the keel which itself was 5.5 m deep. This ensured that reasonable data was collected from the vessel-mounted system in moderate sea conditions. The deep towed body was used throughout the survey at depths of 150 – 900 m for both acoustic survey and target strength/species identification work. The data quality from the deep towed body was far greater than the vessel mounted system and also greatly reduced the near seabed shadow zone (Kloser 1996) (Figure 8.2).

The scientific echo-sounder employed was a SIMRAD EK500 (Version. 5.3) configured with a combination of 12, 38 and 120 kHz transceivers depending on the survey mode. Transducers consisted of; (i) a 38kHz SIMRAD split-beam on the pole and (ii) an EDO Western 38kHz split-beam (6.5º beamwidth), (iii) a 120 kHz SIMRAD split-beam (ES120-7, 7.1º beamwidth) and (iv) a 12kHz single beam, the latter three all mounted on the towed body and rated to a depth of 1,000m, (Table 8.1). Processed and raw acoustic data were logged via ECHO (a custom UNIX based acoustic data manipulation program) for scrutinising, analysis and post processing (Waring *et al* 1994, Kloser *et al* 1998).

The physical characteristics of the seawater, vessel and deep-towed body motion were monitored throughout the voyage. Pressure, temperature and conductivity were measured using a Falmouth FSI CTD probe attached to MUFTI. These measurements were used to obtain the absorption and sound velocity profiles in the region. The motion of the vessel and deep towed body were collected at a rate of 10 Hz with an associated trigger pulse registration. The combination of recording the motion and trigger pulse enabled an algorithm to be developed to compensate for transducer motion.

The acoustic equipment was calibrated with a standard 38.1.mm Tungsten Carbide sphere for all the transducers to obtain the on-axis echo integration constant S_{vc} (Foote 1982; Simrad ver 5.3). This technique combines the electrical and acoustic constants of the system, such as transmitter power, the transmitting and receiving efficiency of the transducer, and receiver gain. The manufacturer of the transducer measured the equivalent beam angle and tests on this value were confirmed for the towed system with a special calibration rig (Kloser *et al* 1998). The split-beam deep-tow transducers were also calibrated from 100 – 400 m to correct for changes with depth in transducer sensitivity and to test for changes in beam pattern (Kloser *et al* 1996). A calibration sphere suspended 15 m directly under the centre of the towed body was lowered through the water column. The seawater propagation parameters of absorption and sound velocity were calculated from the formulae of Francois and Garrison (1982) and MacKenzie (1981), respectively, based upon temperature and salinity profiles obtained during the surveys with a FSI conductivity-temperature-depth recorder (CTD) attached to the towed body.

Acoustic analysis
Two general methods are used to partition the acoustic data to calculate fish biomass using the echo integration method. The first method defined as school based, relies on the identification of distinct schools of toothfish using echogram structure, fish catch and multi-frequency acoustics. The defined schools are classified and bounded using the ECHO software (Waring *et al* 1994). The classified schools are echo-integrated along each acoustic transect and a mean area backscatter obtained. Assuming 100% toothfish in the defined schools, the mean area

$$\overline{\rho_{ij}} = \frac{\overline{s_{Aij}} \dfrac{Ws}{1000}}{4\pi 10^{\frac{TSpt}{10}}} \qquad \text{tonnes n.mile}^{-2} \qquad (1)$$

backscatter is converted to a mean density:

where W_{sor} is the mean toothfish weight in kilograms and TS_{pt} is the mean target strength of toothfish.

Secondly, in mixed species aggregations the species composition as obtained from the demersal trawl or multi-frequency acoustics is used to attribute to the echo integrated echoes. The acoustic energy obtained by summing the calibrated volume backscatter measurements is allocated based on the proportion of numbers of individual fish, their length frequency and the mean target strength for each species.

Taking into account the presence of other fish species, the mean density of toothfish for each

$$\overline{\rho_{ij}} = F_{s\_pt} \cdot \frac{\overline{s_{Aij}}}{\sum\limits_{s=1}^{p} F_s \cdot \pi \cdot 10^{\frac{\overline{TS_s}}{10}}} \cdot W_{s\_pt} \qquad \text{tonnes n.mile}^2 \qquad (2)$$

transect, $\overline{\rho_{ij}}$, is given by:

where F_s is the proportion of each fish species, F_{s_pt} the proportion of toothfish, p the number of fish species, W_{s_pt} is the mean individual fish weight in kilograms, and TS_s is the mean target strength of each fish species.

Target strengths of acoustically dominant species
The target strength for a species, j, of length, L_{ij}, was based on data from the literature (Maclennan and Simmonds 1992) and verified for deep water species by *in-situ* work, (Kloser *et al* 1997, Koslow *et al* 1998), in the form:

$$TS_{ij} = 20\log L_{ij} + B_j$$

where B_j is the acoustic constant for species j.

The mean target strength is calculated from the length frequency histogram data for the species, j

$$\overline{TS_j} = 10\log\left[\frac{\sum\limits_{i=1ton} 10^{\left(\frac{TS_{ij}}{10}\right)} f_i}{\sum\limits_{i=1ton} f_i}\right] \text{dB re m2} \qquad (3)$$

Species identification
As toothfish do not have a gas filled swimbladder their reflectance is expected to be significantly less than the gas-bladdered species, as is the case with orange roughy (Kloser *et al* 1996). This makes the identification and assessment of toothfish very difficult using acoustic methods. A frequency mixing method has been developed and applied that can differentiate the small and medium sized gas swimbladdered species from the non gas-bladdered orange roughy (Kloser *et al* 1999). Using ECHO software the three individual frequencies (12, 38 and 120 kHz) are corrected for known calibration, propagation losses, background acoustic noise and poor data quality due to vessel movement and or electrical noise. These frequencies are then mixed using separate colours to highlight intensity differences between the frequencies. At water depths from 600-800 m the 12 kHz (red) has been found to highlight large gas bladdered species (morids and whiptails) whilst the 38kHz (green) highlights smaller gas bladdered species (myctophids). The 120-kHz (blue) frequency is more pronounced on the orange roughy. We applied the multi-frequency methodology to the region of largest catches (Aurora Trough) of toothfish that occurred during the survey.

Results

Biological sampling

In total 31 trawls were shot away with 5 being unsuccessful after becoming fast on the bottom soon after contact. Twentysix tows were successfully targeted on acoustic marks or towed over known fishing grounds. The catches from these trawls were separated into 5 acoustic groups as described in Table 8.2 based on fish morphology and swimbladder type. The catches were further separated into the four major fishing regions and the proportion by numbers of fish calculated (Table 8.3a). Of note is the low proportion of toothfish for all regions compared with gas bladdered fishes. The mean total length for each acoustic group in each region (Table 8.2a) indicates that the largest toothfish are found in Aurora Trough. The length frequency histogram data were use to calculate (equation 2) the proportion of the acoustic signal attributed to each species (Table 8.3c). Clearly, the highest concentration of toothfish was encountered in Aurora Trough, 44% by numbers (Figure 8.1a). But toothfish only contributed to 18% of the acoustic signal due to the contribution of gas bladdered fishes (Figure 8.1b).

Acoustic sampling

Due to the poor weather, constant winds of 30- 35 knots, the vessel mounted acoustic systems produced poor quality acoustic data and could not be used to identify fish marks (Figure 8.2a). However a 38 kHz pole mounted transducer lowered 3.5 m below the hull produced useful echograms to view general school structure. In contrast our MUFTI towed system operated throughout the voyage at $100 - 400$ m depth produced high quality data (Figure 8.2b). The detection capability of the system at 38 kHz for a 68 cm toothfish of estimated target strength -46.5 dB and 10 dB signal to noise ratio is approximately 1 fish per 1,000 m^3 at 600 m water depth. No schools were found during the broad scale survey that could be identified as originating from toothfish. The schools targeted by trawling contained a high proportion of morid and whiptail species.

We applied the multi-frequency methodology to the region of largest catches (Aurora Trough) of toothfish that occurred during the survey. We towed our deep water MUFTI $50 - 150$ m above the seabed in water depths from $500 - 900$ m. This task was made difficult by the almost constant $30 - 35$ knots of wind with moderate sea conditions. A transect in Aurora Trough along 158.7 E produced a multi-frequency echogram that had an acoustic mark characteristic of a non gas-bladdered fish species (Figure 8.3). A target trawl on this mark by *Austral Leader* caught 930 kg of toothfish in a tow that was on the seabed for 0.57 n.mile before it became fast. The effective catch rate of toothfish for the targeted trawl was 1 630 kg/n.mile. This targeted catch rate is 15 times larger than the average catch rate (108 kg/n.mile std 194 kg/n.mile, excluding this targeted trawl) for the survey or the next highest catch rate being 806 kg/n.mile for a 5.1 n.mile tow on a trawl known as the "Golden Track". Interpretation of the multi-frequency echogram is complicated as a result of the large scatter of the 120-kHz frequency in the water column. This was observed throughout the Aurora Trough region. We interpret this as coming from dispersed targets of low target strengths (probably crustaceans). The mean target strength of targets using the split beam transducer was -63 dB (uncalibrated). More detailed mid-water trawling is required to verify this observation.

Discussion

The deep towed MUFTI acoustic system produced high quality low noise acoustic records with a detection capability of one fish per 1,000 m^3 for a 68 cm length toothfish. No aggregations of toothfish were identified in the broad scale survey. This may be in part due to the limited near seabed sampling limitations of the acoustics. Due to the steep slopes the ability to sample near the seabed was limited to average heights of $10 - 20$ m above seafloor for the MUFTI system. This is a major limitation when acoustic sampling a species such as toothfish that is associated to rough terrain seabed.

The demersal trawling supported the observation that there were no schooling toothfish in the region. The average catch rate for toothfish was 108 kg/n.mile for the 26 successful trawls and reached a peak of 806 kg/n.mile in the Aurora Trough region. This represents a density of between 0.1 and 1.0 fish per 1,000 m^3 and is at the limit of the acoustic detection capability. This shows that acoustics will be of limited use for this species when encountered in these concentrations. The species composition obtained from the trawl catch shows a high proportion of gas bladdered fishes associated with toothfish. In the Aurora Trough region 46 % of the catch by numbers is associated to toothfish. When the composition and target strengths of the various species are accounted for the contribution of toothfish to the acoustic backscatter reduces to 18%. This is due to the large contribution of gas bladdered species such as morids and whiptails. Acoustic surveys will contain unknown biases when there is a high level of species mixture and the target species has a lower target strength.

For many of the deep water species found in this survey the method of estimating target strength is grossly inadequate, but is used here to demonstrate the possible differences in acoustic group target strengths. Specifically the scattering response of swimbladders under pressure will change its resonance frequency and depending on the swimbladder size may have dramatic effects on swimbladder reflectivity. Also many deep-water species have different levels of lipids that are used for buoyancy in addition to their gas-filled swimbladder. This changes the size of the gas-filled swimbladder for a given length of fish and would greatly change the species target strength.

The multi-frequency acoustic data shows that if suitable concentrations of toothfish exist then multi-frequency methods can be used to separate them from the associated gas-filled swimbladdered species. During the survey no significant aggregations of toothfish were found using the acoustic towed body MUFTI and or demersal trawl. With the low densities of toothfish encountered during the survey, acoustic methods will be of limited use for stock assessment purposes.

Acknowledgements

References

Foote, K. G. (1982). Optimizing copper spheres for precision calibration of hydroacoustic equipment. Journal of the Acoustical Society of America 71: 742-747.

Francois, R. E. and Garrison, G. R. (1982). Sound absorption based on ocean measurements. II. Boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America 72: 896-907.

Kloser, R. J. (1996). Improved precision of acoustic surveys of benthopelagic fish by means of a deep-towed transducer. ICES Journal of Marine Science 53: 407-13.

Kloser, R. J., Williams, A. and Koslow, J. A. (1997). Problems with acoustic target strength measurements of a deep water fish, Orange Roughy. ICES Journal of Marine Science 54: 60-73.

Kloser, R. J., Koslow, J. A. and Williams, A. (1996). Acoustic assessment of the biomass of a spawning aggregation of orange roughy (*Hoplostethus atlanticus*, Collett) off southeastern Australia 1990-93. Marine and Freshwater Research 47: 1015-1024.

Kloser, R. J., Koslow, J. A., Ryan, T. and Sakov, P. (1998) Species identification in the deep-water orange roughy fishery using multiple frequencies. ICES Fisheries Acoustic Science and Technology working group.

Kloser, R. J., Ryan, T. E., Williams, A. and Soule, M. (1999). Development and implementation of an acoustic survey of orange roughy in the Chatham Rise spawning box from an Industry Vessel, CSIRO report for the Orange Roughy Management Company.

MacKenzie, K. V. (1981). A nine-term equation for sound speed in the oceans. Journal of the Acoustical Society of America 70: 807-812.

MacLennan, D. N. and Simmonds, J. E. (1992). Fisheries Acoustics. Chapman and Hall.

SIMRAD Fisheries Division. (1993). SIMRAD EK500 service and technical manual, SIMRAD, Horten Norway.

Waring, J. R., Kloser, R. J. and Pauly, T. (1994). Echo – Managing Fisheries Acoustic Data. In 'Proceedings of the International Conference on Underwater Acoustics University of New South Wales, Dec. 1994'. pp.22-24. (Australian Acoustical Society: Darlinghurst Public School, NSW.)

Table 8.1 Acoustic information and relevant calibration results from the *Southern Surveyor* voyage in January 1999.

Transducer	Manufacturer	Locations	Equivalent Beamwidth (dB re 1 steradian)	Beamwidth (degrees)
120kHz	Simrad	MUFTI	-20.6	7
38kHz	EDO western	MUFTI	-21.1	6.5
12kHz	MASA	MUFTI	-10	40
38kHz	Simrad	Pole	-20.7	7.3

Table 8.2 Acoustic species groups used to estimate target strengths for conversion of the acoustic data from *Southern Surveyor* voyage in January 1999.

Acoustic Species Group	Description	Target strength constant (B)	Reference
1	Bladderless toothfish high oil content	83.2 dB	Kloser *et al* 1996
2	Large gas bladders mainly Morids cods	67.4 dB	Foote 1987
3	Small gas bladders mainly Whiptails	71.9 dB	Foote 1987
4	Others with no gas bladders	84 dB	estimate

Table 8.3 a-c Summary of trawl catches for the 4 regions surveyed: Aurora Trough (AT), Bishop and Clerk (BC), Hasselbourough Ridge (HR), Colgate Valley (CV). Summary is separated into the 4 acoustic species groups, with toothfish represented as group 1. Table c represents the proportion that each acoustic species group contributes to the total acoustic target strength.

8.3a Percentage of acoustic species group in each region by numbers

Region	Species group				No. of trawl
	1	2	3	4	
AT	44	13	35	8	16
BC	30	5	20	45	3
HR	8	0	0	91	2
CV	11	39	35	16	10

8.3b Mean total length (cm) of acoustic species group in each region

Region	Species group				No. fish caught
	1	2	3	4	
AT	68	34	27	17	4821
BC	66	23	23	13	20
HR	66	31	13	23	1889
CV	49	46	29	19	2527

8.3c Percentage that each acoustic species group contributes to the total acoustic target strength in each region

Region	Species group			
	1	2	3	4
AT	18	50	31	0
BC	34	26	36	4
HR	25	7	0	68
CV	1	87	11	0
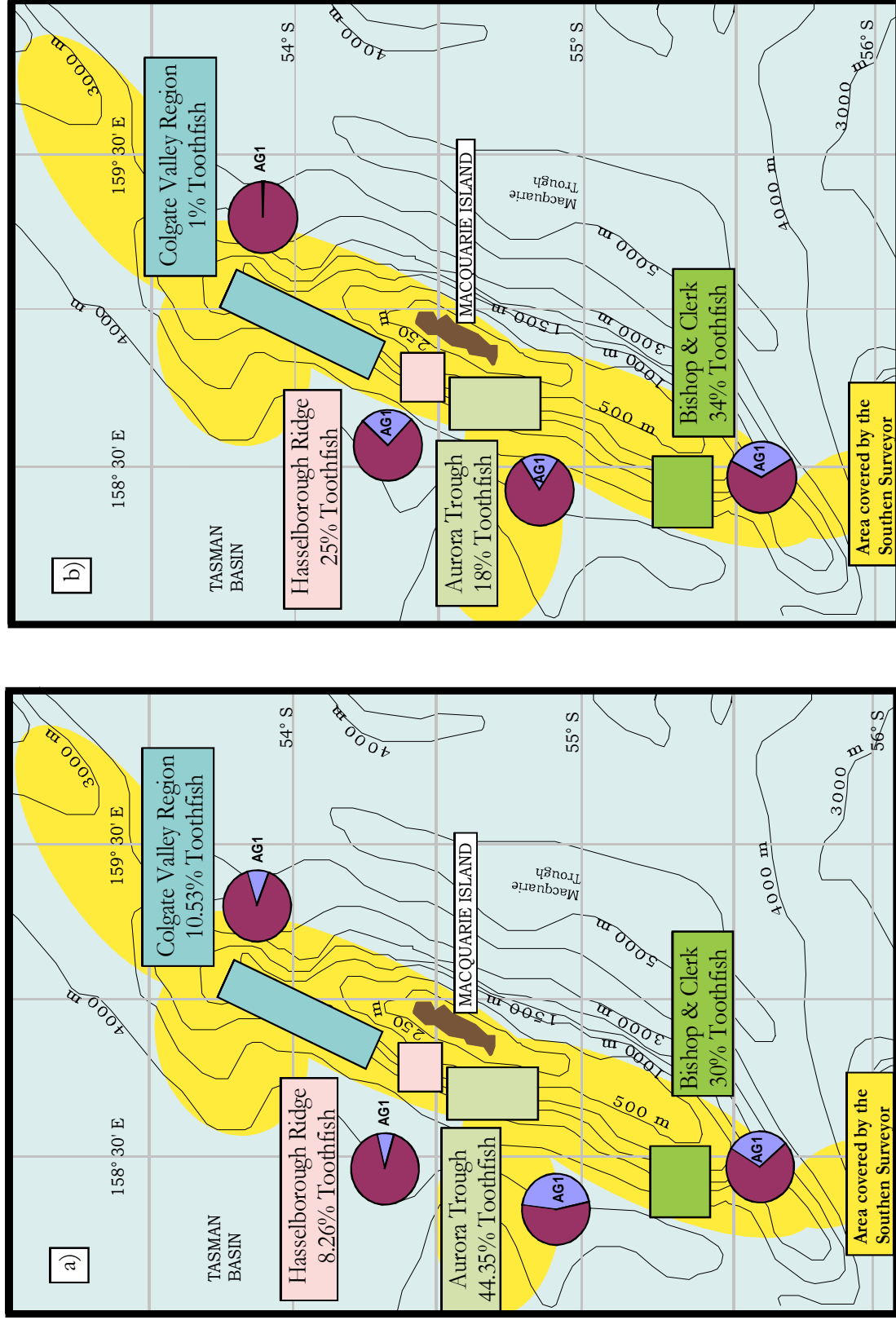
Figure 8.1 Contribution to near seabed acoustic backscatter of toothfish for the major areas of Aurora Trough, Bishop and Clerk, Hasselborough Ridge and Colgate Valley with underlining bathymetry, a) proportion by numbers, b) proportion by acoustic backscatter.

Figure 8.2 Example of acoustic data from hull mounted (a) and towed transducer (b) showing improved data quality and reduced near seabed sampling using the deep towed transducer.

a.)   Echogram from uncalibrated 28kHz hull mounted system. Unusable for echointegration due to high noise, sidelobe interference and dropouts. Typically the data quality of the hull mounted system was worse than what is shown here
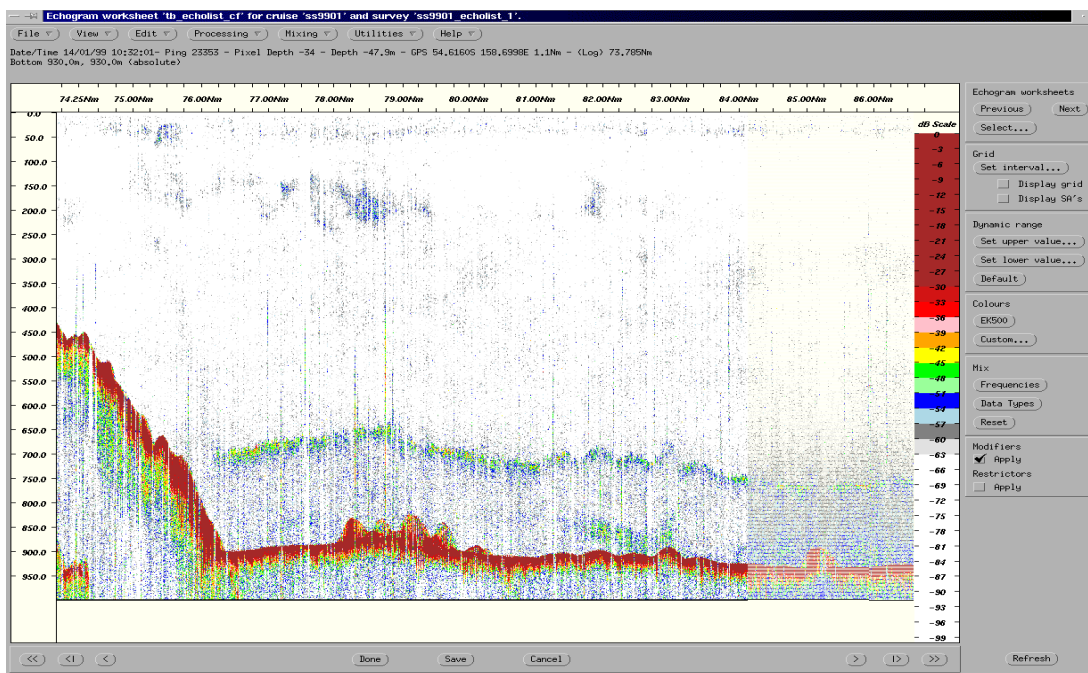
b.)   Echogram from calibrated 38kHz deep towed body towed at 250 metres depth showing improved signal.

ACOUSTIC ASSESSMENT OF TOOTHFISH ABUNDANCE
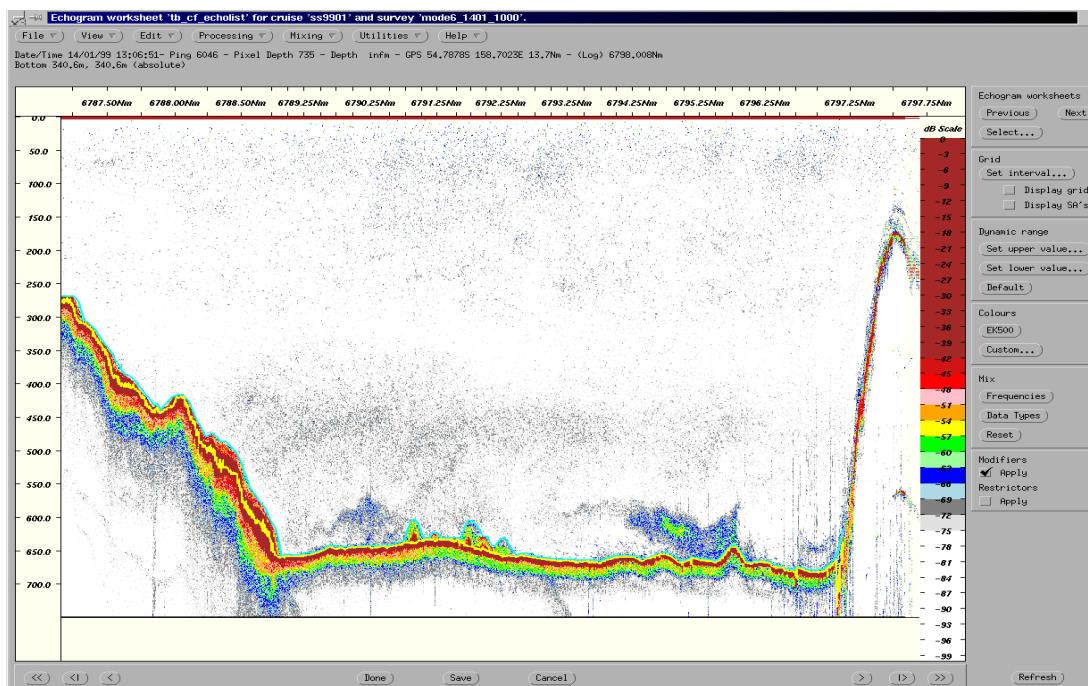
Figure 8.3 MUFTI tow in Aurora Trough along 158.7 E showing a composite image of 12 (red), 38 (green) and 120 (blue) kHz acoustic recordings. The mixing of the frequencies has been optimised dynamically to highlight the amplitude differences. The 12 kHz is interpreted to highlight the large gas-bladdered species (morids and whiptails > 300 mm in length), 38 kHz highlights small gas-bladdered species (50 – 150 mm in length) and the 120 kHz highlights the toothfish and large crustaceans.
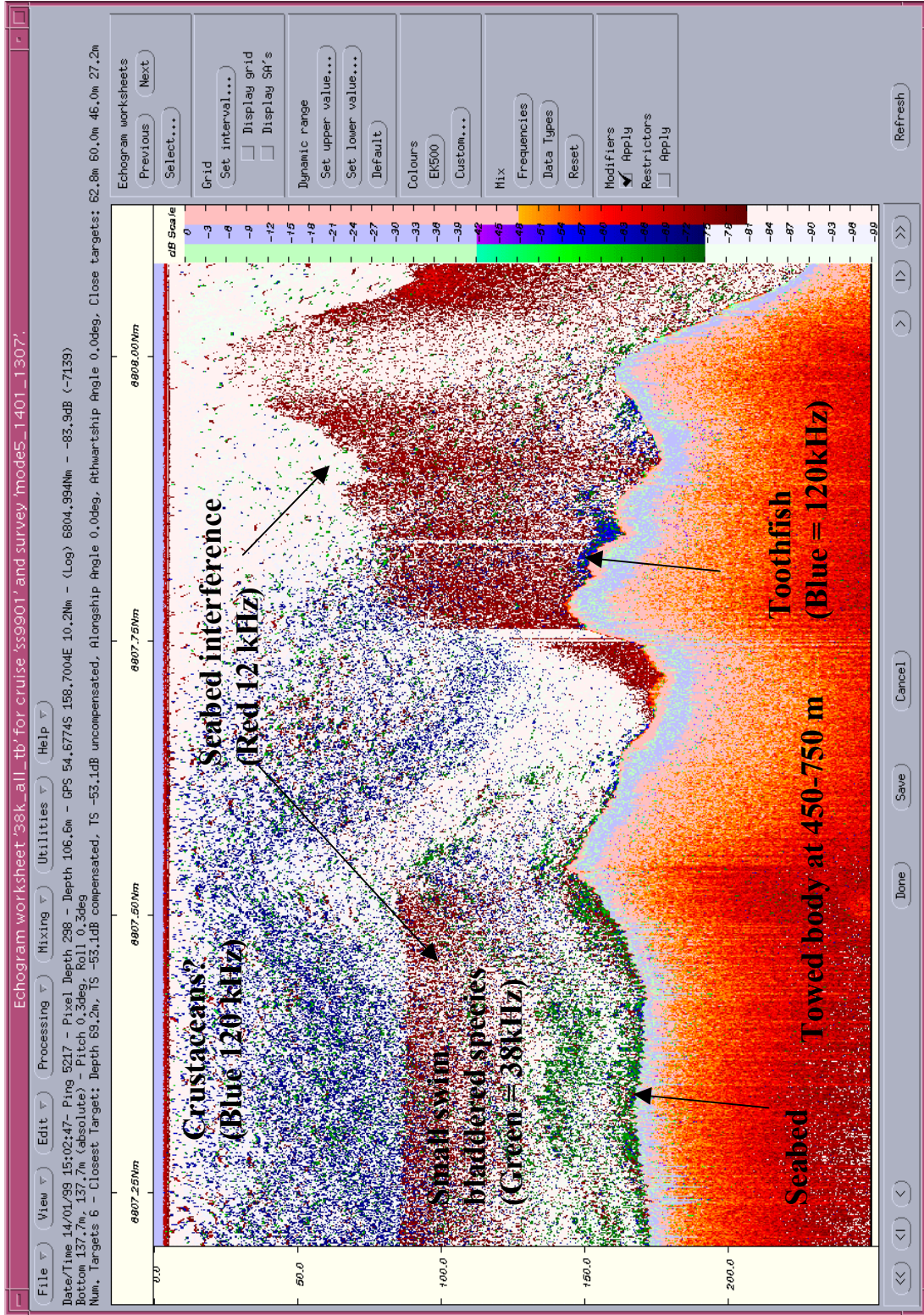
9. Midwater fish communities

Dick Williams, Alan Williams, Mark Lewis, Tim Lamb, Rudy Kloser and Xi He

Summary
The mesopelagic fauna was studied at five sites in the vicinity of Macquarie Island: a deep water site to the west of the ridge, two sites on the ridge near fishing grounds, a site in one of the major gaps in the ridge to the north of the island and a site to the north of the gap near the continuation of the ridge. All sites were sampled with an International Young Gadoid Pelagic Trawl fitted with a multiple cod end to sample four depth strata: 1,000-750m, 750-500m, 500-250m and 250m to surface. For all sites except the northernmost, samples were taken by day and by night. After excluding gelatinous zooplankton, total biomass was similar at the two sites on the Ridge and the Ridge Gap, but was lower at the offshore and furthest north sites. At most sites the 1,000-750m depth stratum contained the majority of the biomass during the daytime, but vertical migration causes a shift to shallower depths at night, especially at the deep-water western site and Ridge Gap. The two sites on the ridge show much less vertical migration. Principal vertically migrating species are a range of myctophid fish and *Stomias* spp, whereas *Bathylagus antarcticus*, an important prey species for toothfish, shows only a weak vertical migration that would keep the majority of its population within the depth range where it would be encountered by toothfish. Multivariate analysis of catch compositions between sites, depth strata and time of day, revealed no significant difference between sites or day and night, but a highly significant difference between depth strata.

Introduction
Toothfish are known to feed on a variety of mesopelagic fish and cephalopods (Chapter 15, Goldsworthy *et al*. 2001 and In press). Observations by fisheries observers during the commercial fishing operations confirmed that this is also the case at Macquarie Island and Chapter 15 deals with a detailed study of toothfish diet that again confirms the mesopelagic origin of the majority of its components.

In order to place the diet study in context with potential food availability and to attempt some analysis of the quantity of potential food available in different habitats, a survey of the mesopelagic fauna in a number of sites thought to represent different habitat types was conducted.

Methods
The mesopelagic fauna was sampled at five sites with an International Young Gadoid Pelagic Trawl (IYGPT) fitted with a MIDOC multiple cod-end. This allowed sampling in four depth strata: 1,000-750, 750-500m, 500-250 and 250m-surface, in the one haul. In each depth stratum the net was towed obliquely through the depth range for 30 minutes; the hauling speed of the winch was set so that the net arrived at the boundary of the next depth stratum at the same time as the cod-end was pre-set to change.

Two samples during the daytime and two at night were attempted at each station, but at most stations it was only possible to obtain one night sample because of the shortness of the night (Table 9.1)

The Deep West station was 25 to 35 n miles to the west of the island where the water depth is >4,500m, and was selected to represent oceanic conditions before any influence of the Macquarie Ridge would have been felt. The stations in Aurora Trough and Northern Valleys were chosen to represent the two locations from where the bulk of the commercial catch of

toothfish has been taken. These sites are where toothfish are known to aggregate and where intensive feeding has been observed on a number of occasions. Both sites are large valleys in the Macquarie Ridge; Aurora Trough is near the western boundary of the ridge and 400 to 900m deep, and the Northern Valleys are near the centre of the ridge and 500 to 1,200m deep. The Ridge Gap station was sited in the large gap in the Macquarie Ridge to the north of the island, 40 n miles wide at its narrowest point and up to 4750m deep, through which it was thought the Sub Antarctic Front passes (see Chapter 7). This station was chosen in the hope of sampling the community of the frontal zone, which would be expected to show elements of the subantarctic fauna to the south and the subtropical fauna to the north (Orsi *et al.* 1995). Finally, a station well to the north of the Ridge Gap (North Ridge) was chosen to sample what was expected to be subtropical fauna. This location was on the western boundary of the Macquarie Ridge where water depth was about 1,800m.

Catches were sorted immediately they came on deck to the lowest taxonomic grouping possible. We were able to sort most fish to species level, but most invertebrates could only be sorted to family or higher level. The number of specimens in each group was recorded and their weight taken to the nearest 0.1g and the samples, except for some large medusae, were retained frozen. After the voyage was completed each sample was re-examined to check identification, take length frequencies of fish and collect samples for other studies such as otoliths, stomachs, and material for DNA analysis and calorimetry.

Community analysis
Catch compositions, expressed as proportional catch in weight for each sample, were used to represent fish community structure. Prior to the analysis, an arcsine square root transformation was applied to the proportional catch:

$$y_{ij} = \frac{2}{\pi} \sin^{-1} \sqrt{x_{ij}}$$

where y_{ij} = transformed proportional data for variable *i* and sample *j*
         x_{ij} = proportional data for species *i* and sample *j* before transformation.
This arcsine square root transformation was selected over other transform methods as it is frequently used for proportional data (Sokal and Rohlf 1995).

To test if catch compositions are different between sampling stations, a non-parametric statistical testing method (multiple response permutation procedure, MRPP), was used (Zimmerman *et al.* 1985; McCune and Mefford 1999). MRPP tests the null hypothesis of no difference between two or more groups of multivariate data. The grouping must be *a priori*. In our analysis, groups were defined as stations, depths, and day-night samples. Bray-Curtis dissimilarities were used in the MRPP as distance measures.

Results
Table 9.2 gives total catches per net, corrected for volume filtered. Figure 9.1a shows a comparison of the total catch from all depth strata at each station. This shows that the Ridge Gap and nearby Northern Valleys stations produced the greatest biomass both by day and night, with the more southerly stations of Deep West and Aurora Trough being similar to each other in producing lower biomass, particularly at night. The North Ridge station had the least biomass. Medusae, principally the coronates *Atolla wyvillei* and *Periphylla periphylla*, make up a large proportion of the total catch but were caught erratically, often in large numbers. These occasional large catches of medusae tend to distort the pattern of distribution of biomass between the different stations and depths. As these occur at all stations, and do not form part of the toothfish diet (see Chapter 15), little information is lost by removing them from the analysis. Figure 9.1b shows that without gelatinous plankton, the biomass during the daytime is similar at Aurora Trough and Ridge Gap but much lower at the other three stations. At night, all stations have a similar biomass except Deep West, where the biomass remains similar to the daytime

level. Note that with gelatinous plankton excluded the maximum biomass is less than one tenth of that with gelatinous plankton included.

Figures 9.2a-e show the percentage of the total biomass caught in each depth stratum by day and by night for each station, with gelatinous plankton included in the data. In most cases the 1,000-750m stratum contained the majority of the biomass, typically between 50% and 90%. In the shallower strata biomass was generally evenly distributed, with a tendency to a greater percentage of biomass during the night than during the day. Exceptions were Northern Valleys at night, where biomass was roughly equally distributed between the 1,000-750m and 500-250m depth strata; Deep West at night where nearly 80% of the biomass was within the 500-250m stratum; and North Ridge during daytime where there was a much more even distribution between the strata than at the other sites.

Removing the data on gelatinous plankton (Figure 9.3a-e) does not radically affect the overall pattern of biomass distribution, but some consequences are noteworthy. The percentage of biomass in the 1,000-750m stratum is generally reduced, with a consequent increase in most of the shallower strata. The pattern of distribution of biomass between the depth strata is not much different for Aurora Trough and Deep West sites, but in Northern Valleys there is a marked increase in percent biomass in the 750-500m and 250-0m strata. At the Ridge Gap site there is a much more even distribution between all depth strata, but at North Ridge most of the biomass is now in the two deepest strata.

Table 9.3 shows that the catch compositions were not significantly different between most sampling stations at a significance level of 0.05. The only marginally significant difference occurred between the North Ridge and Ridge Gap with p value of 0.0487. However, as each sample is tested four times with other samples, a significant level of 0.0125 (= 0.05 / 4) is considered to be more appropriate. Thus, the difference between the North Ridge and Ridge Gap, with p value of 0.0487, become non-significant.

The MRPP tests on the catch compositions between day and night trawls showed marginally significant difference (p value = 0.0399). When the test was conducted on each sampling station separately, however, no significant difference in the catch compositions between day and night trawls was found at any station (p value > 0.2966).

Table 9.4 shows that the catch compositions between the four depth strata were highly significantly different with p values < 0.0013. The most significant differences occurred between the deepest trawls (1,000-750m) and shallower depths (p values < 0.0001).

Discussion
Biomass at the Deep West site was considerably less than at the three sites on or near Macquarie Ridge (Aurora Trough, Northern Valleys and Ridge Gap) during both day and night samples, although it was about equal to the daytime biomass at Northern Valleys (Figure 9.1b). This suggests that there is some concentrating effect by the Macquarie Ridge on the mesopelagic fauna. As the majority of the biomass is found at depths below 500m at Aurora Trough and Northern Valleys, this concentrating effect of the Ridge would have most effect at depths where toothfish is thought to feed. All three ridge-sites are places where relatively low densities of mesopelagic fauna advected from the oceanic waters to the west by the West Wind Drift might be concentrated. Aurora Trough, and to a lesser extent Northern Valleys, are north-south orientated valleys close to the western boundary of the Macquarie Ridge. Aurora Trough also has a small opening to the west. The Ridge Gap is one of only two gaps through which the West Wind Drift can pass through the Macquarie Ridge, and this concentration of flow and possible associated turbulence will also concentrate the associated mesopelagic fauna. The small number of stations and short time over which sampling was conducted, however, do not allow definite

conclusions to be made on this point. Further studies over a longer time period and involving more stations are necessary to confirm this indication.

Diurnal vertical migration is evident at all stations. In the Deep West station, the majority of the biomass moves from the 1,000-750m stratum during daytime to the 500-250m stratum at night (Figure 9.3b). At Aurora Trough and Northern Valleys there is a less obvious difference between day and night samples exemplified by a more even distribution of biomass between the depth strata at night than during the day (Figure 9.3a and c). At Ridge Gap there is again a marked difference between distributions by day and night with the majority of the biomass in the two deepest strata by day changing to an even distribution between the depths at night (Figure 9.3d).

Among the more abundant species a range of diurnal behaviour is evident. The myctophid fish species *Protomyctophum bolini*, *Krefftichthys anderssoni*, *Lampanyctus achirus* and *Gymnoscopelus braueri* and the stomiid fish *Stomias gracilis* all show strong upward movement at night; generally from below 500m to the 500-0m depth range (Figure 9.4). Exceptions are *P. bolini* that moves between 750-250m by day to 500-0m at night, and *K. anderssoni* that appears to have a bimodal distribution during the day at >500m and near the surface, with an even depth distribution at night. This may be an artifact of sampling, however, as 83% of the daytime catch in the 250-0m stratum came from Station 104 at Ridge Gap, which was not competed until 20:09, when this species may have already reached the upper stratum during its normal nocturnal ascent. Other species show weak diurnal vertical migration, eg. the deep-sea smelt *Bathylagus antarcticus* and the euphausiid *Euphausia triacantha*, while others show virtually none, eg. the ostracod *Gigantocypris mulleri* (Figure 9.4). *B. antarcticus* is one of the major diet components of toothfish, and the weak diurnal vertical migration it displays means that the majority of its population remains within the depth range of toothfish throughout the daily cycle.

These observations are consistent with the results of the MRPP analysis that show a highly significant difference between depths, especially between the 1,000-750m depth-stratum and the shallower strata (Table 9.4). However, as a change of stratum between day and night is not complete for most taxa, especially at Aurora Trough and Northern Valleys, there is no significant difference between day and night samples as a whole. These results are also consistent with acoustic information taken at the same time as the net samples. Figure 9.5 shows a sample echogram of day and night conditions in the Northern Valleys. During the day, most backscatter is observed from the region around 500m and below, whereas at night most backscatter is contained in the top 500m and especially in the top 250m, indicating the general rise of many species from the depths below 500m to above 500m as shown in Figure9.3.

Despite the differences in submarine topography and a latitude range of 140 miles, the community analysis using MRPP showed that there was little difference in the species composition between sites (Table 9.3). The greatest difference was between North Ridge and Ridge Gap, where the proximity of the Subantarctic Front may have had an effect. There were no significant differences between any the stations on the Ridge (Aurora Trough and Northern Valleys), or between them and the deep-water stations of Deep West or Ridge Gap. Species composition by both number and weight was dominated by a range of species of myctophid fish from the genera *Protomyctophum*, *Krefftichthys*, *Electrona*, *Gymnoscopelus* and *Lampanyctus*, and other fish such as *Bathylagus sp.*, *Stomias* spp. and *Borostomias* sp. Among invertebrates, coronate medusae, the ostracod *Gigantocypris mulleri*, the hyperiid amphipod *Themisto gaudichaudi*, *Euphausia triacantha* and *E. vallentini* and the decapod crustaceans *Pasiphaea sp.* and 'red carid' were typical of all stations.

Some small differences were apparent, however. The sites on Macquarie Ridge, Northern Valleys and in particular Aurora Trough, produced a number of benthopelagic shelf-dwelling

fish species in the deepest net, eg. *Halargyreus johnsoni*, *Coryphaenoides subserrulatus* and *Melanostigma gelatinosum*. In these locations, the deepest net would have been within 100-200m of the bottom. The more northerly stations at Ridge Gap and North Ridge also contained a few individuals characteristic of the Subantarctic Front and waters to the north, such as *Electrona subaspera*, *Phosichthyus argenteus*, *Polymetne sp* and *Protomyctophum (Hierops) sp*. Additionally, the North Ridge station produced other species characteristic of waters north of the Subantarctic Front such as *Diaphus hudsoni*, *Persparsia kopua*, *Woodsia meyerwaardeni* and *Rosenblattia robusta*.

As far as can be judged from the limited sampling undertaken in this program, the Macquarie Island mesopelagic fauna and its behaviour is similar to those near other subantarctic island groups such as Kerguelen and Marion & Prince Edward Islands. Both these island groups are similar to Macquarie Island in lying within the Polar Frontal zone between the Subantarctic Front and the Antarctic Polar Front, although at the longitude of both Kerguelen and Marion/Prince Edward Islands the Polar frontal Zone is much narrower than it is at Macquarie Island. At Kerguelen, only the top 300m was sampled (Duhamel *et al*. 2000) but the fish fauna is very similar to that at Macquarie Island with myctophid fish such as *Electrona antarctica, Gymnoscopelus braueri, G. fraseri, Krefftichthys anderssoni, Protomyctophum bolini* and *P. tenisoni* making up the bulk of the catch. A difference was the presence of large numbers of larvae of *Lepidonotothen squamifrons* and *Muraenolepis marmoratus* that are demersal when adult on the Kerguelen shelf. Although both these species occur at Macquarie Island, they were not represented in the hauls there, even in those taken at stations on the ridge. Vertical distribution was also similar, with *K. anderssoni* being in the top 250m during the day, and species such as *G. braueri* rising at night and *P. bolini* having a more widespread vertical distribution. At Marion/Prince Edward Islands, Perissinotto and McQuaid (1992) reported *K. anderssoni* to be a dominant constituent of a scattering layer that rose from depths of 300-400m during the day, to 50-100m at night. As their sampling equipment was much smaller than that used at Kerguelen and Macquarie Islands, few other fish species were caught.

Acknowledgements

References

Duhamel, G., Koubbi, P. and Ravier, C. (2000). Day and night mesopelagic assemblages off the Kerguelen Islands (Southern Ocean). Polar Biology, 23: 106-112.

Goldsworthy, S. D., Williams, R., Lewis, M., Van den Hoff, J., Young, J. and He, X. (In press). Diets of the Patagonian Toothfish (*Dissostichus eleginoides*) around Macquarie Island. Marine and Freshwater Research.

Goldsworthy, S. D., He, X., Lewis, M., Williams, R., and Tuck, G. (2001). Trophic interactions between Patagonian Toothfish, its fishery and seals and seabirds around Macquarie Island. Marine Ecology Progress Series, 218: 283-302

McCune, B. and Mefford, M. J. (1999). PC-ORD. Multivariate analysis of ecological data, Version 4. MjM Software Design, Gleneden Beach, Oregon, USA.

Orsi, A. H., Whitworth, T and Nowlin, W. D. (1995). On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep Sea Research I, 42: 641-673.

Perissinotto, R. and McQuaid, C. D. (1992). Land-based predator impact on vertically migrating zooplankton and micronekton advected to a Southern Ocean archipelago. Marine Ecology Progress Series, 80: 15-27.

Sokal, R. R. and Rohlf, F. J. (1995). Biometry. W. H. Freeman and Company, New York.

Zimmerman, G. M., Goetz, H. and Mielke P. W. Jr. (1985). Use of an improved statistical method for group comparisons to study effects of prairie fire. Ecology, 66: 606-611.

Table 9.1 List of sampling stations for midwater fish communities around the Macquarie Island during the research voyage SS01/99 by the *Southern Surveyor*.

Station number	Location	Date	Time start	Time end	Day/night
51	Aurora Trough	21 Jan 1999	18.08	20.09	Day
52	Aurora Trough	21 Jan 1999	22.47	00.46	Night
55	Aurora Trough	22 Jan 1999	07.55	09.56	Day
66	Deep West	23 Jan 1999	04.45	06.45	Day
68	Deep West	23 Jan 1999	13.29	15.28	Day
70	Deep West	23 Jan 1999	21.36	23.36	Night
71	Deep West	24 Jan 1999	01.55	03.56	Night
98	Northern Valleys	27 Jan 1999	01.40	03.39	Night
101	Northern Valleys	27 Jan 1999	11.37	13.36	Day
102	Northern Valleys	27 Jan 1999	15.20	17.20	Day
103	Ridge Gap	28 Jan 1999	14.01	16.01	Day
104	Ridge Gap	28 Jan 1999	18.10	20.09	Day
106	Ridge Gap	28 Jan 1999	22.46	00.47	Night
133	North Ridge	31 Jan 1999	16.47	18.47	Day

Table 9.2 Total catch in grams per thousand cubic metres filtered in each station and depth stratum. Where replicate hauls were made, the mean of the two catch weights is given.

	Day				Night			
Depth stratum	1,000-750	750-500	500-250	>250	1,000-750	750-500	500-250	>250
Aurora Trough	62.053	4.633	1.701	0.834	2.138	5.297	3.045	3.788
Deep West	59.322	1.334	9.814	1.808	1.924	0.053	12.459	1.420
Northern Valleys	82.407	5.614	8.040	0.913	99.725	8.446	85.890	4.113
Ridge Gap	264.117	58.856	1.064	4.822	52.687	3.134	4.816	5.880
North Ridge	5.719	5.836	3.580	0.919				

Table 9.3. Probability values (*P* values) of the multi-response permutation procedure (MRPP) between sampling stations on the midwater fish community structure near the Macquarie Island. *P* values greater than 0.05 indicate no significant differences in the community structure between sampling stations.

Station	Aurora Trough	Deep West	Northern Valleys	Ridge Gap
Deep West	0.1912	--------	--------	--------
Northern Valleys	0.1593	0.1608	--------	--------
Ridge Gap	0.1044	0.0741	0.4490	--------
North Ridge	0.0516	0.2863	0.4419	0.0487

Table 9.4. Probability values (*P* values) of the multi-response permutation procedure (MRPP) between four depth strata on the midwater fish catch compositions near the Macquarie Island. *P* values greater than 0.05 indicate no significant differences in the community structure between sampling stations.

Depth stratum (m)	0-250	250-500	500-750	750-1,000
250-500	0.0049	--------	--------	--------
500-750	0.0012	0.0098	--------	--------
750-1,000	0.0000	0.0000	0.0000	--------

Including medusae

Medusae excluded
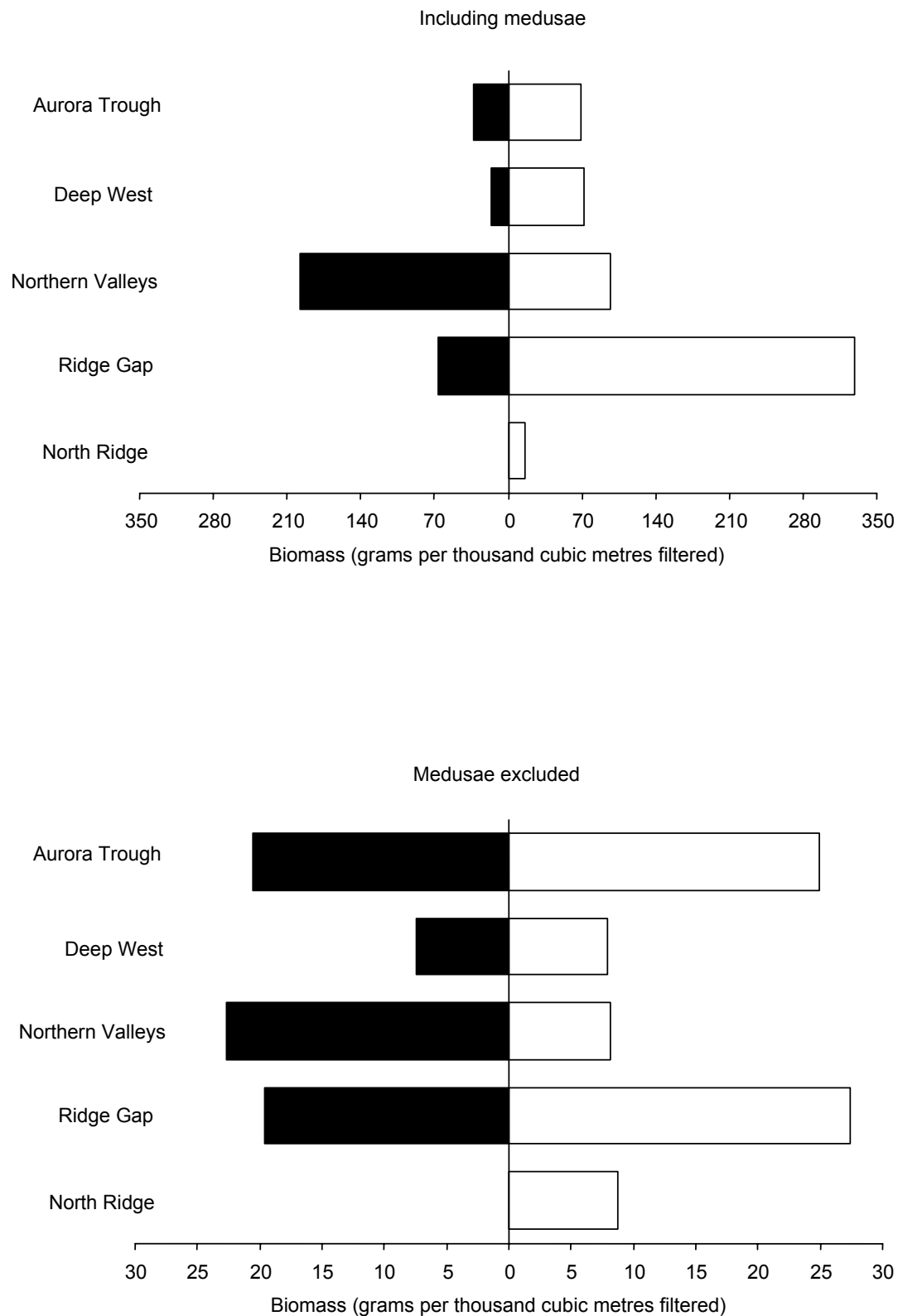
Figure 9.1a-b Total biomass at each station, including and excluding gelatinous plankton, by day and night. Dark bars = night, light bars = day. Only daytime samples were taken at North Ridge. Where replicate hauls were made, the mean of the two catch weights is given.
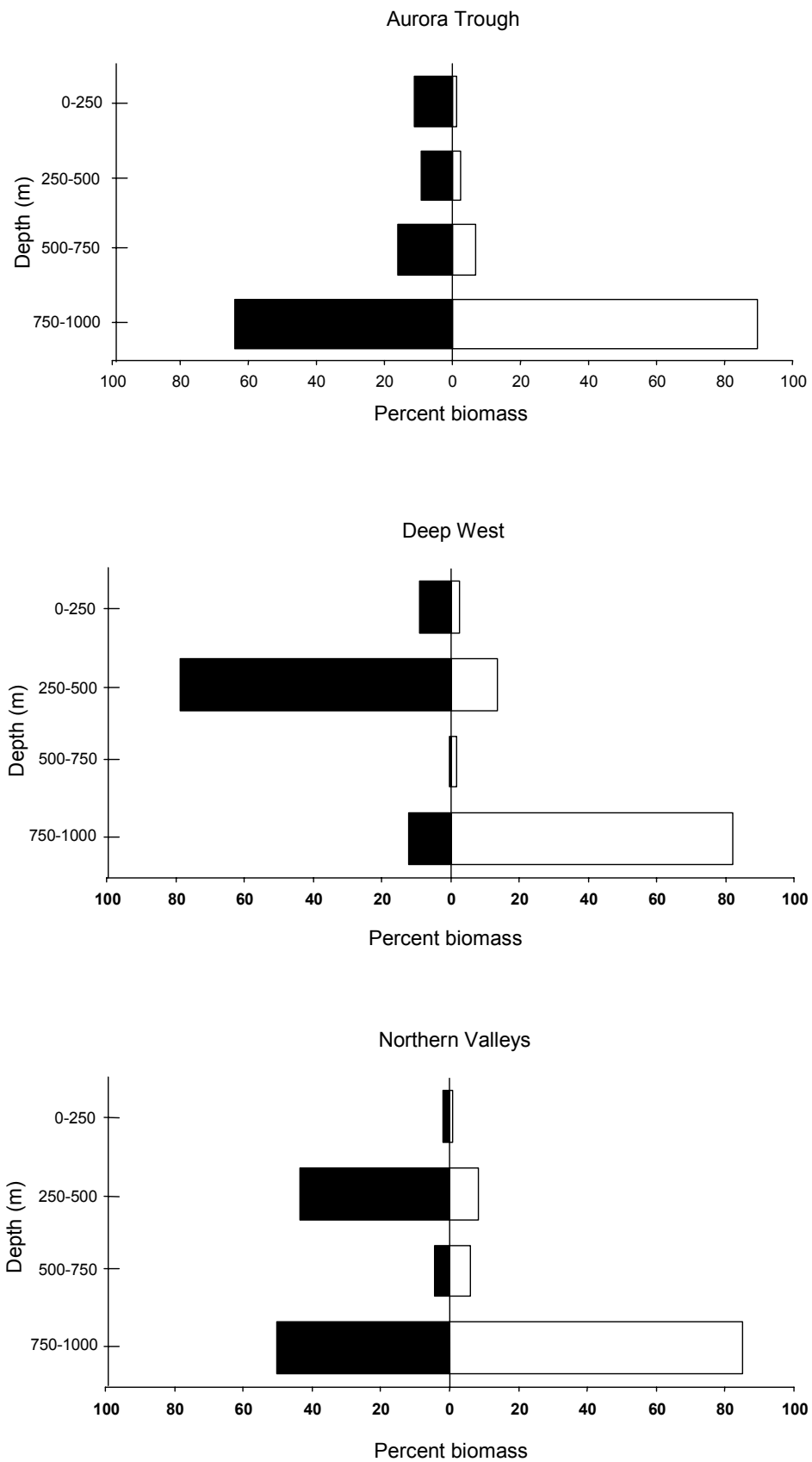
Figure 9.2a-c Depth distribution of percent biomass, including gelatinous plankton, by day and night at Aurora Trough, Deep West and Northern Valleys stations. Dark bars = night, light bars = day.
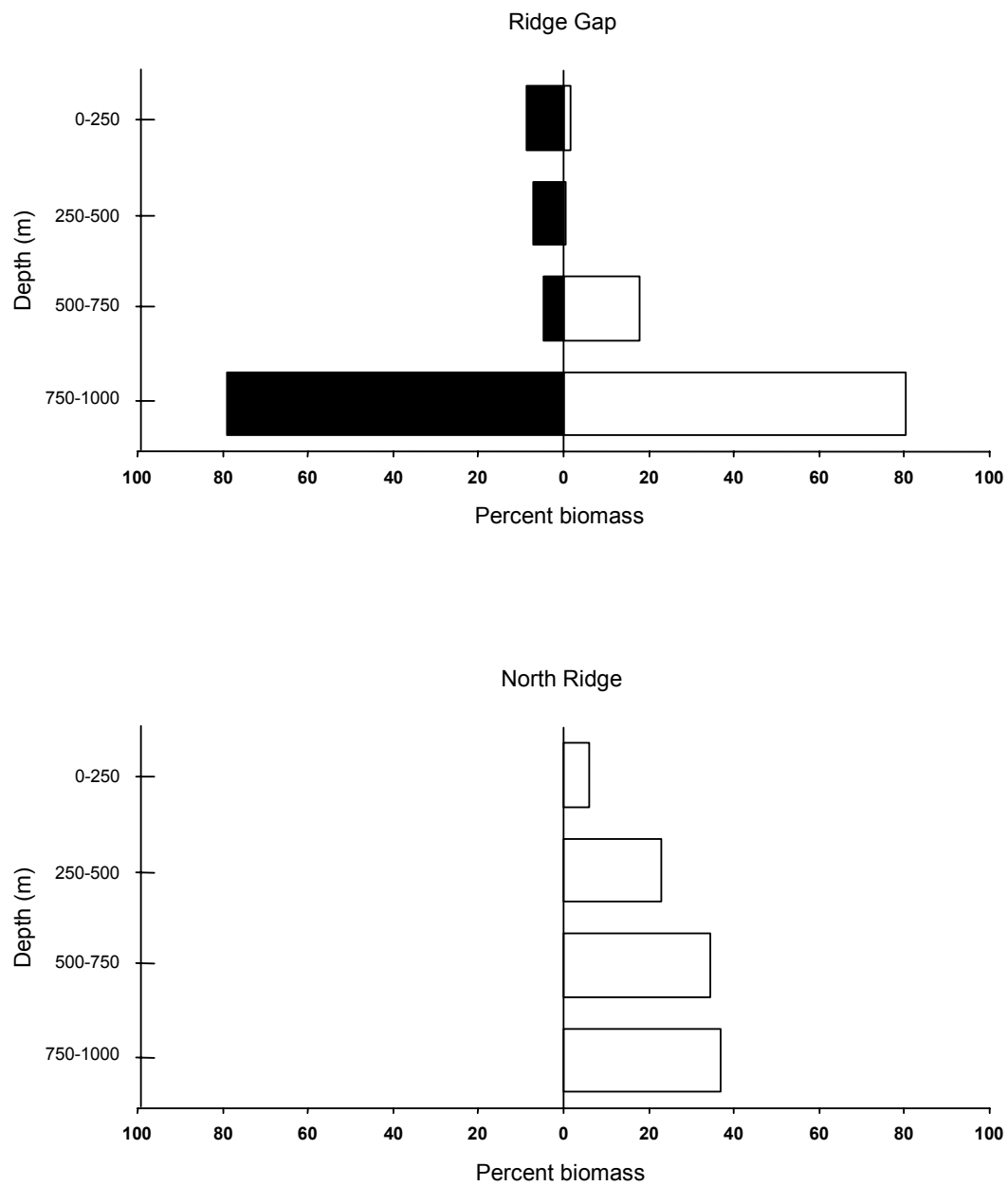
Figure 9.2d-e Depth distribution of percent biomass, including gelatinous plankton, by day and night at Ridge Gap and North Ridge stations. Dark bars = night, light bars = day. Only daytime samples were taken at North Ridge.
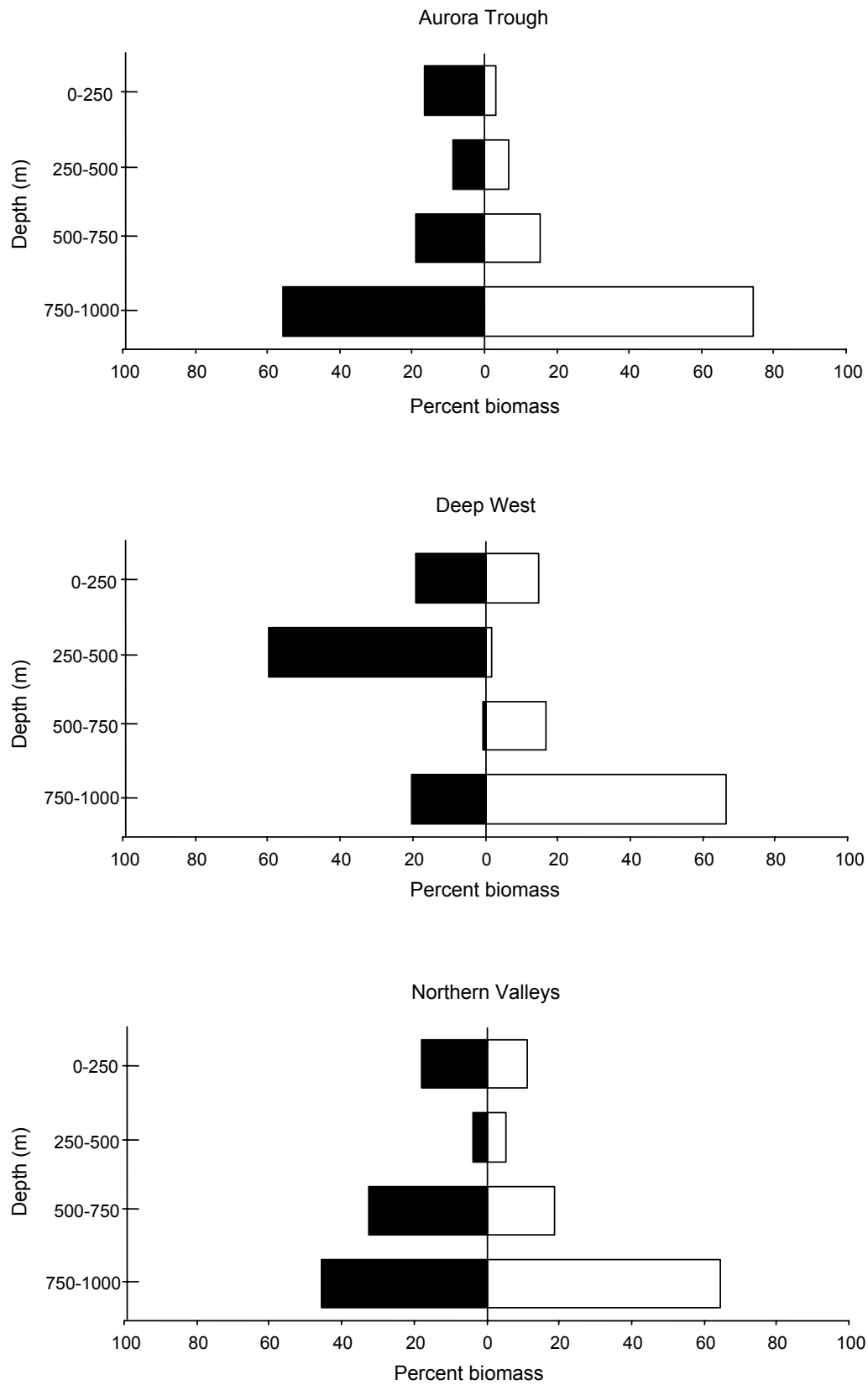
Figure 9.3a-c Depth distribution of percent biomass, excluding gelatinous plankton, by day and night at Aurora Trough, Deep West & Northern Valleys stations. Dark bars = night, light bars = day.

Ridge Gap
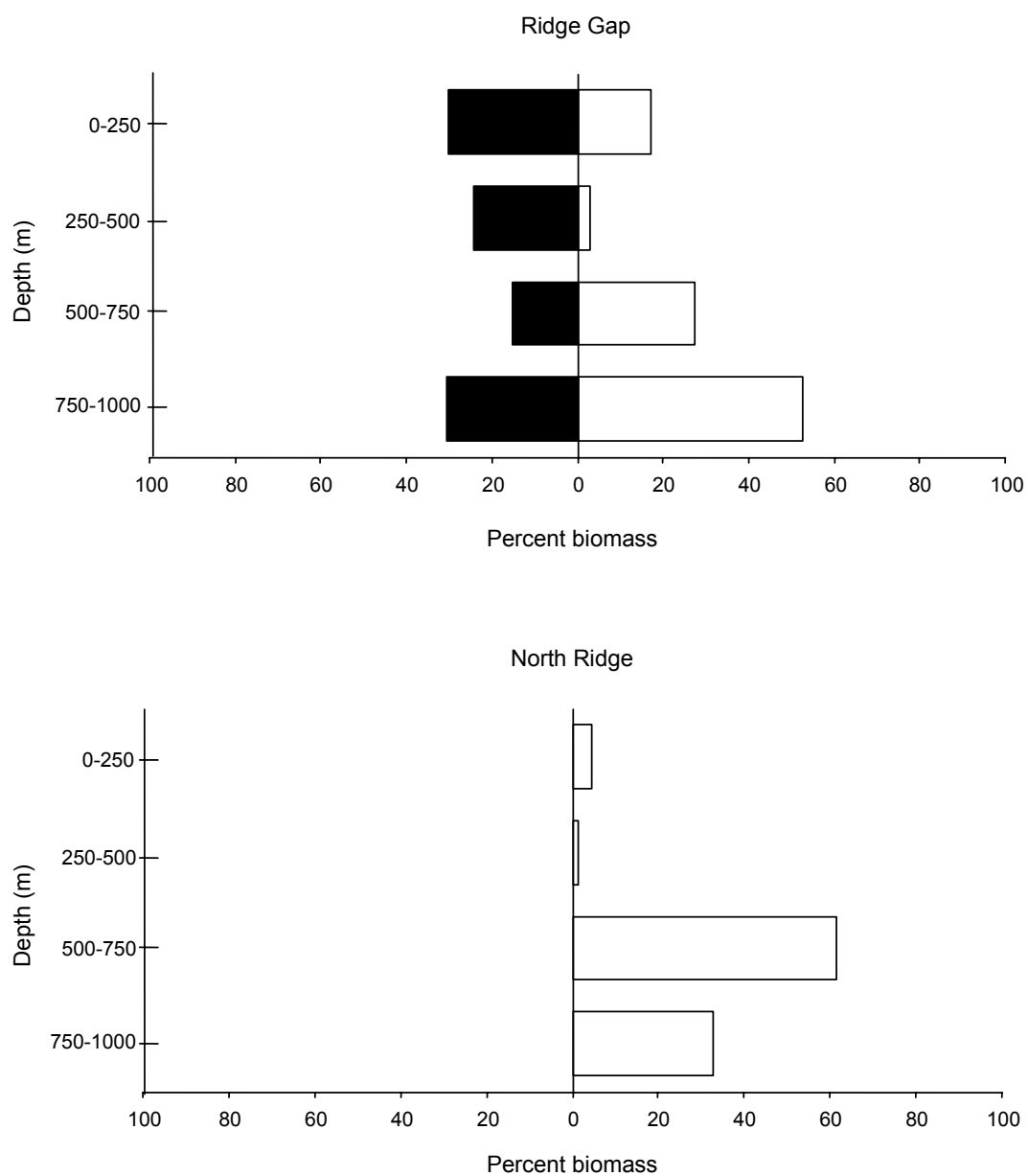
North Ridge

Figure 9.3d-e Depth distribution of percent biomass, excluding gelatinous plankton, by day and night at Ridge Gap and North Ridge stations. Dark bars = night, light bars = day. Only daytime samples were taken at North Ridge.
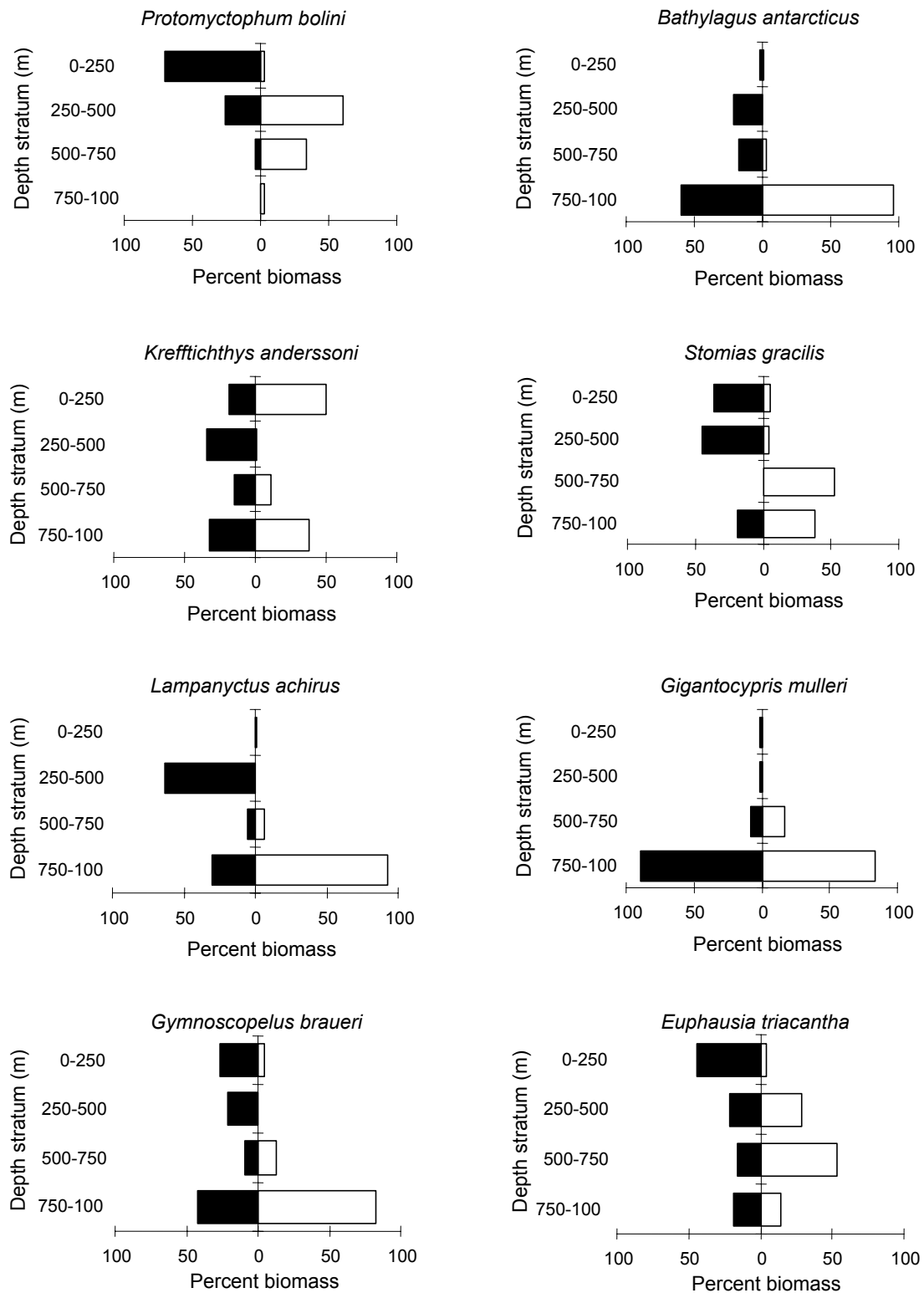
Figure 9.4 Depth distributions of percent biomass by day and night of selected species, all stations combined. Dark bars = night, light bars = day.

Figure 9.5 Water column backscatter a) day, and b) night, at Grand Canyon, at 38 kHz with area backscatter (m^2 n.mile^{-2}) for 250 m depth intervals and averaged over 1 n.mile. Of note is the tight schools observed during the day in the 0- 300 m depth range and these disperse at night.
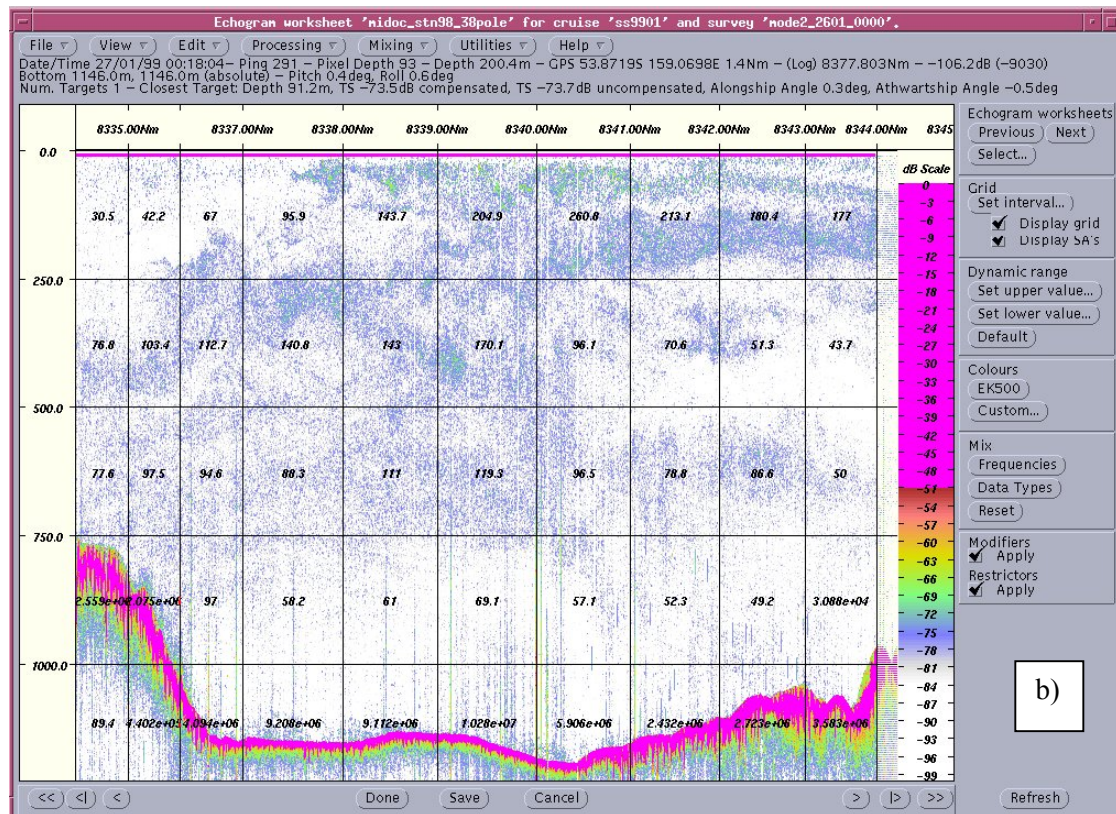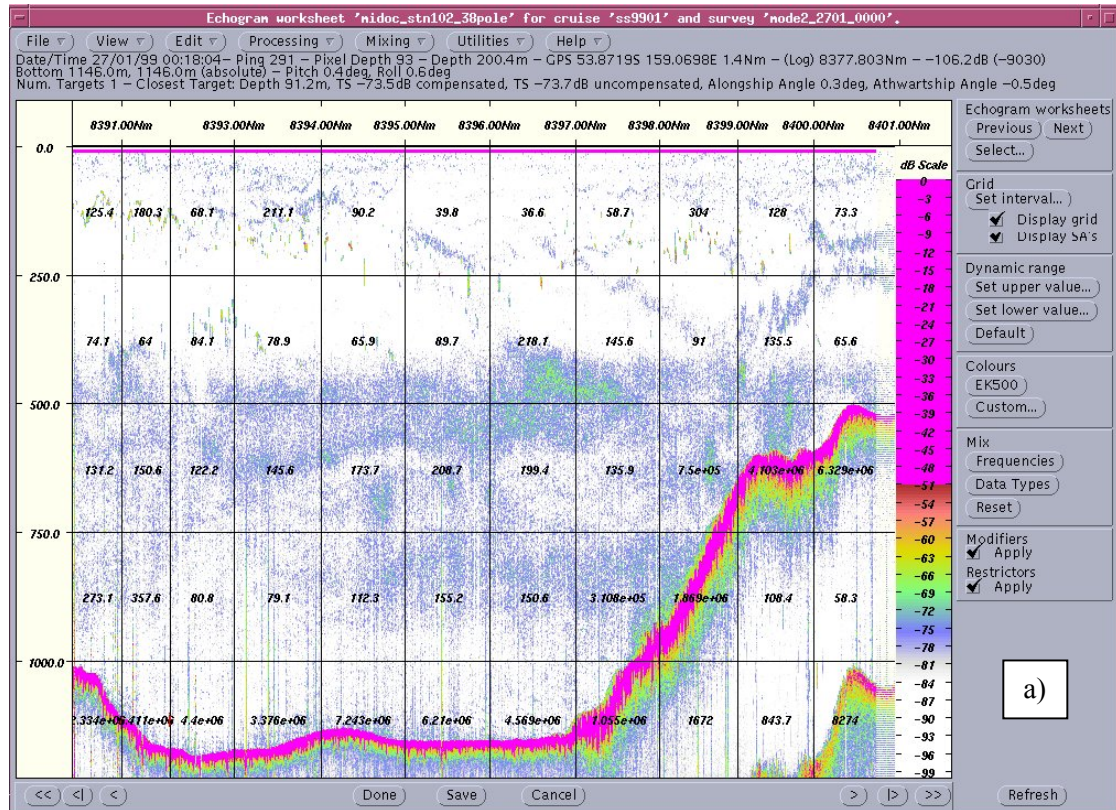
10. Biology and growth of toothfish

Andrew Constable, Dick Williams, Geoff Tuck, Tim Lamb and Sandy Morrison

Summary

The Patagonian toothfish is the largest species in the teleost family Nototheniidae, with the maximum size recorded well above 2 m. Much of the work concerning the biology and ecology of toothfish has been derived from studies around Chile, South Georgia Island and Heard Island and is available mostly in reports to the Scientific Committee for the Conservation of Antarctic Marine Living Resources (SC-CAMLR). This chapter summarises available information on the biology of toothfish and, where possible, updates this information for Macquarie Island using data derived from the research activity undertaken through the fisheries observer program. In particular, this chapter examines the age, growth and selectivity of this species in the Macquarie Island fishery. Toothfish are known as a predominantly benthic dwelling species living on shelf areas around subantarctic islands and the southern latitudes of the South American continental shelf. Young fish are believed to recruit into shallow water and gradually move to deeper waters as they grow and mature. Catches in the fishery have mostly been dominated by fish less than 1,100 mm in size and mostly between 500 and 900 mm. The weight-length relationship of toothfish at Macquarie Island is the same as for other areas. The rate of natural mortality (M) is considered to be low (less than 0.2) because of the longevity of the species, which is thought to be in the vicinity of 35-50 years. No information is available from Macquarie Island on natural mortality. For this study, it is assumed to be similar to Heard Island and a value of M=0.1 is used in the calculations below. Length of maturity is around 975 mm at Heard Island. No information on maturity is available for Macquarie Island as catches are of immature individuals. Ages of fish in catches were estimated from otoliths. Length-at-age data was then used to estimate a selectivity function for Macquarie Island and the parameters of a von Bertalanffy growth model. Both of these were estimated using maximum likelihood techniques with the selection function incorporated into the likelihood function estimating the von Bertalanffy parameters. The resulting estimates were compared to estimates obtained using non-linear regression and other standard techniques. The estimates were also compared to estimates from other areas. Males were estimated to have a much smaller l_∞ and grew more slowly than females, although these differences are not as pronounced as previous analyses for South Georgia. The growth curves of males and females diverge at approximately 10 years of age, which is the expected age of sexual maturity. Growth and size of toothfish at Macquarie Island is consistent with this species in other areas, particularly Heard Island, although growth in the Macquarie Island region may be slightly slower. Notably, the length at age model for the combined sexes at Macquarie Island shows that fish in this area are slightly smaller than toothfish at Heard Island and much smaller than at South Georgia Island at the same age and are consequently older at 1300mm total length. The results of the negative log-likelihood analysis take into account the problems of fishing selectivity and indicate that L_∞ may be overestimated for populations at Heard Island and South Georgia. The age of fish at maturity is likely to be in the order of 12-15 years. The data from Macquarie Island fishery indicates that the fishery concentrates on juvenile fish but is more likely to catch larger fish than at Heard Island. Most biological parameters have now been estimated with a degree of confidence suitable for population modeling. However, the parameter with the greatest uncertainty remains natural mortality.

Introduction

The Patagonian toothfish, *Dissostichus eleginoides* (hereafter referred to as toothfish), is the largest species in the teleost family Nototheniidae, with the maximum size recorded well above 2 m. The general characteristics of toothfish are described in Gon and Heemstra (1990).

Much of the work concerning the biology and ecology of toothfish has been derived from studies around Chile, South Georgia Island and Heard Island (this term will be used for the combined Heard Island and McDonald Islands region). Interim reports of these studies have been submitted to the Scientific Committee for the Conservation of Antarctic Marine Living Resources (SC-CAMLR) through the Working Group on Fish Stock Assessment (WG-FSA). Summary outcomes of the work of WG-FSA can be found in its annual reports annexed to the reports of the Scientific Committee. These reports are available from the Secretariat of the Convention for the Conservation of Antarctic Marine Living Resources – CCAMLR (http:\\www.ccamlr.org).

Information pertaining to toothfish has mostly arisen since the advent of longline fishing around South Georgia in 1987 and through the longline fishery in southern Chile. The rapid expansion of this fishery in the early 1990s and the inappropriateness of standard assessment methods (Parkes *et al.* 1996; Constable *et al.* 2000) led to a special workshop on toothfish in 1995 (WG-FSA 1995 Annex E). The report of this workshop summarised the state of knowledge on this species to that point and remains the foundation report on the biology of this species with some small refinements being reported in recent years. The greatest sources of difficulty in understanding the biology of this species remain to be determining rates of natural mortality and methods to determine age of individual fish. No progress can be made in this report on natural mortality. However, attention is given to recent developments in the methods to determine the age of toothfish.

The aim of this chapter is to summarise available information on the biology of toothfish and, where possible, updating this information for Macquarie Island using data derived from the research activity undertaken through the observer program. In particular, this chapter examines the age, growth and selectivity of this species in the Macquarie Island fishery.

Overview of toothfish biology
Distribution and abundance
Toothfish are known as a predominantly benthic dwelling species living on shelf areas around subantarctic islands and the southern latitudes of the South American continental shelf (Gon and Heemstra 1990). Young fish are believed to recruit into shallow water and gradually move to deeper waters as they grow and mature. Larger fish are found in deeper water (Agnew *et al.* 1999; Constable *et al.* 1999) although this distribution is dependent on the time of the year, possibly related to spawning activity (Agnew *et al.* 1999). Around Heard Island, few adult fish are found in waters shallower than 1,000m (Constable *et al.* 1999), consistent with the pattern observed at South Georgia (Agnew *et al.* 1999) and elsewhere (WG-FSA 1997).

Size
The maximum size of toothfish in the CCAMLR database is 2405 mm (WG-FSA 1999). Typically for South Georgia and Heard Island, toothfish are first detected around 300-400 mm using bottom trawls, corresponding to two and three year-old fish. Longlines catch larger fish, most often greater than 550 mm (WG-FSA 1999).

The sizes of fish caught in the fishery at Macquarie Island are illustrated in Figure 10.1. The catch densities (number per km^2) of fish in each 10 mm length bin are given for Aurora Trough only and for the whole fishery from four separate voyages during 1997-1999. In each haul, the densities-at-length are weighted by the area of the stratum and the number of hauls in that stratum, according to the method summarised in WG-FSA (1999, paragraph 4.127; referred to in the following text as length-densities or length composition). The figure shows that the catches in the fishery have mostly been dominated by fish less than 1,100 mm in size and mostly between 500 and 900 mm.

Parameters for the length-weight relationship used in assessments by WG-FSA vary between South Georgia and Heard Island (Table 10.1, Figure 10.2). The relationship at Macquarie Island is almost identical to that at Heard Island. There is no difference between males and females and between times of year, which was examined by comparing samples taken in March and in October/November.

Mortality

The rate of natural mortality (M) is considered to be low (less than 0.2) because of the longevity of the species, which is thought to be in the vicinity of 35-50 years. In 1999, the CCAMLR Working Group on Fish Stock Assessment revised the values of M used in the yield calculations to be consistent with the growth rates estimated in that year (WG-FSA 1999). In the absence of any direct estimates of M, the WG-FSA uses values of M ranging from 2K to 3K where K is the growth parameter from the von Bertalanffy growth equation. Thus, the WG-FSA agreed to M ranging from 0.13-0.2 year^{-1} at South Georgia and 0.08-0.12 year^{-1} at Heard Island. Estimates of M are expected to be revised in the near future once a proposed method for jointly estimating M and recruitment strength from a time-series of recruitment surveys (Constable and Ball, in review) has been validated. No information is available from Macquarie Island on natural mortality. For this study, it is assumed to be similar to Heard Island and a value of M=0.1 is used in the calculations below.

Reproduction

Reproduction in toothfish has been described in a number of papers to the CCAMLR Working Group on Fish Stock Assessment and summarised in those reports. The current estimate of length, when 50% of the population is mature, is approximately 930 mm at South Georgia (WG-FSA 1999) and 975 mm at Heard Island (Constable *et al,* 1999). These sizes of sexual maturity mostly correspond to the size at sexual maturity of females, whereas males mature at lengths around 800 mm (Everson and Murray 1999). This difference is likely to arise because males seem to mature at a younger age than females (WG-FSA 1998).

Around South Georgia, toothfish are reported to spawn in breeding areas defined by slope position (between 800 and 1,200 m depth) (Agnew *et al.* 1999). Pre-spawning individuals are distributed all around the South Georgia and Shag Rocks shelf slopes with males tending to be in shallower waters than the breeding grounds and females tending to be in deeper waters.

Observations of gonad condition suggest that spawning around South Georgia is mainly during the months July and August (Agnew *et al.* 1999; Everson and Murray 1999). Some evidence suggests that a secondary spawning period may occur in March-May (Everson and Murray 1999). At Heard Island, spawning is thought to occur around June (Duhamel 1991).

Toothfish caught at Macquarie Island are almost entirely juvenile or in the resting stage of gonad development. No information is available on the spawning habitats in this region.

Age determination and length at age in toothfish
Age validation
Kalish *et al.* (1999) described the results of investigations into the estimation of age of toothfish and growth parameters. They used otoliths collected between 1979 and 1996 from the Chilean slope (between 47"s and Cape Horn), Falkland Islands, Heard and McDonald Islands, Kerguelen Island, Macquarie Island, Prince Edward Islands and South Georgia. These were analysed for radiocarbon to determine the accuracy of the otolith thin section method for estimation of toothfish age. Toothfish otoliths analysed for radiocarbon yielded otolith section ages from 2 to 43 years and associated birth dates between 1940 and 1988. The relationship between birth date estimated from the otolith thin sections and carbon 14 measured in the otolith cores showed that carbon-14 was consistent with pre-bomb and post-bomb carbon-14 measured in Southern Ocean surface waters and provided a validation for the age estimates. There were

significant differences in otolith core carbon-14 for the toothfish from different localities, consistent with the broad geographic separation of the collections and indicative of stock separation for toothfish in the southern oceans.

Age – length relationships
The relationship between length and age has been estimated for toothfish from a number of localities using readings of age from transverse sections of otoliths.

Samples of otoliths have been taken during the fishery at Macquarie Island since the early samples used by Kalish *et al.* (1999). In this study, otoliths were collected from random samples of toothfish from commercial catches in 1997-1999. Otoliths were also collected from as many fish greater than 1m total length as possible. Wherever possible, fish were measured and sexed. Otoliths from 618 fish were read by the Central Aging Facility (CAF) following calibration work between readers used by Kalish *et al.* (1999) and the CAF.

Analyses of the length at age data followed the procedure described in Constable *et al.* (1999). Ages were corrected for potential bias in the estimation of the age of the first ring in the otolith and the time since ring deposition. The month of ring deposition at Macquarie Island was examined by estimating the proportion of the year passed since the last ring was deposited. This was estimated as the fraction of the distance from the last ring to the edge of the otolith divided by the distance between the last two rings. The fraction of the year was then subtracted from the date of capture to give an estimate of the month in which the last ring was formed. Frequencies for each month of the number of otoliths that were estimated to form rings in that month are shown in Figure 10.3. The average month of ring formation was June.

The age-length key is presented in Table 10.2.

Fishing selectivity/availability
To date, fishing selectivity/availability of toothfish to trawl fisheries has only been evaluated at Heard and McDonald Islands. In that region, the representation of different lengths of toothfish in the catch was the same as would be expected from the proportion of the population of different length classes found in the fishing grounds (Constable *et al.* 1999). That study showed that gear selectivity was unlikely to influence the size structure in the catch but that movement of the fish into the fishing grounds was a more important factor. In that study, movement of fish into the fishing grounds from shallower water appeared to first occur once the fish were longer than 430 mm and that the lengths for which most fish were present in the fishing grounds was between 500 mm and 700 mm. Fish larger than 700 mm appeared to become more mobile and widespread throughout the available habitat.

The length composition of catches at Heard and McDonald Islands and Macquarie Island were compared to determine whether selectivity was likely to be similar between the two regions. Mean length density distributions for each of six seasons at Macquarie Island and each of three seasons at Heard Island were derived as described above. Each of these nine datasets was converted to cumulative proportions of lengths in the catches (i.e. number of fish less than or equal to that length divided by the total number of fish in the catch) in each area for each of the seasons (Figure 10.4). The results show that both smaller and larger fish are present in large numbers in the catches at Macquarie Island compared to Heard Island, making the selectivity function from Heard Island inappropriate for use in assessments at Macquarie Island.

A selectivity function for the stock at Macquarie Island was estimated from these mean length-density distributions and the age-length key derived above.

The form of the selectivity function is

$$S(l) = \begin{cases} 0 & ; l \leq l_1 \\ \left(\dfrac{l - l_1}{l_2 - l_1}\right) s_1 & ; l_1 < l \leq l_2 \\ \left(\dfrac{l - l_2}{l_3 - l_2}\right)(1.0 - s_1) + s_1 & ; l_2 < l < l_3 \\ 1.0 & ; l_3 \leq l \leq l_4 \\ \left(\dfrac{l_5 - l}{l_5 - l_4}\right)(1.0 - s_2) + s_2 & ; l_4 < l \leq l_5 \\ \left(\dfrac{l_6 - l}{l_6 - l_5}\right) s_2 & ; l_5 < l \leq l_6 \\ 0 & ; l_6 \leq l \end{cases} \qquad (1)$$

where the parameters estimated are each of the six lengths, $l_{1..6}$, in the function and the two selectivities, s_1 and s_2, which are not equal to zero or one. This form was chosen to enable the possibility of having long tails at each extreme of the distribution.

Selectivity at a given length is based on the difference between the expected proportion of fish of that length in the population and the proportion of fish of that length in the catch. The expected number of fish, $n(l)$, at length, l, in the population is governed by the age composition of the stock and the variability in lengths at age, a, given in the age-length key, ALK, such that

$$n(l) = \sum_a R_a e^{-Ma} \frac{ALK_{a,l}}{\sum_L ALK_{a,L}} \qquad (2)$$

where R is the recruitment of a given age class. Equations (1) and (2) are combined to give the expected proportion of fish at length in the catch

$$p(l) = \frac{S(l)n(l)}{\sum_L S(L)n(L)} \qquad (3)$$

The eight parameters of the selectivity function are estimated by minimising the sum of squared differences between the observed and expected proportions at length in the catch. The observed proportions at length were calculated from the length-density distributions arranged to have the same size of length bins as the age-length key. In this study, there are no estimates of recruitment strength for the different year classes in the age-length key. Thus, R is assumed to be constant for all year classes.

The resulting fit of the model is shown in Figure 10.5 with a residual sum of squares of 0.13. Estimates of the parameters are given in Table 10.3 and illustrated in Figure 10.6, in which it is compared to the Heard Island selectivity function.

The changes in length composition of the catches is considered to arise from small fish making up a resident stock in the fishing ground and the availability of larger fish varying over the fishing season (Williams *et al.* 1998). The selectivity function derived above is for the whole population. The selectivity function for when only the resident smaller fish are available to the fishery was estimated by using the length composition of catches for which the CPUE was less than 10 tonnes.km^{-2}. These data were obtained from the fishing voyages in the summers of 1996

and 1997, providing four replicates of mean length composition in catches. The selectivity function was estimated by fixing the selection at length for the smaller fish, according to the selectivity function for the whole population, and by estimating the function for the larger fish (see Table 10.3). The resulting fit of the model is shown in Figure 10.5 and had a residual sum of squares of 0.236. Estimates of the parameters are given in Table 10.3 and illustrated in Figure 10.6.

Estimation of von Bertalanffy growth parameters
von Bertalanffy growth parameters have been estimated from length and age measurement for toothfish from South Georgia Island (South Atlantic), Chile and Heard Island and adopted by the CCAMLR Working Group on Fish Stock Assessment (1999). The South Georgia and Heard Island estimates are shown in Table 10.4 and the consequent growth curves shown in Figure 10.7.

Kalish *et al.* (1999) provide estimates of growth parameters at Macquarie Island based on a total of 994 otoliths collected from the trawl fishery targeting toothfish in the Australian Fishing Zone during the 1995/96 and 1996/97. The majority of the fish in the sample were estimated to be less than 15 years old, far younger than the maximum age in excess of 40 years estimated in the validation study. The estimates of the von Bertalanffy parameters are presented in Table 10.4 and growth curve shown in Figure 10.7. These authors concluded that effective modelling of toothfish growth would require samples that are more representative of the population and should include fish captured by trawling and, from greater depths, by longlining.

In this study, the age-length key (Table 10.2) was combined with the length-density data from the four voyages in which the otoliths were collected (Figure 10.1) to estimate the growth parameters. In the first instance, non-linear regressions were used to estimate the parameters of the von Bertalanffy length at age model. Results are given in Table 10.4 and illustrated in Figure 10.7. An unweighted analysis shows an approximately linear relationship between length and age, consistent with the results of Kalish *et al.* (1999). A more appropriate analysis is to statistically weight each datum by the frequency of that length in the catches to ascertain the densities of lengths in the population, thus correcting for potentially biased samples. Further analyses were undertaken by weighting each datum by the ratio of the density at length in the catches (Figure 10.1) over the number of samples taken for otoliths from the respective length bin. These results give estimates of the parameters consistent with estimates being derived for other areas by WG-FSA (Table 10.4, Figure 10.7).

These approaches do not take account of fishing selectivity, highlighted as problems with such analyses for toothfish by Constable *et al.* (1999) and Kalish *et al.* (1999). An approach to this problem has been addressed by Punt (1999) in assessments of growth in coral trout where they weighted each datum by a probability of a fish of that length being sampled according to the selectivity function. Another factor that may influence the probability of being sampled is the expected survivorship of fish to that age. These two factors were considered in a further analysis of the weighted data using a negative log-likelihood function to estimate the von Bertalanffy parameters. The estimates were obtained from an array of the weighted data, *LA*, with *N* observations, each of which comprises a length, l_i, and age, a_i.

Given the von Bertalanffy function

$$\hat{l}(a) = l_\infty \left(1 - e^{-\kappa(a-t_0)} \right) \tag{4}$$

where $\hat{l}(a)$ is the mean length at age, *a*, l_∞ is the mean length at infinite age, *K* is the instantaneous growth rate, and t_0 is the adjustment for a positive size at time 0.

If recruitment is constant then the probability of sampling a fish of age, *a*, given constant natural mortality, *M*, is:

$$pA(a) = e^{-M \cdot a} \left(1 - e^{-M} \right)$$ (5)

Recruitment strengths for each age could be easily added to this formulation. However, these are unknown for each age in the Macquarie Island data and so are assumed to be constant for these calculations.

The probability density for length, *l(a)*, at a given age is dependent on the von Bertalanffy function and the variance of lengths at that age. This analysis uses a simple formulation for the residuals assuming the residuals are normally distributed about the mean length at age and that the coefficient of variation (CV) for lengths at age is constant across all ages. The CV is estimated along with the other parameters of the growth function. Thus, the probability of observing a given length at age is

$$pl(l(a) \mid \hat{l}(a), CV) = \frac{1}{\sqrt{2\pi} \left(\hat{l}(a)CV \right)} e^{-\frac{(l(a)-\hat{l}(a))^2}{2\left(\hat{l}(a)CV \right)^2}}$$ (6)

The probability of observing fish of length, *l*, is also governed by the selectivity function, *S(l)*, estimated above. This function was adjusted slightly to accommodate the data available to this analysis such that the minimum length first selected to the fishery, l_1, is 290 mm and the maximum length selected to the fishery, l_6, was 1600 mm. This made little difference to the selectivity but allowed all the age-length data to be utilised.

Given a set of von Bertalanffy parameters and a CV for lengths at age, the likelihood of an observed length at age is the product of these three functions (selectivity, mortality and length distribution at age) and standardised by the sum of the products over all lengths at all ages. Thus, the negative log-likelihood function is

$$L(LA \mid l_\infty, \kappa, t_0, CV) = -\sum_{i=1}^{N} \ln \left[\frac{pA(a_i) pl\left(l_i \mid \hat{l}(a_i), CV \right) S(l_i)}{\sum_{y=0}^{\infty} \left[pA(y) \int_0^{\infty} pl\left(l' \mid \hat{l}(y), CV \right) S(l') dl' \right]} \right]$$ (7)

The results of this analysis are presented in Table 10.4 and Figure 10.7.

Estimates of these parameters were obtained for the weighted data for sexes combined and for males and females separately. As expected from results in WG-FSA, males were estimated to have a much smaller l_∞ and grew more slowly than females, although these differences are not as pronounced as previous analyses for South Georgia. These results help explain why the frequency of males in the commercial catches in other regions is less than the frequency of females in fish greater than 1m in length (e.g. Heard Island, AFMA, unpublished data). It is worth noting that the growth curves of males and females diverge at approximately 10 years of age, which is the expected age of sexual maturity.

Notably, the length at age model for the combined sexes at Macquarie Island shows that fish in this area are slightly smaller than toothfish at Heard Island and much smaller than at South Georgia Island at the same age (Figure 10.7) and are consequently older at 1300mm total length (Table 10.4).

The results of the negative log-likelihood analysis take into account the problems of fishing selectivity and indicate that L_∞ may be overestimated for populations at Heard Island and South Georgia. As Kalish *et al.* (1999) concluded, confirmation of this approach could be achieved by adding more larger fish to the analysis.

Concluding Remarks

Growth and size of toothfish at Macquarie Island is consistent with this species in other areas, particularly Heard Island, although growth in the Macquarie Island region may be slightly slower. The age of fish at maturity is likely to be in the order of 12-15 years. The data from Macquarie Island fishery indicates that the fishery concentrates on juvenile fish but is more likely to catch larger fish than at Heard Island. Most biological parameters have now been estimated with a degree of confidence suitable for population modeling. However, the parameter with the greatest uncertainty remains natural mortality.

References

Agnew, D. J., Heaps, L., Jones, C., Watson, A., Berkieta, K. and Pearce, J. (1999). Depth distribution and spawning pattern of *Dissostichus eleginoides* at South Georgia. CCAMLR Science, 6: 19-36.

Constable, A. J. and Ball, I. R. (in review). A method for estimating recruitment and mortality from time series of length-density data. CCAMLR Science.

Constable, A. J., de la Mare, W. K., Agnew, D. J., Everson, I. and Miller, D. (2000). Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). Ices Journal of Marine Science, 57: 778-791.

Constable, A. J., Williams, R., Lamb, T. and van Wijk, E. (1999). Revision of biological and population parameters for Dissostichus eleginoides on the Heard Island Plateau (Division 58.5.2) based on a comprehensive survey of fishing grounds and recruitment areas in the region. Report to the SC-CAMLR Working Group on Fish Stock Assessment.

Duhamel, G. (1991). Biologie et exploitation de *Dissostichus eleginoides* autour des iles Kerguelen (Division 58.5.1). Selected Scientific Papers, 1991 (SC-CAMLR-SSP/8). CCAMLR, Hobart. pp. 85-106.

Gon, O. and Heemstra, P. C. (1990). Fishes of the Southern Ocean. J.L.B. Smith Institute of Ichthyology, Grahamstown, 462pp.

Everson, I. and Murray, A. (1999). Size at sexual maturity of Patagonian toothfish(*Dissostichus eleginoides*). CCAMLR Science, 6: 37-46.

Kalish, J. M., Timmiss, T. A., Pritchard, J. C. and Johnston, J. M. (1999). Validated age and growth of Patagonian toothfish *Dissostichus eleginoides* determined from otoliths. Report to the AFMA Subantarctic Fisheries Assessment Group, November 1999.

Parkes, G., Moreno, C. A., Pilling, G. and Young, Z. (1996). Use of the Leslie stock depletion model for the assessment of local abundance of Patagonian toothfish (*Dissostichus eleginoides*). CCAMLR Science*, 3: 55-77

Punt, A. E. On estimating growth curves for coral trout making allowance for gear selectivity. Unpublished report for Ecologically sustainable effects of line fishing project, CRC Research Centre for Great Barrier Reef.

WG-FSA (1995). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

WG-FSA (1997). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

WG-FSA (1998). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

WG-FSA (1999). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

Williams, R., Lamb, T., Constable, A. and Tuck, G. (1998) History of the Macquarie Island Fishery, 1994-1998. Report to SubAntarctic Fisheries Assessment Group, AFMA.

Table 10.1 Parameters of the length to weight conversion [Weight (kg) = *a*(Total Length - (mm))^b] for toothfish from South Georgia, Heard Island and Macquarie Island (MI).

Sample	a	b
South Georgia (WG-FSA 1999)	4.0×10^{-8}	2.80
Heard Island (WG-FSA 1999)	2.6×10^{-9}	3.21
MI – all data	4.4×10^{-9}	3.14
MI – Males	5.0×10^{-9}	3.12
MI – Females	5.4×10^{-9}	3.11
MI – March	6.7×10^{-9}	3.08
MI – Oct/Nov	4.3×10^{-9}	3.14

BIOLOGY AND GROWTH OF TOOTHFISH

Table 10.2 Age-length key for toothfish randomly sampled from the trawl fishery at Macquarie Island (1997-1999). Lengths (mm) are the mid-point of 50mm length bins. Numbers for length at age show the number of fish sampled of each age in that length bin. (This table does not include all the larger fish used in the growth analyses below.)

Length (mm)	Age (years)																			
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
275		2																		
325	9	11	7																	
375	1	12	23	6	1															
425		7	21	18	4															
475		2	10	21	12	2														
525			4	8	14	14	5													
575				4	6	14	11	10	5	2	2									
625				2	1	10	12	14	8	4	1	1								
675						4	9	11	17	12	5	1		2						
725				1	1	8	8	5	19	16	10	3	1							
775						3	3	4	8	4	7	3	4							
825									1	4	4	8	3			2				
875								2		1	3	1	2	1	1	1	1			
925											1	2	3	1		2				
975											1		4	1		2	1			
1025										1						1				
1075																2	1			
1125																1				
1225																1				
1275																		1		1

Table 10.3 Selectivity function for toothfish at Macquarie Island showing the values of the points of inflection illustrated in Figure 10.6. Low catch per unit effort (CPUE) was less than 10 tonnes km^{-2}.

Parameter	All Data Length (mm)	All Data Selectivity	Low CPUE 1997-1998 Length (mm)	Low CPUE 1997-1998 Selectivity
l_1	365	0	365 (fixed)	0
l_2	365	$s_1 = 0.01$	365 (fixed)	0.01
l_3	695	1.0	695 (fixed)	1.0
l_4	1075	1.0	695	1.0
l_5	1239	$s_2 = 0.01$	1134	0.006
l_6	1239	0	1134	0

Table 10.4 Parameters of the von Bertalanffy growth model estimated for toothfish from Macquarie Island using non-linear regression and negative log-likelihood techniques. Parameters from Kalish *et al.* (1999) are given for their model for Macquarie Island from the 1996/97 combined samples less two outliers. The approximate age at 1300m was estimated using the parameters in this table. The values of the von Bertalanffy model for toothfish at South Georgia and Heard Island (WG-FSA 1999) are given for comparison.

Data	L_∞ (mm)	K	t_0	Residual SE	N	Approximate age at 1300 mm
Macquarie Island						
Combined Sexes						
Kalish *et al.* 1999	2217	0.025	-2.42		994	33
Unweighted	4005	0.013	-3.3	73.0	557	27
Weighted	1477	0.053	-1.2	77.4	557	39
Negative log-likelihood (weighted)				CV (length at age)		
Combined sexes	1855	0.042	-0.781	0.13	557	28
Males	1542	0.054	-0.434	0.14	226	34
Females	1951	0.038	-1.184	0.12	244	28
WG-FSA 1999						
Heard Island	1946	0.041	-1.8			25
South Georgia	1946	0.066	-0.2			17
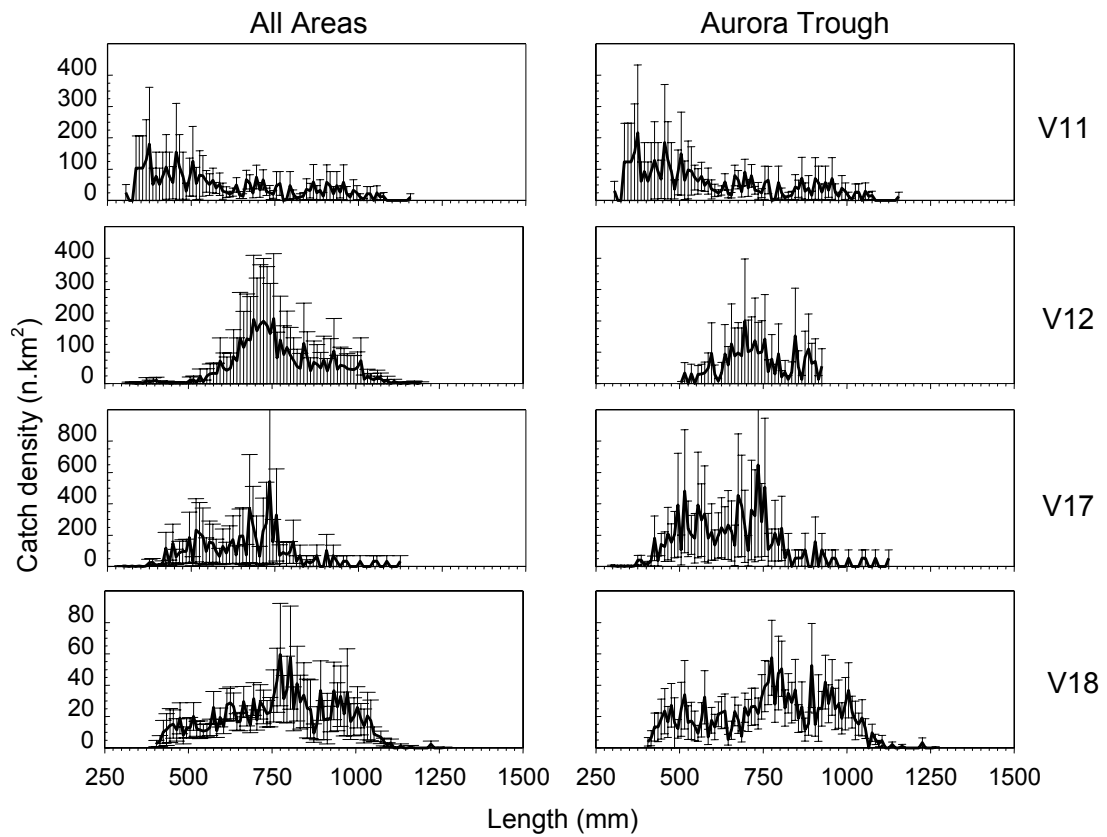
Figure 10.1 Catch densities (number per km^2) of fish in 10 mm length bins are given for Aurora Trough only and for the whole fishery from four separate voyages during 1997-1999 (V11-V18). Error bars are standard errors of estimates of the density of the respective length classes.
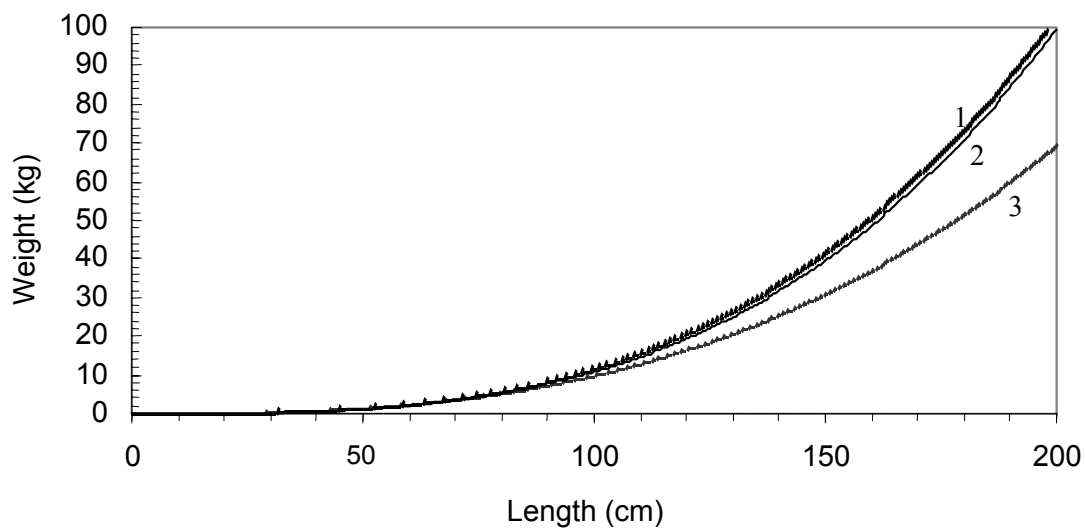
Figure 10.2 Length to weight relationship for toothfish at Macquarie Island (Line 1), Heard Island (Line 2) and South Georgia Island (Line 3).
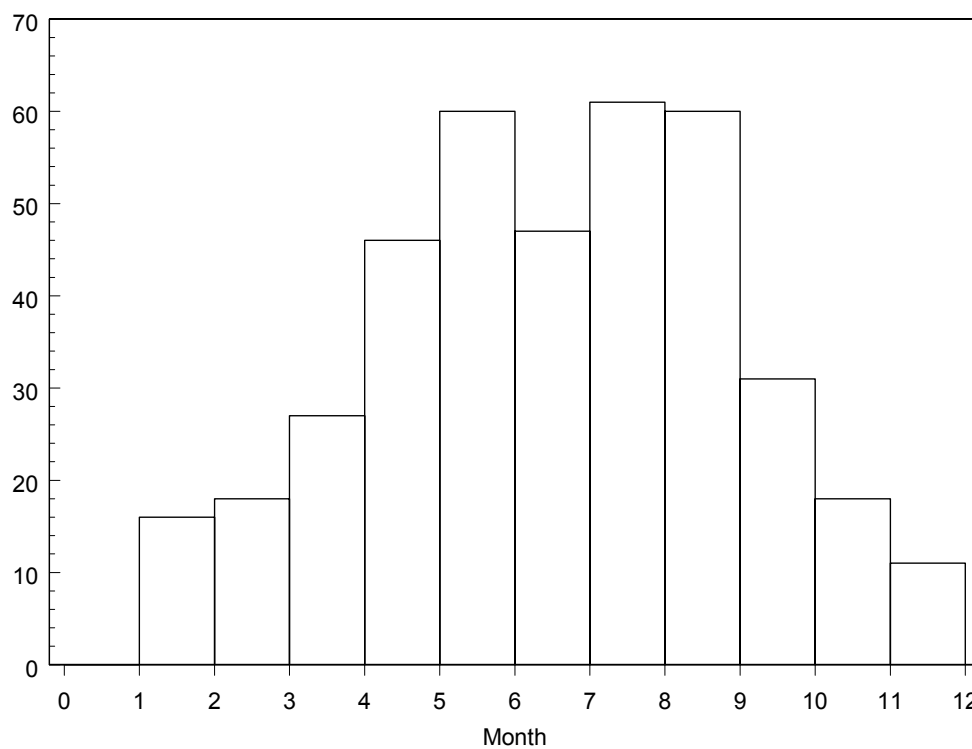
Figure 10. 3 Estimated month of growth ring formation. Frequencies for each month are the number of otoliths that were estimated to form rings in that month. Average month of ring formation was June.
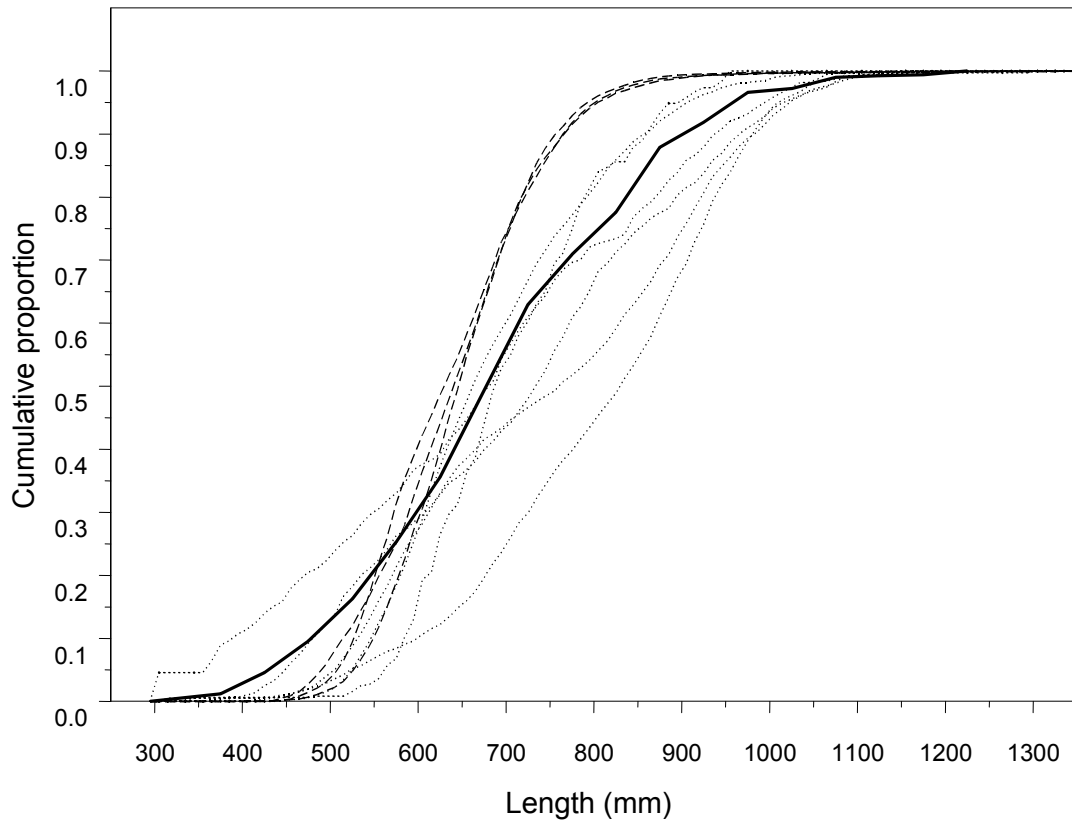
Figure 10.4 Cumulative proportions (by number) of toothfish in the catch from the fishery in the Heard Island (dashed lines – 3 seasons 1998-2000) and Macquarie Island (dotted lines – 6 seasons 1995 – 2000). The solid line represents the expected cumulative proportion of fish in the catch based on the estimated fit of a selectivity function for when all available age classes are present in the fishery.
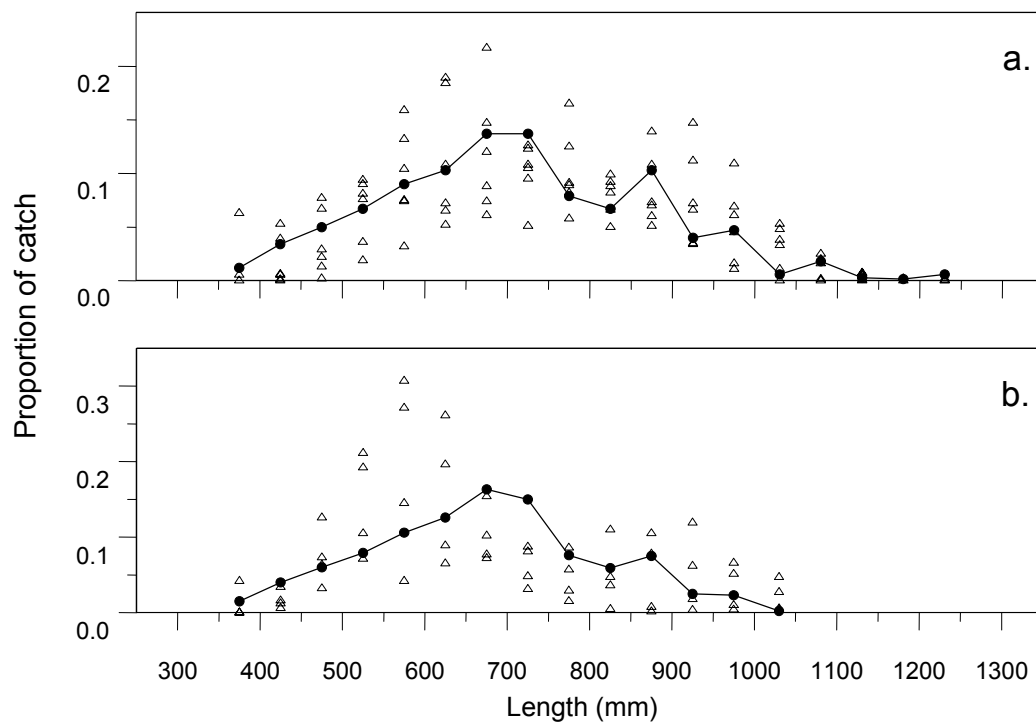
Figure 10.5 Proportion (by number) of toothfish catch in 50 mm length bins. The solid line represents the estimated fit of a selectivity function to the available stock, **a**. - for when all available length classes are present in the fishery, **b**. - for when only smaller fish are available to the fishery.
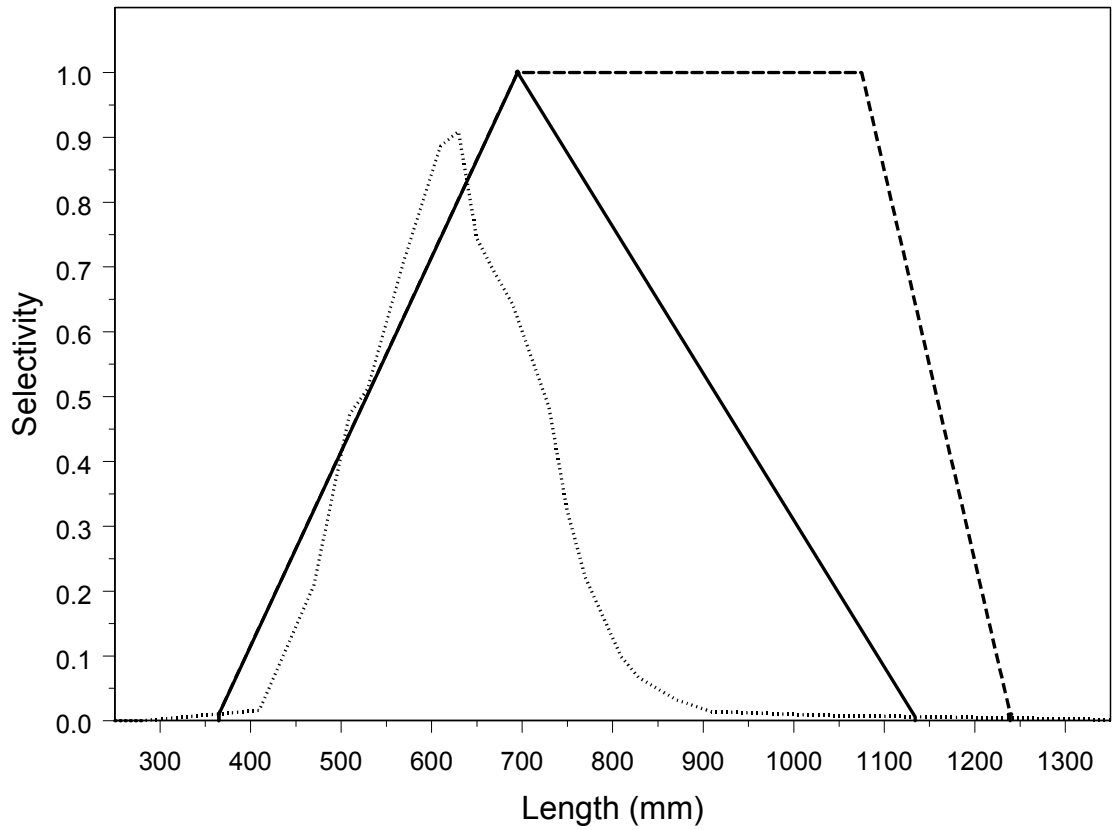
Figure 10.6 Selectivity functions for toothfish estimated for Heard Island (dotted line, Constable *et al.* 1999) and Macquarie Island – for the resident smaller fish (solid line) and the extension of this selection function for when all available length classes are present in the fishery (dashed line).
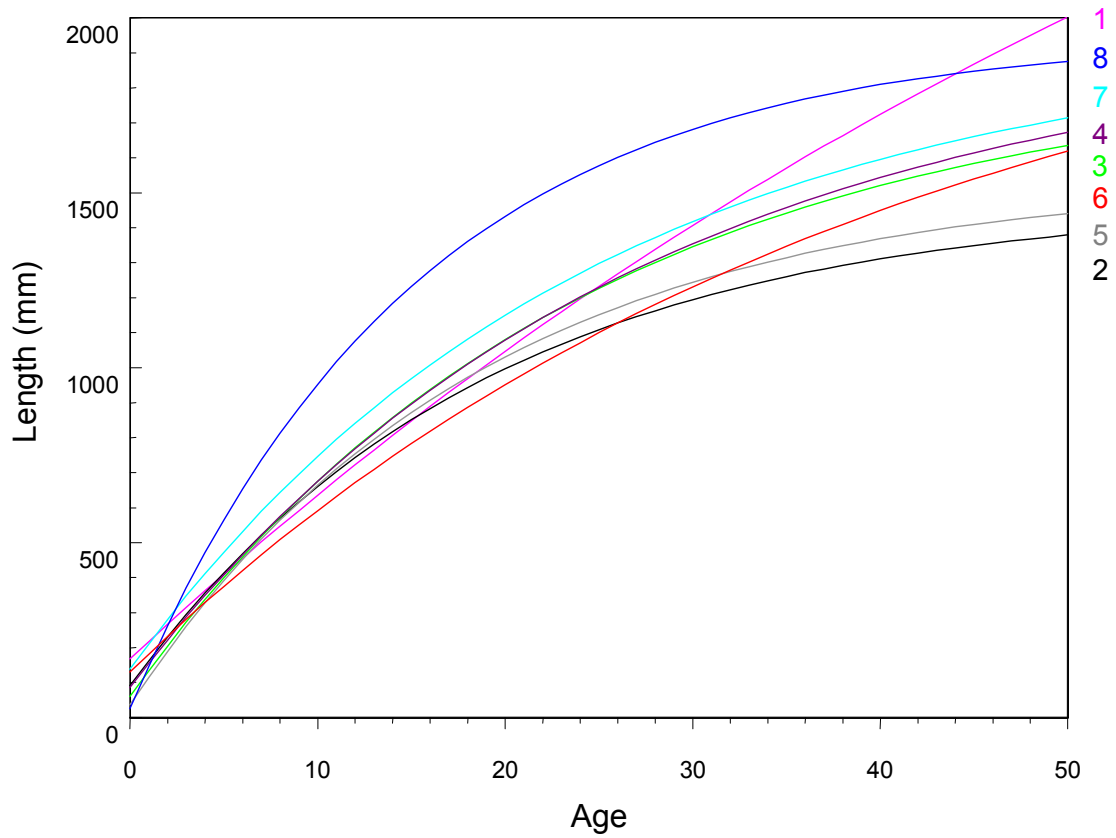
Figure 10.7 von Bertalanffy growth curves for models presented in Table 10.4. 1 = Macquarie Island (MI) unweighted data; 2 = MI weighted by densities at length in catches; 3 = MI negative log-likelihood estimate for all data; 4 = MI negative log-likelihood estimate for females; 5 = MI negative log-likelihood estimate for males; 6 = MI Kalish *et al.* (1999); 7 = Heard Island; 8 = South Georgia.

11. Stock structure of toothfish

Anne Reilly, Bob Ward and Dick Williams

Summary
Studies on genetic markers and a tagging program provided some preliminary information on the degree of interchange of toothfish between two fishing grounds 40 nautical miles apart off Macquarie Island. Five DNA microsatellite loci were identified that showed polymorphism levels appropriate for population structure analysis, and two of these gave results that suggested that samples from the two sites were not homogeneous at the 5% probability level. While the other three loci did not demonstrate this spatial differentiation, combined results across all five loci indicated heterogeneity at the 5% probability level. As the genetic analysis has so far only been performed on small numbers of both fish and loci, these results must be regarded as preliminary. Results from tagging data (Chapter 6) support the inference from the genetic analyses that interchange of fish between the two sites is very low. If confirmed by larger-scale studies, the existence of very localised toothfish stocks will have significant implications for toothfish management.

Introduction
Despite the wide distribution of toothfish in sub-Antarctic waters and the existence of commercial fisheries for this species for the last 13 years, virtually nothing is known about the degree of separation of stocks either within or between its major centres of distribution on the east and west coasts of South America and islands and submarine plateaux of the Indian Ocean Sector (WG-FSA-95, Appendix E, paras 2.29 & 2.44). The CCAMLR Workshop on Methods for the Assessment of *Dissostichus eleginoides* recommended that the level of toothfish mixing between different regions should be determined using, for example, genetic methods and tagging experiments (WG-FSA-95, Appendix E, para 4.1 C (ii)) in order to assess stocks more reliably.

This chapter reports on a pilot study aimed at developing and testing DNA microsatellite markers, with results from a small number of Macquarie Island fish. The long-term aim is to use microsatellite markers to determine the stock structure of toothfish from the Macquarie Island and other Australian fisheries.

Methods
Two main fishing grounds exist for toothfish on the Macquarie Ridge within the 200 nautical mile Australian Fishing Zone around Macquarie Island. One is a large valley 500-800m deep named Aurora Trough, and the other is a complex of valleys 500-1200m deep within a radius of about 5 nautical miles named Northern Valleys. Aurora Trough and Northern Valleys are on the same section of Macquarie Ridge, but separated by about 40 nautical miles. Samples for DNA microsatellite analysis were taken from both these locations during the 1997/98 fishing season. Fish have been tagged in Aurora Trough since the 1995/96 fishing season (October-March), and in the Northern Valleys area since the 1996/97 season.

Development of toothfish DNA microsatellites
Microsatellites are regions of DNA that consist of a (usually) highly variable number of short repeats (such as repeats of the dinucleotide motif CA) flanked by unique DNA sequences. Because they are both abundant and variable, and because they can be examined in samples stored at room temperature in alcohol (greatly simplifying logistics), they are becoming the marker of choice for appropriately equipped laboratories interested in determining genetic population structures.

The first step was to prepare a library of DNA fragments from toothfish. This was accomplished by digesting 20μg of DNA with the restriction enzyme Sau3A, and ligating DNA fragments of size 500 - 750 base pairs into the dephosphorylated BamHI site of the vector, pGEM™-3Zf(+) (Promega) (Reilly *et al*. 1999). Ligated plasmids were transformed into XL-1 Blue supercompetent cells (Stratagene). Cells were plated onto selective media and replicated onto uncharged nylon membrane filters (Boehringer Mannheim).

The library, consisting of approximately 25,000 recombinant clones, was screened for microsatellite repeats with a $(CA)_9$ probe, and later with a combined $(AAT)_9$ and $(AAC)_8$ probe. Probes were 3'-end labelled with digoxygenin molecules, and standard hybridisation and wash conditions were used (Boehringer Mannheim 1995). The nucleotide sequence of positive candidate clones was determined with ABI Prism™ Dye Terminator Cycle Sequencing (Perkin Elmer) using double-stranded plasmid DNA, prepared by the alkaline lysis method (Sambrook *et al*. 1989). Sequencing products were analysed on an ABI377 Prism DNA autosequencer. Approximately 20,000 clones were screened with a $(CA)_9$ non-radioactive probe. Approximately 300 clones were identified as positive with this probe, implying that they contain a CA microsatellite. Many of these clones were sequenced with an automated sequencer and those with CA repeats flanked by unique DNA sequences identified. Another 10,000 clones were probed for AAT and AAC repeats, but only about a dozen clones were identified as positives for these far less common trinucleotide repeats. PCR primers were designed for unique flanking regions of the microsatellite repeats. Oligonucleotides were synthesised by Bresatec, and one primer from each pair was labelled with a fluorescent tag.

Twelve primer pairs were tested. Five pairs gave excellent gel products that could be accurately and repeatedly scored for size variation among fish, and which also showed levels of polymorphism appropriate for population structure analyses. Three of these had dinucleotide repeats (these microsatellite loci were designated *cmrDe2*, *cmrDe9* and *cmrDe30*), and two had trinucleotide repeats (loci *cmrDe4* and *cmrDe13*). The locus notation is in the form *cmrDe2* = CSIRO Marine Research Dissostichus eleginoides clone 2.

For microsatellite analysis, total genomic DNA was extracted from 50 mg of alcohol-preserved muscle samples (Sambrook *et al*. 1989). PCR amplifications were performed in a Perkin Elmer thermocycler 9600 as 25 μL reactions containing 67 mM TrisHCl, pH 8.8; 16.6 mM $(NH_4)2SO_4$; 0.45% Triton X-100; 0.2 mg/mL gelatin; 1.5 mM or 2.5 mM $MgCl_2$ (Table 1); 0.4 μM of each primer; 200 μM dNTPs; 0.5 units Taq F1 DNA polymerase (Fisher Biotech); and ~ 20 ng genomic DNA template. Denaturation for 3 min at 95°C was followed by 35 cycles made up of 30 s at 96°C, 30 s at the annealing temperature (Table 1) and 1 min at 72°C. The final step was a prolonged extension of 20 min at 72°C. The amplified products were diluted, mixed with formamide loading-dye containing Tamra size standards (ABI), heat-denatured and then loaded on a 4% denaturing acrylamide gel. The samples were run on an ABI377 Prism DNA autosequencer and analysed with accompanying software (Genotyper®2.0).

The five loci were examined in genomic DNA extracted from alcohol-preserved muscle samples of toothfish from Northern Valleys and Aurora Trough). About 15 fish from each of these sites were examined.

Results
DNA microsatellites
Three of the loci (*cmrDe4*, *cmrDe13*, *cmrDe30*) had between 7 and 12 alleles each, the fourth (*cmrDe2*) had 16 and the fifth (*cmrDe9*) was still more variable with 23 alleles. All these loci yielded good amplification products that could be readily scored. Genotypes for each locus were determined, and allele frequencies estimated (Table 11.1).

A Monte-Carlo statistical test (Roff and Bentzen 1989) was used to determine whether samples from the two sites were genetically homogeneous. Two of the five loci showed *P* values less than 5%, suggesting that the two samples were not homogeneous (see Table 2). Locus *cmrDe13* showed the strongest evidence of differentiation (*P*=0.025). At this locus, eight copies of allele 180 were present in the Northern Valleys sample and only two in the Aurora Trough sample, while for allele 186, only one copy was present in Northern Valleys and eight in Aurora Trough. Combining the individual probabilities (Sokal and Rohlf 1981) for each locus of 0.025, 0.044, 0.135, 0.244 and 0.637 gave the overall low *P* value of 0.019, again indicating a lack of genetic homogeneity and showing that there were genetic differences between the two sites. A Monte-Carlo χ^2 test (Zaykin and Pudovkin 1993) was used to determine whether the observed genotype frequencies in each sample accorded with Hardy-Weinberg equilibrium. With the exception of locus *cmrDe30* at site 2 (*P* = 0.038), no samples deviated significantly from Hardy-Weinberg expectations. These data are summarised in Table 11.2.

Discussion
This pilot study successfully developed and deployed five microsatellite loci on collections of toothfish muscle samples from two Macquarie Island sites. Genetic variation within sites was extensive, and although sample sizes were low, there was evidence of significant genetic differences between the sites. This suggests that gene flow between them is restricted, and that there is little mixing between the two (Reilly and Ward 1999).

The evidence from the tagging study corroborates this conclusion, indicating very low interchange rates between the two grounds (Table 6.2, Chapter 6). As this study is based on large numbers of tags, there is a good chance that such a conclusion is reliable.

For such a large and apparently active predatory fish with pelagic eggs and larvae, it is surprising that genetic differentiation between two relatively close sites was indicated, or that such little interchange was revealed by the tagging studies. Although we recognise that the DNA results are limited because they are based on very few samples at this stage, we have five excellent and variable microsatellite loci working for the toothfish, which overall show significant genetic differentiation between sites only 40 nautical miles apart. More microsatellite loci can readily be developed and deployed to describe further the stock structure of this increasingly valuable fish. Larger sample sizes must also be used.

If this degree of localisation of toothfish stocks at Macquarie Island is confirmed in subsequent studies, and is ultimately found to be applicable in other areas, the assessment of current fisheries will have to be made on a finer geographical scale.

Acknowledgements
We thank the master and crew of *Austral Leader* and the fisheries observers for providing samples for microsatellite DNA testing and for carrying out the tagging program.

References
Boehringer Mannheim (1995). The DIG System User's Guide for Filter Hybridization. Boehringer Mannheim GmbH Biochemica, Mannheim, Germany.

Reilly, A. and Ward, R. D. (1999). Microsatellite loci to determine stock structure of the Patagonian toothfish, *Dissostichus eleginoides*. Molecular Ecology, 8: 1753-1754.

Roff, D. A. and Bentzen, P. (1989). The statistical analysis of mitochondrial DNA polymorphisms: χ^2 and the problem of small samples. Molecular Biology and Evolution, 6: 539-545.

Sambrook, J., Fritsch, E. F. and Maniatis, T. (1989). Molecular Cloning: a Laboratory Manual, 2nd edn. Cold Spring Harbor Laboratory Press, New York.

Sokal, R. R. and Rohlf, F. J. (1981). Biometry, 2nd edn., WH Freeman and Co., USA, 770-782.

Zaykin, D. V. and Pudovkin, A. I. (1993). Two programs to estimate significance of χ^2 values using pseudo-probability tests. Journal of Heredity, 84: 152pp.

Table 11.1 Allele sizes (base pairs), numbers of alleles, and frequencies. Sample sizes are numbers of genes examined (equals twice the number of fish as each fish carries two genes at each locus). NV=Northern Valleys; AT=Aurora Trough.

Locus	Allele size	NV	AT	Overall	Locus	Allele size	NV	AT	Overall
cmrDe2	119	2	0	0.030	*cmrDe9*	212	1	0	0.016
16 alleles	121	0	1	0.015	23 alleles	216	0	1	0.016
	123	6	2	0.121		221	1	0	0.016
	125	2	3	0.076		222	2	2	0.063
	127	1	3	0.061		224	3	0	0.047
	129	1	2	0.045		226	3	1	0.063
	131	1	2	0.045		228	4	7	0.172
	133	2	3	0.076		230	5	1	0.094
	135	2	3	0.076		232	0	1	0.016
	137	4	2	0.091		234	3	3	0.094
	139	2	1	0.045		236	0	1	0.016
	141	4	3	0.106		238	3	0	0.047
	143	3	3	0.091		240	4	2	0.094
	145	3	0	0.045		242	0	1	0.016
	147	1	2	0.045		248	1	1	0.031
	149	0	2	0.030		250	0	1	0.016
	Total	34	32	66		252	0	1	0.016
						254	1	0	0.016
cmrDe13	171	1	0	0.015		256	0	2	0.031
7 alleles	174	0	2	0.029		259	1	1	0.031
	177	21	20	0.603		263	0	2	0.031
	180	8	2	0.147		267	0	1	0.016
	183	2	1	0.044		271	2	0	0.031
	186	1	8	0.132		284	0	1	0.016
	189	1	1	0.029		Total	34	30	64
	Total	34	34	68					
					cmrDe4	260	0	1	0.016
cmrDe30	161	4	0	0.069	12 alleles	266	1	1	0.031
9 alleles	165	2	1	0.052		269	3	4	0.109
	167	0	1	0.017		272	4	7	0.172
	171	1	0	0.017		275	8	3	0.219
	173	17	16	0.569		278	8	3	0.172
	175	6	1	0.121		280	1	3	0.063
	177	1	5	0.103		283	2	6	0.125
	179	0	1	0.017		286	3	2	0.078
	181	1	1	0.034		289	1	0	0.016
	Total	32	26	58		294	2	0	0.031
						300	1	0	0.016
						Total	34	30	64

Table 11.2 Data analysis of the five microsatellite loci at two fishing grounds off Macquarie Island. Ground 1 = Northern Valleys, Ground 2 = Aurora Trough. Sample size is numbers of fish examined. The probability of inter-sample homogeneity (P) is shown along with Hardy-Weinberg observed (Ho) and expected (He) heterozygosity values and their associated P value, HW(P).

Locus	Ground	Sample size	Alleles (n)	Allele size range (bp)	Homogeneity (P)	Ho	He	HW (P)
cmrDe4	1	17	11	266-299	0.244	0.882	0.849	0.999
	2	15	9	260-287		0.933	0.851	0.999
cmrDe13	1	17	6	171-189	0.025	0.588	0.557	0.118
	2	17	6	174-189		0.588	0.590	0.570
cmrDe9	1	17	13	212-270	0.135	1.000	0.905	0.995
	2	15	18	216-284		1.000	0.904	0.996
cmrDe30	1	16	7	161-181	0.046	0.813	0.660	0.515
	2	13	7	165-181		0.588	0.651	0.038
cmrDe2	1	17	14	119-147	0.637	1.000	0.898	0.998
	2	16	14	121-149		0.824	0.917	0.996

12. Bycatch and fishery interactions

Dick Williams, Barbara Wienecke, Tim Lamb, Esme van Wijk and Graham Robertson

Summary
From 1997 to 2000, bycatch and contacts between seabirds and seals and fishing gear were recorded during the conduct of the Macquarie Island fishery for toothfish. A total of 47,042 seabird and seal sightings were made. Of 631 shots and hauls during the observation period, 263 shots and 344 hauls were observed for wildlife interactions. Contacts between wildlife and fishing gear were noted in 58 and 124 of observed shots and hauls respectively. Of 637 interactions observed in total, none appeared to result in any injuries. The only other incident reported was the death of one southern elephant seal that may have died in the net. The low number of serious incidences can probably be ascribed to the absence of a netsonde cable and other preventative measures. Bycatch of fish and invertebrates averaged 8.48% of total catch in all hauls (5.13% finfish and 3.35% invertebrates), and was relatively low in the established fishing grounds of Aurora Trough/Caroline Trough (2.23%) and Northern Valleys (12.0%) compared to the exploratory hauls in other locations (52.93%). In both fishing grounds percentage bycatch has risen from the 1998/99 season onwards, coincident with a decline in toothfish catches. The vast majority of fish bycatch is common and widespread species and is not considered a threat to their populations either locally or globally. While some invertebrate types may be vulnerable to fishing operations, these are predominantly found outside the established fishing grounds where fishing effort is low. Marine Protected Areas and Tasmanian State Waters also protect over 40% of the seabed area in the central section of the Macquarie Ridge where all the known fishing grounds are located. However, if toothfish catches remain low or new vessels gain access to the fishery the consequences for bycatch need to be considered carefully.

Introduction
In recent years, marine wildlife and fisheries interactions have attracted attention because of large numbers of seabirds and thousands of seals reported dying in large-scale commercial fishing operations (King 1984, Ogi 1984, Brothers 1991, Perez and Loughlin 1991, Miller *et al*. 1996). Although accurate information on the numbers of birds being killed is difficult to obtain, commercial fishing operations have been implicated as contributing to the decline in populations of, for example, albatrosses (Prince *et al*. 1998) and other seabird populations (Woehler 1996). Very high mortality of seabirds has been reported from longline fisheries where seabirds dive for baited hooks, get caught and drown (Brothers 1991). Seals and other marine mammals appear to avoid longliners but tend to get caught in trawl nets. For example, over the past decade the trawl fishery for squid around New Zealand's subantarctic Auckland Islands (50°40'S, 166°10'E) claimed around 775 of the endangered Hooker's sea lions *Phocarctos hookeri*, (Anon. 1999). Statistics of this kind warrant concern and it is not surprising that the establishment of new fisheries face close scrutiny, especially if active near World Heritage areas, such as Macquarie Island.

Another source of worldwide concern over trawling operations has been the effects on benthic communities of the nets and associated gear dragging across the seabed (Dayton 1998, Koslow and Gowlett-Holmes 1998, Freese *et al*. 1999). Effects on previously undisturbed grounds can be detected after only a relatively small amount of fishing, and can remain for a considerable time after fishing ceases (Tuck *et al*. 1998).

Austral Leader has been the only vessel licensed to catch toothfish around Macquarie Island. Since 1996, an observer program, implemented by the Australian Fisheries Management Authority (AFMA), has enabled data to be collected with regard to bycatch on every voyage. In

addition, interactions between wildlife and the vessel and its fishing gear have been recorded and counts of seabirds and seals made during trawl operations. Wildlife/vessel interactions are most likely to occur during net setting and hauling activities when food becomes available to seabirds and seals. Protocol for observations of wildlife/fishing gear interactions were prepared by the Australian Antarctic Division and AFMA. Licence conditions require that all fatalities and other major incidents be reported to AFMA within 24 hours.

Our objectives were to determine the kind and extent of bycatch and contacts between wildlife and the fishing vessel and its trawl operations; to monitor trends over time, and to assess the direct impact that the fishing vessel and its gear had on wildlife attending it. We describe here the results of observations between September 1997 and February 2000.

Materials and methods
Data collection
AFMA observers collected data on seabird and seal interactions during six summer voyages to Macquarie Island between 30 September 1997 and 14 February 2000. Data collected by observers on earlier voyages were not analysed in this report because information was not collected or recorded in a standard way. Observations were made from the stern gantry during fishing operations and were recorded on standardised forms. During shots, observers monitored wildlife interactions with fishing gear and/or the vessel from the initial deployment of the net until the first 500 m of cable were released. During hauls, observations were made while the last 500 m of cable were pulled in and until the net was completely on board. Due to the drag resistance of the net in water plus the drag of about 1,000 m of warp, the cables emerge at a steep angle to the water about 4 m astern of the ship. The time and duration of each observation session were recorded. Each observed incident was described in terms of the time when the interaction occurred, a contact code (Table 12.1), a contact point describing the gear that was involved in the contact, and a code describing the fate of the animal ranging from no apparent damage to death (Table 12.4).

The numbers of birds and seals following the vessel within 300 m were also counted to provide a measure of their abundance during hauls. The sum of counts, however, reflects the numbers of bird sightings, not the numbers of individual birds because it was impossible to separate individuals on consecutive counts; the same bird may have been counted more than once in several counting sessions. Observers counted for two to five minutes before the trawl doors were secured as most birds remained on the water at that time, making a relatively accurate count possible. The noise of the doors reaching the vessel appeared to be a signal for birds, especially black-browed albatrosses (*Thalassarche melanophrys)*, to take off and fly around rapidly.

Although the Macquarie Island fishery started in November 1994, bycatch is only analysed here starting in the 1996/97 season that began in December 1996. This is because bycatch was not recorded in a systematic or consistent way before then. Beginning in December 1996, the entire contents of the net were dropped into the fish pounds and bycatch was sorted from target species by the factory hands either in the processing line or in the fish pounds. Observers then sorted the bycatch and recorded the total number and weight of specimens in each grouping. Taxonomic groupings for non-fish species tended to be broad because observers were usually unfamiliar with the complex higher taxonomy of invertebrates and reference material was scarce. Research hauls have not been included in this analysis and large sharks are dealt with separately because the irregular occurrence of such large animals distorts the data. Bycatch species have been grouped to illustrate the major components, but in some instances the groupings also reflect the ability of the observers to identify certain taxa. For example, the grouping Corals/Sponges exists because observers are frequently unable to distinguish sponges from soft corals, and "other invertebrates" may include animals listed separately in other groups when the observers have not identified them as such.

Sleeper Sharks (*Somniosus antarcticus*) are caught regularly, but in low numbers. These sharks can be large (up to 5.1m long and 1.3 tonnes in weight) and are dealt with separately to avoid distorting the data on other bycatch. Sleeper Sharks are usually very inactive when on deck. Specimens were measured (total length) and the sex noted. Except for rare occurrences when the shark was obviously dead or severely injured they were tagged in the trailing edge of the first dorsal fin with a cattle ear tag (Allflex Australia, Brisbane) and released. Five specimens have been retained for taxonomic study.

Identification of seabirds
The field guides of Harrison (1988) and Onley and Bartle (1999) were used to identify seabirds. Because of the difficulties in identifying birds to species level in poor visibility or at night, numbers of southern and northern giant petrels were aggregated and referred to as giant petrels. Similarly, royal and wandering albatrosses were combined and are referred to as 'great albatrosses'.

Results
Because of the small number of voyages seasonal effects were not investigated. Incidences where birds landed on the vessel were not included in the analysis as such events do not occur exclusively on fishing vessels. All birds that landed on the vessel were released unharmed.

Observation coverage
Observers were present on every voyage to Macquarie Island during the period covered by this study and aimed to monitor 60% of shots and hauls for seabird and seal interactions. However, inclement weather often made observations impossible. Observations were made during 263 (42%) shots and 344 (55%) hauls of the 631 trawls, and wildlife interactions were noted during 58 (22%) observed shots and during 124 (36%) of the hauls that were monitored (Table 12.2).

Observers monitored events during shots and hauls for 47 h and 106 h, respectively, and the average length of observation sessions per voyage ranged from 10 to 17 minutes during shots and 13 to 19 minutes during hauls.

Observers aimed to monitor all hauls for bycatch. As they were not able to be present in the factory at all times, however, they relied on the crew to sort the bycatch from some hauls and keep it aside for later examination. For some hauls, particularly in the early stages of the program, this was not done. Also, occasionally more than one haul was mixed in the pounds and so bycatch was reported for a batch of several hauls combined. Where there was any doubt about the quality of the data from a haul, they were discarded from the analysis. The data in Tables 12.5-12.7 show that 78% of all hauls representing 51% of the toothfish catch have been successfully monitored for bycatch.

Seabird and seal counts
Overall, 47042 sightings of seabirds and seals were recorded (Table 12.3). Giant petrels (*Macronectes* spp.) and black-browed albatrosses were most numerous comprising 49.1% and 31.7% of all sightings respectively. Only nine seal sightings were recorded during observation periods.

Wildlife/fishing gear interactions
During shooting
Only three species were seen to interact with fishing gear and black-browed albatrosses were by far the most common (170, 71%, Table 12.4). Of the 120 contacts observed between these birds and any fishing gear, 103 occurred when the birds attempted to grab fish from the net. The second most frequent interactions involved giant petrels (27%) most of which also had contact with the net. Albatrosses and giant petrels both tended to be sitting on the water when the

contact occurred. Only four great albatrosses were seen to approach the net. No bird came to harm during net setting operations.

During hauling
About three times as many contacts involving black-browed albatrosses were counted during hauling than during shooting and virtually all were with the bird on the water having light contact with the warp wires (Table 12.4). The number of giant petrels also increased when the net was brought to the surface, but in contrast to the albatrosses that flew around the stern of the ship the giant petrels remained on the water and attacked the net. No bird was seen to sustain any serious injuries or die.

Only two marine mammals were encountered. On a single occasion a fur seal was seen swimming around the net but it did not touch it. During one haul, a juvenile male southern elephant seal (*Mirounga leonina)* was discovered dead in the trawl net. There were no external injuries and the animal appeared generally in good condition. The likely cause of death was by drowning after it had been caught in the net.

Bycatch amount and composition in the toothfish fishery
Table 12.5 details the weight in kg of bycatch by major taxon in each of the fishing grounds. Principal fishing locations fall into two main areas in which grounds are close together, but the areas are widely separated. The selection of these two areas (Aurora Trough/Caroline Trough (AT/CT) and Colgate Valley/Grand Canyon/Beer Garden (Northern Valleys)) is supported by data on fish movements inferred from the tagging program, which shows that fish move between grounds within an area, but not between areas. All other fishing locations within the Macquarie Island AFZ have been grouped under "Other Grounds". These represent prospecting shots covering a wide area of Macquarie Ridge, with no concentration of shots in any one place. Tables 12.6 and 12.7 present the same data for each bycatch taxon expressed as a percentage of total weight caught, including toothfish (Table 12.6) and as a percentage of total bycatch caught (Table 12.7).

Overall, 78.4 tonnes of bycatch have been recorded, representing 8.48% of the total catch (Tables 12.5 & 12.6). In terms of gross weight Corals/Sponges (23.8 tonnes), *Macrourus carinatus* (22.8 tonnes), other macrourids (15.5 tonnes), Lithodid crabs (4.8 tonnes) and *Antimora rostrata* (4.3 tonnes) are the largest components. Overall bycatch is low compared to the catch of target species.

Although Northern Valleys account for 61.3 tonnes of the total bycatch, which is 12.0% of the total catch in that area, the greatest percentage of bycatch in total catch (52.9%) is recorded in Other Grounds (Tables 12.5 & 12.6). This reflects the prospecting nature of hauls in Other Grounds. AT/CT had the lowest overall percentage of bycatch in the total catch of 2.23%. In both the established fishing areas of AT/CT and Northern Valleys, percentage of bycatch in the total catch increased markedly in the 1998/99 and 1999/00 seasons, probably a reflection of the general low catches of toothfish in those seasons (see Chapter 6). In previous seasons percentage of bycatch was low in the two established fishing areas, but slightly higher in the Northern Valleys than in AT/CT. The high catch of corals and sponges in the 1997/98 season in Northern Valleys was due to the vessel widening its search for aggregations of toothfish that had recently dispersed (see Chapter 6), which lead to hauls covering parts of the ridges between the valley features.

Principal components of the bycatch are generally similar at all fishing locations, with some variations in individual seasons (Table 12.7). The rat-tail *Macrourus carinatus*, other macrourids, Corals/Sponges and Lithodid Crabs (principally the large *Lithodes murrayi*) constitute the bulk of the bycatch. In 1997/98 the percentages of Other Macrourids were higher than in other years, while at the same time the percentages of *M. carinatus* were lower, which

may indicate that *M. carinatus* was being lumped in with Other Macrourids. All macrourids together with the morid cods *Antimora rostrata* and *Halargyreus johnsoni* were most common in the 1998/99 and 1999/00 seasons when toothfish were scarce. This may reflect more intensive searching in deep water during those seasons, where these fish are more abundant. Corals/Sponges were uncommon at AT/CT but formed a consistently high proportion of the bycatch in the Northern Valleys. The converse is generally true for Lithodid Crabs, although the percentage of these was low in 1998/99 at AT/CT but high in 1996/97 in the Northern Valleys. Over all seasons, fish bycatch exceeds that of invertebrates in the established fishing grounds, particularly in the 1998/99 season, but in the Other Grounds invertebrates form a greater percentage of the bycatch than fish overall.

Because the occurrence of Sleeper Sharks in the catch is such a noteworthy event, data are available from the entire fishery, including the first season when observers were not present, and data from research as well as commercial hauls have been included in the analysis. Table 12.8 shows that 49 of the 60 Sleeper Sharks caught in the Macquarie Island fishery have been taken in the Aurora Trough/Caroline Trough area, which implies that Aurora Trough/Caroline Trough is an area where the sharks are particularly abundant or more susceptible to capture. When the data are standardised for fishing this is confirmed. The number of hauls and toothfish catch compared to catch of Sleeper Shark is substantially lower for Aurora Trough and Colgate Valley than for most other areas (Table 12.8). One feature common to Aurora Trough, Caroline Trough and Colgate Valley is that they are all features close to the western margin of the Macquarie Ridge.

Discussion
Seabird and seal interactions
Heavy rain, snow or fog made observations difficult at times, as did very high numbers of birds behind the vessel. Seabirds most commonly came in contact with warp cables and net (Table 12.4). Contacts with the net were considered intentional as the birds attempted to extract small fish caught in the mesh, while contacts with the warp cables were considered accidental. Birds wheeling around the stern tended to touch the warp cables with their wings but appeared to be wary of the gear and seemed to be able to judge its movement and generally avoid contact. One elephant seal probably drowned in the net. Until recently, many seabird deaths in other fisheries were caused by netsonde monitor cables that extended from the top of the aft gantry to some 20m behind the stern of the ship. The number of seabirds killed by collisions with fishing gear was at least six times higher on vessels using netsonde cables compared to those using alternative net monitoring devices and most fatalities were caused by these cables (Weimerskirch *et al.* 2000). The licence conditions for the Macquarie Island fishery prohibit the use of netsonde cables and this has undoubtedly led to a reduction in seabird interactions. The licence conditions also prohibit the discharge of any offal in order to reduce the attractiveness of vessels to seabirds and minimise incidental mortality.

These results are encouraging; they show that a commercial fishery is able to operate without causing significant mortalities among wildlife attending the vessels.

It is currently impossible to assess the impact of fatalities on a population level, as life history parameters essential for such an analysis (e.g. accurate estimates of population size) are unavailable for most species. However, the seabirds interacting with fishing gear generally comprised abundant species and no mortalities were recorded. Hence, the interactions reported here are unlikely to affect species at their population level. Of course, any serious interactions involving rare and/or endangered species are likely to have a significant impact. For example, the population of wandering albatrosses *(Diomedea exulans)* at Macquarie Island presently consists of only 10 breeding pairs (Gales 1998). A single fatality could have serious consequences for this already diminished population. However, so far in the Macquarie fishery only 13 interactions involving great albatrosses have been recorded; all of them a light contact

with no apparent injury (Table 12.4). It is not possible to determine from the data how many of these interactions were with wandering albatross, as "great albatrosses" can be either royal or wandering albatross.

Under current licence conditions and operational procedures, harmful interactions between wildlife and fishing gear were considered rare and the physical risk to seabirds and seals posed by the Australian toothfish trawler seems to be minimal. Since the abandonment of netsonde cables, warp cables appear to be the most dangerous gear components to seabirds.

Observer programs can provide valuable information and should be implemented in all fisheries. Now that baseline data are established, a review of the observation procedure should be conducted to evaluate the frequency of observations necessary to provide an overview of the effect the fishery has on wildlife. Observation times during the day should be randomised and all possible fatalities (inside and outside observation times) should continue to be reported immediately. The presence of an endangered species in the vicinity of fishing grounds may require a more intensive observation effort to safeguard the conservation status of this species.

Bycatch
In both established fishing grounds overall bycatch was low in the 1996/97 and 1997/98 seasons but rose from the 1998/99 season onwards when toothfish catches declined. This confirms observers' reports that good catches of toothfish contain little bycatch, whereas poor toothfish catches usually contain appreciable amounts of bycatch. In most cases therefore absolute bycatch (in kg per haul) rose after the 1997/98 season (Figure 12.1) as well as the percentage of total catch represented as bycatch. In "Other Grounds", bycatch has been more consistent both absolutely and relatively because these grounds are all prospecting shots invariably with little or no toothfish.

Overall, about 60% of all bycatch is fish species (Table 12.7). Most of these are active benthopelagic species, in particular *Macrourus carinatus* but including other macrourids, morids and *L. squamifrons* that would be expected to be caught along with toothfish. The catch of *M. carinatus* as a percent of total catch (Table 12.6) increases significantly from the 1998/99 season onwards in the established fishing grounds, particularly in the Northern Valleys where fishing tended to go deeper in these years and so had a greater impact in the distribution range of this species.

"Other Grounds" by contrast tend to have more invertebrates than fish in the bycatch. These grounds are much more varied in habitat; they are often the tops of ridges, flats or valley sides as distinct from the two established fishing grounds that are for the most part in valleys with black sand or cobble/rock substrate. Invertebrate groups, especially sponges and corals but also crabs and echinoderms are thus much more common in the bycatch from the "Other" grounds. The Northern Valleys generally produce slightly more benthos bycatch than Aurora Trough, possibly because they have a more rocky or stony substrate than Aurora Trough, which tends to have a sandy floor. A significant increase in invertebrate bycatch in the Northern Valleys during the 1999/00 season (Table 12.6) could be due to the vessel exploring more widely around the ground, especially in Beer Garden, and encountering more varied benthic habitat, as was the case in the 1997/98 season in Colgate Valley and Grand Canyon when the initial toothfish aggregations disappeared.

During the whole period of this assessment, which includes all but the first two years' fishing in Aurora Trough, the impact of the toothfish fishery on bycatch species appears to be slight. In the two established fishing grounds total catch of the main fish bycatch species *M. carinatus*, other macrourids and morids has totalled only 43 tonnes in a toothfish catch of 840 tonnes (Table 12.5). None of the principal fish bycatch species is considered rare or endangered; in fact they

are some of the commonest and most widespread species in subantarctic waters (Gon and Heemstra 1990).

No data on bycatch are available for other subantarctic trawl fisheries that can be used to put the Macquarie Island data into context. A comparable fishery for which bycatch data are available is the Tasmanian Orange Roughy trawl fishery, conducted in comparable depths (>700m) in cool-water rocky slope areas. Table 12.9 shows that bycatch off Tasmania constituted 3.5 to 11.18% of the total catch, which is higher than that in Aurora Trough in 1996-1998 but in the same range in 1999-2000 when toothfish catches declined (Table 12.6). Similarly the Tasmanian fishery bycatch is in the same range as that in the Northern Valleys in 1996-1998, but lower in 1999-2000 when the toothfish catches declined. Bycatch composition was very different, however, with the amount of benthos (= invertebrates) from Tasmania (Table 12.9) being similar to or less than that from the Macquarie Island grounds (Table 12.7). The fish bycatch from Tasmania is very diverse with numerous species of sharks & rays and oreos & dories dominating, whereas at Macquarie Island comparatively few species of macrourids and morids dominate.

Among the invertebrate bycatch only corals/sponges and lithodid crabs have been taken in appreciable amounts (Table 12.5). Lithodid crabs are common and widespread, but corals and sponges can be susceptible to disturbance from fishing or other activities because they can have very specific habitat requirements and slow growth and replacement rates. Most of the catches of these invertebrate groups have been taken in "Other Grounds" where over all seasons 30.6% of the catch has been invertebrates (Table 12.6). This is not surprising as the nature of prospecting dictates that a wide range of different habitats will be sampled. As none of the "Other Grounds" produced worthwhile quantities of toothfish and the effort in these areas was very low compared to that in the established fishing grounds, the impact of fishing in these areas on benthos is slight. In the established fishing grounds, invertebrate bycatch does not exceed 5% of the total catch overall (Table 12.6). It is consistently lower in Aurora Trough than in the Northern Valleys. These results are consistent with a survey of benthos conducted in January 1999. This showed that in the deep sediment filled valleys to which trawling is largely confined, benthos is usually not very abundant (except in some locations close to Beer Garden) and is composed of small, widely distributed species of probably low conservation concern (Butler *et al*. 2000). In the central region of the Macquarie Ridge, where all the known fishing grounds are located, over 40% of the sea-floor area less than 1,000m deep is protected from fishing, either in a Category 1 Marine Protected Area or as Tasmanian State Waters. This, together with the lack of fishing grounds outside the established grounds in the valley systems where benthos bycatch is low, suggests that the fishery does not in its present form have a serious impact on benthic communities generally. However in the last two years when toothfish catches have declined and trawls have tended to cover more extensive areas around the known fishing grounds, the percentage of bycatch has increased. This trend needs to be monitored carefully, especially in the Beer Garden region where there are rich benthic communities nearby (Butler *et al*. 2000). Also, any new entrants to the fishery will have to repeat the prospecting phase in order to establish their own fishing grounds. This potential impact should be considered when deciding on licences for the fishery.

References

Anon. (1999). Hooker's sea lions: victims of squid fishing.
http://www.nzwwa.com/education/conservation/forest-
bird/brochure/hooker/sealion.htm

Brothers, N. (1991). Albatross mortality and associated bait loss in the Japanese longline fishery
in the Southern Ocean. Biological Conservation, 55, 255-268.

Butler, A., Williams, A., Koslow, J. A., Gowlett-Holmes, K., Barker, B., Lewis, M. and Reid,
R. (2000). A study of the Conservation Significance of the Benthic Fauna Around
Macquarie Island and the Potential Impact of the Patagonian Toothfish Trawl Fishery.
CSIRO, Hobart.

Dayton, P. K. (1998). Reversal of the burden of proof in fisheries management. Science, 279:
821-822.

Freese, L., Auster, P. J., Heifetz, J. and Wing, B. L. (1999). Effects of trawling on seafloor
habitat and associated invertebrate taxa in the Gulf of Alaska. Marine Ecology Progress
Series, 182: 119-126.

Gales, R. (1998). Albatross populations: status and threats. Albatross biology and conservation
(eds G. Robertson and R. Gales), pp. 20-45. Surrey Beatty and Sons, Chipping Norton,
New South Wales.

Gon, O. and Heemstra, P. C. (eds.) (1990). Fishes of the Southern Ocean. J.L.B. Smith Institute
of Ichthyology, Grahamstown.

Harrison, P. (1988). Seabirds, an identification guide. Croom Helm, London.

King, W. (1984). Incidental mortality of seabirds in gillnets in the North Pacific. Status and
Conservation of the world's seabirds. (eds J. P. Croxall, P. G. H. Evans, and R. W.
Schreiber), pp. 709-716. ICBP Technical Publication No 2, Paston Press, Norwich.

Koslow, J. A. and Gowlett-Holmes, K. (1998). The seamount fauna off southern Tasmania:
Benthic communities, their conservation and impacts of trawling. Final report to
Environment Australia and the Fisheries Research Development Corporation. FRDC
Project 95/058

Miller, C. M., Oosthuizen, W. H. and Wickens, P. A. (1996). Cape fur seals trapped in trawling
gear: age structure, sex ratio, seasonality and distribution. South African Journal of
Marine Science, 17: 105-111.

Ogi, H. (1984). Seabird mortality incidental to the Japanese salmon gill-net fishery. Status and
Conservation of the world's seabirds. (eds J. P. Croxall, P. G. H. Evans, and R. W.
Schreiber), pp. 717-722. ICBP Technical Publication No 2, Paston Press, Norwich.

Onley, D. and Bartle, S. (1999). Identification of seabirds of the Southern Ocean: a guide for
scientific observers aboard fishing vessels. Te Papa Press, Wellington.

Perez, M. A. and Loughlin, T. R. (1991). Incidental catch of marine mammals by foreign and
joint venture trawl vessels in the U.S. EEZ of the North Pacific, 1973-88. NOAA
Technical Report NMFS 104.

Prince, P. A., Croxall, J. P., Trathan, P. N. and Wood, A. G. (1998). The pelagic distribution of South Georgia albatrosses and their relationships with fisheries. Albatross biology and conservation (eds G. Robertson and R. Gales), pp. 137-167. Surrey Beatty and Sons, Chipping Norton, New South Wales.

Tuck, I. D., Hall, S. J., Robertson, M. R., Armstrong, E. and Basford, D. J. (1998). Effects of physical trawling disturbance in a previously unfished Scottish sea loch. Marine Ecology Progress Series, 162: 227-242.

Weimerskirch, H., Capdeville, D. and Duhamel, G. (2000). Factors affecting the number and mortality of seabirds attending trawlers and longliners in the Kerguelen area. Polar Biology, 23: 236-249.

Woehler, E. (1996). Concurrent decreases in five species of Southern Ocean seabirds in Prydz Bay. Polar Biology, 16: 379-382.

Table 12.1 Contact codes describing the interactions between seabirds and seals and fishing gear for the toothfish fishery around Macquarie Island.

Code	Definition
Seabirds	
1	bird sits on water, very light contact with vessel/gear
2	bird sits on water, heavy contact with vessel/gear; bird may be dragged underwater
3	bird flying; light contact with vessel/gear; does not deviate from course
4	bird flying, heavy contact with vessel/gear; bird deviates from course and/or dragged underwater
5	bird snagged on loose wire ends (e.g. splice ends)
6	high speed collision with vessel gear
7	bird caught in net
8	bird snagged on net while attempting to feed
Seals	
1	seal sighted within 50 m of net but no contact made
2	light contact with net
3	seal climbs on net
4	seal caught in trawl net

Table 12.2 Number of observations of shots and hauls in the Macquarie Island toothfish fishery from 1997 to 2000.

Variable	Total number	Number observed	Percent observed
Number of voyages	6		
Number of trawls	631		
Number of shots observed		263	42
Number of shots when interactions observed		58	22
Number of hauls observed		344	55
Number of hauls when interactions observed		124	36

Table 12.3 Counts of sightings of seabirds and seals during toothfish fishing operations around Macquarie Island from 1997 to 2000. Percentages given in brackets.

Name	Scientific name	Total numbers counted (%)
ALBATROSSES:		
Great (Amsterdam, Wandering, Southern and Northern Royal)	*Diomedea amsterdamensis, D. exulans, D. epomophora, D. sanfordi*	2965 (6.3)
Black-browed (Southern and Northern)	*Thalassarche melanophrys*	14913 (31.7)
Buller's	*D. bulleri*	35 (0.1)
Grey-headed	*D. chrysostoma*	68 (0.1)
Shy	*D. cauta*	340 (0.7)
Light-mantled	*Phoebetria palpebrata*	73 (0.1)
Sooty	*P. fusca*	4 (0.0)
PETRELS:		
Cape	*Daption capense*	364 (0.8)
Southern Fulmar	*Fulmarus glacialoides*	15 (0.0)
Blue	*Halobaena caerulea*	1 (0.0)
Giant (Northern and Southern)	*Macronectes halli, M. giganteus*	19750 (49.1)
White-chinned	*Procellaria aequinoctialis*	6 (0.0)
Grey	*P. cinerea*	33 (0.1)
Antarctic	*Thalassoica antarctica*	1024 (2.2)
Storm	*Oceanites, Fregetta spp.*	669 (1.4)
OTHER BIRDS:		
Kelp Gulls	*Larus dominicanus*	115 (0.2)
Sooty shearwaters	*Puffinus griseus*	239 (0.5)
Prions	*Pachyptila spp.*	2659 (5.7)
Cormorants	*Phalacrocorax spp.*	14 (0.0)
Skuas	*Catharacta spp.*	24 (0.1)
Penguins		45 (0.1)
MAMMALS:		
Antarctic fur seal	*Arctocephalus gazella*	9 (0.0)
Total		47042

Table 12.4 Summary of contacts between wildlife and fishing gear at Macquarie Island observed during shots (S) and hauls (H).

	Black-browed albatrosses		Great albatrosses		Giant petrels		Others	Total birds	Seals[b]
	S	H	S	H	S	H	H only		H only
CONTACT CODE									
1. bird: on water, light contact with vessel/gear; seal: near net but no contact	115	352	4	9	37	102	2[a]	621	1
2. bird: on water; heavy contact; dragged under; seal: light contact with net	1	0	0	0	1	0	0	2	0
3. bird: flying; light contact; remains on course; seal: climbs on net	3	0	0	0	6	1	0	10	0
4. bird: flying; heavy contact; deviates from course; and/or dragged under water; seal: caught in net	0	0	0	0	0	0	0	0	0
5. bird snagged on loose wire ends	0	0	0	0	0	0	0	0	0
6. high speed collision with vessel gear	0	0	0	0	0	0	0	0	0
7. bird caught in net	0	0	0	0	0	0	0	0	0
8. bird snagged on net while attempting to feed	0	0	0	0	0	0	0	0	0
no data entry	1	1	0	0	2	0	0	4	0
Totals	120	353	4	9	46	103	2	637	1
CONTACT POINT									
1. warp wire	16	352	0	0	6	1	0	375	0
2. trawl doors	0	0	0	0	0	0	0	0	0
3. backstrops, bridles, sweeps	0	0	0	0	0	0	0	0	0
4. net	103	0	4	9	38	102	2	258	1
5. vessel	0	0	0	0	0	0	0	0	0
6. paravanes (includes towing wire)	0	0	0	0	0	0	0	0	0
7. other	1	1	0	0	2	0	0	4	0
FATE									
1. no apparent injury	120	350	4	8	46	103	2	633	1
2. possible minor injury	0	0	0	0	0	0	0	0	0
3. possible major injury	0	0	0	0	0	0	0	0	0
4. death	0	0	0	0	0	0	0	0	0
5. unknown	0	0	0	0	0	0	0	0	0
no data entry	0	3	0	1	0	0	0	4	0

[a] one shy albatross, one kelp gull; [b] In addition one Elephant Seal was found dead in the net, but not observed during routine observation.

BYCATCH AND FISHERY INTERACTIONS

Table 12.5 Catches (kg) of major bycatch groups by fishing area and season in the Macquarie Island toothfish fishery. AT/CT=Aurora Trough/Caroline Trough; Northern Valleys=Colgate Valley, Grand Canyon and Beer Garden. Toothfish catch within seasons has been removed to retain commercial confidentiality.

Fishing area	Fishing season	Total hauls	Total toothfish catch	Hauls observed	Toothfish catch observed	*Macrourus carinatus*	Other macrourids	*Antimora rostrata*	*Halargyreus johnsoni*	*Lepidonotothen squamifrons*	Other fish	Jellyfish	Corals/Sponges	Lithodid crabs	Other crustaceans	Cephalopods	Echinoderms	Other invertebrates	Total bycatch Weight	Total catch
AT/CT	96/97	143	-	72	-	295	7	9	3	4	33	47	32	569	15	307	10	1	1332	-
AT/CT	97/98	106	-	96	-	358	446	27	4	76	34	111	34	1295	3	29	8	0	2425	-
AT/CT	98/99	36	-	24	-	3610	37	264	352	35	142	100	22	82	3	36	14	1	4695	-
AT/CT	99/00	25	-	25	-	254	0	7	0	0	5	25	8	144	0	7	1	0	451	-
AT/CT	Total	310	724425	217	390176	4516	490	308	359	114	214	283	95	2090	21	379	33	2	8904	399080
Northern Valleys	96/97	81	-	26	-	51	1	1	0	52	11	12	704	342	0	30	30	0	1235	-
Northern Valleys	97/98	278	-	271	-	181	13819	633	329	166	187	43	15075	1276	4	53	113	26	31905	-
Northern Valleys	98/99	99	-	81	-	15505	594	3201	1960	86	131	580	3367	343	4	150	49	3	25973	-
Northern Valleys	99/00	26	-	26	-	975	4	77	10	0	10	9	950	100	0	14	41	0	2190	-
Northern Valleys	Total	484	924450	404	449469	16712	14418	3911	2299	304	339	645	20096	2062	8	246	234	29	61303	510772
Other Grounds	96/97	1	-	1	-	100	0	2	0	0	0	0	2	1	0	0	0	9	114	-
Other Grounds	97/98	28	-	28	-	117	547	55	41	32	17	7	2278	34	2	12	7	4	3152	-
Other Grounds	98/99	68	-	36	-	1170	23	60	16	1071	25	219	776	570	2	78	4	30	4046	-
Other Grounds	99/00	33	-	33	-	170	0	12	0	0	9	62	583	50	0	23	1	0	910	-
Other Grounds	Total	130	7526	98	7311	1557	571	128	57	1103	51	288	3638	656	4	113	13	43	8223	15534
All Grounds	All Years	924	1656400	719	846956	22786	15479	4347	2715	1521	604	1216	23829	4808	34	738	279	75	78430	925385

BYCATCH AND FISHERY INTERACTIONS

Table 12.6 Bycatch as percent of total weight caught by fishing area and season in the Macquarie Island toothfish fishery. AT/CT=Aurora Trough/Caroline Trough; Northern Valleys=Colgate Valley, Grand Canyon and Beer Garden.

Fishing area	Fishing season	Total number of hauls	Hauls observed	*Macrourus carinatus*	Other macrourids	*Antimora rostrata*	*Halargyreus johnsoni*	*Lepidonotothen squamifrons*	Other gish	Jellyfish	Corals/Sponges	Lithodid crabs	Other crustaceans	Cephalopods	Echinoderms	Other invertebrates	Total bycatch	All fish bycatch	All invertebrates
AT/CT	96/97	143	72	0.16	0.00	0.01	0.00	0.00	0.02	0.03	0.02	0.31	0.01	0.17	0.01	0.00	0.74	0.19	0.54
AT/CT	97/98	106	96	0.21	0.26	0.02	0.00	0.04	0.02	0.06	0.02	0.75	0.00	0.02	0.00	0.00	1.40	0.55	0.86
AT/CT	98/99	36	24	9.26	0.09	0.68	0.90	0.09	0.36	0.26	0.06	0.21	0.01	0.09	0.03	0.00	12.04	11.38	0.66
AT/CT	99/00	25	25	4.09	0.00	0.12	0.00	0.01	0.09	0.40	0.12	2.33	0.00	0.11	0.02	0.00	7.28	4.30	2.98
AT/CT	Total	310	217	1.13	0.12	0.08	0.09	0.03	0.05	0.07	0.02	0.52	0.01	0.09	0.01	0.00	2.23	1.50	0.73
Northern Valleys	96/97	81	26	0.15	0.00	0.00	0.00	0.15	0.03	0.04	2.07	1.01	0.00	0.09	0.09	0.00	3.64	0.34	3.29
Northern Valleys	97/98	278	271	0.04	3.36	0.15	0.08	0.04	0.05	0.01	3.67	0.31	0.00	0.01	0.03	0.01	7.76	3.73	4.04
Northern Valleys	98/99	99	81	24.86	0.95	5.13	3.14	0.14	0.21	0.93	5.40	0.55	0.01	0.24	0.08	0.00	41.64	34.43	7.21
Northern Valleys	99/00	26	26	28.23	0.11	2.23	0.29	0.00	0.28	0.27	27.51	2.90	0.00	0.40	1.19	0.01	63.41	31.14	32.27
Northern Valleys	Total	484	404	3.27	2.82	0.77	0.45	0.06	0.07	0.13	3.93	0.40	0.00	0.05	0.05	0.01	12.00	7.44	4.57
Other Grounds	96/97	1	1	87.57	0.18	1.75	0.00	0.00	0.00	0.00	1.75	0.88	0.00	0.00	0.00	7.88	100.00	89.49	10.51
Other Grounds	97/98	28	28	2.93	13.69	1.36	1.01	0.79	0.42	0.17	56.98	0.86	0.05	0.31	0.18	0.10	78.85	20.21	58.65
Other Grounds	98/99	68	36	11.19	0.22	0.57	0.15	10.24	0.24	2.10	7.42	5.46	0.02	0.75	0.04	0.29	38.70	22.63	16.08
Other Grounds	99/00	33	33	17.61	0.00	1.21	0.02	0.04	0.89	6.40	60.19	5.18	0.01	2.37	0.11	0.00	94.04	19.77	74.27
Other Grounds	Total	130	98	10.02	3.67	0.83	0.37	7.10	0.33	1.85	23.42	4.22	0.03	0.73	0.08	0.28	52.93	22.32	30.62
All Grounds	All Years	924	719	2.46	1.67	0.47	0.29	0.16	0.07	0.13	2.58	0.52	0.00	0.08	0.03	0.01	8.48	5.13	3.35

BYCATCH AND FISHERY INTERACTIONS

Table 12.7 Bycatch of individual groups as percentage of total bycatch weight by fishing area and season in the Macquarie Island toothfish fishery. AT/CT=Aurora Trough/Caroline Trough; Northern Valleys=Colgate Valley, Grand Canyon and Beer Garden.

Fishing Area	Fishing season	Total number of hauls	Hauls observed	*Macrourus carinatus*	Other macrourids	*Antimora rostrata*	*Halargyreus johnsoni*	*Lepidonotothen squamifrons*	Other fish	Jellyfish	Corals/Sponges	Lithodid crabs	Other crustaceans	Cephalopods	Echinoderms	Other invertebrates	All fish bycatch	All invertebrates
AT/CT	96/97	143	72	22.13	0.56	0.71	0.20	0.27	2.49	3.55	2.38	42.70	1.13	23.07	0.72	0.11	26.35	73.65
AT/CT	97/98	106	96	14.78	18.39	1.12	0.18	3.12	1.40	4.57	1.40	53.40	0.12	1.18	0.33	0.01	38.99	61.01
AT/CT	98/99	36	24	76.87	0.78	5.62	7.49	0.74	3.02	2.14	0.46	1.74	0.06	0.77	0.29	0.01	94.52	5.48
AT/CT	99/00	25	25	56.17	0.02	1.60	0.00	0.09	1.17	5.43	1.68	31.95	0.05	1.52	0.33	0.00	59.04	40.96
AT/CT	Total	310	217	50.72	5.50	3.46	4.03	1.28	2.41	3.18	1.07	23.47	0.24	4.26	0.37	0.03	67.40	32.60
Northern Valleys	96/97	81	26	4.13	0.09	0.04	0.00	4.20	0.92	1.01	56.98	27.72	0.00	2.42	2.46	0.01	9.39	90.61
Northern Valleys	97/98	278	271	0.57	43.31	1.98	1.03	0.52	0.59	0.13	47.25	4.00	0.01	0.17	0.35	0.08	48.00	52.00
Northern Valleys	98/99	99	81	59.70	2.29	12.32	7.55	0.33	0.50	2.23	12.96	1.32	0.02	0.58	0.19	0.01	82.69	17.31
Northern Valleys	99/00	26	26	44.52	0.17	3.52	0.45	0.00	0.44	0.43	43.37	4.58	0.00	0.63	1.87	0.01	49.10	50.90
Northern Valleys	Total	484	404	27.26	23.52	6.38	3.75	0.50	0.55	1.05	32.78	3.36	0.01	0.40	0.38	0.05	61.96	38.04
Other Grounds	96/97	1	1	87.57	0.18	1.75	0.00	0.00	0.00	0.00	1.75	0.88	0.00	0.00	0.00	7.88	89.49	10.51
Other Grounds	97/98	28	28	3.71	17.36	1.73	1.28	1.00	0.53	0.22	72.26	1.09	0.07	0.39	0.23	0.12	25.63	74.37
Other Grounds	98/99	68	36	28.91	0.57	1.48	0.40	26.47	0.63	5.42	19.18	14.10	0.05	1.93	0.11	0.75	58.46	41.54
Other Grounds	99/00	33	33	18.73	0.00	1.28	0.02	0.04	0.95	6.80	64.01	5.51	0.01	2.52	0.12	0.00	21.02	78.98
Other Grounds	Total	130	98	18.94	6.94	1.56	0.69	13.41	0.62	3.50	44.25	7.98	0.05	1.38	0.15	0.53	42.16	57.84
All Grounds	All Years	924	719	29.05	19.74	5.54	3.46	1.94	0.77	1.55	30.38	6.13	0.04	0.94	0.36	0.10	60.50	39.50

Table 12.8 Summary of capture of Sleeper Sharks around Macquarie Island, as compared to fishing operations and toothfish catches.

Area	No. of hauls	Total toothfish caught (tonnes)	No. Sleeper Sharks caught	Hauls/Sleeper	Tonnes toothfish/Sleeper
Aurora Trough	892	2085	49	18.2	42.6
Colgate Valley	130	154	5	26.0	30.8
Grand Canyon	141	485	3	47.0	161.7
Beer Garden	218	287	3	72.7	95.7
Others	182	19	0	-	-

Table 12.9 Retained catch and bycatch observed in the fishery off Eastern and Western Tasmania in depths greater than 700m (original data from J. Garvey, BRS, pers. comm.).

Year	Retained catch (kg)	Composition of retained catch (% by weight)			Discarded catch (kg)	% of total discarded	Composition of discarded catch (% by weight)					
		Orange Roughy	Other fish	Crustacea molluscs			Sharks rays	Macrourids	Oreos Dories	Other fish	Crustacea molluscs	Benthos
1992	31705	93.51	6.49	0	3990	11.18	27.32	2.99	65.64	0.85	0	3.20
1993	165404	92.48	7.51	0.004	20181	10.87	52.87	1.14	12.80	2.53	0.61	30.05
1994	105086	98.70	1.30	0	3823	3.51	14.38	3.17	62.92	13.75	1.65	4.13

Figure 12.1 Trends in mean seasonal bycatch per haul for three fishing areas around Macquarie Island. AT/CT=Aurora Trough/Caroline Trough.
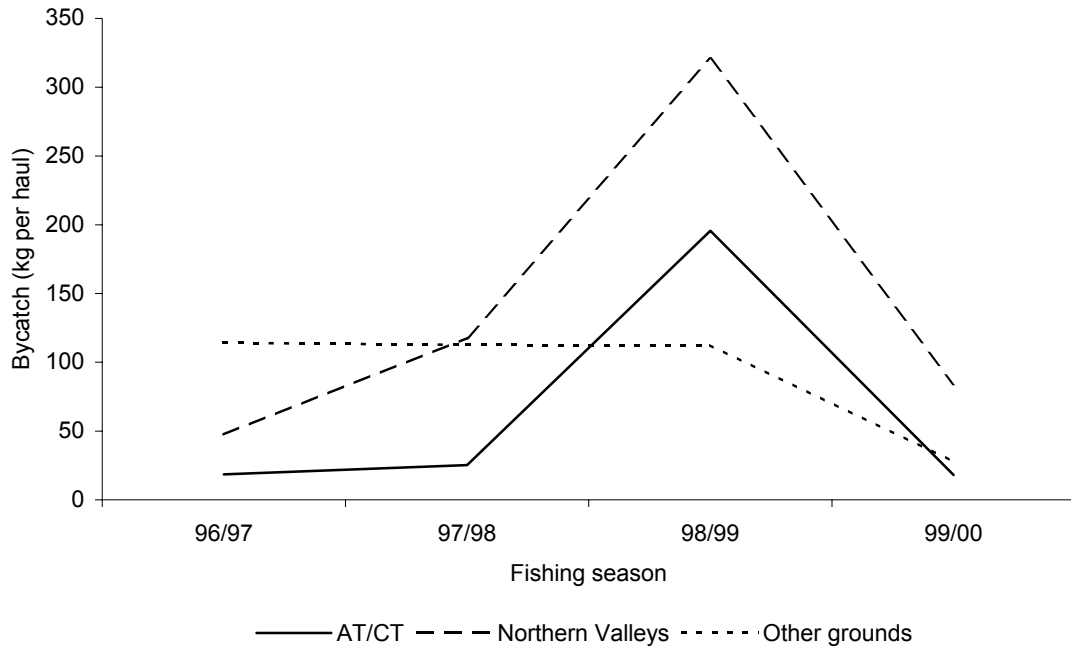
13. Stock assessment of Macquarie Island toothfish

Geoff Tuck, Dick Williams, Xi He, Tony Smith, Andrew Constable, Bill de la Mare, Bill Hearn and Robert Campbell

Summary
This chapter presents an assessment of the harvested population of Patagonian toothfish *(Dissostichus eleginoides)* at Macquarie Island based on data from a tag-recapture experiment initiated during the 1995/96 fishing season. An initial examination of standardised catch rates, which are assumed to be a relative index of apparent abundance, is also presented.

The tag-recapture assessments use population models that include dynamics of tagged and un-tagged fish, daily releases, catches, recaptures, natural mortality, and annual net recruitment to assess the populations of the main fishing regions of Macquarie Island: Aurora Trough and the Northern Valleys. The pre-tagging abundance is estimated by applying a Petersen approach and maximum likelihood methods. The models assume that the recaptures are Poisson distributed, and the recapture expectations are conditional on catch numbers and previous recaptures. Three assessment models are considered: one that makes no assumption about selectivity (the "no-selectivity model" or NS Model) and two that attempt to account for apparent decreasing availability with length (Models S1 and S2). Model S1 assumes a maximum age or length above which a fish is no longer available to the gear. Each released fish is assigned a length of time in the available population according to its estimated release age. Once this time has elapsed, the fish is removed from the analysis. Model S2 assumes that the likelihood of recapturing a tagged fish is proportional to the selectivity function. Two alternative sets of daily catch data are also considered. Firstly, daily catch data set Catch A, which for all seasons uses the daily number and weight of measured fish and, secondly, data set Catch B which uses the above method for seasons after 1997/98 but uses factory production records for seasons prior to 1997/98. Data set Catch B has been used in all previous assessment reports.

For daily catch data Catch A, the NS model estimated that pre-tagging available abundance was between 0.5 and 1.0 million fish in Aurora Trough and between 4 and 10 million fish in the Northern Valleys region. Results were sensitive to the daily catch data set applied, with Catch A generally providing lower initial estimates of biomass than Catch B. Estimates of net recruitment were occasionally negative suggesting that emigration may have exceeded immigration. The estimated percentage of the pre-tagging available biomass remaining using Model NS was about 40% in Aurora Trough and 7% for the Northern Valleys region. In general, the selectivity models estimated a lower initial available biomass, and a lower percent remaining, than Model NS.

By applying Generalised Linear Modelling techniques to the Macquarie Island catch and effort data, relative indices of apparent abundance were calculated. The standardised catch rates showed a marked decline over the duration of the fishery. However, uncertainty remains with respect to the degree of the decline. Several factors have a strong influence on the resulting indices. The main influential factors are the inclusion of high catch rate observations, the unbalanced nature of the data and the particular effects included in the models.

Both assessment techniques predict substantial declines in available abundance. This reduction in available biomass is greater than can be explained by the fishery catches even in the absence of recruitment. Currently, the spatial and temporal dynamics of the populations at Macquarie Island remain uncertain. Hypotheses being explored to explain the dynamics include that (i) a small resident population exists at Macquarie Island, but that occasional large influxes of fish

are part of a broader, transient population, or (ii) the fish have remained in the area but have become unavailable to the gear (e.g. by dispersing in the water column, moving to untrawlable ground or escaping detection).

Introduction - The Tag-Recapture Stock Assessment Model
Bottom-set longline and trawl fisheries for Patagonian toothfish (*Dissostichus eleginoides*) have developed in waters around several of the Southern Ocean's sub-Antarctic islands. Recently, a trawl fishery for Patagonian toothfish developed within Australian waters surrounding Macquarie Island. The fishery began in November 1994 with one fishing vessel licensed to fish the Macquarie Island toothfish stock. Two fishing regions have since been discovered: the Aurora Trough region (which includes the fishing grounds Aurora Trough and Caroline Trough), and the Northern Valleys region (which includes the Colgate Valley, Beer Garden and the Grand Canyon grounds).

A tagging experiment to collect data on fish abundance and population dynamics began in 1995/96 at Aurora Trough and the following season within the Northern Valleys region. Following the initial season of tagging, a Total Allowable Catch (TAC) for Aurora Trough was set at 750 tonnes (Table 13.1). This was subsequently reduced, and in the administrative seasons of 1999 and 2000 no targeted fishing for Patagonian toothfish was permitted in the Aurora Trough region. However, a 40 tonne research quota was permitted to continue monitoring the Aurora Trough population and its recruitment.

Separate analyses are conducted on the Aurora Trough and the Northern Valleys region as part of the annual review and assessment process. While the applications described in this chapter focus only on these regions, numerous other regions surrounding Macquarie Island have been explored (including the release of tagged fish from these regions). These areas are not analysed here.

The abundance of a population is often estimated by the joint analysis of tag-return and catch data by the Petersen approach and its extensions. Many of these modifications allow estimates of recruitment (Fischler, 1965; Jolly, 1965; Seber, 1965). Semi-parametric models, where some model attributes are specified parametrically and others non-parametrically, have been used to analyse daily release and recapture tagging data when it is not feasible to parameterise fishing mortality rates (Hearn et al., 1987; Leigh, 1988; Barndorff-Nielsen et al., 1989; Leigh et al., 2000). As these models analyse only tag-return data, only mortalities can be estimated, not population abundance. It is difficult to set up a likelihood function in a conventional way with these models, although the solutions they present are either maximum-likelihood or close to it.

The model used to assess the Macquarie Island Patagonian toothfish stock is a modification of the de la Mare and Williams (1997) model that unifies the semi-parametric approach with the Petersen method. It gives an estimate of the pre-tagging abundance of Patagonian toothfish accessible to the fishery and the net annual recruitment. We assume that Aurora Trough and the Northern Valleys regions are distinct populations. This assumption is supported by a preliminary genetic study (Reilly et al., 1998) and the apparent lack of movement between regions suggested by the tagging experiment (Williams et al., 1998). We also assume that tag recaptures are conditional on catches and previous recaptures of other fish, and are Poisson distributed.

The tag-recapture model we propose can only estimate the available abundance and not the total abundance of the stock. As defined by Marr (1951), availability is the degree (a proportion) to which a population is accessible to the efforts of a fishery. The trawl fishery at Macquarie Island selects a certain size or age-range of fish; these are the "available" fish to the fishery. Changes in oceanographic conditions and population movements can also influence their availability.

Thus, unless changes in the availability of the population can be determined, only the available abundance of the fished population can be measured.

Estimation of Tag-Detection Rates
Since the 1995/96 fishing season, over 4400 Patagonian toothfish have been tagged in the waters around Macquarie Island, of which over 500 have been recaptured. A high proportion of these fish were double-tagged with visible plastic and electronic tags. In the 1996/97 season, an electronic tag detector was installed on the vessel. Unfortunately, the electronic detector was initially not fully effective, so less than 100% of the electronic tags were detected

Tag-recapture experiments rely on the tags being discovered and reported when the fish is captured. This may not occur if tags are lost from the fish, or if tagged fish are not detected. From the recapture of multiple tagged fish in this fishery, a reasonable assumption can be made that tag loss is negligible. A potential effect of not including tag loss could result in over-estimating abundance. Likewise, as many individual fish were recaptured several times, tagging mortality was assumed to be zero.

The non-detection of tagged Patagonian toothfish has been a problem, especially with the electronic tags. If it is assumed that the probability of detecting the two types of tags is independent, then the total number of tagged fish (r) in the catch can be estimated using the moment estimator[1],

$$ r = n_v n_e / n_{ve}, $$

where n_v and n_e are the number of tagged fish detected either visually or electronically, and n_{ve} is the number detected by both methods. Table 13.2 shows the number of tags detected by each method by season. For example, in the 1996/97 season $n_v = 33 + 36 = 69$, $n_e = 11 + 36 = 47$ and $n_{ve} = 36$, giving an estimate of $r = 90.08$. As a total of 80 fish were detected, the estimated detection rate is $\lambda = 0.888$. The estimated detection rate for 1996/97 is used for season 1995/96, as the electronic detector was not operational at that time. In 1997/98 and 1998/99 the estimated detection rates increased to over 0.95.

Catch, Releases and Recaptures
Two alternative sets of daily catch data are considered here. Firstly, daily catch data set Catch A which, for all seasons, uses the daily number and weight of measured fish (Method C1), and secondly data set Catch B which uses the above method for seasons after 1997/98 but uses factory production records for seasons prior to 1997/98 (Method C2). Only data set Catch B was used in the assessment reports by de la Mare and Williams (1997) and Tuck et al. (1998, 1999). Tuck et al. (2000) considered both catch data sets. Each of these methods is defined in Appendix 1.

Table 13.3 shows a summary by season of the catch (in numbers of fish), releases of tagged fish and recaptures from Aurora Trough. The tagging experiment began in Aurora Trough in early January 1996 and the first season's tagging concluded in late March with 490 releases. There were 42 recaptures during the season, most of which were in March. The longest time-at-liberty for a tagged fish during the first season was 78 days. The numbers of released fish were fairly evenly distributed across the first season, with releases mainly of between 10 and 20 fish. The largest release, 51 tagged fish, was on the 28th of March 1996.

---

[1] This equation states that the fraction of all recaptures detected visually, n_v/r, is assumed to equal the fraction of all recaptures detected electronically that were also detected visually, n_{ve}/n_e. Rearranging this equation for total recaptures yields, $r = n_v n_e/n_{ve}$.

Under a precautionary approach to the management of the population, the Aurora Trough ground was closed to commercial fishing for season 1998/99. However, a research quota of 40 tonnes was allocated to maintain the tagging program and population monitoring. With the reduction in quota, catches and recaptures were greatly reduced. However, a substantial number of tagged fish were released. The low catches and a high proportion of the releases occurring late in the season may explain the low number of recaptures from within the 1998/99 season. Catch in season 1999/2000 was poor, however 566 fish were tagged and released. Only 8 tagged fish were recaptured during the summer 1999/2000 and June 2000 cruises.

Catches and releases began in the Northern Valleys region during January 1997, with 45 tagged fish being released on the 1st of January. During the first tagging season only 3 tagged fish were recaptured from a total of 540 releases (Table 13.4). These were recaptured on the 18th, 22nd and 23rd of January 1997 after 16, 1 and 2 days free respectively. The low number of recaptures may be due to small catches being experienced after most of the tagged fish had been released, and the apparently large abundance of fish.

During the 1997/98 season there were another 538 releases. Recaptures totalled 129, of which 53 were from 1996/97 tagged fish and 76 from within the 1997/98 season. The 1998/99 season saw a reduction in catch and a corresponding reduction in the number of recaptures. From a total of 312 releases, 9 were recaptured within the season. This trend continued during the summer 1999/2000 and June 2000 cruises, with poor catches and only 3 tagged fish recaptured. However, a substantial number of fish were tagged during the summer cruise (272), but only 2 fish were released during June 2000 (these were re-releases).

Only 2 tagged fish have transferred between Aurora Trough and the Northern Valleys. A tagged fish released in Colgate Valley on the 22nd of October 1997 was recaptured 87 days later on the 17th of January 1998 in Aurora Trough, and a fish released on the 12th of November 1997 in Aurora Trough was recaptured in the Northern Valleys on the 22nd of January 1999 after 436 days-at-liberty

Methods
Because tag releases and recaptures occur throughout the fishing period, we used a semi-parametric or daily model to account for daily catch, releases and recaptures. In this analysis it is assumed that there is neither recruitment nor emigration during the fishing season. Net recruitment into the available stock between seasons is estimated when more than one year of tag returns are available.

The probability of recapturing a tagged fish depends on the number of tagged fish in the water, the size of the fishable stock and the availability of the stock. The total expected number of tag returns from a single catch will then depend on the probability of recapture and the size of the catch (Petersen's equation[2]). The probability of recapture will vary with time as tagged fish are released and recaptured, and as the size of the population changes with catches and recruitment.

The No-Selectivity (NS) Model
Let N_t be the number of available fish in the population on day t, and C_t the number of fish caught on day t, then

$$N_t = (N_{t-1} - C_{t-1})S, \tag{1}$$

---

[2] Provided tagged fish have mixed with the un-tagged population, Petersen's equation states that the proportion of marked fish in the population, m/N, should equal the proportion of recaptured fish in the catch, r/C. Rearranging this equation for recaptures yields, $r = Cm/N$.

where $S = exp(-M/365)$ and M is the annual natural mortality rate. This is the daily version of the catch equation used in Virtual Population Analysis (VPA) (Gulland, 1965; Murphy, 1965; Pope, 1972). Uncertainty remains regarding the value of M and so two values are considered that adequately reflect the range of uncertainty, $M=0.1$ and $M=0.16$ (SC-CAMLR, 1998; Constable *et al.*, 2000).

The number of fish available to the gear prior to the tagging experiment is N_0 and the reference day is taken as 1 July. One year later, R_y recruits are added to the population. The between-season "net recruitment" is a measure of the net change in available abundance between seasons. Hence, recruitment (in the usual sense) of young fish is not explicitly modelled, but is aggregated with availability and movement effects.

Using the catch equation, the number of tagged fish in the population on day t is

$$m_t = (m_{t-1} - r_{t-1}^*)S + p_t,$$ (2)

where p_t is the number of tagged fish released on day t. The total number of recaptured fish on day t is given by

$$r_t^* = r_t / \lambda_i,$$ (3)

where r_t is the observed number of recaptures and λ_i is the recapture rate for season i (Table 13.2). The number of observed recaptures on day t is assumed to follow a binomial distribution, $r_t \sim B(\beta_t, C_t)$, with mean μ_t defined by

$$\mu_t = E[r_t] = \lambda_i \frac{m_t}{N_t} C_t = \beta_t C_t.$$ (4)

As there are large catches (or samples), the Poisson distribution approximates the binomial distribution, and thus $r_t \sim Po(\mu_t)$, inferring random, non-clumped returns.

Maximum likelihood estimates of virgin available abundance, N_0, and net recruitment in year y, R_y, are then found by maximising the log-likelihood function given by

$$\ln L(r; N_0, R_y) = \sum_{t:\mu_t \neq 0} (r_t \ln(\mu_t) - \mu_t).$$ (5)

Selectivity Models
The Patagonian toothfish caught in the trawl fishery at Heard and McDonald Islands and Macquarie Island are predominantly between 450 mm and 1,000 mm long (Williams et al., 1998; Constable et al., 1999). This observed length-frequency is related to both gear selectivity and fish availability. Evidence from deep-set longline toothfish fisheries at other sub-Antarctic Islands where large fish are caught in greater numbers, and the infrequent but evident catch of large fish at Macquarie Island, suggests that their availability at Macquarie Island decreases with length. This is likely to arise as a result of smaller fish being segregated from adult fish, with the adults tending to be found in deeper water (SC-CAMLR, 1998). Model NS assumes that all tagged fish remain available to the gear regardless of age or length. As such it is possible that the model assumes there are more tagged fish available than there are in reality, which would lead to an over-estimation of available abundance. This is because Petersen's equation (and Model NS) assumes that abundance is proportional to the number of tagged fish in the

population. Hence, for the same catch and number of recaptures, the population estimate will be biased upward if the number of tagged fish available is, in fact, lower than anticipated.

Two models are described to consider the sensitivity of the parameter estimates to the 'loss' of tagged fish from the available population. The first selectivity model (Model S1) assumes that all tagged fish are available to the gear for a period of time determined by their length at release. The basic assumption is that small fish will remain in the available population for a longer period of time than large fish. A fixed age, A_{max}, (or length) is assigned as the age at which tagged fish are no longer available to the gear. Each fish is given a 'lifetime' in days that it remains available to the gear, after which it is removed from the tagged population (i.e. from equation (2)).

Each release is aged according to parameters from a von Bertalanffy growth curve, given by

$$a = t_0 - \ln(1 - L / L_\infty) / k,\qquad(6)$$

where L_∞ is the asymptotic length of a fish, k is a growth-rate parameter and t_0 is the age at which a hypothetical fish is of length 0 cm. The number of days that it is 'alive' is then the maximum age less its estimated age at release. All recaptures are included in the model regardless of their length at recapture. The von Bertalanffy growth curve parameters have been estimated from model fits to age-length data for Macquarie Island Patagonian toothfish pooled across sexes and seasons (Chapter 10) and are: L_∞=185.5cm, k=0.042 and t_0=-0.781.

The second selectivity model, Model S2, assumes that the likelihood of recapturing a released fish is a function of selectivity. Every released fish is aged according to the von Bertalanffy growth curve (equation (6)) using its recorded release length and then grows accordingly on a daily basis. The selectivity of a tagged fish is assumed to be a function of its length l, and is given by equation (1) of Chapter 10 and illustrated in Figure 13.1. This assessment model assumes that the selectivity is constant across all years and is given by the narrow 'triangular' selectivity curve estimated for resident fish (see Table 14.2 and associated text).

The expected number of surviving available tagged fish is then the sum of the selectivity of all released fish that have not been recaptured yet,

$$m_t = \sum_j s(l_t^j) \exp(-(t - t_r^j)M / 365),\qquad(7)$$

where $s(l_t^j)$ is the selectivity of tagged fish j which has length l on day t and the exponent term gives the probability of survival of tagged fish j from the day of its release t_r^j to the current day t. Equation (7) replaces equation (2) in the description for the NS Model. A derivation of equation (7) is given in Appendix 2.

Model sensitivity to mixing
As the tagged fish are released in a group, they possibly do not mix with the un-tagged population for some days. This can bias estimates of abundance. For example, if tagged fish remain near the vessel and are recaptured shortly after release, then the assessment model is likely to under-estimate abundance. Likewise, if tagged fish (or the vessel) move to another region, tagged fish will be under-represented in the catch and estimates of abundance will be biased upward.

We follow the simple procedure used by Hearn (1986), Tuck et al. (1998) and Leigh et al. (2000) to allow a period of time for tagged fish to mix with the general population.

Let,

δ = the number of days for tagged fish to fully mix with the un-tagged population.

To explore the sensitivity of the model to δ, tagged fish recaptured within δ days are removed from the analysis, i.e. both the release and recapture events are removed from the input data. As there can be no recaptures within δ days from a release (and thus no expectation of a recapture), the day of all releases must be shifted forward by δ days. However, as the tagged fish have truly been in the water an additional δ days, the number of fish released must also be discounted by δ days of natural mortality.

Confidence Limits
The likelihood profile method (as applied by Hilborn and Walters, 1995) is used to calculate a 95% confidence set around a point estimate of a parameter, *N*. The confidence limits defining the boundary of the confidence set are defined as those values of N_{sub} that satisfy,

$$L(r; N = N_{sub}) - L(r; N = N_{opt}) = \chi^2_{1,1-\alpha} / 2, \qquad (8)$$

where $L(r;N = N_{opt})$ is the negative log-likelihood corresponding to the maximum likelihood estimate (giving N_{opt} as the point estimate), and $L(r;N = N_{sub})$ is the lowest negative log-likelihood when N is set to the sub-optimal value N_{sub}. The value of the chi-squared distribution with one degree of freedom at confidence level $1-\alpha$ is given by $\chi^2_{1,1-\alpha}$. For $\alpha = 0.05$, the right-hand side of equation (8) is equal to 1.92.

Results for the Aurora Trough Region
Model NS
Figure 13.2 shows the proportion of recaptured tagged fish that remain in the analysis for the Aurora Trough region when the time to full mixing, δ, is increased. If there are no tagged fish remaining in the analysis ($\delta > 78$) then the model cannot estimate both pre-tagging available abundance and the 1996 net recruitment.

For Model NS, Figure 13.3 shows the point estimates and 95% confidence limits for pre-tagging available abundance and net recruitments as a function of δ. These model results assume M=0.1 and apply daily catch data set Catch A. The largest value of δ considered is 50 days, as for values greater than this, less than 15% of the recaptured tagged fish remain in the analysis to estimate pre-tagging available abundance and 1996 recruitment (Figure 13.2).

If it is assumed that tagged fish mix with un-tagged fish immediately ($\delta = 0$), then the estimate of pre-tagging available abundance (on 1 July 1995) is approximately $N_0 = 0.72$ million fish. The 95% confidence limits around this estimate are $L_{95} = 0.63$ and $U_{95} = 0.94$ million fish for the lower and upper confidence limits respectively. When δ increases, there is an initial increase in the abundance estimate up to $\delta = 8$, with $N_0 = 1.0$ million fish. This increase is likely to be due to the large number of recaptures shortly after release. From the Petersen equation, abundance is inversely proportional to the number of recaptures, and as δ increases these recaptures are removed from the analysis, and the population estimate increases. Between $\delta = 8$ and $\delta = 25$, estimates remain between 0.9 and 1.0 million fish. Thereafter estimates decline to about 0.7 million fish. Note that as δ increases the confidence limits also increase, as there are fewer recaptures for the analyses. For $\delta = 10$ the estimated pre-tagging available abundance is $N_0 = 0.9$ million fish.

Estimates of net recruitment (i.e. net change in available abundance between seasons) in 1996 are generally negative until $\delta = 38$. Negative values suggest a net exodus of available fish

between seasons 1995/96 and 1996/97. This exodus may have been due to emigration exceeding immigration (and local recruitment to the available population). For $\delta = 10$ the estimate for 1996 recruitment is $R_{96} = -0.16$ million fish.

Estimates of recruitment for years 1997 and 1998 show less sensitivity to δ than do estimates of first-year recruitment and abundance. This is largely because of the greater number of tag recaptures for a particular δ, which assists the model's estimation of parameters. However, the estimate of 1999 recruitment shows much larger confidence limits (ranging over 1 million fish compared to approximately 0.2 million fish in the previous two years). This is because only 8 fish were recaptured during the summer 1999/2000 and winter 2000 cruises, and catches were substantially less than in previous years (Table 13.3).

As the models keep an account of daily changes in available abundance for the duration of the tagging experiment, estimates of population trajectories can be displayed. For $\delta = 10$, Figure 13.4 shows the predicted trajectories of available abundance for the NS Model and selectivity Model S2 for the two catch data sets. There is a marked difference in the predicted trajectory of available abundance depending on which catch data set is used. For Catch B the initial estimate of abundance is approximately 1.4 million fish, compared to 0.94 for Catch A. The estimate of abundance on the final day (1 July 2000) is approximately 0.5 million fish for both data sets. This difference is much less evident when considering the available biomass trajectories. The available biomass was calculated by multiplying the daily available abundance by the average annual weight of fish caught in the Aurora Trough region (Table 13.5). Figure 13.4 shows the estimated available biomass decline from about 5,000 tonnes to 2,000 tonnes over the five seasons of fishing. Note that while the 1999 recruitment shows an increase in available abundance, the biomass shows a corresponding decrease due to the low mean weight per fish in season 1999/2000. The mean weight per fish for the June 2000 cruise was applied from 1 April 2000, resulting in a small increase in biomass.

Estimates of the percent remaining in available abundance and biomass are shown in Figure 13.5. These values are determined by taking the final estimate of available abundance and dividing by the estimated pre-tagging available abundance, discounted by 1 year of natural mortality. Depending on the level of mixing, the estimates of percent remaining are between 40% and 80% of the initial available abundance, and between 30% and 50% of the initial available biomass. As mentioned in the introduction, these figures relate to the abundance that is available to the fishery (i.e. the available abundance) and not to the total abundance of the population. Also, the large estimated reduction in available abundance and biomass observed in 1996, which is principally responsible for the overall decline since 1995, could not have been due to fishing alone. It is important to note the large confidence limits associated with the 1999 recruitment value as this level of uncertainty reflects directly onto these depletion estimates.

The Selectivity Models
Figure 13.6 shows an application of Model S1 with M=0.1, Catch A and where tagged fish remain in the available population until they are estimated to be of age $A_{max} = 18$. If the growth parameters are $t_0 = -0.781$, $L_\infty = 185.5$, and $k = 0.042$, then a fish of age 18 is approximately 101cm in length. Over 95% of the measured fish in the catch from Aurora Trough are less than 101 cm in length. The available abundance and biomass trajectories are less than predicted by the NS Model for all δ values.

Figure 13.7 shows the estimated pre-tagging available abundance and recruitments with 95% confidence limits for Model S2 with M=0.1, Catch A, growth parameters $t_0 = -0.781$, $L_\infty = 185.5$, and $k = 0.042$ and the selectivity function illustrated in Figure 13.1. The point estimates for Model NS are also displayed for comparison. Estimates of pre-tagging available abundance are less than those estimated by the NS model. For δ=10, the value of N_0 is 0.70 million fish

compared to 0.94 million fish for Model NS. The predicted 95% confidence limits are also much tighter, as they are for the recruitment estimates. Apart from the 1998 recruitment estimate (of ~0.20 million fish), this model predicts essentially negligible recruitment to the Aurora Trough region since the beginning of the fishery.

Figure 13.4 shows the trajectories of available abundance and biomass for the above model (Model S2) with δ=10 and when the two catch data sets are applied. As seen with Model NS, there is a substantial difference between estimates of abundance when applying the two data sets, but little when considering available biomass. As observed in Figure 13.7, the selectivity model predicts a much lower abundance than Model NS over all seasons of the fishery, with the initial available biomass decreasing from approximately 3600t to 1200t. A comparison of several of the models' trajectories is shown in Figure 13.6. There is clearly little difference in estimates when natural mortality is increased from $M = 0.1$ to $M = 0.16$. Estimated levels of depletion are shown in Figure 13.5. Most models show a decline of between 40% and 80% in available abundance and between 25% and 50% in biomass depending on the assumed level of mixing.

Results for the Northern Valleys Region
Model NS
Figure 13.8 shows the estimates of pre-tagging available abundance for the Northern Valleys region assuming M=0.1 and applying Catch A. As there were only three tags recaptured in the first season of tagging, the 95% confidence intervals are very broad. The estimated upper bound is over 100 million fish for δ>2. The largest value of δ considered is 16 as that is the longest duration of a tag being at-liberty before recapture in the first season of tagging. Point estimates of initial available abundance varied between 4.0 and 9.6 million fish depending on δ. Estimates of 1997 recruitment also varied considerably with values between R_{97} = -3.0 million fish and R_{97} = -8 million fish. The estimated level of recruitment in 1998 is approximately zero for all values of delta, while for 1999 it is approximately 0.5 million fish. However the 95% confidence limits for the 1999 recruitment estimate range between zero and 4 million fish. This increased uncertainty is because there were only 3 recaptures during the June 2000 cruise, and none during the summer 1999/2000 season. Catch over this period was also extremely small, being less than 2500 fish.

Figure 13.9 shows the predicted trajectories of available abundance and biomass for the NS model and Model S2. A large decline in available abundance and biomass is clearly evident from the first to second seasons. The biomass decline is exacerbated by a decrease in the mean weight of fish for the 1997/98 season (Table 13.6). Depending on the model and the catch data set used, there are large variations in estimated initial available abundance and biomass. The NS model estimate of initial available abundance is N_0 = 7.3 million fish for Catch A and N_0 = 9.7 million fish for Catch B. The final estimate of abundance is 0.9 million fish for both catch data sets. It should be noted that this substantial decline could not have been due to fishing alone, as less than 90,000 fish were caught in season 1996/97 (Table 13.4).

The Selectivity Models
The point estimates of pre-tagging available abundance and recruitments are shown in Figure 13.10 for Model S2. The point estimates for Model NS are also displayed for comparison. Estimates of pre-tagging available abundance are smaller than for the NS model. For δ=10, the value of N_0 is 5.2 million fish compared to 7.3 million fish for Model NS. The predicted 95% confidence limits are also much tighter, as they are for the recruitment estimates. The 95% confidence limits remain broad for the 1999 recruitment estimate, the 95% confidence limit ranging between –0.14 and 2.5 million fish. Figure 13.11 shows the predicted trajectories of available abundance and biomass for each of the assessment models (with δ=10). As with results from Aurora Trough, the trajectories appear relatively insensitive to the choice of M. The

trajectories from Model S2 show an initial available abundance of approximately 5.2 million fish, declining to 0.64 million fish at 1 July 2000. Likewise, available biomass decreases from 31,500t to about 2,000t.

The percentage of available abundance and biomass remaining in the Northern Valleys region is shown in Figure 13.12 (for M=0.1 and Catch A). The estimates range between 10% and 25% in available abundance and between 7% and 14% in available biomass, depending on the assumed level of mixing, δ. If the first season is excluded, then the estimated available abundance has actually increased by 29%, while the available biomass has decreased by only 1% (using Model S2). As mentioned for the Aurora Trough region, it is important to note the large confidence limits associated with the 1999 recruitment value as this level of uncertainty reflects directly onto the depletion estimates in Figure 13.12.

Discussion

The assessment model for Macquarie Island Patagonian toothfish presented here is a novel modelling approach to the estimation of abundance of an exploited fish population where tag-recapture data provide the basic monitoring information. The model takes account of the exact time of catches, releases and recaptures. It readily allows for delayed mixing of the tagged fish with the general population. The data requirements of the model are rather stringent, particularly for daily catch numbers, which may not be practical for many fisheries. However, the Macquarie Island Patagonian toothfish fishery does meet these requirements.

Decreasing availability with length has meant that the catch from the trawl fisheries for Patagonian toothfish is generally composed of small, young fish (Williams et al., 1998; Constable et al., 1999). It is likely therefore that older, larger, tagged individuals are moving out of the available population (to deeper water for example). To account for this two assessment models were considered. The first assumes a maximum age exists above which fish are not selected. A length of time in the available population is then assigned to each released fish. When applied to the Macquarie Island toothfish fishery, this model - referred to as Model S1 - predicts a lower final available abundance than does the NS Model. This is because the latter model assumes that all tagged fish, once released, remain in the available population until they are either caught or die of natural causes. Thus the number of released fish available to the gear is over-estimated and as a Petersen approach is used, where abundance is proportional to the number of marked fish in the population, an over-estimate of abundance results. The bias associated with estimating the number of marked fish in the available population (and hence the bias in the estimate of available abundance) is likely to increase over time as more tagged fish move out of the available population. The second selectivity model considered, Model S2, explicitly defines the selectivity function for the population and assumes that the likelihood of recapture fluctuates with selectivity. As a tagged fish ages and grows, its selectivity, and hence probability of recapture, changes accordingly. This model predicts a substantially smaller overall biomass than the other models. While potentially providing a more appropriate model to assess tagged fish populations, it relies more heavily on parameter estimates of growth and selectivity. Model results presented here were shown to be sensitive to the parameters chosen for the selectivity function. The bias associated with having incorrect parameter estimates is currently being explored.

Analyses of the sensitivity of the assessment models to mixing (i.e. the duration until tagged fish mix with un-tagged fish) indicated that parameter estimates were not overly sensitive to mixing over a wide range of possibilities. Likewise, parameter estimates were not sensitive to changes in growth parameters and natural mortality (Figure 13.6 and Figure 13.11; Tuck et al., 1998). As the model assumes that the likelihood of recaptures is Poisson, the validity of this assumption for the Macquarie Island toothfish data was tested with Greene's (1993) algorithm. The Northern Valleys region data conform to the Poisson hypothesis over all seasons, as does the Aurora Trough data if the recapture event where 17 tagged fish are recaptured from the same

release 18 days before is excluded. Note that the inclusion of this event does not change the point estimates of parameters, but tends to broaden the confidence limits of the point estimates.

All tag-recapture assessment models predict a decline in available abundance in the Northern Valleys region in 1997, and potentially in the Aurora Trough region in 1996, which could not have been due to fishing alone. The net loss may be due to emigration (of a 'transient' population) exceeding immigration. However, there is little direct evidence of broad-scale migration within the Macquarie Island region: only two tagged fish have transferred between Aurora Trough and the Northern Valleys (there is evidence of movement between grounds within the Northern Valleys region). This is supported by preliminary results from genetic analyses, which indicate that exchange between the sites is very low (Reilly *et al.*, 1998). These are surprising results given the proximity of the two main fishing regions.

Introduction - Standardisation of Catch and Effort Data
This section presents an initial exploration and analysis of the catch and effort data obtained from the Macquarie Island Patagonian toothfish fishery. Catch rate data are frequently used to obtain a relative measure of apparent abundance of a harvested stock. Relative indices of abundance reflect fluctuations in density and, while not being an exact measure of the biomass, are assumed to be proportional to the density of the sampled population. While raw or nominal catch rates (total catch divided by total effort) can be used, undue weighting of high effort cells may bias the indices produced. In addition, changes in the fishery or the environment may strongly influence catch rates in any particular year. As such, changes in catch rates may not be due to changes in stock abundance alone. Tuck and Campbell (1999) presented a detailed exploration of Generalised Linear Models (GLMs) applied to the Macquarie Island fishery. Following this work, a sub-set of the models reflecting greater statistical relevance is considered here.

Data Summary
Data have been provided from the catch and effort database maintained by the Australian Antarctic Division. This section presents a summary of the catch and effort data used in this analysis. The data consist of individual records for each trawl and provide information on the following:

1) location (Aurora Trough, Caroline Trough, Colgate Valley, Beer Garden, Grand Canyon, New Grounds)
2) season
3) date (day, month, year)
4) catch (tonnes)
5) effort: swept area (km^2)
6) fishing depth (metres)
7) skipper (coded 1 to 3)

The locations Aurora Trough and Caroline Valley have been combined into a single location for this analysis. Likewise, data from Colgate Valley, Beer Garden and Grand Canyon have been combined into the single location given the title Northern Valleys. The within-location sub-regions have been aggregated due to their relative proximity and tagging evidence that suggests a reasonable level of between region mixing. However, Aurora Trough and the Northern Valleys have been separated for this analysis as evidence from genetic studies and tagging (only two tagged fish having moved between the regions) suggests that each of these populations may be considered as a single unit for management purposes. Areas of exploration outside of these locations (i.e. New Grounds) have not been included in the analysis. Data from the first season (1994/95) was also not included in the analysis as the majority of shots were exploratory and the main grounds were yet to be found. The data for Aurora Trough extends from 1995/96 to 1999/2000. The Northern Valleys were not discovered until the 1996/97 season. A summary is also provided for the winter 2000 cruise, however these data are not included in the standardisation. Note also that the tagging program began in Aurora Trough during 1995/96.

The data were examined for erroneous records such as those with no effort recorded. There were 12 observations with no effort recorded and these were removed from the analysis. Extremely large catch rates were observed in both areas during their first season. The influence of these records is examined by filtering out the high catch rate records, as they may have undue influence on results and could potentially be the result of human error (e.g. accidental miss-reporting, or data punching errors). The months of operation range between October and March in summer, with a single winter cruise in June 2000 (see Table 13.7 and 13.8). March records are only observed in season 1995/96 in Aurora Trough. Unbalanced data sets can lead to poor estimates of parameters and biases in indices of abundance, and as such the month of March and the winter cruise were removed from the catch rate standardisation. Likewise, as records for months October and November are only found in seasons 1997/98 and 1998/99, these months have been combined into a single level for analysis.

Tables 13.9 and 13.10 show tables of catch rates (tonnes per km^2) over all seasons for both Aurora Trough and the Northern Valleys. The distribution of catch rates is clearly very broad, with the majority of records showing catch rates below 20 t/km^2, but with a substantial number of records in the hundreds and even thousands of tonnes per km^2 during the initial seasons of the fishery.

The fishing depth field is defined as the greater of the recorded start and finish depths. While not giving an exact measure of the depth at which fish were caught, it should give a reasonable measure of the relative difference in depth between hauls. In Aurora Trough the main fishing depth lies between 700m and 1000m. For the GLM analysis the depth factor was stratified into 3 levels according to catch rate trends, namely D<700m, 700≤D<900, D≥900m. Figure 13.13 shows the catch rate as a function of depth in Aurora Trough. The Northern Valleys show two main depths at which fishing occurs, namely between 650m and 800m and another mode between 1100 and 1300m (Figure 13.14). For the GLM analysis, depth was stratified into depths, 650≤D≤800m, 800≤D≤1100, D≥1100m.

There have been 3 skippers during the 5 seasons since 1995/96. Unfortunately, not all have participated in the fishery in each season or month (Tables 13.11 and 13.12). The highly unbalanced nature of the data set in this instance reduces the power of the analyses to determine the relative influence of different skippers on fishing success. While skippers (and mates) may well be a significant contributing factor to observed and standardised catch rates, caution should be taken when interpreting results with skipper included as a model effect.

Methods

Catch rate data are frequently used to obtain a relative measure of apparent abundance of a harvested stock. For this purpose, catch rates are assumed to be proportional to the density of the sampled population. While raw or nominal catch rates (total catch divided by total effort) can be used, undue weighting of high effort cells may bias the indices produced. In addition, changes in the fishery or the environment may strongly influence catch rates in any particular year. As such, changes in catch rates may not be due to changes in stock abundance alone.

The standard method used to account for these biases and changes in the fishery is General Linear Modelling (McCullagh, and Nelder, 1989). Factors that may influence catch rates can be either continuous (e.g. sea surface temperature) or categorical (e.g. skipper). The models in this paper have season, month, depth and skipper as categorical effects. A month factor is included, as some months appear to produce larger catch rates than others (January, in particular). Following Tuck and Campbell (1999) the model considered in this paper is:

Model 1: Season, Month, Depth, Skipper

Log Normal Model

$$\ln\left(\frac{C_{s,m,h}}{E_{s,m,h}} + b\right) = m + a_s + a_m + a_d + K + e$$

where $C_{s,m,h}$ and $E_{s,m,h}$ are the catch and effort for a particular season s, month m and haul h,

β is a constant used to avoid the problems of a zero catch rate.

μ is the intercept,

α is the factor for each of the terms in the model (season, month, depth etc.), and

ε is an error term assumed to be independent, normal random variables with zero mean and constant variance, $N(0, \sigma^2)$.

For a particular model, the value taken for β is 2% of the mean nominal catch rate over all seasons. The mean nominal catch rates are shown in Tables 13.13 and 13.14. Sensitivities to filtering the data for extreme catch rate values with potentially large and undue effects on model results are also explored. Three filtering schemes are considered, (i) CPUE<2000t/km^2, (ii) CPUE<400t/km^2, and (iii) CPUE<200t/km^2.

The seasonal indices of abundance relative to the final year of fishing are calculated using the following formula:

$$I_s = \frac{\exp(\boldsymbol{m} + \boldsymbol{a}_s + \boldsymbol{s}^2/2) - \boldsymbol{b}}{\exp(\boldsymbol{m} + \boldsymbol{a}_f + \boldsymbol{s}^2/2) - \boldsymbol{b}}$$

where α_f is the parameter estimate for the final season (1999/2000).

Results

Tables 13.13 and 13.14 show the unstandardised catch rate indices for the three catch-rate filtering schemes. Filtering the high catch rate observations can have a marked effect on the average catch rate. The overall decline from the nominal catch rate being 36:1 and 51:1 in Aurora Trough, while in the Northern Valleys the range is greater, namely 87:1 to 644:1. Note that for Aurora Trough only season 1995/96 is affected by filtering the high catch rate observations. The CPUE<400t/km^2 filter is not shown as there was only one record with a catch rate between 400t/km^2 and 2000t/km^2 and hence the indices under these filtering schemes were very similar. Removing records with a catch rate of greater than 200t/km^2 removes approximately 1% of records from the Aurora Trough region and 4% of records from the Northern Valleys.

Tables 13.15 and 13.16 show the standardised indices of relative abundance using Model 1 for each region. The rate of decline is approximately 46:1 in Aurora Trough for both filtering methods. These indices are similar to those observed in the nominal catch rate.

For the Northern Valleys, the models show a decline of between 33:1 and 182:1 and show similar uncertainty as to the magnitude of the decline as the nominal catch rates. The skipper effect was not as significant as the other model factors, generally being only marginally below the 5% significance level. If the skipper effect is removed from the analysis, the indices show a similar rate of decline between the first and last season as the models with the skipper effect, however the season effect is highly significant. For the Northern Valley region, the model with skipper appears to be explaining much of the decline in observed nominal catch rates (especially between the first two seasons) by suggesting a large skipper effect. The large changes seen in the nominal catch rates are being attributed to the effect of differences in the fishing success of the different skippers. As previously mentioned, as the data for skipper is very unbalanced and in some instances provides little contrast, these results and their interpretation should be treated with due caution. An examination of the residuals (Figures 13.15 and Figure 13.16) shows that due to the large variation in catch rates the model does not fit the catch rates well at the extremes (Pierce and Schafer, 1986).

Discussion

The analyses presented in this section suggest that there continue to be substantial declines in available abundance of Patagonian toothfish in both of the major fishing grounds. The level of the decline is uncertain as the indices are sensitive to the degree of filtering, and the factors included in the models. This sensitivity is likely to be due to several factors, including (a) the short duration of

the fishery (b) the unbalanced nature of the data, providing little contrast between modelled factors, (c) confounding between skipper and season/month effects, (d) the large variation in catch rates between seasons and months, and (e) the influence of large catch rate values in the data.

Tuck et al. (1999) uses the joint analysis of tagging data and relative indices of abundance (Tuck and Campbell, 1999) to estimate pre-tagging available abundance and net recruitment. A similar likelihood framework to that described in the first section of this chapter is applied, with an additional likelihood term for the relative index observations. Similar results were found to those of the tag-recapture analysis. However, in some circumstances this model appeared to have difficulty balancing the conflicting signals from the CPUE and the tagging data from Aurora Trough. The same problem was not encountered when fitting to the Northern Valleys data. This may have been due to the greater uncertainty within the tagging data (due to only 3 tags being recaptured in the first season in the Northern Valleys) and the somewhat similar substantial declines seen between the CPUE series and the tagging data. While showing promise for future assessments, methods that jointly fit the tagging data and catch rate series need further examination, and caution should be taken when interpreting the results.

Conclusion

Results from both the tag-recapture and catch per unit effort assessments indicate that fishing pressure may have been higher than would be desirable in the longer term during the initial seasons at Macquarie Island. Estimates of available biomass at the conclusion of the year 2000 season from the tag-recapture models in Aurora Trough show a decline to approximately 30% of the pre-tagging available biomass, while in the Northern Valleys region this figure may be much less than 30%. While consistently indicating a decreasing trend in relative abundance, the catch rate analyses was inconclusive with regard to the magnitude of the decline. Depending on the error model and effects, the data filter and the model for balancing the data set, the magnitude of the decline varied between 6:1 and 21:1 in Aurora Trough and between 3:1 and 28:1 in the Northern Valleys region.

Estimates of net recruitment of available biomass from the tag-recapture analysis have fluctuated greatly for both grounds. In Aurora Trough estimates suggest an overall decline in available biomass during the first two years of approximately 2,000t to 3,000t. This was followed by a positive recruitment (in terms of available biomass) of approximately 1,000t in year 1998. Estimates of net recruitment in 1999 were more uncertain but showed negligible or perhaps negative recruitment. The current level of available biomass in Aurora Trough is estimated to be at a similar level to that at the beginning of the 1996/97 season (i.e. about 1,000t to 2,000t). The Northern Valleys region shows a dramatic decline in available biomass between the first and second seasons. The available biomass levels of season 1996/97 have not been observed since. Estimated net recruitments have been negligible, and the current estimated available biomass is similar to that estimated at the beginning of the 1997/98 season.

In all of the assessment models considered, emigration appears to have exceeded immigration between some fishing years. The most notable event appears to have occurred in the Northern Valleys region in 1997. The estimated reduction in biomass was greater than can be explained by the fishery catches even in the absence of recruitment. Currently, the spatial and temporal dynamics of the populations at Macquarie Island remain uncertain. Hypotheses being explored to explain the dynamics include that (i) a small resident population exists at Macquarie Island, but that most fish are part of a broader, transient population, or (ii) the fish have remained in the area but have become unavailable to the gear (e.g. by dispersing in the water column, moving to untrawlable ground or escaping detection).

References

Barndorff-Nielsen, O. E., James, I. R. and Leigh, G. M. (1989). A note on a semi-parametric estimator of mortality. Biometrika 76: 803-805.

Constable, A. J., Williams, R., Lamb, T. and van Wijk, E. (1999). Revision of biological and population parameters for *Dissostichus eleginoides* on the Heard Island Plateau (Division 58.5.2) based on a comprehensive survey of fishing grounds and recruitment areas in the region. CCAMLR WG-FSA 99/68.

de la Mare, W. K. and Williams, R. (1997). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies. Sub-Antarctic Fisheries Assessment Group document. SAFAG-97/6. Australian Fisheries Management Authority, Canberra.

Fischler, K. J. (1965). The use of catch-effort, catch sampling and tagging data to estimate a population of blue crabs. Trans. Amer. Fish. Soc. 94: 287-310.

Greene, W. H. (1993). Econometric Analysis. Macmillan, New York.

Gulland, J. A. (1965). Estimation of mortality rates. Annex to Arctic Fisheries Working Paper Group Report. Paper presented to ICES Annual Meeting, 1965 (mimeo).

Hearn, W. S. (1986). Mathematical methods for evaluating marine fisheries. PhD thesis. University of New South Wales. 195p.

Hearn, W. S., Sandland, R. L. and Hampton, J. (1987). Robust estimation of the natural mortality rate in a completed tagging experiment with variable fishing intensity. J. Cons. Int. Explor. Mer. 43: 107-117.

Hoenig, J. M., Barrowman, N. J., Pollock, K. H., Brooks, E. N., Hearn, W. S. and Polacheck, T. (1998). Models for tagging data that allow for incomplete mixing of newly tagged animals. Can. J. Fish. Aquat. Sci. 55: 1477-1483.

Hilborn, R. and Walters, C. J. (1995). Biomass dynamic models: users manual. FAO Computerised Information Series (Fisheries) No. 10. Rome, FAO. 62p.

Jolly, G. M. (1965). Explicit estimates from capture-recapture data with both death and immigration-stochastic models. Biometrika 52: 225-247.

Kalish, J. M., Timmiss, T. A., Pritchard, J. C., Johnston, J. M. and Duhamel, G. (1999). Validation and direct estimation of age and growth of Patagonian toothfish *Dissostichus eleginoides* based on otoliths. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/2. Australian Fisheries Management Authority, Canberra.

Leigh, G. M. (1988). A comparison of estimates of natural mortality from fish tagging experiments. Biometrika 75: 347-353.

Leigh, G. M., Hearn, W. S. and Pollock, K. H., Submitted. Time-dependent instantaneous mortality rates from multiple tagging experiments with exact times of release and recovery. Ecol. Environ. Stat.

Marr, J. C. (1951). On the use of the terms "Abundance", "Availability" and "Apparent Abundance" in fishery biology. Copeia, No. 2, pp. 163-169.

McCullagh, P. and Nelder, J. A. (1983). *Generalized Linear Models*. Chapman and Hall, New York.

Murphy, G. I. (1965). A solution of the catch equation. J. Fish. Res. Board Can. 22, 191-202.

Pierce, D. A. and Schafer, D. W. (1986). Residuals in generalised linear models. J. American Statistical Assoc. 81: 977-986.

Pope, J. G. (1972). An investigation of the accuracy of virtual population analysis using cohort analysis. ICNAF Res. Bull. 9: 65-74.

Reilly, A., Ward, B. and Williams, R. (1998). Preliminary results of investigations into the stock structure of Patagonian toothfish around Macquarie Island. Sub-Antarctic Fisheries Assessment Group document. SAFAG-98/4/4. Australian Fisheries Management Authority, Canberra.

SC-CAMLR (1998). Report of the 17th Meeting of the Scientific Committee. Scientific Committee for the Conservation of Antarctic Marine Living Resources, Hobart.

Seber, G. A. F. (1965). A note on the multiple recapture census. Biometrika 52: 249-259.

Tuck, G. N. and Campbell, R. A. (1999). Standardisation of Catch and Effort Data for the Patagonian Toothfish (*Dissostichus eleginoides*) Fishery of Macquarie Island: A Preliminary Analysis. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/5. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Williams, R., Constable, A., Smith, A. D. M., He, X. and Hearn, W. S. (1998). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-1998. Sub-Antarctic Fisheries Assessment Group document. SAFAG-98/4/2. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Williams, R., Smith, A. D. M., He, X. and Constable, A. (1999). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-1999. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/3. Australian Fisheries Management Authority, Canberra.

Walker, T. I., Taylor, B. L., Hudson, R. and Cottier, J. P. (1998). The phenomenon of apparent change of growth rate in gummy shark (*Mustelus antarcticus*) harvested off southern Australia. Fish. Res. 39: 139-163.

Williams, R., Lamb, T., Constable, A. and Tuck, G. N. (1998). History of the Macquarie Island fishery: 1994-1998. Sub-Antarctic Fisheries Assessment Group document. SAFAG-98/4/6. Australian Fisheries Management Authority, Canberra.

Table 13.1 The Total Allowable Catch (TAC) for the Macquarie Island Patagonian toothfish fishery. The total quota for the Macquarie Island fishery could not include more than the prescribed amount from the Aurora Trough region. * Measures were available to allow an increase in the TAC if the average catch per unit effort exceeded a specified amount.

	TAC (tonnes)	
Administrative Period	Aurora Trough	Total Macquarie Region
1 Sept 1996 – 31 Aug 1997	750	1,000
1 Sept 1997 – 31 Dec 1998	200	1,500
1 Jan 1999 – 31 Dec 1999	40	600[*]
1 Jan 2000 – 31 Dec 2000	40	540[*]

Table 13.2 Number of tags detected visually and electronically (TIRIS) and the detection rate by season.

Season	Total tags detected	Detected both TIRIS & visually (n_{ve})	Detected TIRIS only	Detected visually only	Estimated no. recaptured (r)	Rate (λ)
1996/97	80	36	11	33	90.08	0.888
1997/98	297	144	15	138	311.45	0.954
1998/99	40	13	1	26	42	0.952
1999/2000	9	6	0	3	9	1.000

Table 13.3 Seasonal catch, release and recapture figures for the Aurora Trough region. Releases include re-released fish.

Season	Catch Method A	B	Released	Recaptures 1995/96	1996/97	1997/98	1998/99	1999/2000	June 2000	Total
1995/96	180,399	258,618	490	42	58	28	4	0	0	132
1996/97	79,138	104,262	485		37	44	7	0	0	88
1997/98	45,599	78,485	637			118	18	3	0	139
1998/99	12,188	14,654	583				8	3	1	12
1999/2000	1,975	1,975	566					0	1	1
June 2000	634		1						0	0
Total	319,933	458,628	2,762	42	95	190	37	6	2	372

Table 13.4 Seasonal catch, release and recapture figures for the Northern Valleys region. Releases include re-released fish.

Season	Catch Method A	B	Released	Recaptures 1996/97	1997/98	1998/99	1999/2000	June 2000	Total
1996/97	82,909	89,026	540	3	53	5	0	1	62
1997/98	87,953	106,284	538		76	9	0	0	85
1998/99	12,902	13,090	312			9	0	0	9
1999/2000	801	801	272				0	2	2
June 2000	1,623	1,623	2					0	0
Total	186,188	210,825	1,664	3	129	23	0	3	158

Table 13.5 The mean weight (kg) by season of fish caught in the Aurora Trough region by daily catch estimation method.

Aurora Trough	1995/96	1996/97	1997/98	1998/99	1999/2000	Win 2000
Catch A	5.16	3.53	4.11	4.32	2.9	3.3
Catch B	3.61	4.69	2.38	4.09	2.9	3.3

Table 13.6 The mean weight (kg) by season of fish caught in the Northern Valleys region.

Northern Valleys	1996/97	1997/98	1998/99	1999/2000	Win 2000
Catch A	6.03	4.35	3.14	1.58	3.22
Catch B	5.62	3.60	2.77	1.58	3.22

Table 13.7 The total number of records by season and month in Aurora Trough with average catch rate (t/km^2) and standard deviation. Records for the months of October and November have been combined in column Oct/Nov.

			Month						*n*
Season	Oct	Nov	Oct/Nov	Dec	Jan	Feb	Mar	June	E[CPUE] *StD*[CPUE]
1995/96				25	58	82	116		281
				1.46	109.8	50.6	5.65		40.0
				0.72	202.0	49.3	14.23		103.7
1996/97				47	53	43			143
				28.95	23.58	17.85			23.62
				24.77	28.70	19.17			25.07
1997/98	38	16	54	4	41	6			105
	20.25	6.35	16.13	1.79	9.3	7.04			12.4
	25.47	7.77	22.6	2.68	11.6	7.29			18.2
1998/99	3	6	9	11	32				52
	8.4	6.4	7.1	4.2	12.6				9.8
	13.4	10.9	10.9	7.3	19.9				16.8
1999/2000					14	11			25
					1.8	0.6			1.25
					4.7	0.9			3.6
June 2000								5	5
								1.4	1.4
								1.0	1.0
Monthly *n*	41	22	63	87	198	142	116	5	611

Table 13.8 The total number of records by season and month in the Northern Valleys Region with average catch rate (t/km^2) and standard deviations. Records for the months of October and November have been combined in column Oct/Nov.

			Month					*n*
Season	Oct	Nov	Oct/Nov	Dec	Jan	Feb	June	E[CPUE] *StD*[CPUE]
1996/97					65	16		81
					248.68	1.84		199.92
					613.44	3.83		557.51
1997/98	27	2	29	146	88	13		276
	5.3	0.13	4.9	28.8	7.0	3.6		18.11
	7.5	0.18	7.3	82.7	14.4	8.4		61.7
1998/99	9	15	24	40	40			104
	0.17	0.35	0.3	1.43	3.6			2.0
	0.25	0.48	0.4	1.43	7.6			4.95
1999/2000					16	10		26
					0.25	0.07		0.18
					0.92	0.10		0.7
June 2000							19	19
							2.15	2.15
							3.33	3.33
Monthly *n*	36	17	53	186	209	39	19	506

Table 13.9 The catch rate (t/km^2) by season for the Aurora Trough region. The number in a cell represents the number of records with a catch rate between that row and the previous row's catch rate, e.g. there were 29 records with a catch rate between 1 and 5 t/km^2 in season 1996/97.

CPUE (t/km^2)	1994/95	1995/96	1996/97	1997/98	1998/99	1999/2000	June 2000
0	24	6	1	2	10	9	1
1	42	10	4	5	14	10	0
5	158	112	29	32	8	5	4
10	40	25	22	27	6	0	0
15	12	9	14	14	1	0	0
20	5	12	15	9	4	1	0
25	2	9	9	6	2	0	0
50	1	31	29	6	5	0	0
100	0	35	16	2	2	0	0
150	0	15	4	2	0	0	0
200	0	8	0	0	0	0	0
300	0	7	0	0	0	0	0
400	0	1	0	0	0	0	0
400+	0	1	0	0	0	0	0
Hauls	284	281	143	105	52	25	5

Table 13.10 The catch rate (t/km^2) by season for the Northern Valleys. The number in a cell represents the number of records with a catch rate between that row and the previous row's catch rate, e.g. there were 3 records with a catch rate between 300 and 200 t/km^2 in season 1997/98.

CPUE (t/km^2)	1996/97	1997/98	1998/99	1999/00	June 2000
0	19	15	19	12	1
1	10	78	43	13	9
5	11	71	35	1	7
10	3	27	4	0	1
15	6	26	1	0	1
20	1	8	1	0	0
25	1	12	0	0	0
50	6	20	1	0	0
100	6	9	0	0	0
150	3	4	0	0	0
200	0	0	0	0	0
300	0	3	0	0	0
400	3	2	0	0	0
500	3	0	0	0	0
1,000	5	1	0	0	0
2,000	2	0	0	0	0
4,000	2	0	0	0	0
Hauls	81	276	104	26	19

Table 13.11 The number of records for each skipper in each season at Aurora Trough (AT) and the Northern Valleys (NV).

Season\Skipper	AT			NV		
	A	B	C	A	B	C
1995/96	0	116	165	-	-	-
1996/97	0	100	43	0	65	16
1997/98	0	54	51	0	29	247
1998/99	9	0	43	24	0	80
1999/2000	25	0	0	26	0	0
June 2000	0	0	5	0	0	19

Table 13.12 The number of records for each skipper in each month at Aurora Trough (AT) and the Northern Valleys (NV).

Month\Skipper	AT			NV		
	A	B	C	A	B	C
Oct/Nov	9	54	0	24	29	0
Dec	0	47	40	0	0	186
Jan	14	53	131	16	65	128
Feb	11	0	131	10	0	29
March	0	116	0	0	0	0
June	0	0	5	0	0	19

Table 13.13 The unstandardised CPUE series for Aurora Trough. All records from March have been removed (only effects season 95/96). The potential for outliers is considered by removing records with a CPUE greater than 2,000t/km^2 and 200t/km^2 respectively. The indices in brackets are relative to the 1999/2000 season.

Filter	(i) CPUE<2,000	(iii) CPUE<200
n	743	734
E[CPUE]	22.63	18.14
1995/96	64.14 (51.3)	45.38 (36.3)
1996/97	23.62 (18.9)	23.62 (18.9)
1997/98	12.40 (9.9)	12.40 (9.9)
1998/99	9.85 (7.9)	9.85 (7.9)
1999/2000	1.25 (1.0)	1.25 (1.0)
June 2000	1.40 (1.12)	1.40 (1.12)

Table 13.14 The unstandardised CPUE series for the Northern Valleys. The potential for outliers is considered by removing records with a CPUE (t/km^2) greater than 2000, 400 and 200 respectively. The indices in brackets are relative to the 1999/2000 season.

Filter	(i) CPUE<2,000		(ii) CPUE<400		(iii) CPUE<200	
n	504		493		485	
E[CPUE]	30.6		13.5		8.75	
1996/97	128.9	(644)	32.0	(160)	17.3	(87)
1997/98	18.1	(90.5)	15.3	(76)	10.5	(53)
1998/99	2.0	(10)	2.0	(10)	2.0	(10)
1999/2000	0.2	(1.0)	0.2	(1.0)	0.2	(1.0)
June 2000	2.1	(10.5)	2.1	(10.5)	2.1	(10.5)

Table 13.15 Standardised catch per unit effort using Model 1 for Aurora Trough by filter method (i) CPUE<2,000 and (iii) CPUE<200t/km^2 and with a log Normal error structure.

Filter	(i)	(iii)
r^2	0.46	0.45
1995/96	45.66	47.42
1996/97	12.82	14.42
1997/98	6.83	8.89
1998/99	4.77	6.16
1999/2000	1.00	1.00

Table 13.16 Standardised catch per unit effort using Model 1 for the Northern Valleys by filter method (i) CPUE<2,000 (ii) CPUE<400 and (iii) CPUE<200t/km^2 and with a log Normal error structure.

Filter	(i)	(ii)	(iii)
Error	Log Normal		
r^2	0.39	0.40	0.45
1996/97	182.65	41.94	33.24
1997/98	125.28	28.46	21.43
1998/99	31.71	7.15	5.53
1999/2000	1.00	1.00	1.00
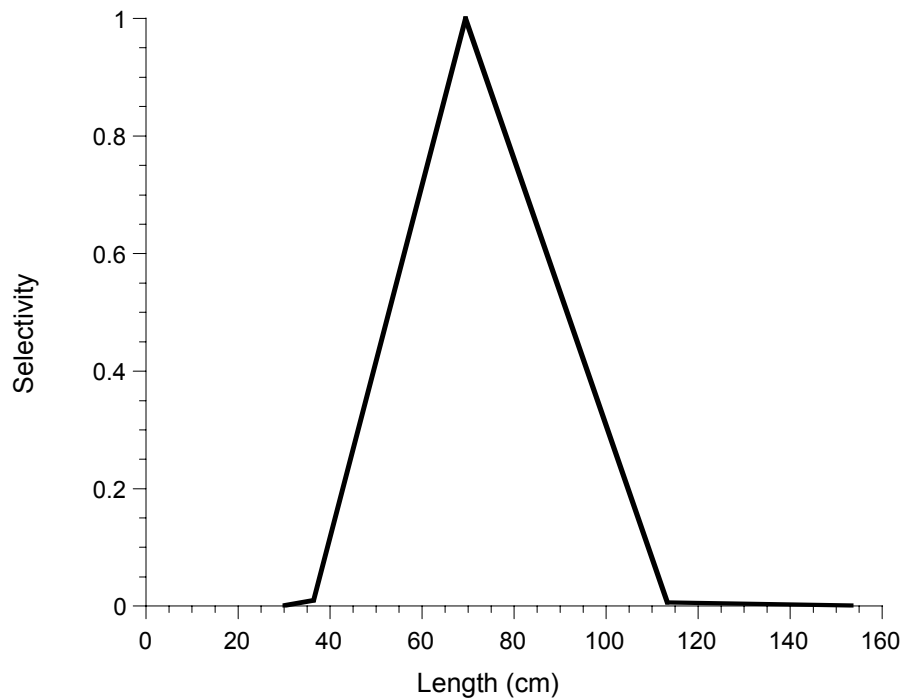
Figure 13.1 The selectivity function described by equation (7) as applied in Model S2. The parameters for the displayed curves are l_{50}=55, l_{95}=65 and β=0.1, 0.05.
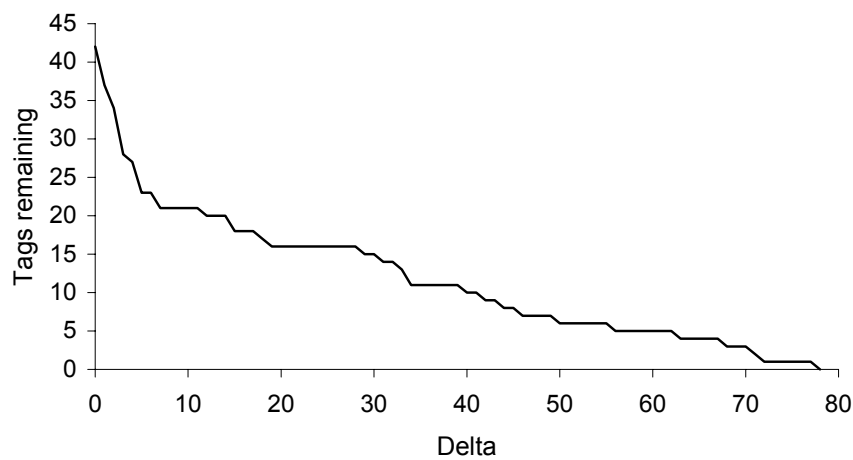
Figure 13.2 The number of tags that are recaptured that remain in the analysis to estimate the first tagging season abundance as a function of δ. There were 43 tagged fish recaptured during 1995/96 of which the largest days-at-liberty was 78.
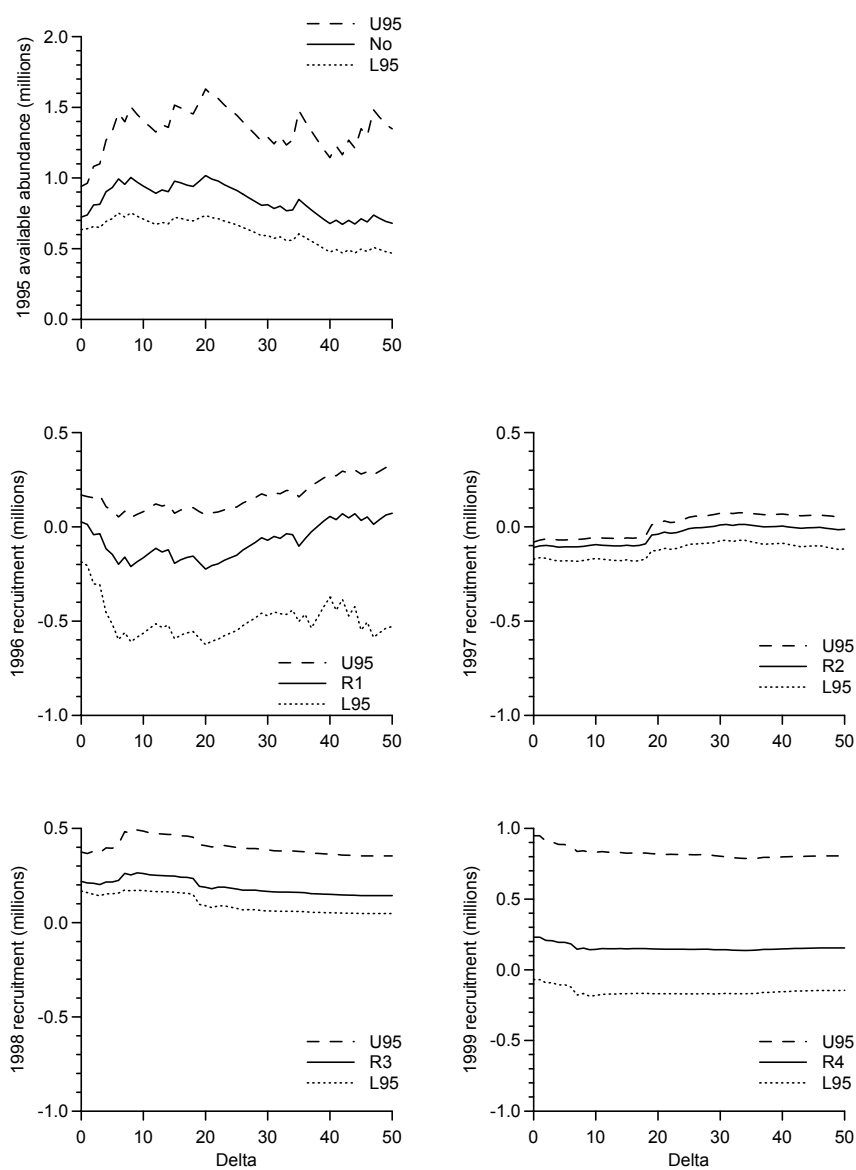
Figure 13.3 Estimated pre-tagging abundance (No) and net recruitments (R1, R2, R3 and R4) in Aurora Trough with 95% confidence intervals for assessment Model NS, catch data set A and *M*=0.1.
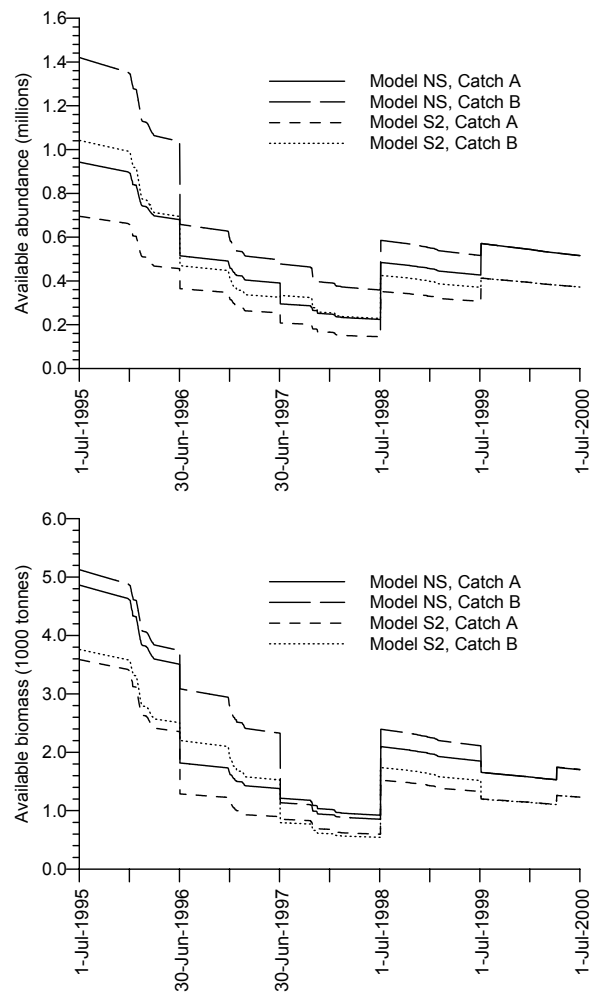
Figure 13.4 The predicted trajectories of available abundance and biomass for Aurora Trough showing the contrast between results when using the two daily catch estimation methods (Catch A and B) and the two assessment methods (Models NS and S2). Note also that M=0.1 and δ=10.
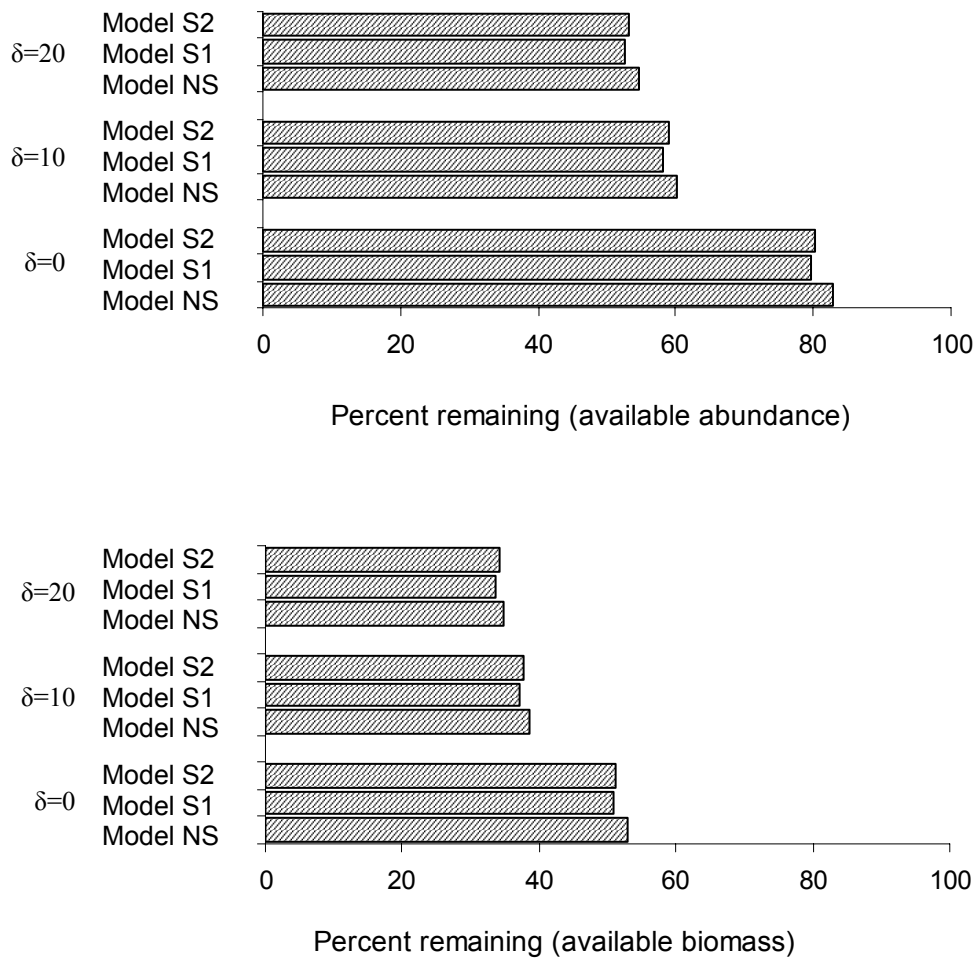
Figure 13.5 The estimated percentage of available abundance and biomass remaining in the Aurora Trough region according to model specification (see text). Note that *M*=0.1 and daily catch estimation method Catch A was applied here.
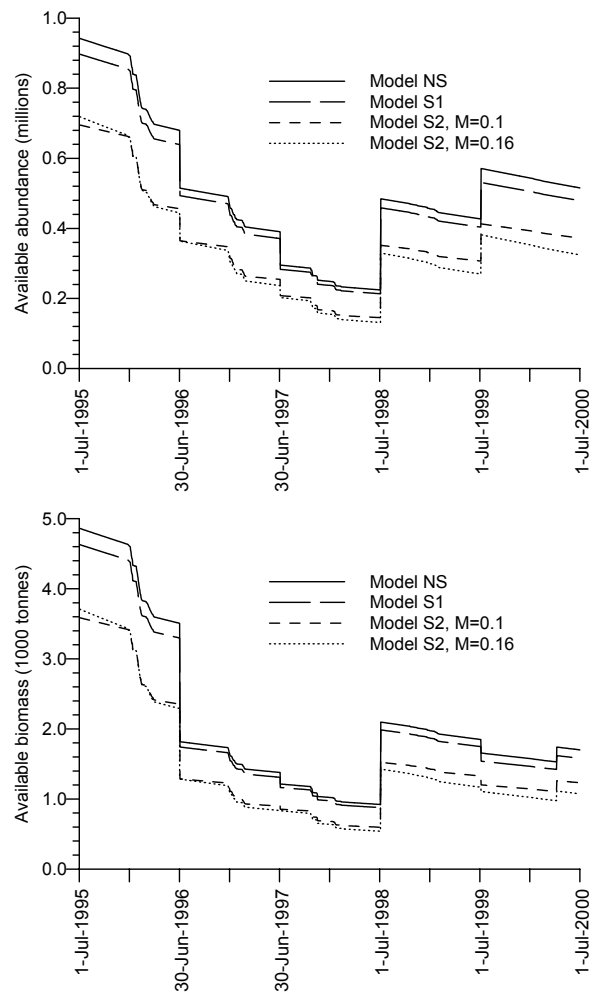
Figure 13.6 The predicted trajectories of available abundance and biomass for Aurora Trough showing the contrast between the assessment methods. For an explanation of the models and their parameters, see the text. Note that M=0.1 (unless stated otherwise), δ=10 and daily catch estimation method Catch A were applied here.

Figure 13.7 Estimated pre-tagging abundance (No) and net recruitments (R1, R2, R3 and R4) in Aurora Trough with 95% confidence intervals for assessment Model S2, catch data set A and *M*=0.1.
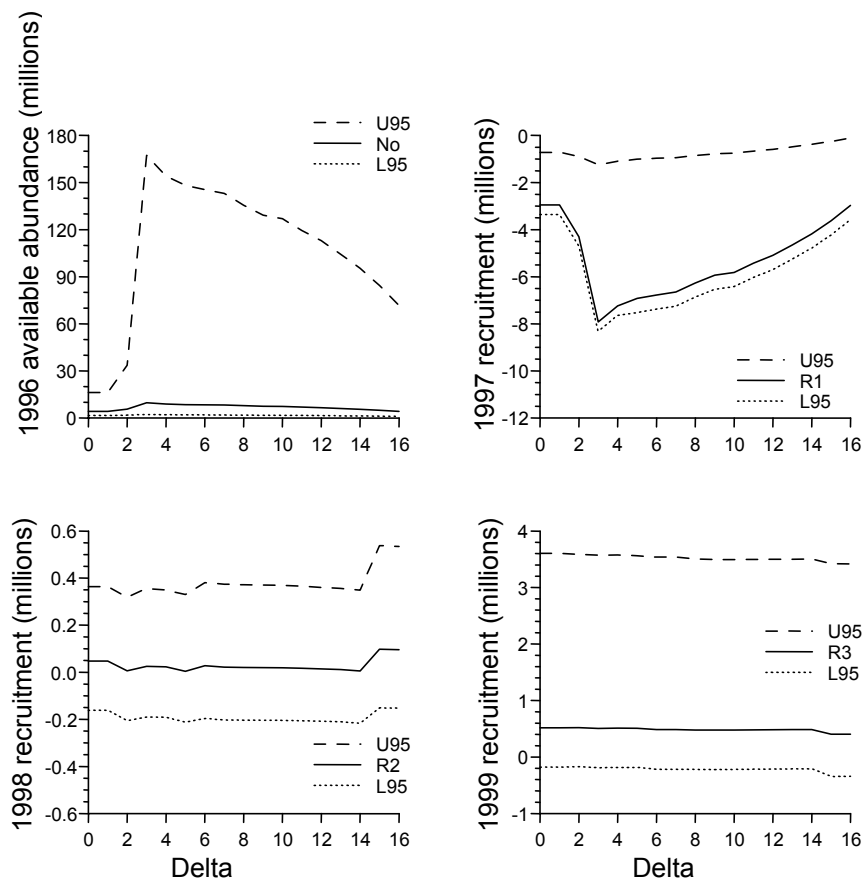
Figure 13.8 Estimated pre-tagging abundance (No) and net recruitments (R1, R2, and R3) as a function of delta in the Northern Valleys region with 95% confidence intervals for assessment Model NS, catch data set A and M=0.1.
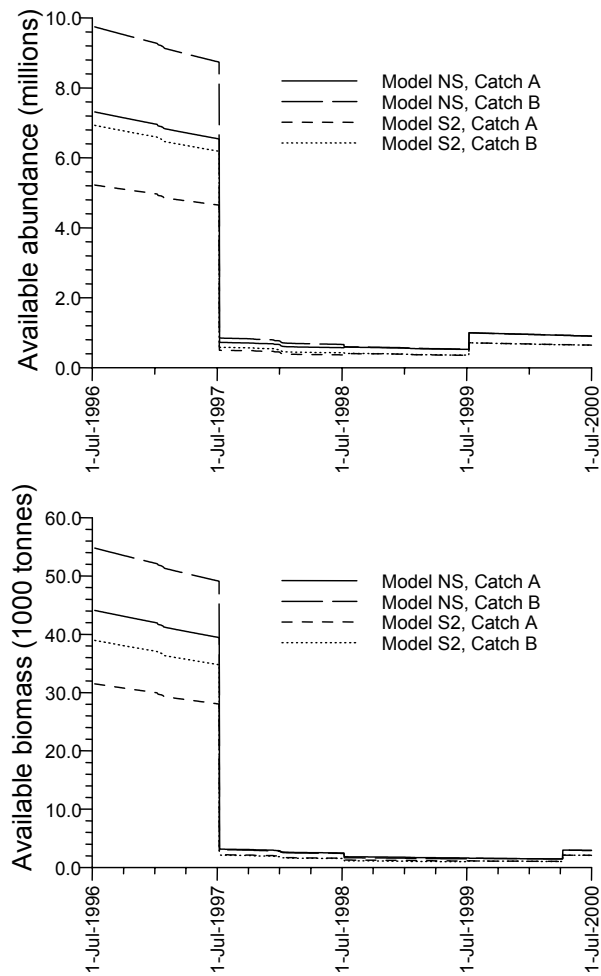
Figure 13.9 The predicted trajectories of available abundance and biomass for the Northern Valleys showing the contrast between results when using the two daily catch estimation methods (Catch A and B) and the two assessment methods (Models NS and S2). Note also that M=0.1 and δ=10.
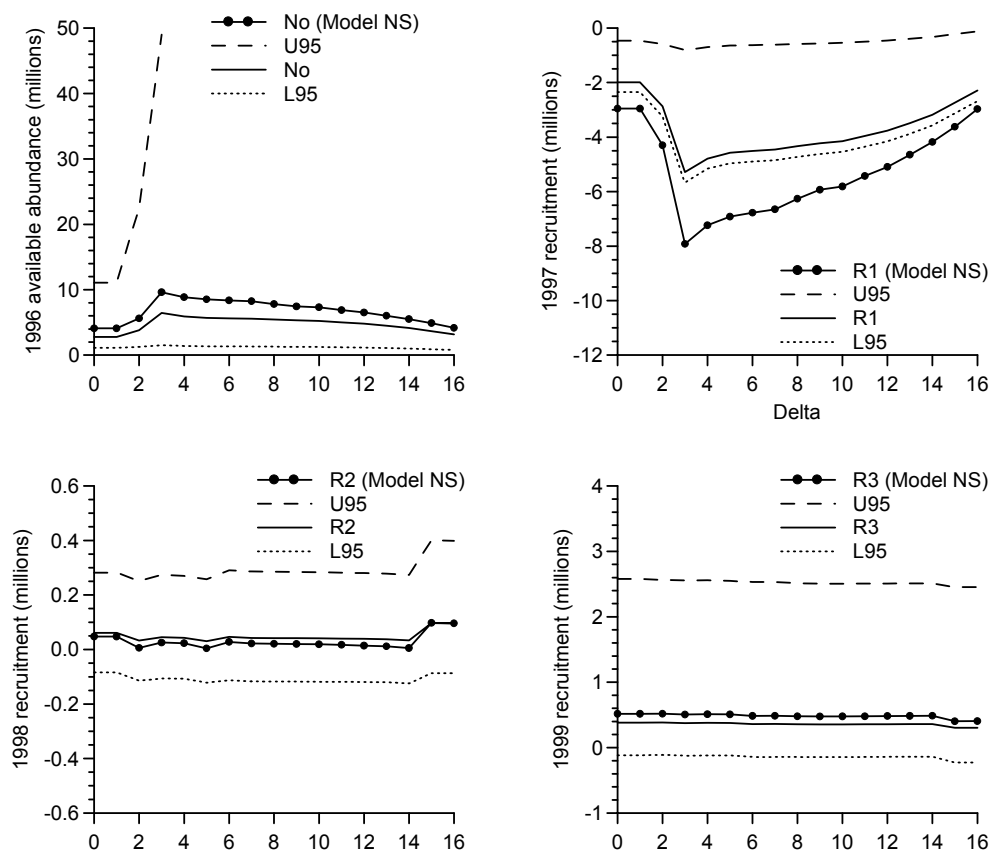
Figure 13.10 Estimated pre-tagging abundance (No) and net recruitments (R1, R2 and R3) in the Northern Valleys with 95% confidence intervals for assessment Model S2, catch data set A and M=0.1.
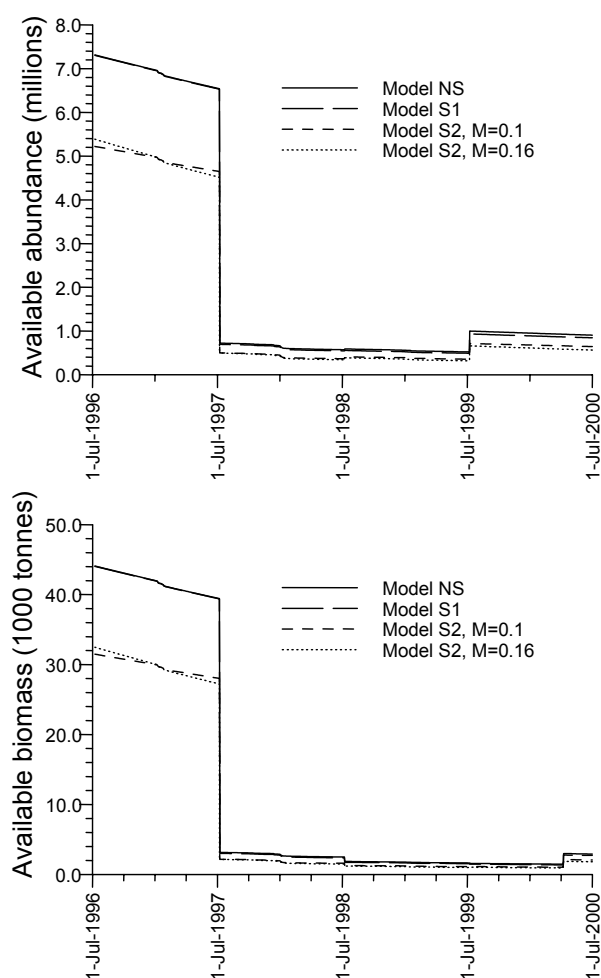
Figure 13.11 The predicted trajectories of available abundance and biomass for the Northern Valleys showing the contrast between the assessment methods. For an explanation of the models and their parameters, see the text. Note that $M=0.1$ (unless stated otherwise), $\delta=10$ and daily catch estimation method Catch A were applied here.
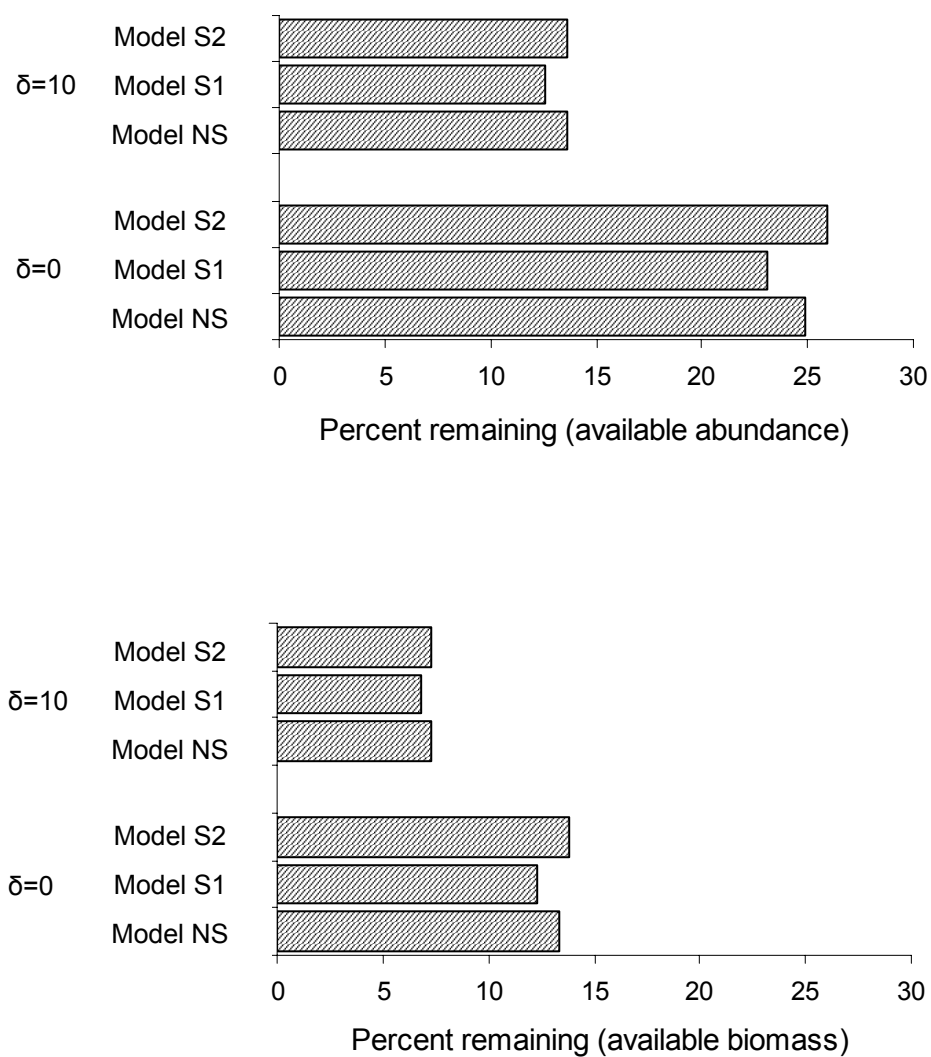
Figure 13.12 The estimated percentage of available abundance and biomass remaining in the Northern Valleys region according to model specification (see text). Note that *M*=0.1 and daily catch estimation method Catch A was applied here.
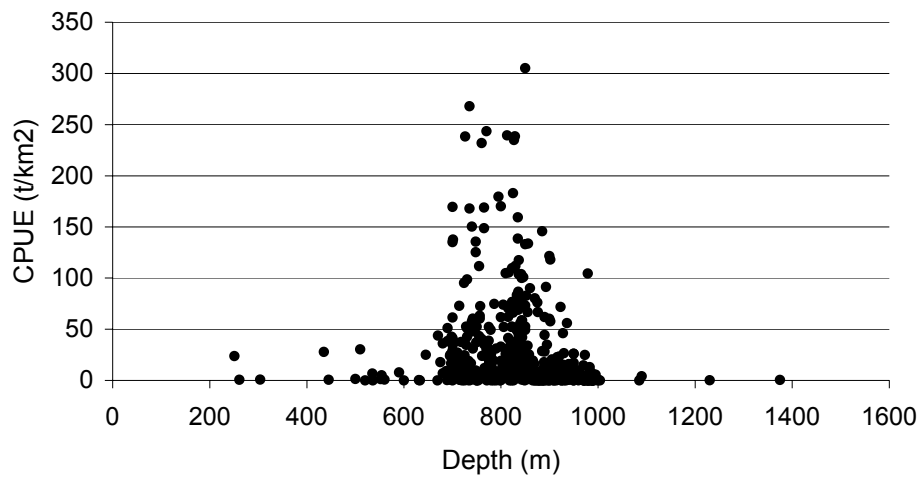
Figure 13.13 The catch rate (t/km^2) at Aurora Trough as a function of depth. One record with a catch rate of 1504 t/km^2 and depth 723m is not shown in order to enhance the resolution of the presented figure.
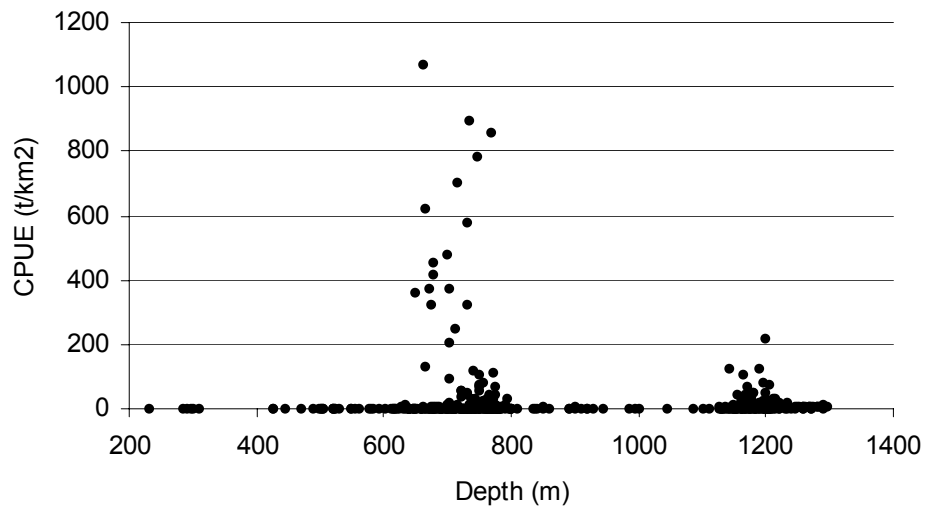
Figure 13.14 The catch rate (t/km^2) of toothfish from the Northern Valleys as a function of depth. Three records with a catch rate greater than 1200 are not shown in order to enhance the resolution of the presented figure. These catch rates (with depth) are 1900 (658), 2147(633), and 3861(639).
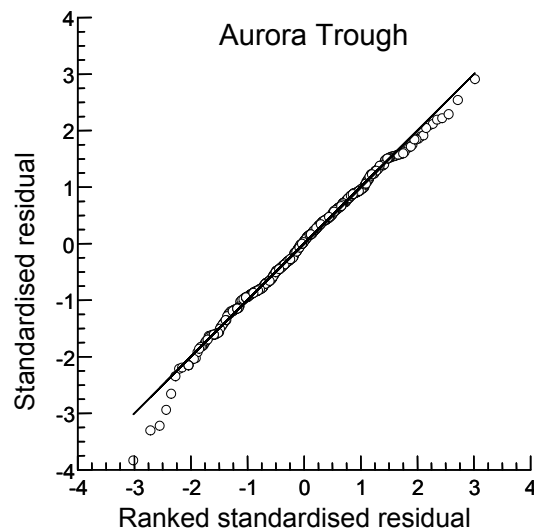
Figure 13.15 A normal probability plot of the standardised residuals for Model 1 and CPUE<2,000t/km^2 for Aurora Trough. The linear plot indicates the expected relationship if the hypothesis of normally distributed residuals is to be accepted.
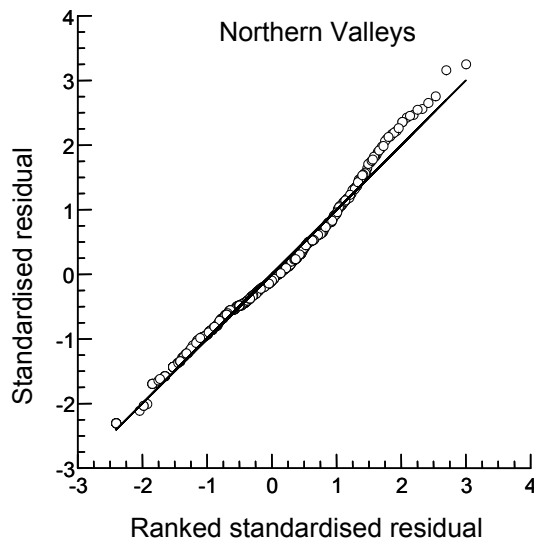
Figure 13.16 A normal probability plot of the standardised residuals for Model 1 and CPUE<200t/km^2 for the Northern Valleys. The linear plot indicates the expected relationship if the hypothesis of normally distributed residuals is to be accepted.

Appendix 13.1
Daily Catch Estimation Method C1

The catch on day *t* is estimated as

$$C^t = \sum_{sg} C^{sg,t}$$

where $C^{sg,t}$ is the catch of a particular size group on day *t*. $C^{sg,t}$ is then given by,

$$C^{sg,t} = \frac{n_T^{sg}\, \overline{w}_T^{sg}\, f^{sg}}{\overline{w}_F^{sg}}$$

where
n_T^{sg} is the number of trays of each size grade *sg*

$\overline{w}_T^{sg}$ is the average weight of a tray of size grade *sg*

f^{sg} is the conversion factor for fish of size grade *sg,* and

$\overline{w}_F^{sg}$ is the average weight of a fish of size grade *sg.*

Daily Catch Estimation Method C2

The catch on day *t* is estimated as

$$C^t = \frac{w_{ad}^t}{\overline{w}_F}$$

where
w_{ad}^t is the total adjusted landed weight on day *t*

$\overline{w}_F = \dfrac{w_{Tot}^t}{n_F^t}$ is the mean weight per fish

w_{Tot}^t is the total weight of measured fish, and

n_F^t is the number of fish weighed on day *t*.

Appendix 13.2

For Model S2 the term for the expected number of available tagged fish (equation (8)) is derived in the following manner.

Assume that the catch (in numbers) on a given day t of age a is given by,

$$C_a^t = qE^t s_a N_a^{T,t},$$

(A13.2.1)

where $\quad q \quad$ is the catchability constant

$\quad E^t \quad$ is the effort (swept area) on day t

$\quad s_a \quad$ is the selectivity of a fish of age a, and

$\quad N_a^{T,t} \quad$ *is the total number of fish in the population of age* a *on day* t.

Then the total catch over all ages on day t is,

$$C^t = \sum_a C_a^t = qE^t \sum_a s_a N_a^{T,t}$$

(A13.2.2)

Consider the number of recaptures of tagged fish on day t. If the tagged population is well mixed with the un-tagged population, then tagged fish of age a are recaptured on day t with probability,

$$F_a^t = \frac{C_a^t}{N_a^{T,t}}.$$

(A13.2.3)

Therefore, the total expected number of recaptures on day t is,

$$E[r^t] = \sum_a \alpha_a^t F_a^t = \sum_a \frac{\alpha_a^t C_a^t}{N_a^{T,t}}$$

(A13.2.4)

where α_a^t is the number of tagged fish that are of age a on day t. Thus,

$$E[r^t] = \sum_a \frac{\alpha_a^t qE^t s_a N_a^{T,t}}{N_a^{T,t}} = qE^t \sum_a \alpha_a^t s_a$$

(A13.2.5)

Now, from Petersen's equation (equation (4)) we have,

$$E[r^t] = \frac{m^t C^t}{N^{av,t}}$$

(A13.2.6)

where $\quad m^t \quad$ is the number of marked fish available on day t, and

$$N^{av,t} = \sum_a s_a N_a^{T,t}$$

(A13.2.7)

is the number of available fish in the population on day t.

Using equations (A13.2.2) and (A13.2.7),

$$E[r^t] = \frac{m^t q E^t \sum_a s_a N_a^{T,t}}{\sum_a s_a N_a^{T,t}} = m^t q E^t \qquad \text{(A13.2.8)}$$

Equating equations (A13.2.8) and (A13.2.5) gives,

$$E[r^t] = m^t q E^t = q E^t \sum_a \alpha_a^t s_a \qquad \text{(A13.2.9)}$$

and therefore,

$$m^t = \sum_a \alpha_a^t s_a \qquad \text{(A13.2.10)}$$

This equation is equivalent to equation (7) if the age groups are small enough so that individual tagged fish are considered. In this case the alpha term becomes the probability that tagged fish i has survived to day t.

14. Initial evaluation of management strategies for the Macquarie Island toothfish fishery

Geoff Tuck, Tony Smith, Andrew Constable, Xi He, Sakari Kuikka and Neil Klaer

Summary
This chapter examines the performance of a range of management strategies applicable to the Macquarie Island toothfish fishery. Many of the uncertainties about the dynamics of the population are incorporated into the simulation framework, and management strategies that are robust across these uncertainties are explored. The resource and fishery dynamics are simulated from 1995 until 2050 using an operating model to represent the future 'true' dynamics of the system. For each management strategy and set of assumption about the dynamics of the resource, the future of the fishery is simulated 50 times. The management strategies are evaluated by considering their performance as related to specified management objectives.

The initial results from an evaluation of various management strategies for the Macquarie Island toothfish fishery appear to suggest that fishing operations have a smaller impact on the resource than one might expect. However, this result is conditional on several key factors. These are that (a) selection applies to a narrow range of ages, (b) spawning fish contribute to local recruitment only, (c) economic constraints (through leaving triggers) lead the vessel to abandon fishing in poor catch conditions, (d) effort is limited, and (e) assessment estimates of key biological parameters are reasonable. If any of these factors are false, then results show that the impact on the stock can be substantial.

An evaluation of management strategies showed that feedback policies, with appropriately chosen parameters, can satisfy sustainability criteria and maintain catch levels under most of the scenarios considered. Other management strategies considered can dramatically impact the stock. The development of the management strategy evaluation software now provides a flexible tool to evaluate harvest strategies when applied to complex dynamical resource models.

Introduction
Assessments of the population of toothfish at Macquarie Island have indicated that the population has undergone major changes in fishable abundance since the fishery began in the summer of 1994/95 (Chapter 13). The spatial and temporal dynamics of the population remains largely uncertain. For example, it is unclear whether the population at Macquarie Island is a single well-mixed stock, or is composed of two or more local populations, or whether transient fish having a more cosmopolitan habit occasionally joining the resident fish (Chapter 11). To a large extent, several other key components of the fishes' biology also remain uncertain. These include its reproductive biology, growth, natural mortality and the relationship between fishable abundance and total abundance (Chapter 10). The challenge for managers is to establish methods for managing the harvested populations that recognise these uncertainties and which satisfy, to a reasonable degree, various, often conflicting, management objectives

Management objectives for this fishery were discussed at a workshop attended by managers, industry and scientific representatives in April 2000 (Tuck 2000). Management goals included both conservation and utilisation objectives. Likewise, management strategies for the fishery have been discussed at various meetings of the sub-Antarctic fisheries assessment group (SAFAG4, SAFAG7, SAFAG10). A management strategy is a set of pre-agreed rules for selecting management actions, designed to achieve specified management objectives. Apart from the objectives, the components of a management strategy are the sampling program, the assessment and a decision rule that translates the data from the sampling program and information from the assessment into a TAC. The management objectives (and their

corresponding performance measures) and management strategies are outlined in detail in following sections of this chapter. The aim of this chapter is to consider alternative management strategies and examine their performance against a range of management objectives under various assumptions that encompass the system's uncertainties. The method used to evaluate these strategies is called Management Strategy Evaluation (MSE). MSE does not attempt to find an 'optimal' strategy, but rather explicitly outline the trade-offs inherent in managing stocks with potentially competing objectives.

The basic method for evaluating performance is Monte Carlo simulation; an insightful mechanism to explore complex systems. This method involves the simulation of the fishery from its beginning to a pre-determined future year (2050 in this instance). An 'operating model' is used to simulate the 'true' dynamics of the toothfish population and the fishery, to generate future catch, tag releases and tag returns. An assessment model is applied to both historical and future (simulated) data to give an estimate of the status of the population (which is known through the operating model). Feedback management strategies can then use the annual estimated current status to set catch quotas. Once a scenario[1] and a management strategy have been chosen for evaluation, the biology and fishery dynamics are simulated (50 times). A range of performance statistics is produced for each simulation and management strategy/scenario combination. The performance statistics are combined over all simulations and tabulated to provide a summary of the performance of the particular management strategy for a given scenario. These summaries provide a means of comparing the performance of each management strategy across many scenarios.

Results from the analyses presented in this chapter are preliminary. The MSE software can be used to illustrate the potential effects of management strategies given particular assumptions about resource dynamics. The results, while presented quantitatively, should be interpreted qualitatively. The model is used to compare the decision alternatives (management strategies), not to predict exact future catch or population biomass. A special, and a dominant, feature of the model is that it includes vessel reaction to changes in catch rates. This model component was included to assess the effects of behavioural elements of the fishery.

In this work, it is important to clearly distinguish between several inter-related and often confused terms. The stock assessment methods used in this chapter and Chapter 13 are only able to estimate *available* abundance (we also refer to this as *fishable* abundance). Available abundance is quite distinct from *total* abundance and *spawning* abundance, and may be substantially more extensive (both spatially and in total magnitude) than available abundance. Total abundance includes every individual (juvenile and adult) within a reproductively distinct population (whether available to the gear or not). Spawning abundance is the abundance of those fish of the population that are sexually mature.

There are two factors which influence the available abundance (i) *gear selectivity* (the probability of capture on encounter) and (ii) *availability* (the probability of encounter by the fishing gear; Marr (1951)). While gear type will influence gear selectivity, oceanographic conditions and population movements can strongly influence the availability of fish. These two factors are generally functions of age or length, and can vary within and between seasons. In this chapter the combined function of gear selectivity and intra-annual availability at age is called the *selectivity* function. Inter-annual fluctuations in availability are also modelled within the resource model. Inter annual fluctuations provide yearly variations in availability of specific age groups within a season

---

[1] A scenario is a specific set of assumptions about the dynamics of the resource. The scenarios can represent the model or parameter uncertainties of the system.

Methods

The general methodology used to evaluate management strategies is similar to that applied by Smith *et al.* (1996) and Polacheck *et al.* (1999). There are five main components:

1. An operating model that simulates the population and fishery dynamics in both historical and future years
2. A sampling model that generates the data available for assessing the resource from the "true" state of the resource as simulated in the operating model
3. An assessment model that uses the data from the sampling model to provide estimates of resource status
4. A harvest strategy component that determines management actions based on the results of the assessment model and/or specified decision rules. Note that some harvest strategies do not include yearly assessments.
5. A component for the calculation of an appropriate set of performance statistics

The first four components are sequentially iterated to simulate a time series of future population sizes, management actions, and catches. Each simulation has different random values that influence (a) daily variation in catchability, (b) the daily level of effort, (c) the daily number of released and recaptured fish, (d) the annual transient biomass, (e) annual observation error in mean weights of fish, and (e) annual fluctuations in recruitment. However, for efficacy of comparison of performance measures under differing management strategies and/or differing scenarios, the realised random variables for effort, catchability, recruitment, observation error and the transient biomass remain constant across management strategy/scenario combinations. For example, for a particular simulation and particular year within that simulation, the random variable determining recruitment will remain the same across all management strategy/scenario combinations. The results can then be used to evaluate the performance of a particular management strategy for a specific set of assumptions about the dynamics of the resource without doing large numbers of replicate trials to get unbiased results for comparison.

Figure 14.1 provides a diagrammatic representation of the management strategy evaluation framework. Each of the MSE components for the toothfish management strategy evaluation is broadly described below, with additional details in the appendices.

1. Operating model
The biological component of the operating model
The operating model simulates the population and the fishery dynamics on a daily basis. The biological model of the toothfish population is a sex and age-structured dynamical population model based on standard catch and population dynamic equations (Mace and Doonan 1988, Smith *et al.* 1996). However, alternative models were developed in order to account for specific ecological scenarios regarding the fishery at Macquarie Island. Where possible best estimates of population parameters were applied and where key uncertainties existed plausible alternatives were used for sensitivity analyses.

Chapter 13 highlighted the inter-annual variability in available abundance in both Aurora Trough and the Northern Valleys regions. In particular, there were occasional large changes that could not be explained by the fishing process. Both fishing regions showed occasional large catches of predominantly large fish, but more frequent periods of small catches. This indicates that availability alters within and between fishing seasons. Within the model structure here, selectivity and availability were combined using the basic equation:

$$C = qEN$$

where C is the catch, E is a measure of effort and N is a measure of abundance. The constant of proportionality *q* is called the *catchability coefficient* and literally defines the proportion of the

stock taken with one unit of effort. However, as the types of gear being applied and variations in availability (e.g. oceanographic conditions on the day) influence the catch, the likelihood of catching fish of a certain size will vary. Let the inter- and intra-annual fluctuations in availability be given by v^y and v_a^t, functions of year and of age and day (within a season) respectively. Let g_a define the gear selectivity for age a. Define $s_a^t = g_a v_a^t$ as the selectivity function[2]. Then the catch of age a fish in year y on day t can be modelled as,

$$C_a^{y,t} = \hat{q} s_a^t v^y E^t N_a^{y,t},$$

where $\hat{q}$ is the catchability for fully selected and available fish (Quinn II and Deriso 1999). This equation and the derivation of its parameters are described further in Appendix 14.3. As Methot (1990) and Quinn and Deriso (1999) explain, the estimation of gear selectivity and availability is problematic unless survey estimates of abundance in unfished regions are available (in addition to knowledge of how oceanography and spatial dynamics affects abundance; see Chapter 10). In this chapter we have made several assumptions about selectivity and availability and tested the management strategies for their robustness against these assumptions.

Three population models were developed to consider the possibility of an occasional influx of fish into a fishing region. These are:

(i)   A single stock model, where large fish occur in the catch due to a change in resident stock availability.

(ii)   A single stock model with years of zero recruitment when no young fish are recruited to the population

(ii)   A two stock model, where a second transient population of fish moves into the region.

The single stock model assumes that there is only one well-mixed population of fish harvested in any one ground (e.g. Aurora Trough). Due to variations in environmental conditions, larger fish from this population occasionally become available to the fishery. These fish form part of the reproductive population of this stock. The relative distribution of available numbers-at-age is determined by the selectivity function, which is composed of a gear selectivity curve and an availability-at-age curve.

Two selectivity functions have been estimated (Appendix 14.2 and Chapter 10). The magnitude of the daily catch rate was assumed to be a reasonable indication of the availability of large or small fish. As such, the length composition of catch for which catch rates were less than 10 t/km² was used to estimate the selectivity when only resident smaller fish were available. All length composition data were used to estimate the broader selectivity curve. In projections, the duration of the broader availability for the resident stock is chosen randomly between BS_{low} and BS_{high}. An examination of catch rate records over seasons 1995/96 to 1999/00 shows that periods of high catch rates (>10 t/km²) varied between 1 day (1999/00) and 62 days[3] (which essentially encompassed the full 1996/97 season). Hence, the potential duration of the broader selectivity is assumed to be between $BS_{low} = 0$ and $BS_{high} = 90$ days (the full season). The period of broader selectivity is assumed to begin on a random day within the summer season. Further examination of length frequencies will provide more robust estimates of these parameters.

---

[2] Note that we do not attempt to define explicit functions for gear selectivity at age nor availability at age; rather we combine them into a single function and refer to the combined function from this point on as the selectivity function.

[3] Catch rates less than 10 t/km² existed but were infrequent within the stated extended periods of high catch rates.

The growth, mortality and selectivity parameters have been described in Chapter 10 and are listed in Table 14.1. The assumed stock-recruitment relationship is of the Beverton-Holt type. Log-normal distributed errors about the relationship were assumed.

The second resource model attempts to account for the observed poor recruitment for this fishery. A recruitment model was constructed that allows periods (years) where there has been complete spawning failure, i.e. no zero year old fish are produced (or survive) to join the population. In this model, such periods are triggered using a uniform distribution and a probability given by one in every EZR_y years. The number of years of zero recruitment is then determined from a uniform distribution ranging from EZR_{low} and EZR_{high} years (Appendix 14.1). Due to the short duration of the fishery and a lack of data, it is difficult to estimate some of the parameters of the model and so indicative values were chosen to give insights into the potential behaviour of the models and performance of the management strategies. A duration of between 3 and 5 years was chosen for the zero recruitment episodes with a probability of another zero recruitment period beginning once the previous one is finished given as 0.2. The zero recruitment episodes are relatively frequent in order to highlight the potential effects of zero recruitment on management strategies. Closer examination of aging data and length frequencies may give more robust estimates of these parameters.

The third model with two stocks assumes that there is a second non-resident (transient) population of fish that moves into the region occupied by resident fish and can be caught and tagged. These fish are reproductively isolated from the resident fish. To reflect current uncertainties with regard to the magnitude of the annual influx of transient fish, the biomass is determined randomly as a linearly declining distribution from a biomass of 0 to a maximum biomass (Appendix 14.2). The maximum biomass is assumed to be $B_{max} = 30,000$ tonnes following anecdotal estimates from the Northern Valleys region during the 1996/97 season. The two stocks model is supplementary to the first, i.e. the resident stock model described above does not change with the addition of the second stock. The historical level of exploitation does not influence the annual magnitude of available biomass that immigrates to the region.

The first two models are believed to represent the situation occurring in Aurora Trough, whereas the third model attempts to account for the dramatic estimated changes in available abundance in the Northern Valleys region. Clearly these resource models vary considerably in their assumptions and one of the aims of management strategy evaluation is to provide management strategies that are robust (in terms of performance) across all resource models and other key uncertainties.

The fishery component of the operating model
The fishery simulator models the daily processes of catch, tagging, recapture and the behavioural dynamics of the fishing operation (Figure 14.2). For each day of the season (assumed to be 90 days over the summer months of December to March) a decision is made to fish or not and whether to leave the fishery (due to catch meeting the quota or if catch rates are sufficiently poor). If fishing occurs then the catch is determined according to the level of effort, catchability, availability and abundance of fish (Appendix 14.3). From these fish, some may be tagged and released and there may also be tagged fish recaptured amongst the catch. Catch rates are recorded and if sufficiently high over a period of time, there may be an increase in quota (see TAC triggers below) and an increase in the daily fishing frequency.

If catch rates are consistently poor over a number of fishing days, then the vessel may depart the region on economic grounds. Specifically, if the mean catch rate over LT_{days} is less than LT_{cr} then the vessel ceases fishing and departs the region. However, a 'last chance' clause allows the vessel to remain fishing if recent catch rates are high, even though the long-term average catch rate is poor. Thus, if the mean catch rate over the last LC_{days} ($<LT_{days}$) days is greater than LC_{cr} then the vessel does not depart the region and remains fishing for an additional LC_{extra} days. If

after LC_{extra} days conditions have improved, the vessel continues fishing. This clause allows the vessel to remain fishing after a good catch when it may have left the ground otherwise (Appendix 14.3). *Austral Leader* skipper, Halli Stefannson, provided approximate values for the leaving trigger parameters and model sensitivity to these values was then explored.

The historical component of the operating model and conditioning
The historical model uses known data from the fishery (such as catch, effort, and tagging data) and a population dynamics model to establish a current realisation of the population (numbers-at-age) to take into the projections (see Appendix 14.4). The model has been conditioned using the historical data from Aurora Trough. These data were chosen over the Northern Valleys because of the large fluctuations in available abundance observed in the Northern Valleys and the greater uncertainty in initial abundance (due to few tag returns in the first season) documented in Chapter 13. In addition, the overall ranking of management strategies is unlikely to be substantially altered according to the chosen historical data due to the considerable number of future years over which simulations are run.

The initial numbers-at-age are determined from an initial total number of available fish N_0^{av}, the selectivity on day 1, and the natural mortality M. The stock assessments (see Chapter 13) provide estimates of the initial total available number of fish for various plausible biological and catch scenarios and under different assessment models. The range of uncertainty in the estimates of initial available numbers was considered by taking the estimate of available abundance from the most plausible assessment model and how biases in this estimate (taken as a percentage of this value) might affect the outcome. The assessment parameters are listed in Table 14.2, and Table 14.3 shows the initial available numbers used ($N_0^{av,*} = 695,413$) and the percentage points considered for sensitivity analyses.

The initial numbers-at-age the population is projected forward, applying natural mortality only, until a catch day occurs. The fishing mortality is then calculated and the estimated catch-at-age is removed from the population numbers. If the recorded catch rate for a particular day is greater than 10 t/km², then the broader selectivity function is used to calculate catch-at-age. This process is repeated for all catch days during a season. It is assumed that there is no measurement error in the historical daily catch (in numbers of fish) data. However, observation error of the annual estimated mean weight of a fish is assumed and is taken into the projections (Appendix 14.3).

Tagged and released fish are assigned an age and sex according to (i) the measured length of the released fish, (ii) the growth function and (iii) the estimated daily catch-at-age and sex (Appendix 14.4). At the completion of each day, tagged fish experience natural mortality and at the completion of each historical season, recruitment to the population occurs and numbers-at-age are updated. Finally, at the completion of the historical years, the simulation carries forward the estimated numbers-at-age into the projection component of the evaluation (Figure 14.1).

2.   Sampling model
Tagging
The tagging program has been discussed in detail within Chapter 6. For the management strategy evaluation, as with the real fishery, it is assumed that tags are assigned to fish in proportion to the length frequency in the catch. Managers can decide approximately how many tagged fish are released in each season, n_{tag}. However, if economic factors are such that the vessel leaves the ground after a short duration or the TAC has been caught, then it is possible that not all tags will have been deployed. A full description of the model for tagging and recapturing fish can be found in Appendix 14.3.

Length measurement

For each simulated fishing day the proportion of fish caught that are above a certain length, LEN_{len}, is measured. This information can be used for the TAC length trigger described below (Table 14.4).

3.   Assessment model

The assessment model used in the MSE is exactly the same as that described in Chapter 13. However, some modifications were made to improve simulation run-time. Namely, as recent estimates of net recruitment do not overly rely on previous years' values, only parameters for the most recent two years are free to be estimated. All other parameter values remain fixed at their previously estimated value. As such, only two parameters are estimated each year, as opposed to $N_{years} = N_h + N_s$ if all parameters continue to be estimated (i.e. if there are 55 historical and simulated years, then there would be 55 parameters estimated by the 55th year).

Occasionally an annual assessment is not possible due to either too few tag returns or lack of convergence in the minimisation routine that estimates the assessment's parameters. Likewise, the fewer tag returns the greater the uncertainty in the parameters of the assessment, with the potential for unreasonably large estimates of abundance. If the number of tag returns in year y is less than TR_y, there is no convergence in the minimisation routine or unreasonably large (negative or positive) estimates of net recruitment are produced, then no annual assessment is performed. It is then assumed that there has been no net recruitment, and that the estimated available biomass for year y is that estimated from the previous year, less the catch and natural mortality,

$$\hat{B}^{av,y} = e^{-M_A}(\hat{B}^{av,y-1} - \widetilde{C}_w^y),$$ (1)

where $\hat{B}^{av,y-1}$ is the estimated end-of-season available biomass in year *y-1*,

$$\hat{B}^{av,y-1} = \overline{w}_A^{y-1}\hat{N}^{av,y-1}$$ (2)

$\overline{w}_A^{y-1}$ is the mean weight of a fish in year *y-1* (Appendix 14.3),

$\hat{N}^{av,y-1}$ is the estimated end-of-season available numbers in year *y-1* from a previous assessment,

M_A is the annual instantaneous natural mortality used in the assessment, and

$\widetilde{C}_w^y$ is the total catch in biomass in year *y*.

It could be assumed that the recruitment is non-zero and set to the last estimable non-zero value. However, due to potentially large inter-annual fluctuations in net recruitment (both positive and negative) the conservative and more stable value of zero was chosen.

The stock assessment model used, unless stated otherwise, is the S2 model described in Chapter 13. This model assumes that the likelihood of recapture of each tagged fish changes in time as a function of its selectivity. The assumed selectivity is the 'one stock, base selectivity' curve (see Figure 14.11 and associated text). It is assumed that all tagged fish mix with un-tagged fish after $\delta = 10$ days and that natural mortality is $M_A = 0.1$. The assessment parameters are listed in Table 14.2. Note that many of the parameter values used in the assessment model were the same as those used in the operating model. This assumes that the parameters were known exactly. This was done to explore the biases in the model even with 'well-known' parameters. Mismatches in the parameters between assessment and operating models should be considered in future work.

4. *Management strategies*

A management strategy is a set of pre-agreed rules for selecting management actions, designed to achieve specified management objectives. The components of a management strategy are the sampling program, the assessment and a decision rule that translates the data from the sampling program, and information from the assessment into a TAC. The sampling program and assessment have been discussed above. There are four main decision rules that have been taken into the MSE analyses considered in this chapter. These are:

(*i*)   Fixed TAC or constant annual catch,

$$Tac_y = \gamma \hat{B}_0^{av}, \text{ for all projected } y \qquad (3)$$

where $0 \le \gamma \le 1$, and $\hat{B}_0^{av}$ is the estimated initial available biomass from an assessment using the historical data.

(*ii*)   Fixed TAC with triggers to alter TAC while fishing conditions are favourable,

$$Tac_y = \gamma \hat{B}_0^{av}, \text{ for all projected } y, \text{ with triggers.} \qquad (4)$$

(*iii*) TAC altered according to current estimates of available biomass, with triggers if fishing conditions are favourable,

$$Tac_y = \theta \hat{B}^{av,y-1}, \text{ with triggers} \qquad (5)$$

where $0 \le \theta \le 1$, and $\hat{B}^{av,y-1}$ is the estimated end-of-season available biomass in year *y-1* from an annual assessment.

(*iv*)   User defined fixed TAC. This allows special cases to be considered such as (a) no set TAC, so the fishery is driven by economic factors only, and (b) zero catch to consider population recovery.

The first decision rule assigns the TAC as a fraction of the estimated initial available biomass from an assessment, B_0. The applied fraction, γ, is chosen to satisfy the decision rules of CCAMLR (SC-CAMLR-XIII, 1994). In CCAMLR, the TAC is updated with new estimates of the pre-exploitation biomass. This is not applied in this case. This will be called the Fixed TAC decision rule or policy. The second decision rule assigns an initial TAC as that defined above, but triggers are allowed which increase the TAC if conditions are favourable. The triggers are discussed below. The third decision rule assigns the TAC as a fraction, θ, of the estimated end-of-season available biomass from an assessment, $\hat{B}^{av,y-1}$. The parameters of the decision rules and TAC triggers are given in Table 14.4.

TAC triggers

The TAC triggers, which increase the quota in favourable conditions, have been included in order to evaluate management strategies that allow the fishery to exploit high biomass levels when they occur. Sudden within-season changes in available biomass are currently not predictable and therefore they are not easily included in a fixed TAC, assigned before the beginning of the season. The within season TAC triggers attempt to account for these unpredictable increases in biomass.

The catch rate trigger (CT)
If conditions are favourable then an increase in the TAC can occur. If the mean catch rate is above CT_{cr} over CT_{days} days then the initial TAC = Tac_y increases to TAC = $\omega \, Tac_y$ (where $\omega \geq 1$). Correspondingly, if the mean catch rate over CT_{days} days decreases below CT_{cr} then the TAC reverts to the original value, Tac_y. If after a day's fishing the total catch is greater than the current TAC, fishing ceases and the vessel departs the ground.

The length trigger (LEN)
If there has been an increase in the mean length of fish available to the fishery then an increase in the TAC can occur. This trigger attempts to account for the occasional observed increase in larger fish, which may be attributed to the influx of transient fish (Furlani *et al.* 2000). If the mean proportion of fish greater than LEN_{len} in length is greater than LEN_{prop} over LEN_{days} then the TAC switches to TAC = $\omega \, Tac_y$ (as above). If the proportion falls below LEN_{prop} then the TAC reverts to Tac_y, unless the catch rate trigger maintains the higher TAC value.

<u>*Perfect information*</u>
For those management strategies where an assessment is performed, either on (real) historical data for decision rules 1 and 2 or annually for decision rule 3, it is possible to consider the performance of the management strategy if the true available biomass were used instead of an estimated value. In the 'perfect information' case, the true available biomass from the operating model is used to assign the TAC. This allows an examination of biases in the assessment results. Thus, in the formulations above,

$$\hat{B}_0^{av} = B_0^{av}, \text{ and}$$
$$\hat{B}^{av,y-1} = B^{av,y-1}, \tag{6}$$

where B_0^{av} and $B^{av,y-1}$ are the true initial and annual end-of-season available biomass from the operating model.

5. <u>*Management objectives and performance measures*</u>
Management objectives are broadly defined goals, while performance measures are used to compare and evaluate alternative harvest strategies that are tested in the simulation framework. A workshop involving managers, industry representatives and scientists was conducted in April 2000 to discuss appropriate objectives and performance measures for the Macquarie Island fishery (Tuck 2000). The workshop agreed that the following objectives and corresponding performance measures should be considered and where possible taken into the MSE framework. The formulation of these performance measures is described in Appendix 14.5.

Maximise the discounted expected net returns over N_y *years.*
An indication of the profitability of the toothfish fishery can be gained by an examination of the mean annual catch and its variation. As large-scale changes in catch can be costly in terms of an operator's ability to forecast operating levels (and associated costs), the mean annual change in catch will also give some insights into the economic efficiency of a harvest strategy. A more detailed, but preliminary, examination of optimal economic harvesting strategies for this fishery, including expected net returns, can be found in Langenkamp (2000).

    1)   Mean annual catch over all projected years and simulations
    2)   Mean annual change in catch.

Ensure minimum viable catches and catch rates each year.
As with objective (a), this objective attempts to maintain the economic health of the fishery. The frequency of years that the TAC could not be caught is included as a performance measure as this gives an indication of the economic efficiency of a management procedure for a particular

scenario. In times of poor catches and catch rates the operators may decide to cut their voyage short, as such we include as a performance measure the mean frequency of 'leaving' the fishery.

3) Mean annual frequency that catch was less than the TAC,
4) Mean annual frequency that the leaving trigger has been fired, e.g. the CPUE averages less than 5 t/km^2 over 8 days.

Minimise the probability that the stock will fall below various levels relative to the unfished biomass.
This objective is concerned with the conservation of the stock and maintaining adequate levels of recruitment through the conservation of the spawning biomass. The performance measures are:

5) The mean proportion remaining in spawning biomass at year Y_{last}
6) The mean annual frequency that spawning biomass is less than 50% of virgin spawning biomass

Reduce levels of uncertainty in assessments.
This aim is to give some indication of how well the assessment models are performing and hence improve our understanding of the current status of the stock. Specifically, we are interested in how robust the assessment methods are to various model uncertainties. This is achieved through measures of accuracy (relative bias) and precision (the root mean square error) in the assessment.

7) The relative bias in the estimated available biomass.
8) The relative root mean square error (RMSE) in the estimated available biomass.

Provide cost-effective levels of monitoring to achieve management objectives.
This objective requires the examination of differing levels (and thereby cost) of tagging effort required to provide an adequate assessment of the stock. Performance measures for this objective include (12) and (13) above and the number of times an assessment was unable to be performed due to inadequate monitoring (e.g. too few tag returns).

9) Mean annual frequency that an assessment was unable to be performed.

Results
The parameters used for the simulations are listed in Tables 14.1 to 14.4. Projections were over 50 years, with 50 simulations per management strategy/scenario combination. The first section of the results outlines the key behavioural aspects of the evaluation. Certain parameters have a strong effect on performance measures and more detailed sensitivity tests were conducted on these parameters. The second section looks more closely at the management strategies and how they performed across a variety of performance measures and across several resource scenarios.

Seven management strategies are considered for evaluation purposes. These are:

1. No TAC. This assumes that there is no restriction on catch (through a TAC), and fishing is only constrained by economic considerations. No tagging or annual assessment is conducted.
2. Fixed TAC set at $\gamma = 0.1$ of an estimate of the pre-exploitation abundance. This management strategy uses an annual assessment to estimate the initial available biomass, and the TAC is a fixed proportion γ of this value. There are no catch rate triggers to increase the quota.
3. Feedback $\theta = 0.1$, $T = 50$. This management strategy assumes that the annual TAC is set to $\theta = 0.1$ of the available biomass estimated from an annual assessment. Catch rate

triggers allow an increase in quota. Namely if, over 3 fishing days, the mean catch rate is greater than 10 t/km^2, then the TAC doubles. If the mean catch rate falls below 10 t/km^2 over 3 fishing days then the TAC reverts to its previous value. Approximately 50 tagged fish are released per season.

4. Feedback $\theta = 0.1$, $T = 500$. This management strategy assumes that the annual TAC is set to $\theta = 0.1$ of the available biomass estimated from an annual assessment. If conditions are favourable, then catch rate triggers allow the TAC to double (as above). Approximately 500 tagged fish are released per season.

5. Feedback $\theta = 0.1$, PI. This management strategy assumes that the annual TAC is set to $\theta = 0.1$ of the "true" available biomass from the operating model (i.e. perfect information (PI) of available biomass is assumed). If conditions are favourable, then catch rate triggers allow the TAC to double.

6. Feedback $\theta = 0.3$, PI. This management strategy assumes that the annual TAC is set to $\theta = 0.3$ of the "true" available biomass from the operating model (i.e. perfect information of available biomass is assumed). If conditions are favourable, then catch rate triggers allow the TAC to double.

7. $F=0$. This management strategy considers the recovery of the population if there is no fishing whatsoever after the historical years.

General behaviour of the evaluation model

The evaluation of management alternatives was carried out using three different assumptions about the resource dynamics:

(i)   Single stock model ($BS_{low} = 0$, $BS_{high} = 90$),
(ii)   Single stock model with zero recruitment episodes ($EZR_y = 5$, $EZR_{low} = 3$, $EZR_{high} = 5$)
(iii) Two stocks model (existence of a transient population, $B_{max}=30,000$ t)

Each of these resource models attempts to re-create the variability in available biomass observed in assessment results. Figure 14.3 shows an example of two simulations from the single stock model when a feedback management strategy with $\theta = 0.1$ is applied. Figure 14.3(a) shows how dramatically available biomass can fluctuate from year to year. As available biomass is used to assign an annual TAC, these fluctuations can then have an effect on annual yield (Figure 14.3(b)). However, as the spawning population is mostly outside of the selection range, effects on the spawning biomass are generally not realised until later (Figure 14.3(c)). There is also less variability in the spawning stock size because effects are integrated over more age classes and therefore less influenced by recruitment variability.

A critical element of the model is the assumed operational reaction to changes in catch rates. If catch rates are poor then economic constraints (through leaving triggers) that lead the vessel to abandon fishing become very important. Usually this type of modelling study does not include vessel behaviour. The importance of vessel operational behaviour can be seen in Table 14.5. This table shows the relative effects on four performance measures when assuming a feedback TAC decision rule ($\theta = 0.1$, 0.5) with varying levels for the leaving trigger catch rates, LT_{cr} and LC_{cr} and stock-recruitment (steepness) parameter ($h = 0.25$, 0.75). The lower the leaving trigger catch rate values, the more willing operators are to remain fishing when catch rates are poor. The table clearly shows the strong effect on yield and spawning stock biomass as economic constraints are weakened. Not surprisingly as operators become more willing to endure poor catch rates, yield increases and the final (year 2050) spawning stock biomass level decreases. With high leaving trigger catch rate values, there is little difference between TAC parameters $\theta = 0.1$ and $\theta = 0.5$. However, management through θ becomes more important as economic constraints on fishing are removed, i.e. the decline in spawning biomass is greater between $\theta = 0.1$ and $\theta = 0.5$ for weak economic constraints than strong economic constraints. Note that both high and low values for the leaving trigger catch rates give more stable inter-annual changes in

yield than mid-range values. For high values, the vessel nearly always leaves the ground due to a requirement for high catch rates to stay (mean number of fishing days for $LT_{cr} = LC_{cr} = 10$ is 13). This leads to consistently low catches. Low trigger values lead the vessel to remain fishing for extended periods, often through to the completion of the season (mean number of fishing days for $LT_{cr} = LC_{cr} = 1$ is 37) and catches are consistently high. Mid-range values have the vessel remaining if conditions are good, but also leaving relatively soon if catch rates are not sufficient.

If the TAC parameter θ is large (giving larger annual TAC's), even a population with low recruitment (steepness $h = 0.25$) can maintain a spawning biomass of approximately 60% if there are economic constraints that force the vessel to leave if catch conditions are poor. However, if there are almost no economic constraints on fishing, the spawning stock biomass could decrease to less than 30% of non-fished levels, with substantial mean yields maintained through persistent fishing during low catch rate periods.

Table 14.6 shows, for the three resource models, the effect on performance measures of incorrectly estimating the initial available numbers of fish. The true initial value of available numbers used in the operating model is taken as a percentage of a 'best' estimate from an assessment ($N_0^{av,*}$ = 695,413; Chapter 13 and Table 14.2). Whereas the previous single-stock operating model began with $N_0^{av,*}$ available fish, this model uses a specified fraction of $N_0^{av,*}$. Initial total spawning biomass and stock-recruitment parameters are then estimated in the usual manner (see equation A14.1.8). The population numbers-at-age are then projected forward from day 1 and catches and tagging occur. The management strategy applied in projected years is a feedback strategy with $\theta = 0.1$ and perfect information of available biomass. Note that the estimator used does not allow for any learning about initial biomass, i.e. the estimator does not learn over time from its initial mistake. This may be an area where future research could provide a better method for estimating past biomass levels or better reflect the uncertainty in estimates and account for them through appropriate management decisions.

As can be seen in Table 14.6, over-estimating the initial available numbers of fish can have dramatic consequences for the sustainability of the stock. In both single stock resource models, if the true initial available biomass is only 20% of the assessed best estimate, the resident stock spawning biomass would not recover, even using one of the more conservative management strategies considered (feedback decision rule, $\theta = 0.1$). The single stock model with and without periods of zero recruitment produces similar results. This is true for performance measures where means are considered. This is a consequence of the pre-exploitation mean behaviour of the zero recruitment model, in terms of recruitment and numbers-at-age, being equivalent to the single stock model. However, as seen later, there is much greater variation about the mean with the zero recruitment model. To compensate for years with zero recruitment, positive recruitment years have larger numbers of fish being born. The large and small (zero) recruitment years lead to the variation in performance measures (see Figs. 14.5 and 14.8).

The inclusion of a second independent stock appears to have a conserving effect on the local population (compared to the single stock models). This is because the two stocks model increases the available number of fish in the historical years, hence lowering estimated fishing mortality and the catchability of fully selected and available fish $\hat{q}$ (Appendix 14.3). When taken into the projections the lower $\hat{q}$ leads to smaller catches of resident fish and less overall impact. However, fishing can continue to produce large annual yields based on the sustained appearance of transient fish, as the annual influx of these fish is not influenced by the historical extent of harvesting on them.

For the two stocks model, the larger mean annual yields for lower initial population sizes is due to an unusual interaction between the population model and the estimation of the catchability parameters. One would expect $\hat{q}$ to increase with decreasing initial population size. This is the case with the single population models. However, for the two-stocks model, $\hat{q}$ decreases, while $\hat{\sigma}$ and $\hat{\beta}$ increase. The latter two parameters taking large values leads to the increase in catch (equation A14.3.1) with decreasing N_0^{av}. Note also that the mean annual yield of resident fish decreases in magnitude and in relative terms to that harvested from the transient fish as N_0^{av} decreases. The resident mean annual yield is also less than the yield from the corresponding single-stock models (with the exception of $N_0^{av} = 20\% \, N_0^{av,*}$, as the single stock biomass collapses in this instance); hence the more conservative effect on the spawning biomass. The conditioning assumptions for the two stocks hypothesis will be considered further in future work.

Figures 14.4 to 14.6 show for each resource model the trajectories of median (a) available biomass relative to pre-fishing levels, (b) yield, and (c) spawning stock biomass (SSB) relative to pre-fishing levels. Also shown are the 5th and 95th percentiles. The assumed management strategy applies a feedback decision rule to determine the TAC with $\theta = 0.1$ and 500 fish tagged per season. The median trajectory if the true available biomass is known (perfect information), as opposed to it being estimated with an annual assessment, is also plotted.

Figures 14.4 and 14.5 show that for the single stock models the assessment is over-estimating the true available biomass. This is because the assessment model, while able to account for relative changes in selectivity between ages, can not sufficiently account for annual fluctuations in availability (Appendix 14.2). Each year the availability is adjusted by ν^y (as estimated from historical years) in order to model the marked historical annual declines in availability that could not be due to recruitment or yield. Hence the true available biomass is less than that predicted by the assessment model.

The inclusion of zero recruitment episodes (Figure 14.5) leads to greater inter-annual variability in trajectories than the model with annual non-zero recruitment (Figure 14.4). Following extended periods of zero recruitment, available biomass and yield can drop to negligible levels. Periods of good recruitment, increased estimates of available biomass and hence good yields can then follow this. Flowing from the increased fluctuations in yield is the broader percentiles of spawning stock biomass (Figure 14.5(c)) relative to the single stock model (Figure 14.4(c)).

Figure 14.6 shows the great variation in available biomass and yield experienced when a second independent stock is included. Of course, this is dependent on the given size of the maximum biomass; in this case B_{max}=30,000 tonnes. As seen in Table 14.6, the inclusion of the second stock has a conserving effect on the resident population. Figure 14.6(c) shows that the spawning stock biomass of the resident population is, in general, at a higher proportion of initial levels than either of the single stock models.

Currently the spawning stock biomass of toothfish is not observed as part of the yield from the fishery. These figures show that available biomass, whether assessed or perfectly known, poorly reflects changes in spawning biomass (over the 50 year period considered). This indicates that alternative measures are necessary to gain insights into the potential reaction of the spawning population to fishing. However, the next section shows that in certain circumstances estimating available biomass can still provide an effective measure from which to then set TAC's and effectively manage the population without knowledge of the status of the spawning biomass.

Evaluation of management strategies
(i) The single stock resource model
Results are given in Tables 14.7 to 14.10 and Figures 14.7 and 14.8. For the single stock model (Table 14.7), the mean annual yield varies from 91 to 137 tonnes between the management alternatives. The highest mean annual yields are created by the feedback decision rule with $\theta = 0.3$, the fixed TAC decision rule and having no TAC. The fixed TAC decision rule assigns the TAC as a proportion ($\gamma=0.1$) of the estimate of initial available biomass (approximately 3,590 tonnes). The TAC in this case is 359 tonnes, which is then applied in all projected years. This TAC produces large annual yields and in only 15% of years is the TAC actually taken.

Tagging 50 fish per year, as opposed to 500, leads to more frequent inability to do a tag-based assessment. With 50 tagged fish per year, an assessment could not be performed on 10% of simulated years (Table 14.7). However, tagging less fish also appears (incorrectly) to improve estimation (both accuracy and precision). This surprising result is due to the tag assessment's over-estimation of available abundance (Figure 14.4) and the model used to estimate available abundance when no assessment is possible (equation (1)). When an assessment is not possible, recruitment is assumed to be zero. After catch and natural mortality are applied, the estimate of available biomass will be less than that estimated the previous year. As available biomass is over-estimated through the tagging model, the new estimate is closer to the 'true' value than if we had actually been able to perform an assessment.

Table 14.8 shows medians and percentiles of the final simulated year's yield, available biomass and spawning stock biomass when 50 or 500 fish are tagged per season. The perfect information case is also shown for comparison. Variation in available biomass and yield increases when only 50 tagged fish are released per season compared to 500 fish. Note for this model that the variation is not reflected in the spawning stock biomass.

Figure 14.7(a) shows, for the single stock model, the median trajectories of annual spawning stock biomass (SSB) relative to the initial (pre-fishing) level of spawning stock biomass for six management strategies. Trajectories for the fixed TAC policy are not shown as they are similar to those of the $\theta = 0.3$ management strategy. With no restrictions on catch, the 'no TAC' management strategy produces the greatest decline in spawning stock biomass (to approximately 50% of pre-fishing levels by 2050). With no catch the '$F = 0$' management strategy leads to a slow recovery of the population. The feedback decision rule with $\theta = 0.1$ and perfect information is most conservative, followed by the corresponding $\theta = 0.1$ annual assessment based decision rules (which attempt to emulate the '$\theta = 0.1$, PI' rule). Figure 14.8(a) shows the annual probability of the spawning stock biomass falling below 50% of pre-fishing levels for each management strategy. The feedback management strategies with $\theta = 0.1$ show a zero likelihood of having spawning biomass levels fall below 50% of initial levels. However, the 'no TAC' management strategy and feedback management strategy with $\theta = 0.3$ show a likelihood of approximately 0.5 and 0.2 respectively of SSB being below 50% of initial levels by the final simulation year.

(ii) The single stock resource model with episodic zero recruitment
If the population experiences episodes of zero recruitment (Table 14.9), the mean yields are similar to the single stock resource model without zero recruitment but the final spawning biomass is lower. The relative behaviour of the different management alternatives is similar to that of the single stock assumption. There is a decrease in the variability of the mean annual catch and an increase in the number of years when assessments can not be done. Both of these affects arise from extended periods of low catch following poor recruitments.

Figure 14.7(b) shows the median trajectories of annual spawning stock biomass (SSB) relative to the initial (pre-fishing) level of spawning stock biomass for the various management

strategies for the single stock model with zero recruitment episodes. The median trajectories are similar to those observed in Figure 14.7(a). However, there is clearly greater variation in potential population trajectories as indicated in Figure 14.8(b). This figure shows a marked increase in the probability that the spawning biomass is less than 50% of initial levels over the single stock model (Figure 14.8(a)).

(iii) The two stocks model
As expected, assuming a second stock increases mean annual yields and inter-annual variation in yield (Table 14.10). However, the median annual yield is lower than for the single stock models (not shown), reflecting the smaller estimated catchability for the two stocks resource model. This may explain the increased incidence of 'no assessment' years for both 50 and 500 tag releases per year. The spawning stock biomass of the resident stock decreases less than in the single stock models, again due to the applied catchability. As seen in Table 14.6, the mean annual yield of local fish is less than that of the single stock models. This conclusion is also seen in the trajectories of median SSB (Figure 14.7(c)) and the probability that SSB is less than 50% of initial levels (Figure 14.8(c)). The mean annual yield of the fixed TAC policy is least of all the considered strategies, as this management strategy does not have the ability to increase the annual quota if catch rates are good. A fixed TAC decision rule that included catch rate triggers would clearly have performed better with respect to yield in this circumstance, however an example with no triggers was used to illustrate the value of the catch rate triggers.

(iv) Further potential scenarios
While it appears that most of the management strategies provide a reasonable outcome in terms of the sustainability of the resident stock, this may not be the case under certain circumstances. Figure 14.7(d) shows the median trajectories of SSB relative to initial levels if the economic constraints that lead the vessel to depart the ground in poor catch conditions are weakened ($LT_{cr} = LC_{cr} = 1$). Operators now endure poor catch rate periods and there is a consequent effect on SSB. Likewise, if the initial available abundance is over-estimated (by a factor of 2.5 in Figure 14.7(e)) then similar marked declines in SSB can occur.

One of the key considerations for future management of the toothfish fishery is the inclusion of additional vessels. While the current model can not account for more than a single vessel at a time, the effect of increasing effort across a season can be explored. As an extreme example assume that either (a) each time the vessel is triggered to leave due to poor catch rates ($LT_{cr} = LC_{cr} = 5$), another vessel immediately takes its place, or (b) a single vessel operates with no economic constraints ($LT_{cr} = LC_{cr} = 0$). The vessels fish continually until the TAC is taken or the season ends. In this example the season lasts the full year.

Figures 14.9 and 14.10 show, for the three resource models, that the 'no TAC' policy and the feedback management strategy with $\theta = 0.3$ can dramatically reduce SSB. For the two single stock resource models, the feedback management strategy with $\theta = 0.1$ is able to conserve the SSB at approximately 60% of initial levels. This is because the annual TAC is able to restrict effort. However, this policy does not conserve the stock as well when there is a second population being harvested. The greater estimated available biomass produces large TAC's, which previously were rarely caught. Increased effort through an extended season and multiple vessels allows more of the TAC to be caught and hence more of the resident population is taken as part of the annual catch.

Thus, while previous results may have indicated that the leaving triggers could effectively conserve the stock and the influence of management was not substantial, clearly these results show otherwise. As effort is increased, the positive effects of the leaving triggers is diluted and management based on TAC's only can have dire consequences for the stock. Future research should develop a refined TAC setting rule that is robust to all resource scenarios, including the two stocks model.

Discussion

Initial results from an evaluation of potential management strategies for the Macquarie Island toothfish fishery appear to suggest that current fishing operations have a smaller impact on the resource than one might expect, principally because the TAC is not caught in most years. In addition, economic constraints, which force operators to abandon fishing during unfavourable catch conditions, may have the potential to conserve the resource. These features are reliant upon the following factors:

a) Selection is assumed to be narrow, i.e. only a fairly small proportion of the population can be affected by fishing.
b) Spawning fish, which are mostly outside of the selection range, contribute to local recruitment only (there is no emigration).
c) As fishing operations respond to a decreasing biomass through economic triggers (by having a critical mean CPUE value under which fishing is not continued), fishing has a strong self-regulatory mechanism.
d) There is only a single vessel operating over a relatively short season, i.e. effort is limited due to physical and economic constraints.
e) Estimates of virgin abundance are considered reasonable.

While these factors remain, the initial results from this chapter suggest that exploitation of the resource is sustainable in the long-term with minimal management intervention. However, it is highly unlikely that all of these factors are either true or will hold in the future. Taking each point in turn:

a) Selection is very difficult to estimate especially for a stock that experiences dramatic fluctuations in availability such as Macquarie Island toothfish (Chapter 10). Furthermore, it is quite possible that future changes to gear (e.g. longlining) or fishing efficiency (e.g. improved ability to predict 'good' years) could have a substantial effect on gear selectivity and availability. These changes may broaden the range of selection, allowing a greater proportion of the spawning biomass to be harvested.

b) The population dynamics of the Macquarie Island toothfish remains largely uncertain. It is still not clear whether the population is composed entirely of local fish or occasionally experiences input from an external source. If spawning fish contribute to other local or external populations then the spatial dynamics of the stock could be critical to the management of the metapopulation.

c) If economic constraints on fishing weaken then the subsequent increased effort and catch could have a substantial effect on spawning biomass.

d) Currently there is only a single vessel operating at Macquarie Island. However, if effort increases, either through multiple boats, or an increase in season length, then the ensuing increase in catch could substantially impact the spawning biomass if not constrained by appropriate management.

e) Current estimates of available biomass are based on an annual assessment using tag-recapture models (Chapter 13). Several models have been considered, and while improvements are continually being made, uncertainties regarding the estimated parameters remain. The ability of the models to give precise results is highly influenced by the catch and recapture of tagged fish. This is well illustrated by the results from the Northern Valleys, where initial available abundance estimates are highly uncertain due to the recapture of only three tagged fish in the first season. Even with adequate recapture rates, this chapter has shown that estimates of available abundance are biased. This is despite the fact that we have been kind to the assessment model by giving it the 'true' parameters for natural mortality, growth and selectivity from the

operating model. As such, the possibility that we have over-estimated initial available abundance should not be discounted. An important conclusion is that the adjustment of double the TAC may be too high given the uncertainties in the assessments and the failure of the TAC to protect the stock when effort is not controlled.

Having identified these uncertainties, one of the key roles of management strategy evaluation is to identify management strategies that are robust across the uncertainties. Clearly, having no TAC and allowing economic constraints to control fishing is a highly risky option. If any of the above conditions fail, then the impact on the population can be substantial. The fixed TAC policy is highly reliant on a reasonable estimate of initial abundance. In the example considered here the initial abundance is relatively large leading to a high fixed annual TAC. While this produces quite large catches, often the TAC is not caught (potentially leading to economic inefficiencies for operators) and the spawning stock can be reduced by as much as the 'no TAC' policy. While it is not shown here, the inability of this model to adapt to annual fluctuations in biomass should be of some concern with respect to yield. The evaluations undertaken here have not addressed the value of establishing TAC's prior to the onset of the fishery. Thus, its application in this context has not been fully explored. Clearly, there is a need to revise such measures as data is acquired before the full effects of a new fishery are experienced by the spawning stock. While the fixed TAC policy has been based on the CCAMLR precautionary approach, the evaluations here of that policy have not evaluated the performance of the CCAMLR approach. This is because it has not examined how the CCAMLR approach might perform in relation to the median pre-exploitation spawning biomass, being central to the rules of decision adopted in CCAMLR.

The feedback management strategies with $\theta = 0.1$ performed reasonably well across the considered scenarios. Tagging effort played an important role in decreasing the level of uncertainty in estimates of available biomass. Reducing tagging effort increased the likelihood that a tag-based assessment could not be performed and estimates of available biomass showed larger inter-annual fluctuations, producing greater variation in expected annual catch. Surprisingly, these fluctuations did not have a substantial effect on the spawning biomass. While it is encouraging that this management strategy outperformed the others, at least in terms of conservation benefits, it did falter (along with the other policies) under some circumstances. Namely, if initial estimates of abundance are over-estimated or if effort is increased and there are two stocks then spawning biomass may reduce to a larger extent than may be acceptable.

The corresponding feedback strategy with $\theta = 0.3$ leads to greater yields, often to the detriment of spawning biomass. Results from this policy are frequently similar to the 'no TAC' management strategy. If harvesting ceases altogether, the population can take some time before returning to pre-fishing levels. Even after 50 years, the median spawning biomass is less than initial levels for all three resource-models. This is a general consequence of the population being a long-lived species with slow growth rates.

The current management policy for toothfish is analogous to the feedback rule with $\theta = 0.1$. However, it includes a condition that if the full TAC is taken from the resident stock and there is no recruitment to the population, then it is possible that the resident stock has been reduced to the reference level of stock reduction (50% reduction in SSB). Under this circumstance fishing operations would cease (SAFAG11). This 'worst-case' condition has not been included in the management strategies evaluated in this chapter. However, the results from this chapter, where the resident stock reduces substantially with increased effort and a two stocks resource model, highlights its need. This condition should be fully prescribed in future evaluation of management strategies for this fishery so that strategies are robust to all potential resource scenarios.

The software developed to analyse potential management strategies is a flexible tool that, without much effort, can be utilised to consider many management options across a wide range of resource scenarios. However, there are some areas where improvements could be made. Clearly, the method used to determine catch rates is pivotal to the results. While the method used is relatively flexible, estimating three catchability-related parameters from historical data, further examination of these techniques should be considered, along with appropriate analysis of residuals. The historical component of the operating model and, in particular, the model used to condition projections should be considered in future work. This is especially the case when fitting a second stock to historical data, or determining the duration of extended selection. More detailed examination of observed length-densities may assist in this regard.

There are several more scenarios that could be examined now that the basic structure has been developed. For example, the inclusion of a spatial model would allow the analysis of management strategies when more than one stock interacts through recruitment or migration. A management strategy that includes a marine protected area could then be analysed. An appropriate model of selectivity could consider the effect of allowing longlining. As more age groups would be available to the fishery, the move from trawling to longlining may have a marked impact on the population, and hence management. Longlining may also improve estimates of growth parameters. This benefit could be considered in an evaluation of harvest strategies that include longlining. The effects of increasing the number of vessels could also be examined in more detail than was possible here. Initial analyses of increased effort showed that strong impacts could occur if the population is not managed in an appropriate manner.

Acknowledgments

References
Furlani, D., He, X., Williams, R., Lamb, T. and Tuck, G. N. (2000). Analysis of length frequency for the Patagonian toothfish fishery of Macquarie Island: implications of fish movement in and out of fishing grounds. Manuscript.

Hilborn, R. and Walters, C.J. (1992). Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Langenkamp, D. (2000). A bioeconomic study of the Macquarie Island Patagonian toothfish fishery. Thesis submitted as part requirement for the Bachelor of Economics (Honours) Degree, University of Queensland.

Mace, P. M. and Doonan, I. J. (1988). A generalised bioeconomic simulation model for fish population dynamics. New Zealand Fisheries Assessment Research Document 88/4. December 1988, N.Z. Ministry of Agriculture and Fisheries.

Marr, J.C., 1951. On the use of the terms "Abundance", "Availability" and "Apparent Abundance" in fishery biology. Copeia, No. 2, pp. 163-169.

Methot, R.D. (1990). Synthesis model: an adaptive framework for analysis of diverse stock assessment data. Int. North Pac. Fish. Comm. Bull. 50: 259-277.

Polacheck, T., Klaer, N. L., Millar C. and Preece, A. L. (1999). An initial evaluation of management strategies for the southern bluefin tuna fishery. ICES Journal of Marine Science, 56: 811-826.

Press, W. H., Teukolsky, S. A., Vetterling, W. T. and Flannery, B. P. 1995. Numerical Recipes in C, the Art of Scientific Computing: 2nd Edition. Cambridge University Press. Cambridge, UK.

Quinn II, T.J. and Deriso, R.B. (1999). Quantitative fish dynamics. Oxford University Press, New York.

SC-CAMLR-XIII, 1994. Report of the Thirteenth Meeting of the Scientific Committee. Scientific Committee for the Conservation of Antarctic marine Living resources, Hobart. Paragraphs 5.18 – 5.26.

Smith, A. D. M., Punt A. E., Wayte, S. E., and Klaer, N. L. (1996). Evaluation of harvest strategies for eastern gemfish (*Rexea solandri*) using Monte Carlo simulation. In, Smith A. D. M. Evaluation of harvesting strategies for Australian fisheries at different levels of risk from economic collapse. FRDC T93/238, pp 120-164.

Tuck, G. N., Williams, R., He, X., Smith, A. D. M. and Constable, A., (2000). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-2000. Sub-Antarctic Fisheries Assessment Group document. SAFAG-00/10/4. Australian Fisheries Management Authority, Canberra.

Tuck, G. N. (2000). Macquarie Island Patagonian Toothfish Management Strategy Evaluation Workshop: Outcomes. 3 April 2000, CSIRO, Hobart. SAFAG-00/9/. Australian Fisheries Management Authority, Canberra.

Table 14.1 The operating model biological parameters. Numbers in bold are used in basic runs, other numbers listed for a particular parameter are considered for sensitivity tests.

Quantity		Values	
		Male	Female
Natural mortality	M_k	0.1	0.1
Growth parameters	L_∞^k	185.5cm	185.5cm
	κ^k	0.042	0.042
	t_0^k	-0.781	-0.781
Weight-at-age	$\widetilde{a}_k$	5.0×10^{-6}	5.4×10^{-6}
	$\widetilde{b}_k$	3.12	3.11
Maturity	A_m^k	14	14
	S_m^k	3	3
Recruitment	R_{cv}	0.6	
	EZR_y	**0**, 5 years	
	EZR_{low}	3 years	
	EZR_{high}	5 years	
Tag length measurement error	ε_L	10cm	
Maximum age	x	70 years	
Stock-recruitment (steepness)	h	0.25, **0.75**	
Mixing parameters	δ	10 days	
	d_0	4	
Broad selectivity duration	BS^{low}	0 days	
	BS^{high}	**90**, 362 days	
Transient maximum biomass	B_{max}	30,000 tonnes	

		Length	Selectivity
Selectivity parameters	Base selectivity, s	29.5	0.0
		36.5	0.01
		69.5	1.0
		113.4	0.006
		160	0.0
	Broad selectivity, s_{bs}	29.5	0.0
		36.5	0.01
		69.5	1.0
		107.5	1.0
		123.9	0.01
		160	0.0

Table 14.2 The parameters of the assessment model.

Quantity		Values	
Assessment model		S2 (Chapter 13)	
Natural mortality	M_A	0.1	
Days to well-mixed	δ_A	10 days	
Growth parameters	L_∞^A	185.5cm	
	κ^A	0.042	
	t_0^A	-0.781	
Detection rate	λ_y	0.888	
		0.888	
		0.954	
		0.952	
		1.000	
Mean weight (kg)	$\overline{w}_A^y$	5.16	
		3.53	
		4.11	
		4.33	
		2.90	
Selectivity parameters	s_A	Length	Selectivity
		29.5	0.0
		36.5	0.01
		69.5	1.0
		113.4	0.006
		160	0.0

Table 14.3 The parameters of the simulation runs. Numbers in bold are used in basic runs, other numbers listed for a particular parameter are considered for sensitivity tests.

Quantity		Values
Conditioned on fishing ground		Aurora Trough
Historical catch data		Daily catch, effort, tag release/recapture and lengths
Initial available numbers N_0^{av}		695413 (20%, 40%, 60%, **100%**, 150%)
Historical years	N_h	5
Simulated years	N_y	50
Number of simulations	N_s	50

Table 14.4 The parameters of the management system and vessel behaviour. Numbers in bold are used in basic runs, other numbers listed are considered for sensitivity tests.

Quantity		Values
Decision rules	θ, γ	0, **0.1**, 0.3, 0.5
	ω	2
	TR_y	2 tags
	n_{tag}	50, **500** tags
	d_{start},	**1-Dec**, 2-Jul
	d_{end}	**1-Mar**, 29-Jun
Catch rate trigger	CT_{days}	3
	CT_{cr}	10
Length trigger	LEN_{days}	3
	LEN_{len}	75cm
	LEN_{prop}	**0**, 0.3
Leaving trigger	LT_{days}	8
	LT_{cr}	1, 3, **5**, 7, 10
	LC_{days}	2
	LC_{cr}	1, 3, **5**, 7, 10
	LC_{extra}	5
Fishing frequency	FF_{base}	2
	FF_{days}	5
	FF_{cr}	3
	FF_{high}	1

Table 14.5 Effect of leaving triggers (economic factors), stock-recruitment (steepness) *h*, and TAC parameter θ on key performance measures. A feedback management decision rule is applied with perfect information (the true available biomass is known at the time the TAC is decided). The single stock resource model is assumed.

14.5a. Mean annual yield (tonnes).

Leaving trigger, LT_{cr} & LC_{cr}	$h = 0.75$		$h = 0.25$	
	$\theta = 0.1$	$\theta = 0.5$	$\theta = 0.1$	$\theta = 0.5$
10	60	76	47	57
7	75	107	57	74
5	91	135	68	92
3	115	165	84	109
1	132	183	101	126

14.5b. Percentage of final SSB/SSBo

Leaving trigger, LT_{cr} & LC_{cr}	$h = 0.75$		$h = 0.25$	
	$\theta = 0.1$	$\theta = 0.5$	$\theta = 0.1$	$\theta = 0.5$
10	77	72	65	60
7	72	61	60	52
5	66	51	54	42
3	58	40	46	32
1	51	31	37	21

14.5c. Mean change in yield (tonnes)

Leaving trigger, LT_{cr} & LC_{cr}	$h = 0.75$		$h = 0.25$	
	$\theta = 0.1$	$\theta = 0.5$	$\theta = 0.1$	$\theta = 0.5$
10	59	95	46	67
7	70	134	54	93
5	74	161	59	112
3	64	155	54	111
1	43	102	34	75

14.5d. Percentage of years leaving the fishery

Leaving trigger, LT_{cr} & LC_{cr}	$h = 0.75$		$h = 0.25$	
	$\theta = 0.1$	$\theta = 0.5$	$\theta = 0.1$	$\theta = 0.5$
10	84	98	86	99
7	71	94	78	97
5	56	86	64	91
3	31	60	42	74
1	1	4	4	19

Table 14.6(a-d) The effect of varying the initial available abundance on key interest variables across three resource models; (i) single stock, (ii) single stock with zero recruitment episodes, and (iii) two stocks model (B_{max} = 30,000). A feedback decision rule is applied with TAC parameter θ = 0.1 and perfect information of available biomass. The present 'best' estimate for the initial number of available toothfish is $N_0^{av,*}$ = 695,413. Basic values assumed for other parameters (h = 0.75, LT_{cr} = LC_{cr} = 5). Note that spawning stock biomass is given for the local stock only. EZR = episodic zero recruitment resource model.

14.6a. Mean annual yield (tonnes)

Initial available abundance, percentage of $N_0^{av,*}$	Resource Model			
	Single stock	Single stock, EZR	Two stocks	
			Trans	Local
150	110	110	129	116
100	91	91	166	88
60	73	73	216	62
40	61	60	280	47
20	19	18	491	30

14.6b. Percentage of final SSB/ SSBo (local)

Initial available abundance, percentage of $N_0^{av,*}$	Resource Model		
	Single stock	Single stock, EZR	Two stocks
150	74	71	73
100	66	63	69
60	52	49	63
40	34	32	55
20	0	1	37

14.6c. Mean change in yield (local & transient) (tonnes)

Initial available abundance, percentage of $N_0^{av,*}$	Resource Model		
	Single stock	Single stock, EZR	Two stocks
150	99	90	281
100	74	68	317
60	60	55	374
40	55	52	463
20	27	26	784

14.6d. Percentage of years leaving the fishery

Initial available abundance, percentage of $N_0^{av,*}$	Resource Model		
	Single stock	Single stock, EZR	Two stocks
150	55	55	58
100	56	58	63
60	63	63	68
40	65	66	71
20	59	57	73

AN INITIAL EVALUATION OF MANAGEMENT STRATEGIES FOR TOOTHFISH

Table 14.7 Performance of some management alternatives. Single stock model assumed with base-case parameters ($N_0^{av,*} = 695,413$, $h=0.75$). n.a. = Not applicable, t = tonnes

Management/ Assessment Strategy	θ, γ or TAC values	Performance measure							
		Mean annual catch (t)	% mean final SSB/SSB$_o$	Mean annual change of catch (t)	% Catch <TAC	% leaving fishery	% no assessment	Bias in $\hat{B}^{av}$ estimate	RMSE of $\hat{B}^{av}$ estimate
No TAC	No TAC	137	51	168	n.a.	88	n.a.	n.a.	n.a.
Fixed TAC, no triggers	γ=0.1, TAC=359	128	53	144	85	82	n.a.	n.a.	n.a.
50 tagged	θ=0.1	103	62	100	65	63	10	56.06	119
500 tagged	θ=0.1	105	62	101	67	65	0	64.61	142
Perfect information	θ=0.1	91	66	74	58	56	n.a.	n.a.	n.a.
Perfect information	θ=0.3	128	54	142	85	80	n.a.	n.a.	n.a.
No fishing	TAC=0	0	98	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 14.8 Medians (mean in brackets) and percentiles of yield (absolute, in tonnes), available biomass and spawning stock biomass as a fraction of initial levels for the final simulated year Y_{last}. A feedback management strategy is applied with $\theta = 0.1$ and either 50 or 500 tagged fish released per year. The perfect information case is shown for comparison. The single stock resource model is assumed.

Performance measure for day Y_{last}	50 tagged	500 tagged	Perfect information
95th Percentile	1.46	0.77	0.83
$B^{av}/B^{av,o}$	0.50 (0.60)	0.52 (0.53)	0.41 (0.45)
5th Percentile	0.21	0.32	0.21
95th Percentile	331	251	201
Yield	56 (101)	79 (108)	81 (87)
5th Percentile	7	7	7
95th Percentile	0.71	0.70	0.75
SSB/SSB$_o$	0.62 (0.62)	0.61 (0.62)	0.66 (0.66)
5th Percentile	0.57	0.56	0.58

AN INITIAL EVALUATION OF MANAGEMENT STRATEGIES FOR TOOTHFISH

Table 14.9 Performance of some management alternatives. Single stock model assumed with zero recruitment episodes occurring 1 in every 5 non-zero recruitment years, with duration between 3 and 5 years. Base-case values for other parameters ($N_0^{av,*} = 695{,}413$, $h=0.75$).

n.a. = Not applicable, t = tonnes

Management/ Assessment Strategy	θ, γ or TAC values	Performance measure							
		Mean annual catch (t)	% mean final SSB/SSB$_0$	Mean annual change of catch (t)	% Catch <TAC	% leaving fishery	% no assessment	Bias in $\hat{B}^{av}$ estimate	RMSE of $\hat{B}^{av}$ estimate
No TAC	No TAC	137	43	158	n.a.	87	n.a.	n.a.	n.a.
Fixed TAC, no triggers	γ=0.1, TAC=359	125	52	123	83	80	n.a.	n.a.	n.a.
50 tagged	θ=0.1	103	54	93	65	63	14	56.06	128
500 tagged	θ=0.1	105	53	92	66	64	1	66.24	150
Perfect information	θ=0.1	91	57	68	60	58	n.a.	n.a.	n.a.
Perfect information	θ=0.3	128	46	130	86	79	n.a.	n.a.	n.a.
No fishing	TAC=0	0	87	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 14.10 Performance of some management alternatives. Two stocks resource model assumed with B_{max}=30,000 and base-case parameters ($N_0^{av,*}$ = 695413, h=0.75). n.a. = Not applicable, t = tonnes *Values of mean annual yield are the sum of local and transient fish.

Management/ Assessment Strategy	θ, γ or TAC values	Mean annual catch (t) Trans	Local	% mean final SSB/SSB₀	Mean annual change of catch (t)	% Catch <TAC	% leaving fishery	% no assessment	Bias in $\hat{B}^{av}$ estimate	RMSE of $\hat{B}^{av}$ estimate
No TAC	No TAC	310	121	57	609	n.a.	81	n.a.	n.a.	n.a.
Fixed TAC, no triggers	γ=0.1, TAC=359	105	75	73	192	63	62	n.a.	n.a.	n.a.
50 tagged	θ=0.1	240*		70	302	66	63	27	17.87	109
500 tagged	θ=0.1	261*		69	331	68	64	7	35.21	116
Perfect information	θ=0.1	166	88	69	317	67	63	n.a.	n.a.	n.a.
Perfect information	θ=0.3	258	112	61	501	84	73	n.a.	n.a.	n.a.
No fishing	TAC=0	0	0	98	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
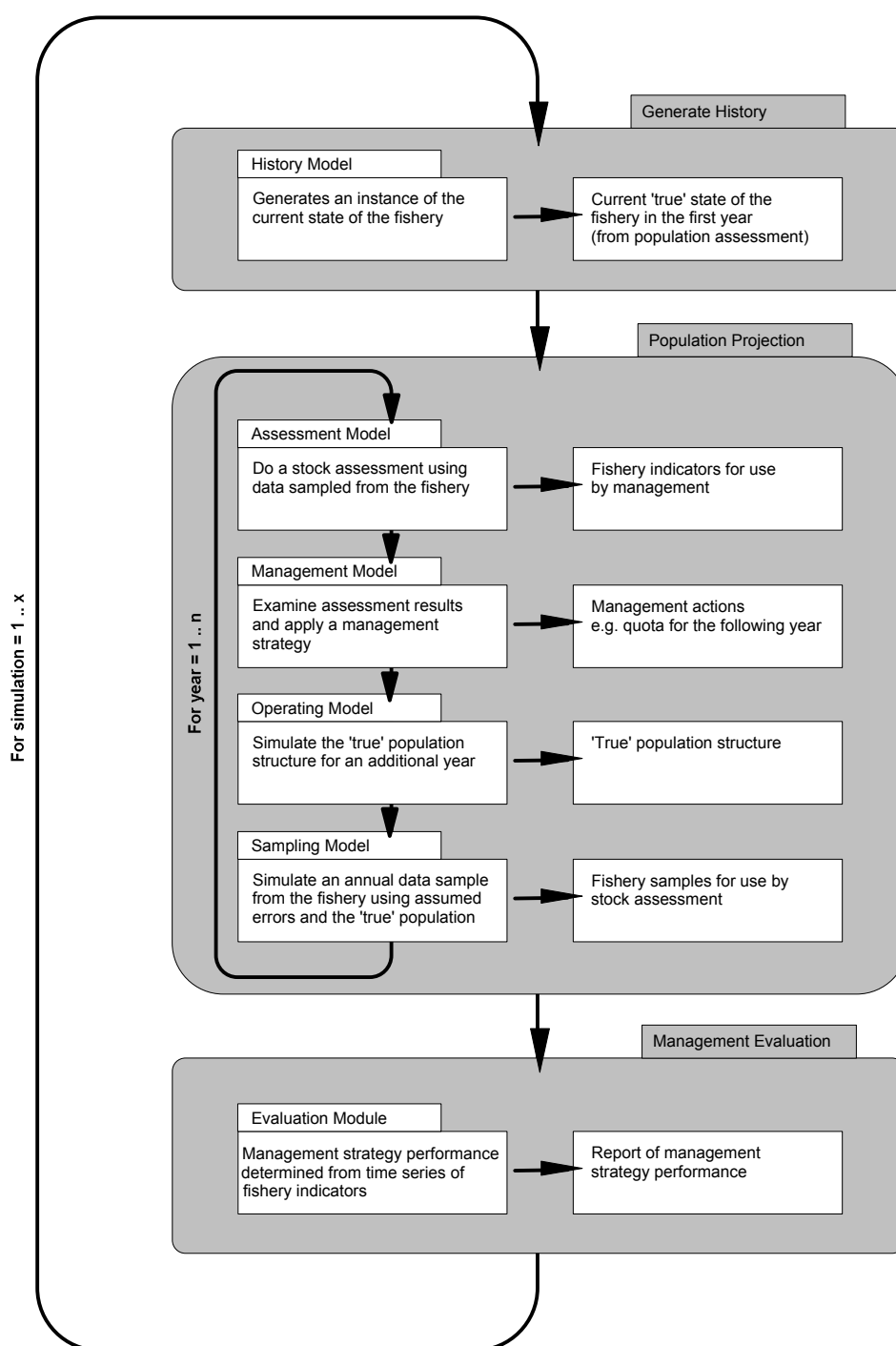
Figure 14.1 A diagrammatic representation of the management strategy evaluation framework for Macquarie Island toothfish (from Polacheck *et al.* 1999).
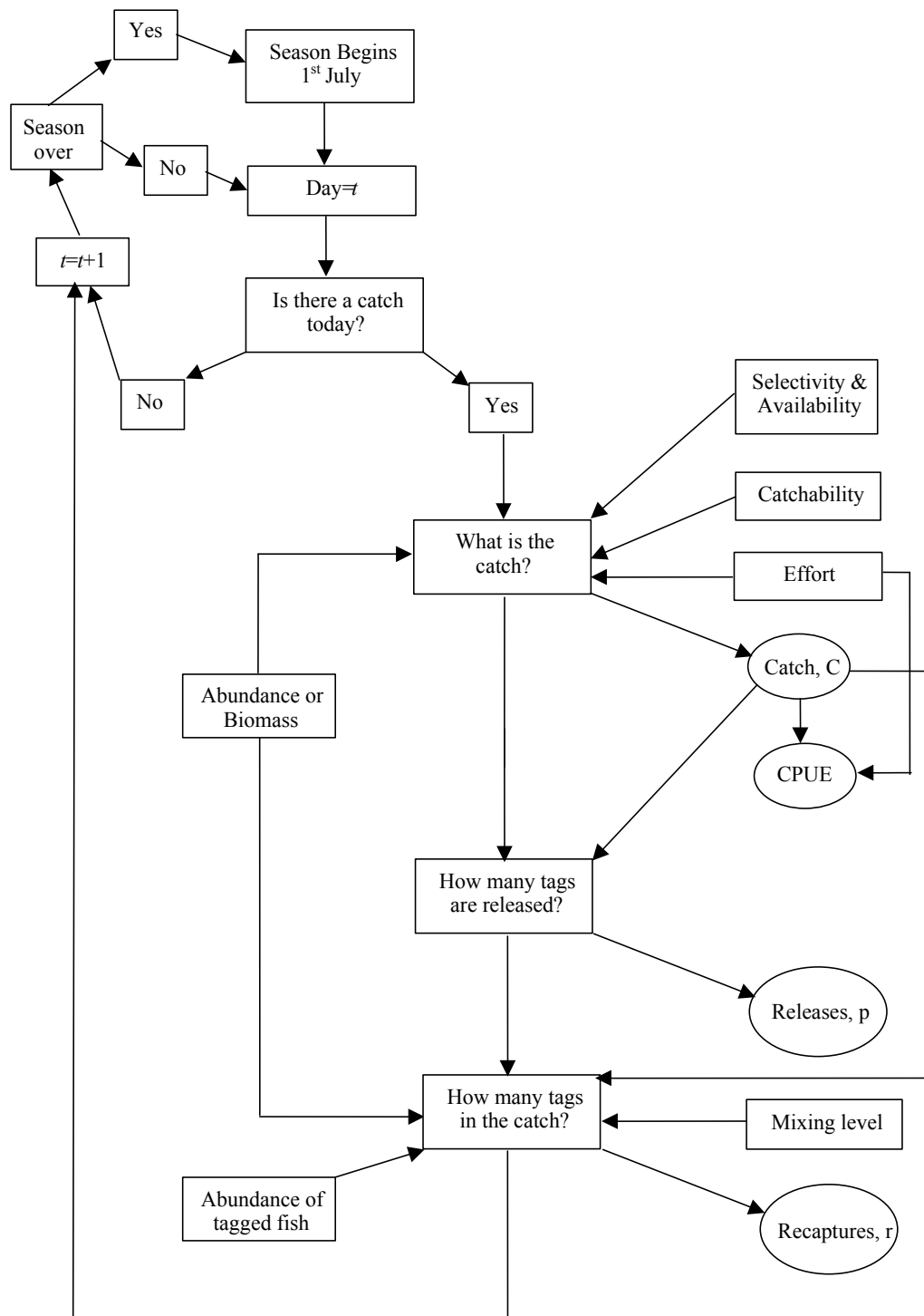
Figure 14.2 The structure of the fishery simulator. The stock assessment inputs (simulator outputs) are enclosed in ellipses.
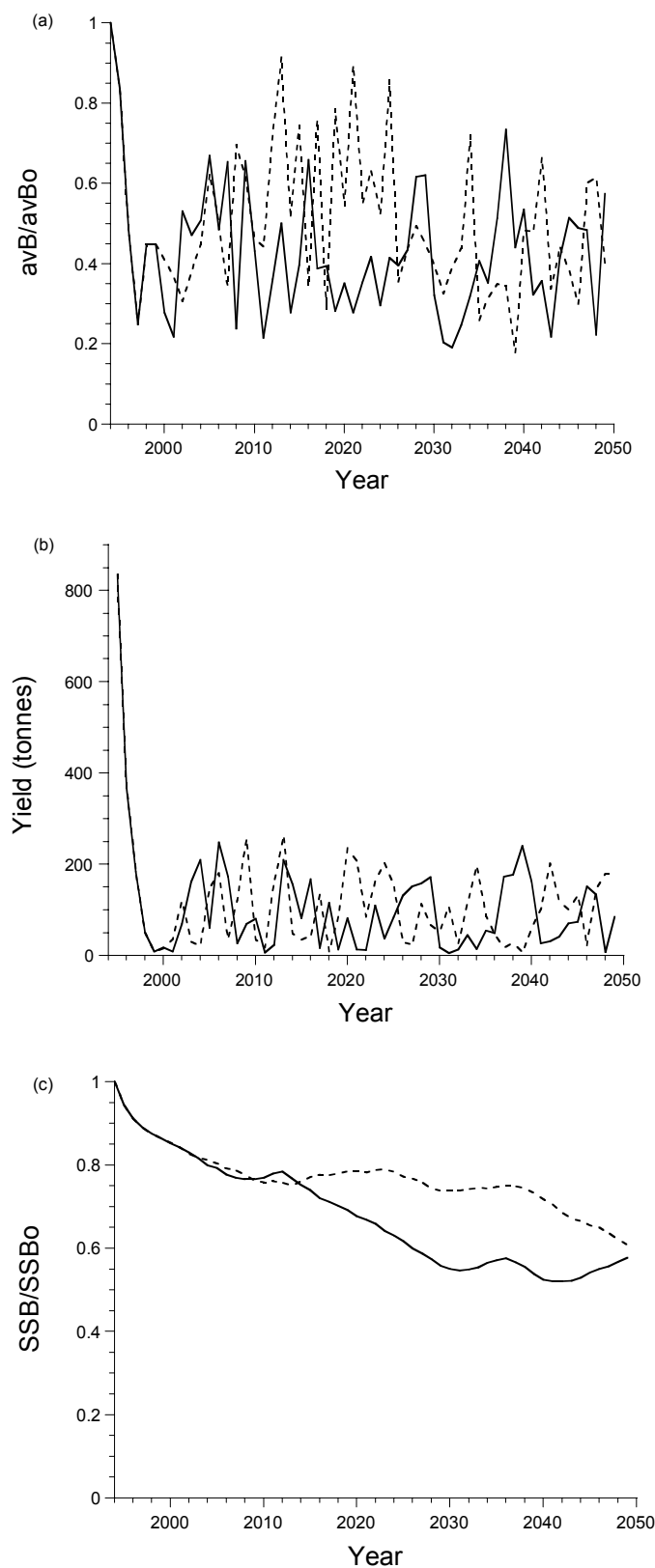
Figure 14.3 Two example trajectories showing (a) available biomass relative to pre-fishing levels, (b) yield and (c) spawning stock biomass relative to pre-fishing levels for the single stock resource model and a feedback management strategy with $\theta = 0.1$.
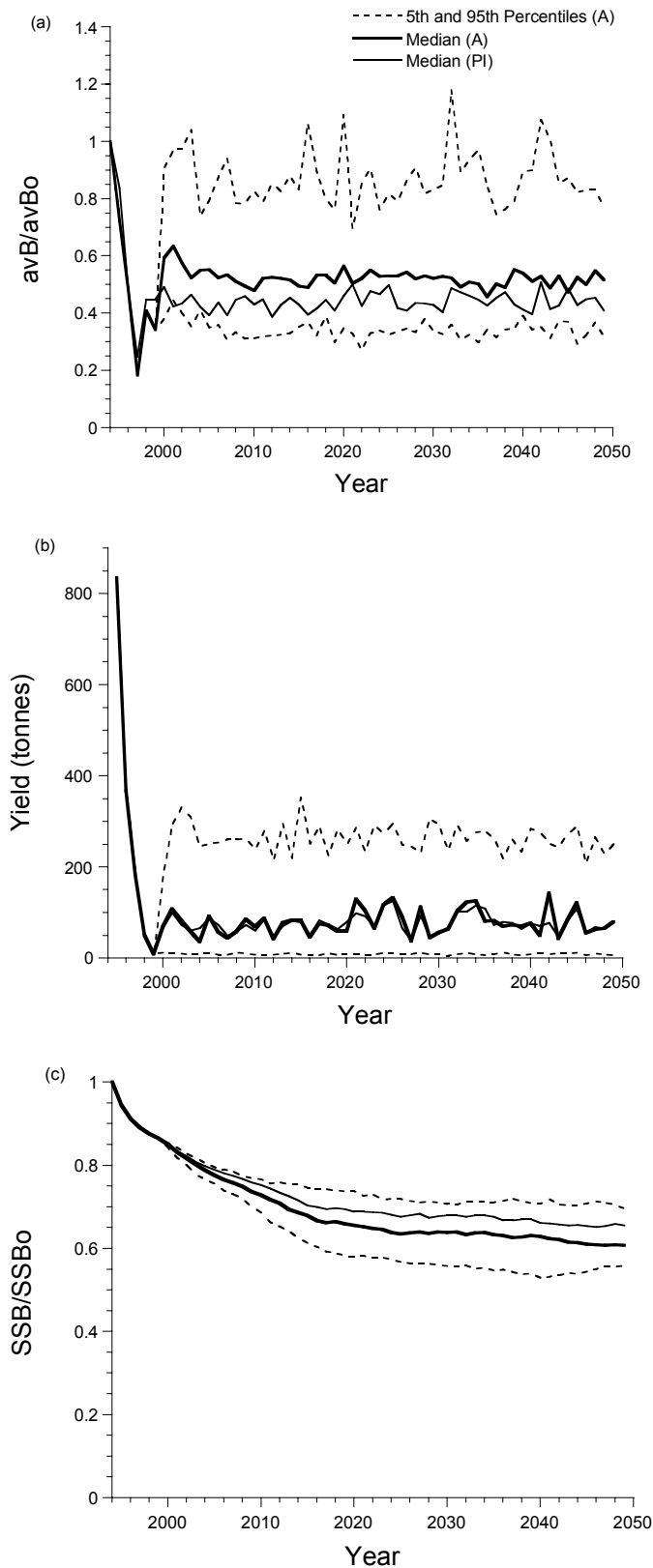
Figure 14.4 Time series of the median, 5th and 95th percentiles for the single stock model, and a feedback decision rule with $\theta = 0.1$, and 500 tag releases per season. (a) Available biomass relative to pre-fishing levels; (A) assessed and (PI) perfect information, (b) annual yield, and (c) spawning stock biomass relative to pre-fishing levels.
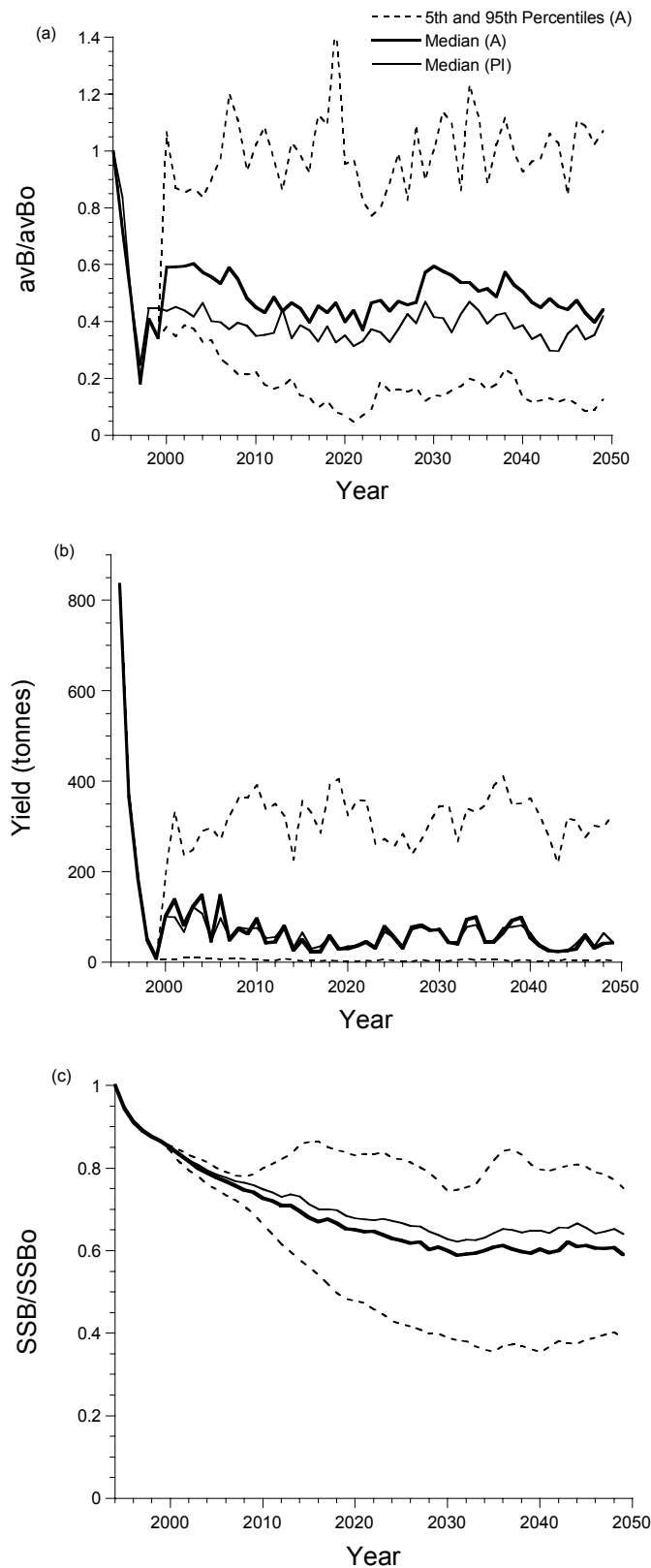
Figure 14.5 Time series of the median, 5th and 95th percentiles for the single stock model with zero recruitment episodes, and a feedback decision rule with $\theta = 0.1$, and 500 tag releases per season. (a) Available biomass relative to pre-fishing levels; (A) assessed and (PI) perfect information, (b) annual yield, and (c) spawning stock biomass relative to pre-fishing levels.
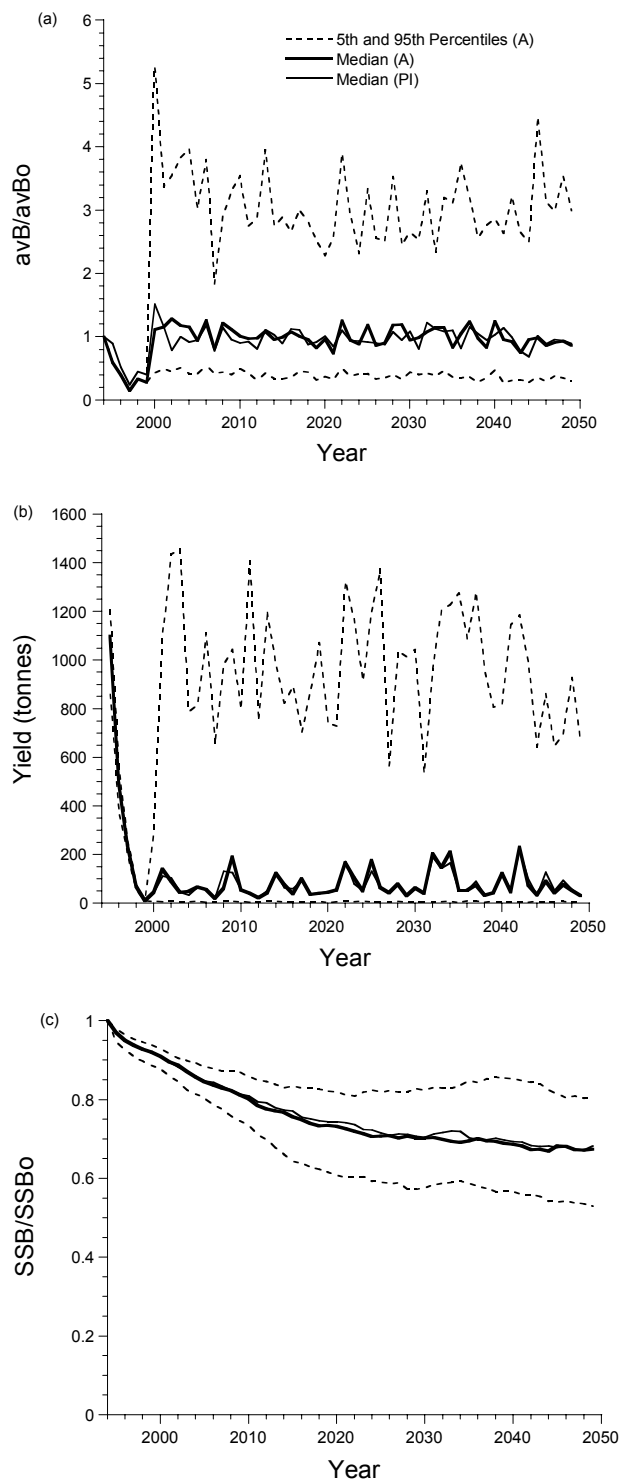
Figure 14.6 Time series of the median, 5th and 95th percentiles for the two stocks hypothesis, and a feedback decision rule with $\theta = 0.1$, and 500 tag releases per season. (a) Available biomass relative to pre-fishing levels; (A) assessed and (PI) perfect information, (b) annual yield, and (c) resident spawning stock biomass relative to pre-fishing levels.
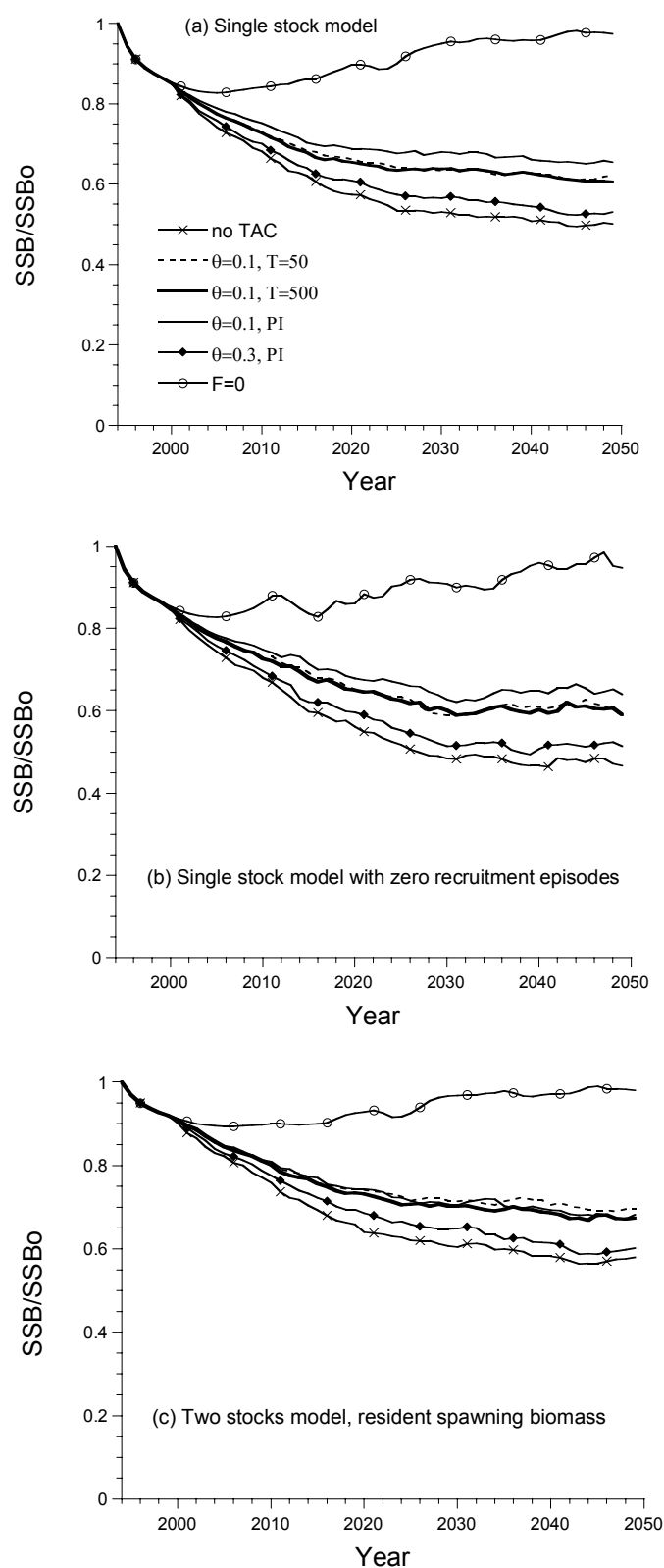
Figure 14.7 Time series of the median spawning stock biomass (SSB) relative to initial SSB for various management strategies. (a) Single stock resource model, (b) Single stock resource model with zero recruitment episodes occurring on average 1 in every 5 (non-zero recruitment) years and of duration between 3 and 5 years, (c) Two stocks resource model.

(d) Single stock model, with weak economic constraints

(e) Single stock model, with initial available abundance over-estimated
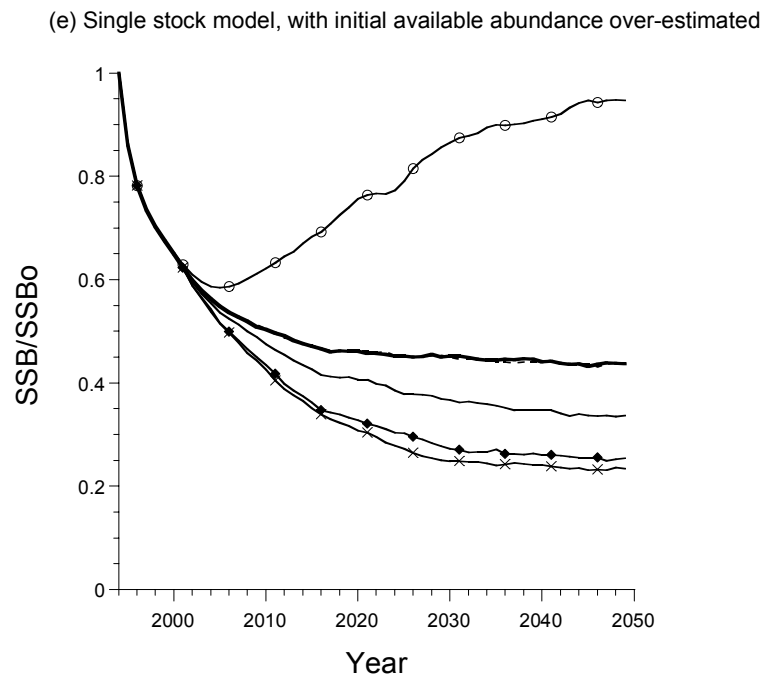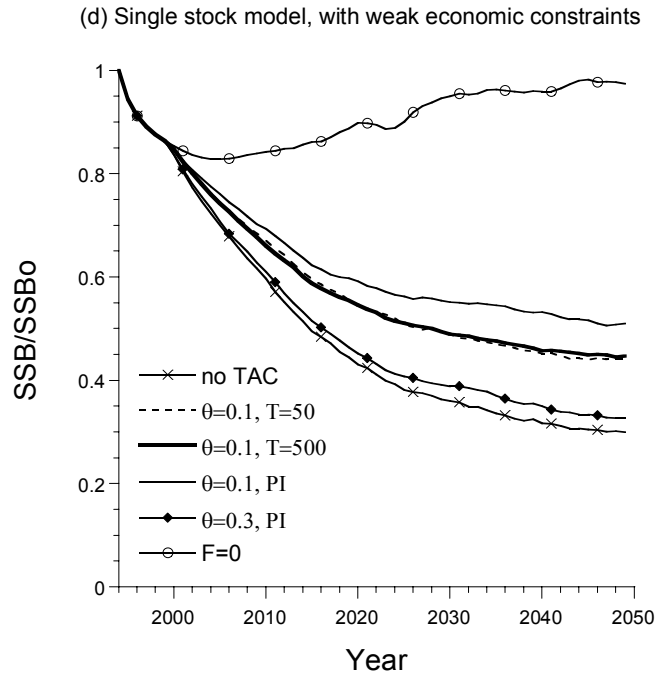
Figure 14.7 (cont) Time series of the median spawning stock biomass (SSB) relative to initial SSB for various management strategies. (d) Single stock resource model, with weak economic constraints allowing the vessel to remain fishing when catch rates are poor, (e) Single stock resource model, with the initial 'true' available abundance 40% of that estimated by the assessment model.
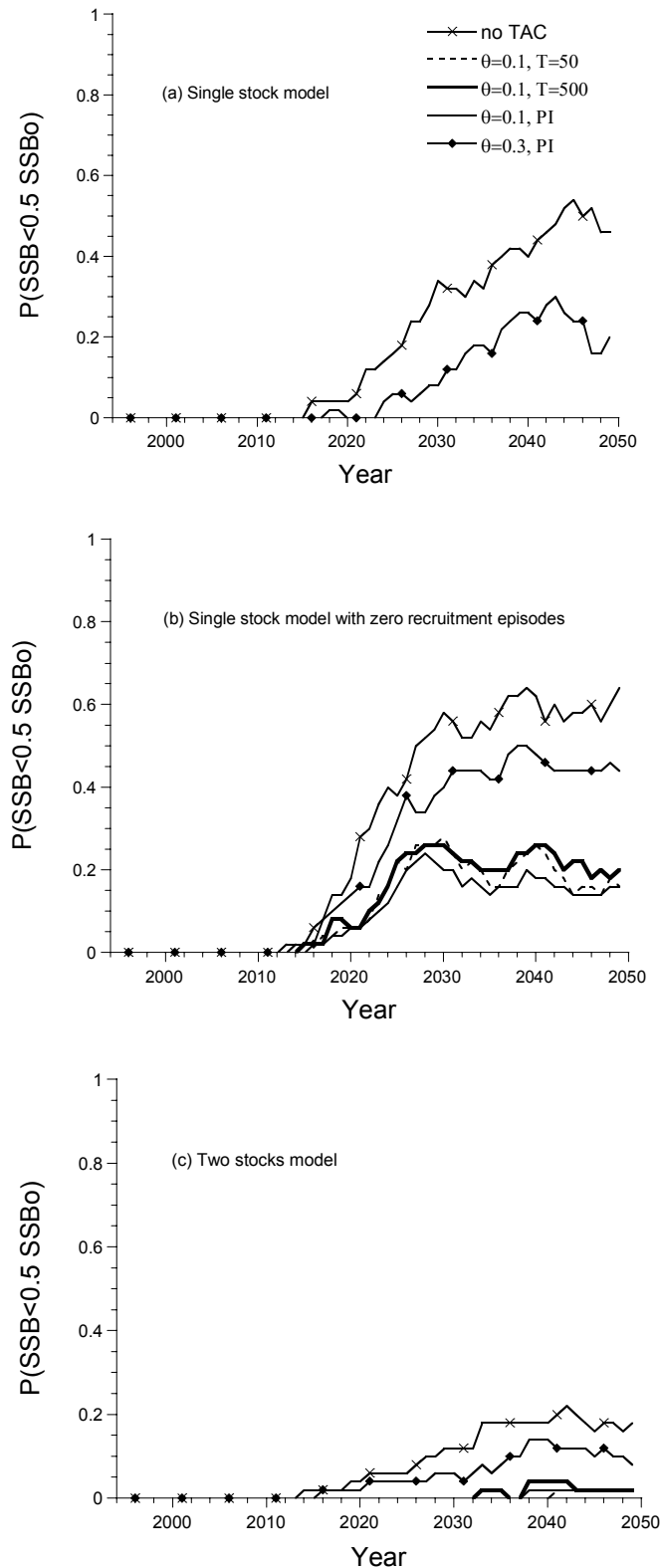
Figure 14.8 Time series of the probability that the spawning stock biomass is less than 50% of initial levels for various management strategies. (a) Single stock resource model (note the θ=1 management strategies have zero probability), (b) Single stock resource model with zero recruitment episodes occurring on average 1 in every 5 non-zero recruitment years and of duration between 3 and 5 years, (c) Two stocks resource model (spawning stock refers to the resident population).
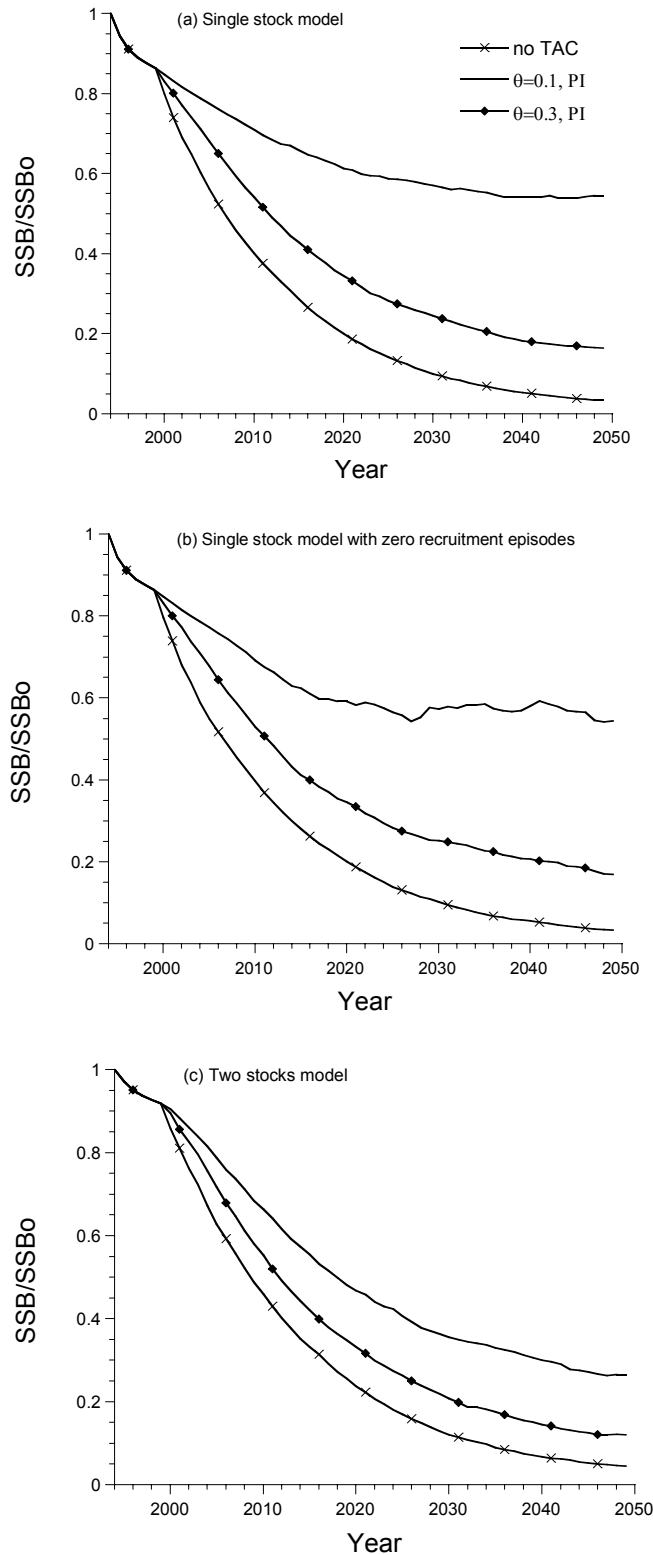
Figure 14.9 Time series of the median spawning stock biomass (SSB) relative to initial SSB for 3 management strategies without economic or effort constraints. (a) Single stock resource model, (b) Single stock resource model with zero recruitment episodes occurring on average 1 in every 5 non-zero recruitment years and of duration between 3 and 5 years, (c) Two stocks resource model.
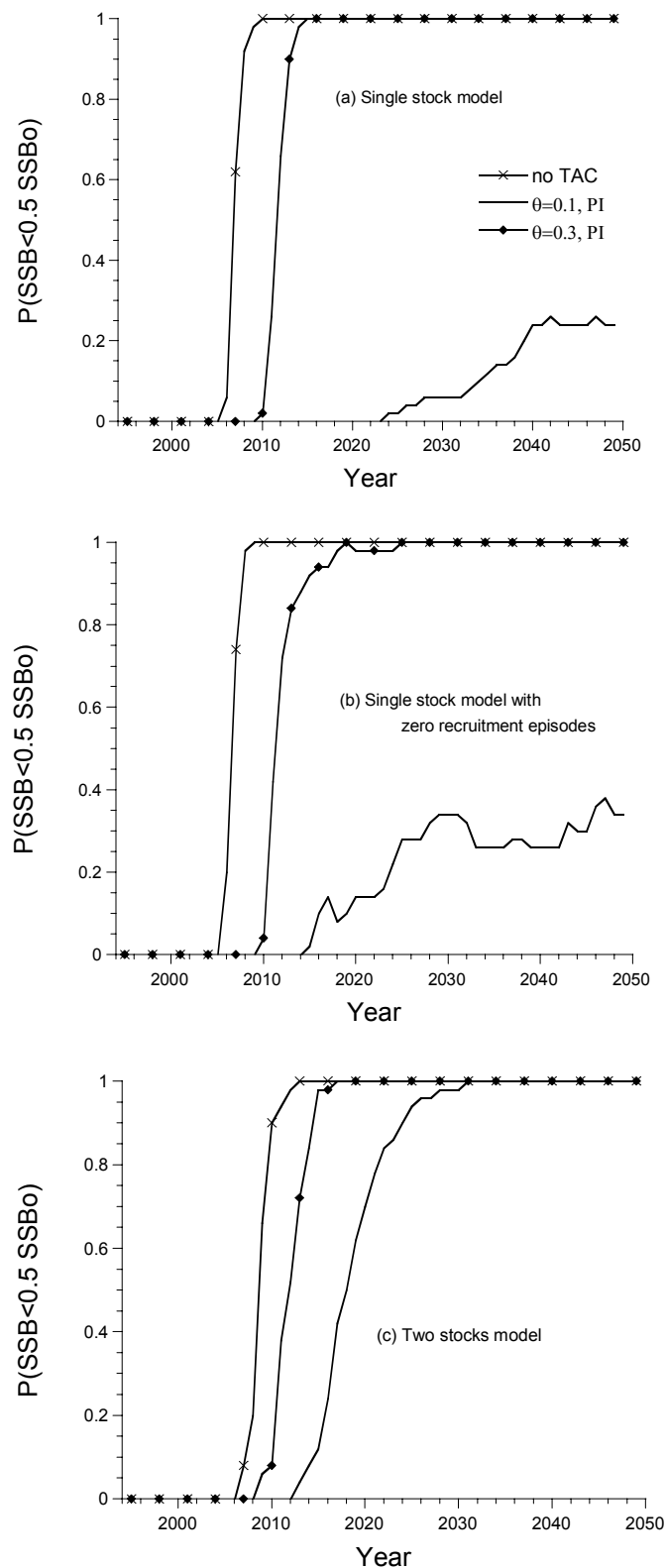
Figure 14.10 Time series of the probability that the spawning stock biomass is less than 50% of initial levels for 3 management strategies with extended fishing effort. (a) Single stock resource model, (b) Single stock resource model with zero recruitment episodes, (c) Two stocks resource model (spawning stock refers to the resident population).
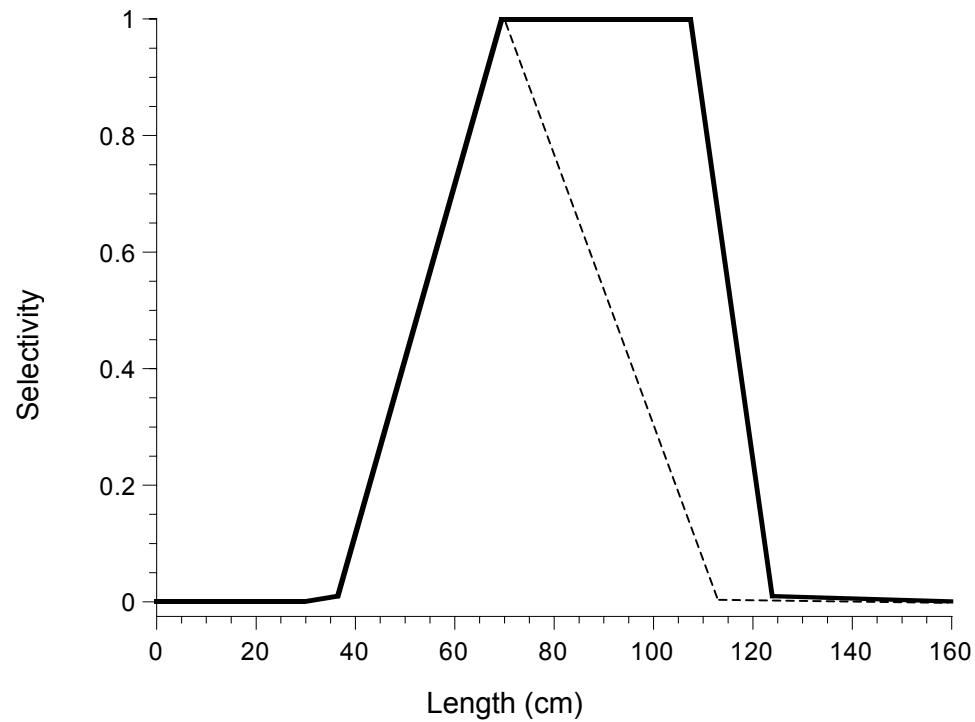
Figure 14.11 The selectivity functions for the single stock of toothfish. The dashed lined represents the base selectivity. The broader selectivity curve incorporates the smaller fish of the base selectivity and additional larger fish that become available if conditions are favourable (see text and Chapter 10).
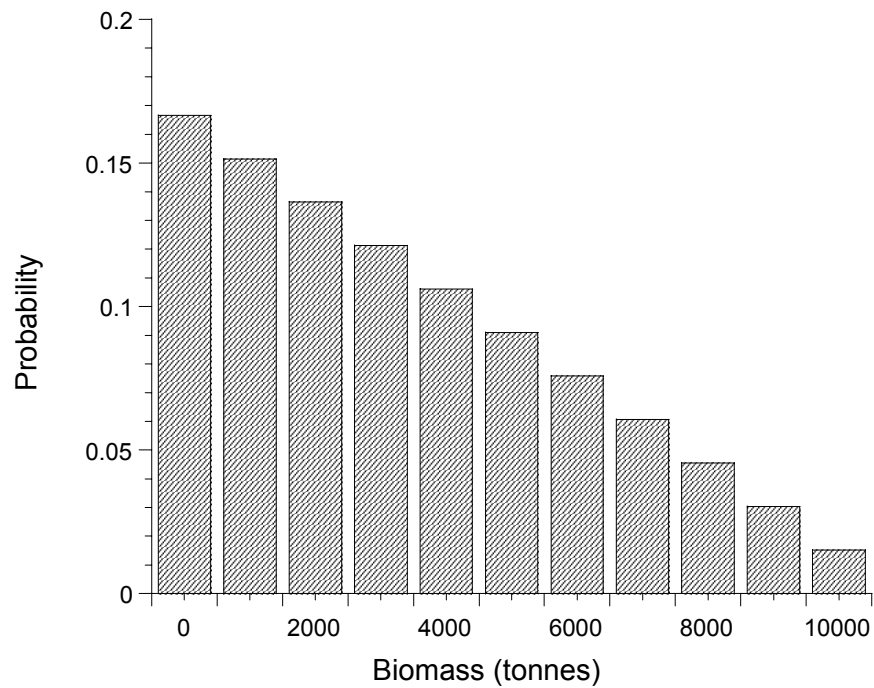
Figure 14.12 The probability distribution of the magnitude of the available biomass of the second (transient) population of toothfish, where B_{max} =10,000 t. The mean of this example distribution is 3,333 t.
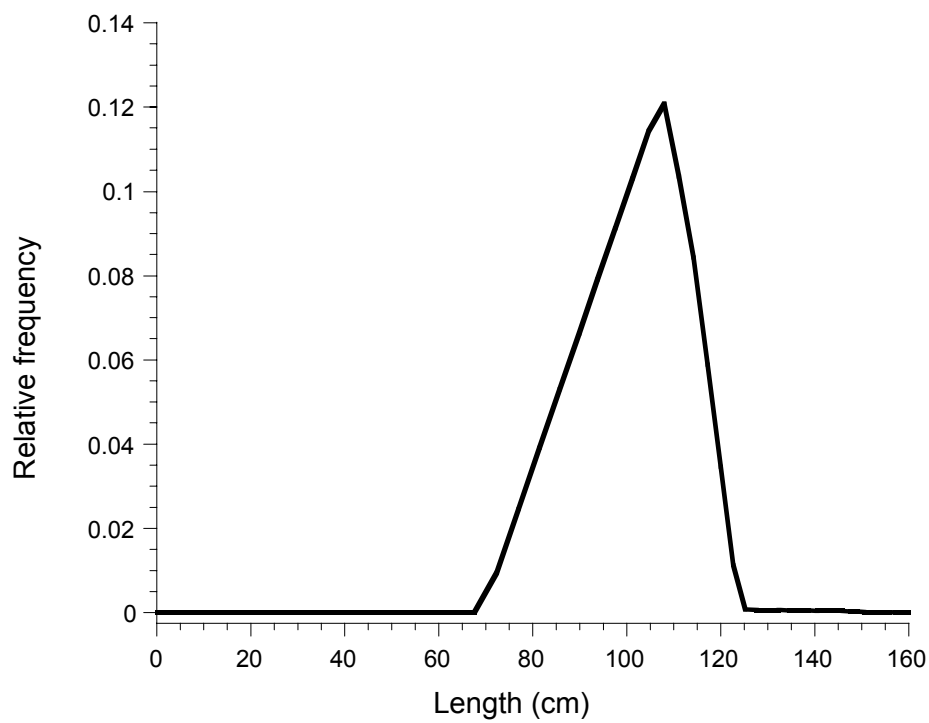
Figure 14.13 The relative frequency of lengths for the second 'transient' population of toothfish.
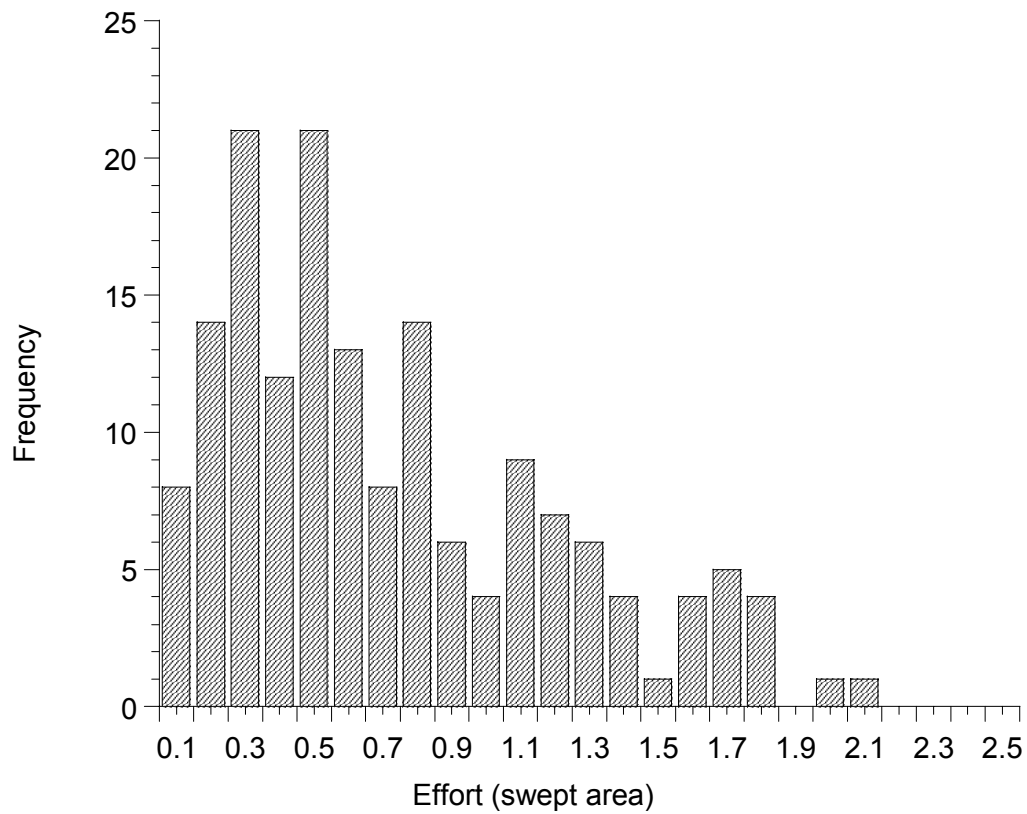
Figure 14.14 A histogram of daily effort (swept area, km^2) in Aurora Trough since 1996/97. For a particular class the frequency value indicates the number of effort records between that class and the previous class.
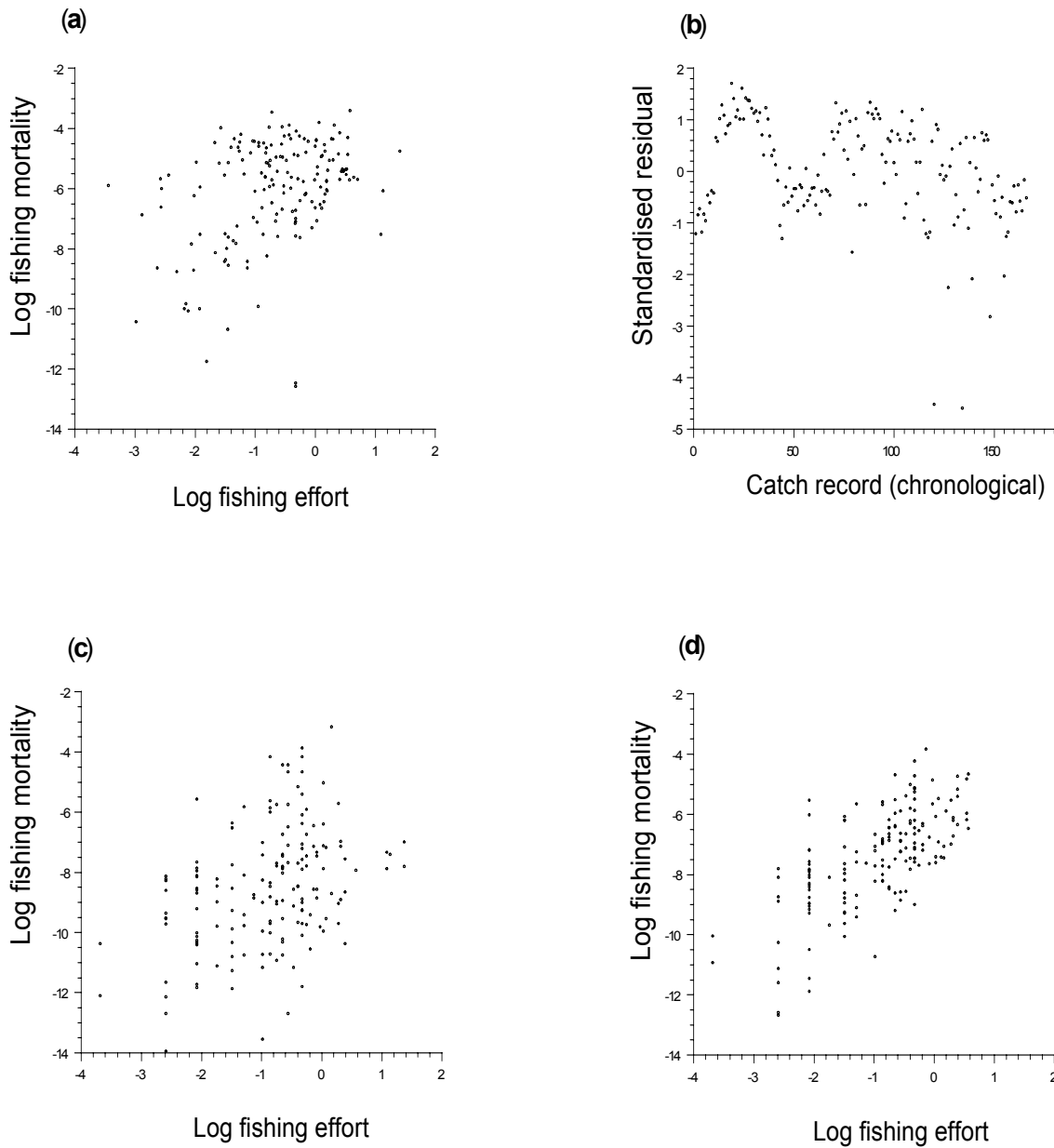
Figure 14.15(a-d) (a) An unfiltered plot of log fishing mortality, ln(*F*) versus log effort ln(*E*) using historical data only. (b) The standardised residual $(= res_t / \vartheta_t)$ versus chronological catch records. (c) Simulated data for ln(*F*) vs ln(*E*) with the first season removed. (d) Simulated data for ln(*F*) vs ln(*E*) with the first season's data removed and extreme catch and effort records removed.
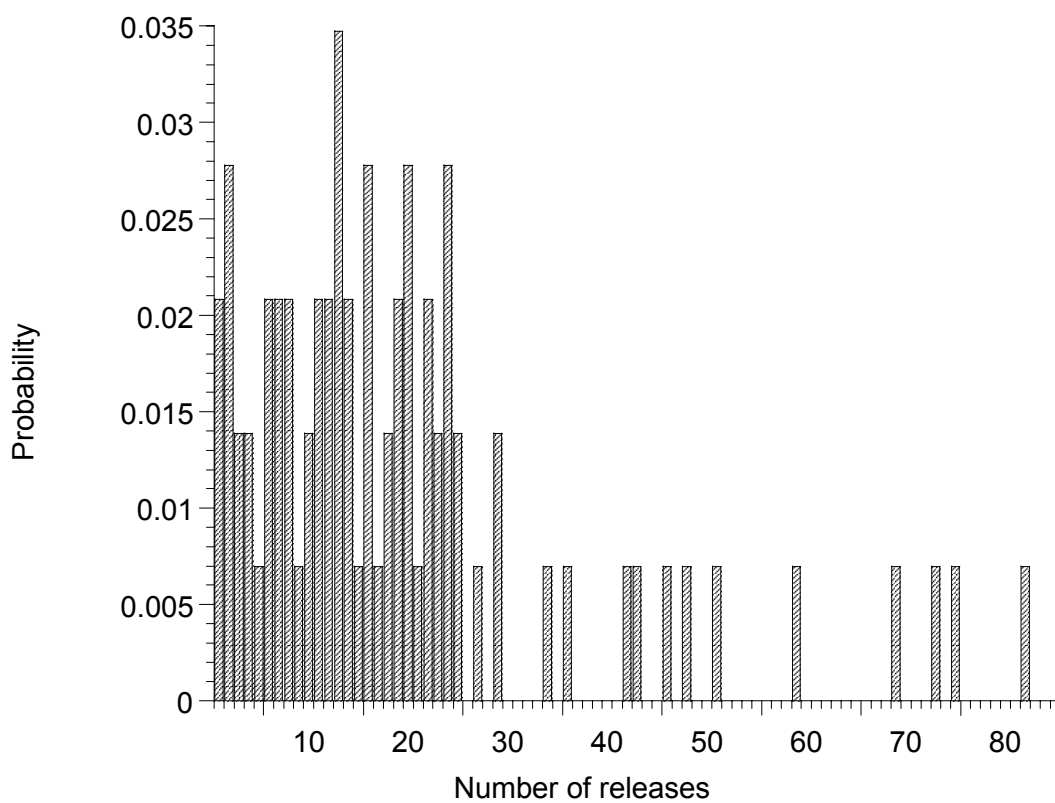
Figure 14.16 The probability distribution of the number of released fish on each haul (from Aurora Trough data). Not shown in this figure are 0 releases with probability 0.42, and 119, 137, 139 and 212 releases, each with a probability of 0.0069.
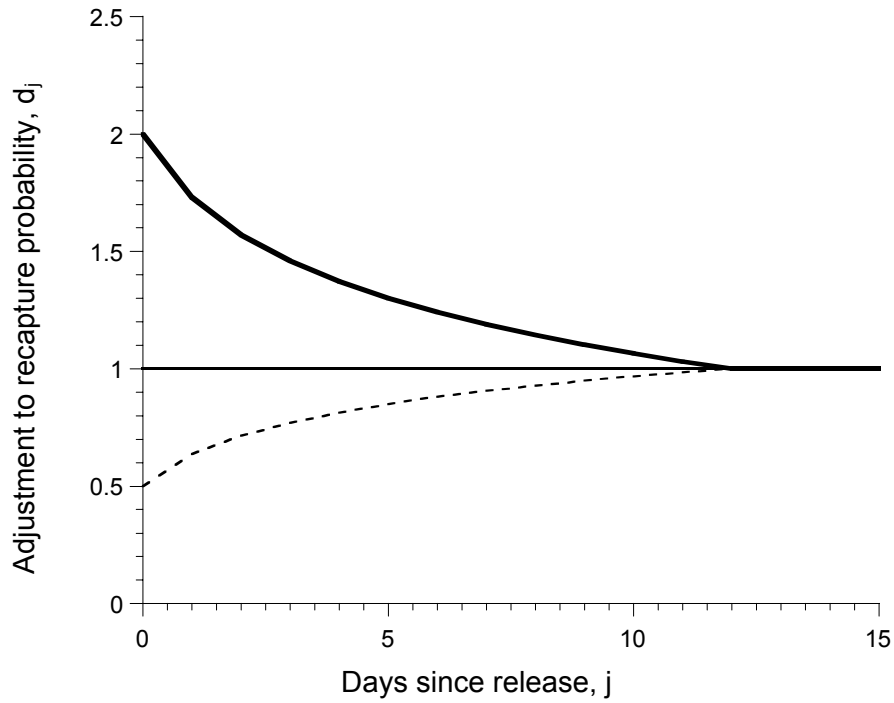
Figure 14.17 The proportional adjustment, d_j, to the number of expected recaptures as a function of the days since tags were released j. The figure shows d_j for $\delta = 12$ and $d_0 = 0.5, 1.0, 2.0$.

Appendix 14.1: The biological model of the operating model
Resource dynamics
The population dynamics model of the un-tagged toothfish is age and sex-structured and considered on a daily basis. The model assumes that natural and fishing mortality also can occur on a daily basis.

The basic dynamics of the population are given by the following equations,

$$
N_{a,k}^{y,t} = \begin{cases} N_{0,k}^{y,1} & \text{if } a=0 \text{ and } t=1 \text{ July} \\ e^{-M_k/365}(N_{a,k}^{y,t-1} - C_{a,k}^{y,t-1}) & \text{if } 1 \le a \le x \\ e^{-M_k/365}(N_{x-1,k}^{y,t-1} - C_{x-1,k}^{y,t-1}) + e^{-M_k/365}(N_{x,k}^{y,t-1} - C_{x,k}^{y,t-1}) & \text{if } a=x \end{cases} \tag{A14.1.1}
$$

where $N_{a,k}^{y,t}$ is the number of fish of age a and sex k on day t of year y

$C_{a,k}^{y,t}$ is the catch of fish of age a and sex k on day t of year y

M_k is the natural mortality for fish of sex k

x is the maximum age

Births, initial conditions and zero recruitment episodes
Births
The number of 0-year-olds in the population of sex k at the beginning of year y is,

$$
N_{0,k}^{y,1} = 0.5 \widetilde{B}^{y,1} (\alpha + \beta \widetilde{B}^{y,1})^{-1} e^{\varepsilon_y^r - \sigma_r^2/2} \qquad \varepsilon_y^r \sim N(0, \sigma_r^2) \tag{A14.1.2}
$$

where $\widetilde{B}^{y,1}$ is the female spawning biomass at the beginning of year y

$$
\widetilde{B}^{y,1} = \sum_a^x f_{a,f} w_{a,f} N_{a,f}^{y,1} \tag{A14.1.3}
$$

σ_r is the standard deviation of the natural logarithm of the multiplicative fluctuations in births

$$
\sigma_r = \sqrt{\ln(R_{cv}^2 + 1)} \tag{A14.1.4}
$$

R_{cv} is the coefficient of variation (cv) of the fluctuations in recruitment

$f_{a,f}$ is the proportion of females at age a of sex k that are mature

$$
f_{a,f} = \begin{cases} 0 & a < A_m^f - S_m^f \\ (1 + e^{-\ln(19)(a-A_m^f)/S_m^f})^{-1} & A_m^f - S_m^f \le a \le A_m^f + S_m^f \\ 1 & a > A_m^f + S_m^f \end{cases} \tag{A14.1.5}
$$

A_m^f is the age at which 50% of females would be mature,

S_m^f is a parameter which describes the extent of gradual maturity of females

$w_{a,k}$ is the weight of fish of age a and sex k

α and β are the parameters of the Beverton-Holt stock-recruitment relationship, with

$$
\alpha = \frac{\widetilde{B}^{0,1}(1-h)}{4h\widetilde{R}^{0,1}} p(Z_{EZR} = 1) \quad \text{and} \tag{A14.1.6}
$$

$$\beta = \frac{5h-1}{4h\widetilde{R}^{0,1}} p(Z_{EZR} = 1),$$ (A14.1.7)

$\widetilde{R}^{0,1}$ is the deterministic equilibrium total number of 0-year-olds on day 1,

$$\widetilde{R}^{0,1} = 2.0 N_0^{av} \left(\sum_a^{x-1} \sum_k e^{-M_k(a-1)} s_a^1 + \sum_k s_x^1 \frac{e^{-M_k(x-1)}}{1 - e^{-M_k}} \right)^{-1}$$ (A14.1.8)

h is the stock-recruitment (steepness) parameter, defined as the fraction of $\widetilde{R}^{0,1}$ expected when the spawning biomass is reduced to 20% of virgin levels,

N_0^{av} is the initial total available numbers of toothfish,

s_a^1 is the selectivity at age a on day 1 (needed to convert available abundance to total abundance), and

$p(Z_{EZR} = 1)$ is the probability of a non-zero recruitment year (see episodic zero recruitment).

Initial conditions

The initial (year $y = 0$) numbers-at-age are given by the equations,

$$N_{a,k}^{0,1} = \begin{cases} 0.5\widetilde{R}^{0,1} e^{-M_k(a-1)} & 1 \le a \le x\text{-}1 & (A14.1.9) \\ \\ 0.5\widetilde{R}^{0,1} e^{-M_k(x-1)} \big/ (1 - e^{-M_k}) & a = x & (A14.1.10) \end{cases}$$

Episodic zero recruitment (EZR)

To take account of the possibility that the Macquarie Island population experiences occasional periods of poor or negligible recruitment, the biological model includes a probabilistic recruitment model of zero recruitment episodes. One in every EZR_y years there is a period of zero recruitments with a duration of between EZR_{low} and EZR_{high} years. Thus the yearly recruitment becomes,

$$N_{0,k}^{y,1} = Z_{EZR} 0.5\widetilde{B}^{y,1} (\alpha + \beta\widetilde{B}^{y,1})^{-1} e^{\varepsilon_y^r - \sigma_r^2 / 2}$$ (A14.1.11)

where Z_{EZR} is a random variable taking the form,

$$Z_{EZR} = \begin{cases} 0 & \text{1 in every } EZR_y \text{ years, followed by } EZR_{len} \sim U[EZR_{low}, EZR_{high}] \text{ years of zero} \\ & \text{recruitment} \\ \\ 1 & EZR_y - 1 \text{ in every } EZR_y \text{ years} & (A14.1.12) \end{cases}$$

Note that the probability that Z_{EZR} is one (and therefore a positive recruitment year) is given by,

$$p(Z_{EZR} = 1) = \frac{EZR_y - 1}{EZR_y - 1 + (EZR_{low} + EZR_{high})/2}. \qquad \text{(A14.1.13)}$$

Growth
The length of a fish of age a and sex k is determined by the von Bertalanffy growth function,

$$L_{a,k} = L_\infty^k (1 - e^{-\kappa^k (a - t_0^k)}). \qquad \text{(A14.1.14)}$$

The weight of a fish of age a and sex k is given by,

$$w_{a,k} = \widetilde{a}_k (L_{a,k})^{\widetilde{b}_k}. \qquad \text{(A14.1.15)}$$

The parameters for the growth function and length-weight relationship have been described in Chapter 10 and are given in Table 14.1.

Appendix 14.2: Single and two stock models and selectivity functions

Single stock model

The selectivity parameters and their derivation have been described in Chapter 10. The selectivity curves described here are a combination of gear selectivity and fish availability. Two curves have been estimated for the selectivity of the Macquarie Island population (Figure 14.11). The magnitude of the daily catch rate was assumed to be a reasonable indication of the availability of large or small fish. As such, the length composition of catch for which catch rates were less than 10 t/km^2 was used to estimate the selectivity when only small resident fish were available. All length composition data were used to estimate the broader selectivity curve. The first, narrower selectivity is the 'base selectivity'. The broader selectivity curve accounts for the observed occasional influx of large fish into the fishery. The single stock model assumes that all fish are part of a single reproductive population. The larger fish, possibly due to favourable oceanographic conditions for prey, occasionally become available to the fishery.

For historical catch records, if the recorded catch rate for a particular day is greater than 10 t/km^2, then the broader selectivity function is used to calculate catch-at-age. For projections, the duration of the broader selectivity, BS_{days}, is generated randomly and takes values between BS_{low} days and BS_{high} days. The period of broader selectivity then occurs randomly within the season, i.e. between day d_{start} and $d_{end} + 1 - BS_{days}$, where d_{start} and d_{end} are the first and last allocated days of the season.

Two stocks model

To account for the possibility that the large changes in available biomass observed at Macquarie Island, and in particular the Northern Valleys, may have been due to the influx of fish from an external population, a second independent stock can be modelled. This population is reproductively isolated from the local population at Macquarie Island. Each year the second stock moves into the area, can be caught and tagged, but is not seen again, i.e. tagged fish from the second stock do not return to be recaptured.

The annual magnitude of the available biomass of the second stock is modelled as a linearly decreasing probability distribution, from 0 to B_{max} tonnes ($B_{max} = n.1{,}000$). Biomass levels are in 1,000 t increments. The probability that the biomass magnitude is $B_i^I = i.1000$ where i can equal 0, ... , n is then,

$$p(B_i^I) = \frac{(n+1) - i}{(n+1)\left(\dfrac{n}{2} + 1\right)} \qquad \text{for } i = 0, \dots, n \qquad (A14.2.1)$$

The mean of the distribution of biomass values taking probabilities defined by equation (A14.2.1) is

$$E(B_i^I) = \frac{1000n}{3}.$$

An example of this distribution for $B_{max} = 10{,}000$ t is shown in Figure 14.12. This figure illustrates the linear decrease in probability from zero to the maximum biomass. The mean is 3,333 t.

The initial annual numbers-at-age of the fish of the second stock is determined by spreading the biomass, $B^{I,y}$, over the available ages or lengths from either an input selectivity distribution, or

the difference between the broad selectivity of the resident stock and its base selectivity. This second assumption assumes that larger fish are mobile and, to match the observed length distribution in the catch data, the numbers-at-age distribution corresponds to the additional available lengths from the resident stock's base selectivity to the broader selectivity (Figure 14.13).

The numbers at age a and sex k at the beginning of year y for the second stock are given by,

$$N_{a,k}^{I,y} = \frac{B^{I,y}}{w_{a,k}} \frac{s_a^I}{\sum_a s_a^I}$$
(A14.2.2)

where s_a^I is the selectivity distribution at age (or length) for the second independent stock. It is assumed that the second stock moves into the fishing region at a random point within the season, in the same manner as the period of broader selectivity for the resident stock.

Annual fluctuations in availability
Stock assessment models have indicated that there have been occasional marked changes in annual available abundance; much greater than can be explained by recruitment or catch (Chapter 13). To model this annual change in availability, each year the available number of fish is adjusted by a constant of proportionality, v^y . This parameter is estimated by considering the historical change in available abundance estimated from an assessment compared to that from the historical component of the operating model, where no annual fluctuations are assumed. Let

$\hat{N}_b^{av,y}$ = the estimated beginning-of-season available numbers in year y from an assessment, and

$N_b^{av,y}$ = the beginning-of-season available numbers in year y from the historical component of the operating model with no annual fluctuations in availablility.

Then,

$$v^y = \frac{\hat{N}_b^{av,y}}{N_b^{av,y}} \quad \text{for historical years } y = 1, \dots, N_h$$
(A14.2.3)

is the estimated annual fluctuation in available abundance for historical year y. Note that $v^1 = 1$. This parameter is then applied to the historical catch equation to determine the daily fishing mortality (equation A14.3.5). For the projections, annual fluctuations in availability, v^y, are selected randomly from the N_h estimated historical values and applied to the operating model's catch equation (A14.3.1).

Appendix 14.3: The fishery component of the operating model
Catch
Catch equation
The simulated catch in numbers of fish of age *a* and sex *k* on day *t* of year *y* is a function of the number of fish available, the effort and the catchability coefficient,

$$C_{a,k}^{y,t} = \hat{q} e^{\varepsilon_t - \vartheta_t^2 / 2} E^t N_{a,k}^{y,t} s_a^t v^y \qquad (A14.3.1)$$

where

$\hat{q}$ is the estimated catchability coefficient for fully selected and available fish,

ε_t is a factor to account for random variation in catchability

with $\varepsilon_t \sim N(0, \vartheta_t^2)$ and

$\vartheta_t = \hat{\sigma}(\hat{q}E^t)^{\hat{\beta}}$. The parameters $\hat{q}$, $\hat{\sigma}$ and $\hat{\beta}$ are estimated from the historical data,

E^t is the fishing effort (swept area in km^2) for day *t*,

$N_{a,k}^{y,t}$ is the total number of fish of age *a*, sex *k* on day *t* of year *y*,

s_a^t is the selectivity of fish of age *a* on day *t*, (a combination of gear selectivity at age and intra-annual fluctuations in availability at age) and

v^y defines the inter-annual fluctuation in availability.

The total catch in tonnes on day *t* of year *y* is then

$$C_w^{y,t} = \sum_{a,k} C_{a,k}^{y,t} w_{a,k} , \qquad (A14.3.2)$$

with catch rate in tonnes per km^2 given by

$$CR^{y,t} = \sum_{a,k} C_{a,k}^{y,t} w_{a,k} / E^t . \qquad (A14.3.3)$$

The cumulative catch in tonnes up to day *t* for year *y* (which can be compared to the annual TAC) is

$$\widetilde{C}_w^{y,t} = \sum_{i=1}^{t} C_w^{y,i} . \qquad (A14.3.4)$$

Effort generation
The distribution of historical daily effort is used to select an effort level on each simulated day. A histogram, of the distribution of effort in Aurora Trough since 1996/97, is shown in Figure 14.14. Where values of effort were greater than 2.5, they were not included. They were considered unusually large (possible human error in reporting) and may have undue influence on results. There were three such values. An effort value for day *t* was selected using the transformation method (Press *et al.* 1995). This method converts the frequencies illustrated in Figure 14.14 to cumulative probabilities C(E^t) and then selects a uniform deviate between zero and one, *e*~U[0,1]. The effort value chosen E^t has the fraction *e* of the cumulative probability being less than C(E^t).

Estimating the catchability coefficient for fully selected and available fish
When applying the historical data, the estimated fishing mortality given the known catch, selectivity and population model is determined from the equation,

$$C_n^{y,t} = (1 - e^{-F^t}) \sum_{a,k} N_{a,k}^{y,t} s_a^t v^y$$

$$= \widetilde{F}^t N^{av,t}, \tag{A14.3.5}$$

where $C_n^{y,t}$ is the catch in numbers on day t of year y, F^t and $\widetilde{F}^t$ are the estimated instantaneous and finite fishing mortalities on day t (which approximate each other for small F) and $N^{av,t}$ is the total number of available fish on day t.

Equating equations (A14.3.1) and (A14.3.5) gives,

$$\widetilde{F}^t = \hat{q} e^{\varepsilon_t - \vartheta_t^2/2} E^t \quad \text{or}$$
$$\ln \widetilde{F}^t = \ln \hat{q} + \ln E^t + \varepsilon_t - \vartheta_t^2/2 \tag{A14.3.6}$$

If we let the residual from this linear relationship be,

$$res_t = \ln \widetilde{F}^t - \ln \hat{q} - \ln E^t \tag{A14.3.7}$$

and

$$\vartheta_t = \hat{\sigma}(\hat{q}E^t)^{\hat{\beta}} \tag{A14.3.8}$$

then the parameters $\hat{q}$, $\hat{\sigma}$ and $\hat{\beta}$ can be estimated by minimising the log-likelihood given by,

$$\sum_t \ln L_t = \sum_t (\ln(\vartheta_t) + res_t^2/2\vartheta_t^2). \tag{A14.3.9}$$

A plot of ln(F) against ln(E) for all of the historical data is shown in Figure 14.15(a). There appears to be a trend showing larger values of ln(E) with smaller variation in ln(F). Also, a plot of the standardised residual versus chronological record shows a clear cyclical trend in residuals in the first season (Figure 14.15(b)). Hence the first season was removed from the estimation procedure. A typical plot of ln(F) versus ln(E) for simulated data with the first season removed is shown in Figure 14.15(c). This shows that the model is not picking up the change in variance with ln(E). The final plot, Figure 14.15(d), shows simulated data for ln(E) and ln(F) with the first season's records removed and values of effort greater than 2.5 (3 records) and catch records with less than 3 fish caught (2 records) filtered from the data. This model shows greater resemblance to the historical plot observed in Figure 14.15(a).

Estimating the annual mean weight of a fish
Observation error has been applied to the annual mean weight of a fish from that of the operating model, $\overline{w}^y$, to that used in an annual assessment, $\overline{w}_A^y$. The assessment uses this value to estimate the available biomass from the estimated available numbers of fish. The error is estimated by considering the deviations between historical mean weights (Table 14.2) and those from the historical component of the operating model (Appendix 14.4),

$$\overline{w}_A^y = \overline{w}^y e^{\varepsilon_w - \sigma_w^2/2} \qquad \text{for historical years } y = 1,\ldots, N_h, \tag{A14.3.10}$$

where ε_w is a factor to account for random variation in annual mean weight, and $\varepsilon_w \sim N(0, \sigma_w^2)$. The standard deviation of the observation errors, σ_w, is estimated using likelihood methods in a similar fashion to the estimation of the catchability parameters described above. Equation (A14.3.10) is then applied in future years to obtain the annual mean weight used in the assessments.

The tagging program
Release of tagged fish
The method used to determine the number of fish released considers the frequency distribution of the historical numbers of tagged fish released per haul from Aurora Trough. For example, there were no tagged fish released in 42% of all hauls, hence the probability of zero releases on any particular day is 0.42. The probability distribution is given in Figure 14.16.

Once the total number of releases on a day has been determined, the number of releases of each age and sex is calculated. The released fishes' age and sex are determined according to the relative proportion of ages and sex in the catch (the transformation method). If the cumulative fraction of the catch up to age a of sex k is given by $Z_{a,k}$, then for each release, if a realisation from a uniform distribution U[0,1] lies between $Z_{a-1,k}$ and $Z_{a,k}$ considering both sexes k then this released fish is assigned age a and sex k. The release length can be determined from the von Bertalanffy growth function (equation A14.1.14) once the age and sex are known.

Tagged fish undergo a daily process of determining whether they have survived natural mortality (in addition to recapture). For each tagged fish a random number is drawn from a uniform distribution U[0,1]. If this number is less than the expected daily mortality rate,

$$\overline{M}^t = 1 - e^{-M_k/365} \tag{A14.3.11}$$

then that particular tagged fish has died.

Tag recaptures
If the tagged population is well-mixed with the untagged population the expected number of recaptures of age a and sex k on day t follows from Petersen's equation, namely

$$r_{a,k}^t = m_{a,k}^t C_{a,k}^t / N_{a,k}^t, \tag{A14.3.12}$$

where $m_{a,k}^t$ is the number of marked fish of age a and sex k on day t.

Thus, an individual tagged fish of age a and sex k is recaptured according to (the probability) F,

$$F_{a,k}^t = C_{a,k}^t / N_{a,k}^t. \tag{A14.3.13}$$

However, this probability will depend on the level of mixing. If tagged fish take δ days to fully mix with untagged fish, then this probability needs to be adjusted by a function which approaches 1 as the time since release j approaches δ. The function used to model the adjustment to the recapture probability, d_j, is given by,

$$d_j = \begin{cases} (1-d_0)\dfrac{\ln(j+1)}{\ln(\delta+1)} + d_0 & j \le \delta \\ \\ 1 & \text{otherwise} \end{cases} \qquad (A14.3.14)$$

and illustrated in Figure 14.17 for various values of d_0.

If d_0 is greater than one then there are more recaptures than expected (tagged fish remain in the vicinity of the vessel) or, if d_0 is less than 1 then there are less recaptures than expected (tagged fish move away from the vessel). Hence, the number of days since release must be tracked for each tagging event.

With the adjustment due to non-mixing, the probability of recapture for a tagged fish of age a and sex k, having been released j days prior to day t, becomes,

$$F_{a,k}^{t,j} = d_j C_{a,k}^t / N_{a,k}^t \qquad (A14.3.15)$$

If a realisation from a uniform distribution U[0,1] is less than $F_{a,k}^{t,j}$ then that particular tagged fish has been recaptured. The recapture length can be determined from the growth functions.

Operational behaviour
Clearly there are economic constraints affecting vessel operations when fishing a species inhabiting the distant waters of the sub-Antarctic. If catches or catch rates over an extended period of time are not sufficient then operators may wish to abandon the toothfish fishery and pursue other species in different areas (e.g. orange roughy or Heard Island toothfish). Also, fishing may involve periods of searching whereby the daily frequency of fishing in an area is different from when fish have been found and catch rates are high.

The leaving trigger (LT) and last chance (LC) clause
If the mean catch rate over LT_{days} is less than LT_{cr} then the vessel ceases fishing and departs the area, unless the mean catch rate over the last LC_{days} days is greater than LC_{cr}, then the vessel continues fishing for an additional LC_{extra} days. The 'last chance' clause to the leaving trigger allows the vessel to remain in the fishery if overall catch rates have been poor, but the most recent catch rates are good. If after LC_{extra} days of fishing, conditions have improved (e.g. the mean catch rate over LT_{days} is greater than LT_{cr}) then the vessel remains in the fishing ground.

The fishing frequency (FF)
The simulated initial fishing frequency is set to one day's fishing every FF_{base} days. However, if either the increased TAC triggers are fired or the mean catch rate over FF_{days} days is greater than FF_{cr}, the fishing frequency increases to fishing every FF_{high} days. The fishing frequency drops back to FF_{base} if these triggers are no longer firing.

Appendix 14.4: The historical component of the operating model
The historical model uses known data from the fishery (such as catch, effort, and tagging data) and a population dynamics model to establish a current realisation of the population (numbers-at-age) to take into the projections. From the initial numbers-at-age determined by equations (A14.1.9) and (A14.1.10), the population is projected forward, applying natural mortality only, until a catch day occurs. The fishing mortality F is then calculated according to equation (A14.3.5) and the estimated catch-at-age is removed from the population numbers. This is repeated for all catch days during a season.

If there has been one or more tagged fish released, then these fish need to be assigned an age and sex. The measured length of the released fish $\widetilde{L}$, the growth function and the estimated daily catch-at-age and sex are used. Assume that the measurement error of the release length is $2\varepsilon_L$ cm. The potential age a and sex k groups that a tagged fish may belong to is then given by those that meet the following inequality,

$$\widetilde{L} - \varepsilon_L < L_{a,k} = L_\infty^k (1 - e^{-\kappa^k (a - t_0^k)}) \le \widetilde{L} + \varepsilon_L. \qquad (A14.4.1)$$

The transformation method (Press *et al.* 1995) then uses the cumulative distribution of the estimated catch numbers of the set of ages and sexes that meet this equality to determine a sex and an age for a tagged fish with release length $\widetilde{L}$. If the release length has not been measured then the total cumulative distribution of estimated catch is used with the transformation method.

At the completion of each day, tagged fish experience natural mortality in the same manner as described in the operating model (equation A14.3.11). At the completion of each season, recruitment to the population occurs according to equation (A14.1.2) and numbers-at-age are updated.

Appendix 14.5: Formulation of management objectives and performance measures

1) Mean annual catch

This is the average catch in tonnes over all years N_y and simulations N_s from year Y_{first} to Y_{last},

$$= \frac{1}{N_s . N_y} \sum_{s=1}^{N_s} \sum_{y=1}^{N_y} C_s^y \qquad\qquad \text{(A14.5.1)}$$

where Y_{first} is the first year of projections
   Y_{last} is the last year of projections, and
   C_s^y is the catch in tonnes in year y of simulation s

2) Mean annual change in catch.

This is the mean difference in catch (tonnes) between consecutive years over all simulations.

3) Mean annual frequency that catch was less than the TAC,

$$= \frac{1}{N_s . N_y} \sum_{s=1}^{N_s} \sum_{y=1}^{N_y} 100.I(C_s^y < \text{Tac}_s^y) \qquad\qquad \text{(A14.5.3)}$$

where $I(C_s^y < \text{Tac}_s^y)$ takes the value 1 if the total catch is less than the quota in year y and simulation s, and 0 otherwise.

4) Mean annual frequency that the leaving trigger has been fired, e.g. the CPUE averages less than 5 t/km^2 over 8 days.

$$= \frac{1}{N_s . N_y} \sum_{s=1}^{N_s} \sum_{y=1}^{N_y} 100.I(\text{Leave}_s^y) \qquad\qquad \text{(A14.5.5)}$$

where $I(\text{Leave}_s^y)$ takes the value 1 if the vessel leaves the fishery in year y, and 0 otherwise.

5) The mean over all simulations of the proportion remaining in spawning biomass at year Y_{last},

$$= \frac{1}{N_s} \sum_{s=1}^{N_s} 100 \frac{\widetilde{B}_s^{last}}{\widetilde{B}_0} \qquad\qquad \text{(A14.5.6)}$$

where $\widetilde{B}_s^{last}$ is the spawning biomass at the end of the last year of simulation s, and

   $\widetilde{B}_0$ is the equilibrium spawning biomass prior to the commencement of fishing.

6) The mean annual frequency that spawning biomass is less than 50% of virgin spawning biomass,

$$= \frac{1}{N_s.N_y} \sum_{s=1}^{N_s} \sum_{y=1}^{N_y} 100.I(\widetilde{B}_s^{y,365} < 0.5\widetilde{B}_s^{0,365}) \qquad \text{(A14.5.7)}$$

where $\widetilde{B}_s^{y,365}$ is the end-of-season spawning biomass in year y for simulation s.

7) The relative bias in the estimated available biomass.
This gives a measure of the accuracy of the assessment method,

$$= \frac{1}{N_s.N_y} \sum_{s=1}^{N_s} \sum_{y=1}^{N_y} 100 \frac{\hat{B}_s^{av,y} - B_s^{av,y}}{B_s^{av,y}} \qquad \text{(A14.5.8)}$$

where $B_s^{av,y}$ and $\hat{B}_s^{av,y}$ are the true and assessed end-of-season available biomass for simulation s in year y.

8) The relative root mean square error (RMSE) in the estimated available biomass.
This gives a measure of the precision of the assessment,

$$= 100 \sqrt{\frac{1}{N_s.N_y} \sum_{s=1}^{N_s} \sum_{y=1}^{N_y} \left(\frac{\hat{B}_s^{av,y} - B_s^{av,y}}{B_s^{av,y}} \right)^2} \qquad \text{(A14.5.9)}$$

9) Mean annual frequency that an assessment was unable to be performed,

$$= \frac{1}{N_s.N_y} \sum_{s=1}^{N_s} \sum_{y=1}^{N_y} 100.I(\text{No Assessment}_s^y) \qquad \text{(A14.5.10)}$$

where $I(\text{No Assessment}_s^y)$ takes the value 1 if there has been no assessment in year y and 0 otherwise.

15. The diet of toothfish and pelagic fish around Macquarie Island

Simon Goldsworthy, Xi He, Dick Williams, Mark Lewis, Anne Gaskett, Catherine Bulman, Jock Young and John van den Hoff

Summary
This chapter describes diet and diet composition of toothfish and 23 pelagic fish species. A total of 1,423 stomach samples of toothfish were taken at two fishing grounds near Macquarie Island over three fishing seasons. Fish were caught at depths ranging from 500 to 1,290m, and ranged in size from 310 – 1,490mm total length. With all samples examined, 462 (32%) stomach samples contained prey items. Toothfish preyed on a broad range of species, including fish, cephalopods and crustaceans (58%, 32% and 10% biomass, respectively), suggesting that they are opportunistic predators. The benthopelagic fish *Bathylagus antarcticus* was the most important fish prey of toothfish (14% dietary biomass), however, nototheniid, macrourid, morid and myctophid fish were also taken. The squid *Gonatus antarcticus* was also an important prey species (16% biomass), however a large number of other cephalopods species were taken in low frequency. Prawns were the most important crustaceans taken (9% of prey biomass). Significant inter-seasonal and inter-fishing ground differences in toothfish diets were found. Dietary composition was not related to fishing depth, or fish size (with the exception of one fishing ground in one season). Results of this study are compared with other studies that have examined the diet of toothfish on the Argentine Shelf, and the southern Atlantic and Indian Oceans. Diets of 23 mesopelagic and bathypelagic fish were also examined. Among these 23 fish species, 13 of them are from the family Myctophidae. Crustaceans (particularly copepods, amphipods and euphausiids) were the dominant prey in 18 species. Fishes were the dominant prey in five species. Further analysis showed that five of the 13 myctophid fishes had a low level of similarity in diet composition between individuals of each species, while the other eight species had significantly high levels of similarity. Cluster analysis and randomisation procedures demonstrated the existence of five trophic guilds among the Myctophidae.

Introduction
Ecological sustainable development (ESD) of the toothfish fishery around Macquarie Island requires an understanding of ecological interactions between toothfish and other components of the ecosystem, especially trophic interactions between toothfish and other main predators. For these reasons, dietary studies of toothfish and other marine predators are required in order to determine the extent of dietary competition between them and hence the potential ecological impacts of a commercial fishery for toothfish in the region.

Meso- and bathypelagic fishes are also significant components of food webs as they are common prey species for top marine predators such as seals, seabirds, and toothfish (Adams *et al.* 1993, Kozlov 1995, Guinet *et al.* 1996). Most pelagic fish in the Southern Ocean are opportunistic meso-zooplanktivores (Tyler and Pearcy 1975, Sabourenkov 1990, Kozlov 1995, Pakhomov *et al.* 1996), consume large amounts of prey and have a very high biomass (Kozlov 1995, Duhamel *et al.* 2000). Species that migrate vertically through the water column to feed at shallower depths, e.g. *Krefftichthys anderssoni* and *Protomyctophum* species, are primary vectors for transferring energy from the sea surface to the deep ocean (Young 1991, Pakhomov *et al.* 1996). Productivity in deep ocean systems relies on this transfer mechanism (Tseitlin 1985, Gordon *et al.* 1995, Koslow 1997).

This chapter examines the diet of toothfish and 23 pelagic species around the Macquarie Island. For toothfish, diets from the two fishing grounds and their inter-annual differences in the diets from each ground were examined. We also examined the influence of fish size and depth-of-capture on diets, and compared the diet of toothfish from other locations with that from

Macquarie Island. For 23 species of pelagic fishes, we describe their diets and compare the diet compositions between individuals of the same species, and between species. For species with sufficient diet samples (all of which were myctophids), trophic guilds based on diet dissimilarities were identified using cluster analysis and a randomised statistical procedure. The analyses presented in this paper provide quantitative classifications and parameters for further analysis and modelling of food webs around Macquarie Island.

Methods

Sample collection

Toothfish stomachs were obtained from fish caught in the vicinity of Macquarie Island at depths of 500 to 1,290 m during voyages conducted by the trawler *Austral Leader*. Stomachs were collected over three fishing seasons, between November 1995 and January 1996, between November 1997 and March 1998, and between November 1998 and January 1999 (hereafter referred to as seasons one, two and three, respectively). Fishing in season one was concentrated to the west of the island (Aurora Trough fishing ground), but during seasons two and three fishing also occurred to the north of the island (Northern Valleys fishing ground). For fish specimens recovered for sampling, the date, location and depth of trawl were noted. The total length and mass of most fish sampled was also recorded. Stomachs were stored frozen until examination in the laboratory.

Specimens of pelagic fish were obtained from pelagic tows conducted at 14 sites in waters surrounding Macquarie Island. Day and night tows by the FRV *Southern Surveyor* were made using a depth-stratified midwater net with opening and closing cod-ends (Williams and Koslow 1997).

Pelagic fish were removed from the nets and preserved in 10% formaldehyde, buffered with seawater. In the laboratory, the fish were identified. The stomachs were removed from a maximum of 35 fish per species and preserved in 10% formaldehyde. The stomachs were later dissected and prey items were identified to the level of class or order, and classified as one of 13 prey types (amphipods, copepods, euphausiids, decapods, ostracods, mysids, crustaceans, fishes, cephalopods, chaetognaths, cnidarians, gastropods, unknown). Items were blotted on absorbent paper, and weighed to the nearest 0.0001g.

Data analysis

Toothfish stomach contents were identified in the laboratory to the lowest possible taxonomic level, and where the degree of digestion permitted, weighed and counted. Individual prey items were weighed (wet mass) in order to determine the contribution to total prey biomass of individual prey taxa. Differences in percentages of non-empty stomachs between fishing grounds and fishing seasons were tested using two-way contingency G tests.

A total of four indices were calculated for each prey category. They were: percent frequency of occurrence (*%F*), percent frequency by number (%*N*), percent frequency by wet mass (%*M*), and index of relative importance (*IRI*). *IRI* (George and Hadley 1979) for each prey category (*a*) was calculated as follows:

$$IRI_a = 100 \frac{IAI_a}{\sum_{a=1}^{n} IAI_a}$$

where *n* is the total number of prey categories and *IAI* is the index of absolute importance (Cortés 1997) calculated as:

$$IAI_a = (\%N_a + \%M_a)\%F_a$$

For the overall analysis of prey composition, prey items were aggregated, usually to family or genus level (Table 15.1). Prey groups that occurred in less than 1% of stomachs were grouped into other fish, other cephalopod and other crustacean categories (Ofish, Oceph and Ocrust,

respectively). For comparisons of the diets of toothfish between fish length, depth of capture and between fishing grounds and seasons, prey categories were reduced further to only include prey groups that contributed 3% or more to total prey biomass. Fish, cephalopod or crustacean groups that constituted less than 3% of prey biomass were combined into the other fish, other cephalopods or other crustacean group categories (OFish, OCeph, OCrust, respectively).

Differences in the diets of toothfish between fish length, depth of capture and between fishing grounds and seasons were tested using the Mantel's test (Mantel 1967, Manly 1991, He *et al.* in prep.). The Mantel's test is a randomized statistical method and its test statistic is the correlation between two matrices. The significance of the test statistic is determined by comparing the test statistic with the distribution of the statistics obtained from randomly reallocating the order of the elements in one of the matrices. For testing differences in the diets of toothfish between fish length, the first matrix, *A*, was defined as the dissimilarity matrix of diet compositions between all pairs of individual fish. The second matrix, *B*, was defined as the difference matrix of fish length between all pairs of individual fish. That is, for *m* individual fish:

$$A = \begin{bmatrix} 0 & & & & \\ a_{2,1} & 0 & & & \\ a_{3,1} & a_{3,2} & 0 & & \\ ... & ... & ... & 0 & \\ a_{m,1} & a_{m,2} & ... & a_{m,m-1} & 0 \end{bmatrix} \text{ and } B = \begin{bmatrix} 0 & & & & \\ b_{2,1} & 0 & & & \\ b_{3,1} & b_{3,2} & 0 & & \\ ... & ... & ... & 0 & \\ b_{m,1} & b_{m,2} & ... & b_{m,m-1} & 0 \end{bmatrix}$$

where,

$$a_{ij} = 0.5 \sum_{h=1}^{n} | P_{ih} - P_{jh} |$$

P_{ih} and P_{ih} are proportions of diet item h for individual fish i and j, n is total number of prey categories, and

$$b_{ij} = | l_i - l_j |$$

where l_i and l_j are the total lengths of fish i and j. For testing differences in the diets of toothfish between fishing grounds, depth or seasons, the first matrix, *A*, was the same as the previously defined matrix. The second matrix, *B*, had b_{kl} values of 1 if $k = l$ and 0 otherwise, where k and l refer to fishing seasons or fishing grounds.

Because both matrices are symmetric, the correlation between all the off-diagonal elements in two matrices is the same as the correlation between the *m(m-1)/2* elements in the lower triangular diagonal parts. The test was conducted for groups where more than 30 individual fish with no empty stomachs were sampled (*m >= 30*). The correlation between two matrices was compared to the distribution of the correlation calculated from randomly reallocating the elements of the *B* matrix 5,000 times. The null hypothesis that there was no difference in diet compositions between fish lengths, fishing grounds or seasons was rejected if the test statistic was smaller or greater than 5% of values in the distribution.

Results
Stomach fullness and mean prey mass
A total of 1,423 toothfish stomachs were collected over three fishing seasons (1995/96, 1997/98, 1998/99) and two fishing grounds (Table 15.2). The percentage of non-empty stomachs collected in each season varied significantly (G-test, $P<0.001$) from 38% (season two) to 85%

(season one). In the second and third seasons of fishing, a significantly greater percentage of stomachs contained prey items in the Aurora Trough ground compared with the Northern Valleys ground (G-test, $P<0.001$ for both) (Table 2). The total mass of prey items in the stomachs of toothfish that contained prey remains ranged from 0.01 to 1,490.6 g. The average mass of prey items was 47.5g ($sd = 91.1$, $n = 863$).

Overall diet
A complete list of prey identified from toothfish stomachs is presented in Table 15.1. The overall percentage frequency of prey items by number, occurrence, mass and *IRI* for all stomachs samples that contained prey items, are presented in Table 15.3. These results indicate that fish were the most consumed prey, accounting for 58% of prey biomass, followed by cephalopods (32%) and crustaceans (10%). The bathylagid fish *Bathylagus antarcticus* was the most important fish prey (14% prey biomas, 14% *IRI*), with myctophid, macrourid and nototheniid fish accounting for smaller percentages of prey biomass and *IRI* (Table 15.3). A large number of cephalopod genera were taken by toothfish including squid, cuttlefish and octopus (Table 15.1). The most important cephalopod in the diet was *Gonatus antarcticus* (16% prey biomass, 5% *IRI*), with all other cephalopods (squid from the genera *Moroteuthis*, *Mastigoteuthis* and octopus from the genus *Cirroteuthis*) occurring in low number and mass (Table 15.3). Prawns were the dominant crustaceans taken (9% biomass, 25% *IRI*) and were the most numerous of all the prey items in the diet (28% of stomachs, Table 15.3). Stone crabs from the genus *Lithodes* were also occasionally taken (1% biomass).

Fish diet relative to body length and depth of capture
Of the 1,423 toothfish sampled in this study, total length of 927 toothfish (65%) were also measured. Their total length (TL) ranged from between 310 to 1,490 mm (mean = 657, $sd = 124$), although only two fish were longer than 1130 mm. There was no significant difference in the diet composition of toothfish of differing lengths caught within each fishing ground and season (Mantel's test: season two- Northern Valleys ground, $n =124$, data value (dv) = 0.007, $P = 0.393$; season two – Aurora Trough ground, $n = 32$, $dv = -0.003$, $P = 0.500$; season three – Northern Valleys ground, $n =166$, $dv = -0.008$, $P =0.591$), with the exception of the Aurora Trough ground in the third season ($n = 108$, $dv = 0.54$, $P = 0.010$). Of the eleven prey categories tested, the most obvious prey category to vary with fish length in the Aurora Trough ground in the third season, was myctophid fish. They accounted for over 65% of total prey biomass in the small toothfish (<450 mm) and were absent in the diet of the largest fish caught (>750 mm) (Figure 15.1). Cephalopods were uncommon in smaller toothfish (<550 mm) but tended to account for around 40% or more of total prey biomass in toothfish larger than 550 mm (Figure 15.1). The depth at which fish were caught within each fishing ground in each fishing season did not significantly influence the diet of toothfish (P>0.10 each ground x season comparison).

Comparison between fishing grounds and seasons
Mantel tests indicated that, in season two and three, the diets of toothfish (biomass of prey) caught in each ground were significantly different from each other (season two: $dv = 0.033$, $P = 0.030$; season three: $dv = 0.052$, $P<0.001$). In season two, fish accounted for 74% prey biomass in the Northern Valleys ground, and 64% prey biomass in the Aurora Trough ground (Table 15.4 and 15.5). Although the biomass of macrourid fishes in toothfish prey was similar for each ground, bathylagid fish accounted for 28% of the prey biomass (37% *IRI*) in the Aurora Trough ground, compared with only 8% (4% *IRI*) in the Northern Valleys ground (Table 15.4 and 15.5). Morid fish accounted for 17% of prey biomass in the Northern Valleys ground, and were absent from the diet of fish in the Aurora Trough ground. Both the overall biomass and species composition of cephalopods also differed between the fishing grounds (Table 15.4 and 15.5). Cephalopods accounted for 33% prey biomass in the Aurora Trough ground (principally from the genera *Gonatus*, *Moroteuthis* and *Mastogoteuthis*), and only 20% in the Northern Valleys ground (principally *Chiroteuthis*, *Moroteuthis* and *Cirroteuthis*). Crustaceans (entirely prawns) were uncommon in the diets of toothfish from the Aurora Trough ground (2%), and more

numerous (6%, but mostly *Lithodes* crabs) in the Northern Valleys ground (Table 15.4 and 15.5).

In season three, fish accounted for more of the prey biomass in the Northern Valleys ground (76%) compared with the Aurora Trough ground (52%), and in contrast to season two, bathylagid fish were the dominant fish prey in the Northern Valleys ground (36% biomass, 49% *IRI*)), but were less important in the Aurora Trough ground (9% mass, 4% *IRI*) (Table 15.4 and 15.5). Nototheniid fish accounted for most of the fish prey biomass in the Aurora Trough ground (18% biomass, 5% *IRI*), although myctophids were most commonly taken (9% biomass, 22% *IRI*). Nototheniid (9% biomass, 1% *IRI*) and myctophid (2% biomass, 1% *IRI*) were less common in the diets of toothfish in the Northern Valleys ground in season three (Table 15.5). Cephalopods (mostly *Gonatus,* 26% biomass, 16% *IRI*) accounted for 41% of the prey biomass in the Aurora Trough ground in season three, but only 18% (mostly *Gonatus* and *Mastigoteuthis* spp.) in the Northern Valleys ground (Table 15.4 and 15.5). Similar to season two, crustaceans (mostly prawns) accounted for only a small percentage of the prey biomass in season three in the Aurora Trough and Northern Valleys grounds (7% biomass, 11% *IRI*; and 2% biomass,1% *IRI*, respectively).

As well as there being differences in the diets of toothfish between fishing grounds within each season of fishing, toothfish diet also differed significantly within fishing grounds between seasons (Table 15.4 and 15.5). In the Aurora Trough ground, the relative importance of fish, and crustaceans in the diet of toothfish (in terms of prey biomass) changed markedly between years, although the biomass and species composition of cephalopods changed little between fishing seasons (Table 15.4). The biomass and relative importance of various fish taxa changed markedly between fishing seasons, especially the relative importance of *Bathylagus (*4-37% *IRI)*, macrourids (0.1-14% *IRI*), myctophids (0.8-22% *IRI*) and nototheniids (0.0-8.1% *IRI*) (Table 4). Prawns were common in the diet of toothfish in the Aurora Trough ground in all years (17-43% *IRI*), although their relative importance and total biomass in the diet varied markedly between years (Table 15.4). In the Northern Valleys ground, although the biomass and relative importance of fish, cephalopods and crustaceans was similar between years, the composition of prey species, particularly *Bathylagus (*4-49% *IRI)*, macrourid (2-9% IRI) and morid (3-11% IRI) fishes differed markedly between seasons (Table 15.5).

Diet of pelagic fish
Prey items were found in 254 of the 349 stomachs examined (Table 15.6). Thirteen major prey groups were identified, including a group of unknown items, usually unidentifiable due to advanced digestion. For all the fishes studied, copepods were the most frequently consumed prey item (Figure 15.2). They occurred in 64% of the stomachs containing food, regardless of the fish species. Amphipods (of which 82% were hyperiids) and euphausiids were also commonly consumed occurring in 35% and 32% of stomachs, respectively. Ostracods were consumed by 13% of the fishes (Figure 15.2).

Fish occurred in nine species (Table 15.6). Two species, *Echiodon cryomargerites* and *Stomias gracilis* were entirely piscivorous. *Phosichthys argenteus*, *Borostomias antarcticus* and one of the myctophids, *Gymnoscopelus bolini*, consumed high proportions of fish (82%, 72% and 87% by wet weight respectively). Small amounts of fish occurred in the diets of four other myctophids, *Electrona carlsbergi*, *G. microlampas* had 12% and 6% fish, respectively, and *E. antarctica* and *E. subaspera* each contained less than 1% fish.

The ten remaining myctophids and the two macrourids, *Coryphaenoides subserrulatus* and *Cynomacrurus piriei*, consumed mostly crustaceans, especially amphipods, copepods and euphausiids (Table 15.6). The four Protomyctophum species also ate predominantly amphipods, copepods and, with the exception of *P. parallelum*, euphausiids and some ostracods.

Thirteen species, all myctophids, had seven or more stomachs containing prey. The Kendall's coefficients of concordance were very low, but they were significant for eight of the 13 species (Table 15.7). The individuals in these eight species had significantly similar diets.

Cluster analysis (Figure 15.2) suggested five trophic guilds based on the dominance of copepods, euphausiids, amphipods and fish in the diets of the 13 myctophids. The randomisation procedure demonstrated that the significant dissimilarity value for the clusters in the dendrogram was 35.8%, confirming the presence of five trophic guilds (Figure 15.2).

Discussion
Toothfish diet
Results from this study indicate that toothfish feeding around Macquarie Island are opportunistic predators that feed on a wide range of prey, from demersal fish and crustaceans, to mesoplegic fishes and cephalopods. The major prey taken by biomass and *IRI* included the bathypelagic fish *Bathylagus antarcticus*, the squid *Gonatus antarcticus* and prawns. Nototheniid, macrourid, morid and myctophid fish were also important. Diet varied considerably both between years, and even over the short geographic distance (about 50 km) between the two fishing grounds. This variability was most apparent in the fish component of the diet, where the importance of *Bathylagus*, morid, macrourid, myctophid and nototheniid fishes varied considerably between seasons and within and between grounds. However, we found no evidence that this variability was related to the size of the fish, or the depth at which they were caught.

Elsewhere, toothfish length and age are thought to increase with water depth, with juvenile fish feeding pelagically and older fish feeding more benthically and in deeper water as they mature (Gon and Heemstra 1990, Gacía de la Rosa *et al.* 1997). In support of this are results from the one fishing ground and year at Macquarie Island where the total length of toothfish was significantly related to dietary differences, the smallest (<450 mm) toothfish caught preyed principally on pelagic myctophid fish (65% prey biomass), which were absent from the diet of the largest fish (>750mm) (Figure 15.1). However, the fact that this was only found in one fishing ground in one season, suggests this pattern is generally false at Macquarie Island.

Diet studies across most of the geographic range are available for toothfish (Table 15.8). Although most studies have only examined the diet based on the frequency of occurrence of prey taxa, such data enable some regional differences in the diets to be seen. Of note is the greater dependence on fish prey, and low abundance of cephalopods in the diets of toothfish in the southern Atlantic and Indian Oceans, relative to Macquarie Island, and the absence of crustaceans in the diets of toothfish on the Argentine shelf (Table 15.8). Notable differences occur in the composition of the fish component of the diet. *Bathylagus* is the most important fish prey at Macquarie Island, which appears absent in the diets of toothfish elsewhere, while nototheniid and channichthyid fishes occur most frequently in the diets of toothfish in the southern Indian and Atlantic Oceans (Table 15.8). Some of these dietary differences can be accounted for by biogeographical differences in the range of prey species. For example, the absence of channichthyid fish in diet of toothfish at Macquarie Island and Iles Crozet is expected, given that fish from this family do not occur in these locations (Williams 1988). However, other differences, such as the importance of *Bathylagus antarcticus* in the diets of toothfish at Macquarie Island but their complete absence in the diet at other subantarctic regions, is not consistent with the wide subantarctic distribution of this species (Gon and Heemstra 1990). The fish diet of toothfish from the Argentine shelf also differs from the other subantarctic regions in that it includes species from more temperate regions (Table 15.8).

Given the marked inter-annual differences in toothfish diet observed at Macquarie Island, there should be caution in interpreting regional difference across their range, where multi-year data are absent. However, there have been several studies of the diet of toothfish undertaken around

South Georgia and Shag Rocks (Tarverdiyeva 1972, Zhivov and Krivoruchko 1990, García de la Rosa *et al.* 1997) (Table 15.9), and these studies indicate broad dietary similarities. Most notable is the importance of notctheniid, followed by channichthyid and myctophid fishes, however, the proportion of the diet made up by these fishes varies somewhat between studies, in particular whether fish were sampled from shelf or slope waters (Table 15.9). Further, the frequency of benthic and pelagic crustaceans species taken (about 14-40% frequency of occurrence) varies between studies, with cephalopods generally occurring in less than 15% of stomachs (Table 15.9). Unfortunately, most studies that have investigated toothfish diet have only used the frequency of occurrence of prey items. Such analyses will tend to overestimate the importance of prey with small biomass, and underestimate the importance of prey with large biomass. For example, prawns occurred in almost one third (28%) of stomachs investigated at Macquarie Island and were the most commonly observed prey items, but accounted for <10% of total prey biomass. Given the generally highly digested state of toothfish stomach contents, and the potential biases of the standard measures of prey importance (frequency of occurrence, number and mass), measures such as the *IRI* may provide a better indication of the importance of various prey taxa in toothfish diet (Cortés 1997, but see Hannson 1998).

Pelagic fish diet
The range of prey consumed by pelagic fish at Macquarie Island was not substantially different from that reported at other locations in the Southern Ocean. The dominance of crustaceans in the diet of the bathylagid and most of the myctophid fish is consistent with previous findings (Young and Blaber 1986; Gorelova and Efrenko 1989; Gon 1990; Hulley 1990; Oven *et al.* 1990; Sabourenkov 1990; Kozlov 1995; Pakhomov *et al.* 1996). Four of the five trophic guilds identified in the myctophids were based on the presence of crustacean prey.

The first trophic guild comprised *E. antarctica, K. anderssoni, P. tenisoni* and *G. braueri*, which consumed mostly copepods (Figure 15.2). *K. anderssoni* is the dominant fish prey (>200,000 tonnes annually) taken by seabirds around Macquarie Island, being important in the diets of royal, rockhopper and king penguins (Hindell 1988; Hull 1999, Goldsworthy *et al.* 2001). This suggests that copepods are a key component of the zooplankton biomass and ultimately support the large penguin populations that breed at Macquarie Island. If allocated to a trophic guild, *C. subserrulatus* (Macrouridae), may be between the copepod and amphipod feeding guilds, although other studies found this species to be mostly piscivorous (CSIRO unpub. data). Unlike *K. anderssoni*, the remaining three myctophid species in this guild (*E. antarctica, P. tenisoni* and *G. braueri*) are uncommon prey species of seabirds and seals near Macquarie Island (Goldsworthy *et al.* 2001).

The species in the second trophic guild, *G. fraseri, G. microlampas* and *G. piabilis*, have more diverse diets than species in the other guilds. Their diets were dominated by euphausiids and amphipods, but all ate some copepods and decapods (Table 15.6). These species appear to have a broader diet than the other myctophids. *G. nicholsi*, a species commonly consumed by fur seals and gentoo penguins (Robinson and Hindell 1996, Goldsworthy *et al*. 1997) at Macquarie Island, was excluded from cluster analysis because there were only two stomachs containing food, but could be allocated to this guild based on similar proportions of copepods and euphausiids in their diet.

Members of the third guild, *E. carlsbergi, P. andriashevi* and *P. bolini* consumed mostly euphausiids (Figure 15.2). The single stomach available for the other macrourid studied, *C. piriei*, was filled entirely with euphausiids, although this species is documented as also consuming fish and copepods (Iwamoto 1990). *E. carlsbergi* is a major prey species of king penguins, with over 120,000 tonnes estimated to be consumed around Macquarie Island annually (Hindell 1988, Goldsworthy *et al.* 2001). This species is one of the most abundant myctophid species in the Southern Ocean (Lubimova *et al*. 1987 in Duhamel *et al.* 2000), and

formed the basis of a commercial fishery in the south-western Atlantic during the 1980s (Kock 1992).

The diets of the fourth trophic guild, *E. subaspera* and *L. achirus*, were dominated by amphipods (Figure 15.2). *E. subaspera* is the most important myctophid consumed by fur seals at Macquarie Island (Goldsworthy *et al*. 1997). *Melanostigma gelatinosum* and *P. parallelum* were excluded from cluster analyses as each had only four stomachs containing prey, however, they could be included in this guild, due to the dominance of amphipods in their diets (91% and 75% respectively). *Bathylagus antarcticus* is the most common fish species in the diet of Patagonian toothfish at Macquarie Island, representing about 14% of the overall dietary biomass (Goldsworthy *et al.* In press), and based on our data, could also be allocated to this trophic guild. Studies of the diet of *B. gracilis* in the south Atlantic Ocean (Gorelova and Kobyliansky 1985) probably refer to *B. antarcticus* (Gon and Heemstra 1990), and indicate that in this region of the Southern Ocean *B. antarcticus* feeds primarily on euphausiids (46% by mass).

G. bolini clusters quite separately from the other species, being the only myctophid that eats mainly fish (87%, Figure 15.2) and cephalopods (Table 15.6). The large amount of myctophid fish found in stomachs of *Gymnoscopelus bolini* was unexpected, as myctophids are generally not piscivorous (Young and Blaber 1986). However, piscivory in the stomiids and in *P. argenteus* has previously been observed (Sutton and Hopkins 1996, Williams *et al.* in prep). *Borostomias. antarcticus* and *S. gracilis* were both almost exclusively piscivorous (Pakhomov *et al*. 1996).

The low variability in individual diet observed for eight of the myctophids (Table 15.7, $p > 0.05$) may be due to schooling behaviour (Tirasin and Jorgenson 1999). As fish tend to congregate in species-specific groups, individuals are likely to be exposed to similar prey environments, and thus opportunism may appear to be species level dietary affinity (Tirasin and Jorgenson 1999). In our study we had small sample sizes (Table 15.6) and no information on the specific times, depths and locations of capture for each fish. This prevented further investigation into whether schooling behaviour was responsible for the low variability we observed between the diets of individuals for some myctophids.

Even at the very general level of prey classification used here, the sub-Antarctic, meso- and bathypelagic fishes around Macquarie Island consumed subtly different proportions of crustacean and fish prey. The extent to which these co-occurring fishes are specialised in their diet may be important in the structuring the food webs around Macquarie Island (Clarke 1980; Pakhomov 1997). Some of these species may not be entirely opportunistic feeders. Further investigation into the application of the five trophic guilds may assist in better defining the trophodynamics of pelagic marine systems around Macquarie Island.

References
Adams, N. J., Moloney, C. and Navarro, R. (1993). Estimated food consumption by penguins at the Prince Edward Islands. Antarctic Science 5: 245-252.

Clarke, T. A. (1980). Diets of fourteen species of vertically migrating mesopelagic fishes in Hawaiian waters. Fishery Bulletin 78(3): 619-640.

Cortés, E. (1997). A critical review of methods of studying fish feeding based on analysis of stomach contents: application to elasmobranch fishes. Canadian Journal of Fisheries and Aquatic Sciences 54: 726-738.

Duhamel, G. (1981). Caracteristiques biologiques des principales especes de poissons du plateau continental des Iles Kerguelen. Cybium 5: 19-32.

Duhamel, G. and Pletikosic, M. (1983). Donnes biologiques sur les Nototheniidae des Ilse Crozet. Cybium 7: 43-57.

Duhamel, G., Koubbi, P. and Ravier, C. (2000). Day and night mesopelgic fish assemblages off the Kerguelen Islands (Southern Ocean). Polar Biology 23: 106-112.

García de la Rosa, S. B., Sánchez, F. and Figueroa, D. (1997). Comparative feeding ecology of Pategonian toothfish (*Dissostichus eleginoides*) in the southwestern Atlantic. CCAMLR Science 4: 105-124.

George, E. L. and Hadley, W. F. (1979). Food and habitat partitioning between rock bass (*Ambloplites rupestris*) and smallmouth bass (*Micropterus dolomieui*) young of the year. Transactions of the American Fisheries Society 108: 253-261.

Goldsworthy, S., He, X., Lewis, M., Williams, R. and Tuck, G. (2001). Trophic interactions between Patagonian toothfish, its fishery and seals and seabirds around Macquarie Island. Marine Ecology Progress Series, 218: 283-302.

Goldsworthy, S., Williams, D. Lewis, M., Young, J. and He, X. (in press). Diets of Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island, Tasmania, Australia. Marine and Freshwater Research.

Goldsworthy, S. D., Hindell, M. A. and Crowley, H. M. (1997). Diet and diving behaviour of sympatric fur seals, *Arctocephalus gazella* and *A. tropicalis*, at Macquarie Island. In: Hindell, M. A., Kemper, C (eds) Marine Mammal Research in the Southern Hemisphere Volume 1: Status, Ecology and Medicine. Surrey Beatty and Sons, Chipping Norton, 151-63

Gon, O. (1990). Bathylagidae: Deep sea smelts. In 'Fishes of the Southern Ocean'. (Eds O. Gon and P. C. Heemstra.) pp.107-110. (J.L.B. Smith Institute of Ichthyology: Grahamstown, South Africa).

Gon, O. and Heemstra, P. C. (1990). Fishes of the Southern Ocean. (J.L.B. Smith Institute of Icthyology, Grahamstown.). 462 pp.

Gordon, J. D. M., Merrett, N. R. and Haedrich, R. L. (1995). Environmental and biological aspects of slope-dwelling fishes of the North Atlantic. In 'Deep-Water Fisheries of the North Atlantic Oceanic Slope'. (Ed A. G. Hopper.) pp.1-26. (Kluwer Academic Publishers: Dordrecht, The Netherlands).

Gorelova, T. A. and Efremenko, V. N. (1989). On the food composition of the larvae of Lantern Anchovies (Myctophidae) from the Scotia Sea. Journal of Ichthyology 29(5): 106-109.

Gorelova, T. A. and Kobyliansky, S. G. (1985). Feeding of deepsea fishes of the family Bathylagidae. Voprosy Ikhtiologii 2: 264-274.

Guinet, C. Cherel, Y., Ridoux, V. and Jouventin, P. (1996). Consumption of marine resources by seabirds and seals in Crozet and Kerguelen waters: changes in relation to consumer biomass 1962-85. Antarctic Science 8: 22-30.

Hannson, S. (1998). Methods of studying fish feeding: a comment. Canadian Journal of Fisheries and Aquatic Sciences 55: 2706-2707.

He, X., Bulman, C., Goldsworthy, S. and Williams, A. (in prep.) Using Mantel test to detect changes of diet composition in fish length.

Hindell, M. A. (1988). The diet of the king penguin *Aptenodytes patagonicus* at Macquarie Island. Ibis 130: 193-203.

Hull, C. L. (1999). Comparison of the diets of breeding royal (*Eudyptes schlegeli*) and rockhopper (*Eudyptes chrysocome*) penguins on Macquarie Island over three years. Journal of Zoology 247:507-529.

Hulley, P. A. (1990). Myctophidae: Lanternfishes. In 'Fishes of the Southern Ocean'. (Eds O. Gon and P. C. Heemstra.) pp.146-178. (J.L.B. Smith Institute of Ichthyology: Grahamstown, South Africa).

Iwamoto, T. (1990). Macrouridae: Grenadiers. In 'Fishes of the Southern Ocean'. (Eds O. Gon and P. C. Heemstra.) pp.195-206. (J.L.B. Smith Institute of Ichthyology: Grahamstown, South Africa).

Kock, K-H. (1992). Antarctic fish and fisheries. Cambridge University Press, Cambridge. 359pp.

Koslow, J. A. (1997). Seamounts and the ecology of deep-sea fisheries. American Scientist 85: 168-176.

Kozlov, A. N. (1995). A review of the trophic role of mesopelagic fish of the family Myctophidae in the Southern Ocean ecosystem. CCAMLR Science 2: 71-77.

Manly, B. F. J. (1991) Randomization and Monte Carlo methods in biology. (Chapman and Hall. New York.). 281 pp.

Mantel, N. (1967). The detection of disease clustering and a generalized regression approach. Cancer Research 27: 209-220.

Oven, L. S., Konstantinova, M. P. and Shevenko, N. F. (1990). Aspects of reproduction and feeding of myctophids (Myctophidae) in the Southwest Atlantic. Journal of Ichthyology 30(2): 115-127.

Pakhomov, E. A. (1997). Feeding and exploitation of the food supply by demersal fishes in the Antarctic part of the Indian Ocean. Journal of Ichthyology 37(5): 360-380.

Pakhomov, E. A., Perissinotto, R. and McQuaid, C. D. (1996). Prey composition and daily rations of myctophid fishes in the Southern Ocean. Marine Ecology Progress Series 134: 1-14.

Robinson, S.A. and Hindell, M.A. (1996). Foraging ecology of gentoo penguins *Pygoscelis papua* at Macquarie Island during the period of chick care. Ibis 138: 722-731.

Sabourenkov, E. N. (1990). Mesopelagic fish of the Southern Ocean – summary results of recent Soviet studies. Selected Scientific Papers. (Scientific Committee for CCAMLR: Hobart). 573 pp.

Sutton, T. T. and Hopkins, T. L. (1996). Species composition, abundance, and vertical distribution of the stomiid (Pisces: Stomiiformes) fish assemblage of the Gulf of Mexico. Bulletin of Marine Science 59(3): 530-542.

Tarverdiyeva, M. I. (1972). Daily food consumption and feeding patterns of the Georgian cod (*Notothenia rossi marmorata* Fisher) and the Patagonian toothfish (*Dissostichus eleigenoides* Smitt) (Fam. Nototheniidae) in the South Georgia area. Journal of Ichthyology. 12: 684-692.

Tirasin, E. M. and Jorgensen, T. (1999). An evaluation of the precision of diet description. Marine Ecology Progress Series 182: 243-252.

Tseitlin, V. B. (1985). Energetics of fish populations inhabiting seamounts. Oceanology 25(2): 237-239.

Tyler, H. R. Jnr. and Pearcy, W. G. (1975). The feeding habits of three species of Lanternfishes (Family Myctophidae) off Oregon, USA. Marine Biology 32: 7-11.

William, R. (1988). The nearshore fishes of Macquarie Island. Papers and Proceedings of the Royal Society of Tasmania 122: 233-245.

Williams, A. Koslow, J. A., Terauds, A. and Haskard, K. (In prep.). Feeding ecology of fishes from the mid-slope micronekton community off southern Tasmania, Australia.

Williams, A. and Koslow, J. A. (1997). Species composition, biomass and vertical distribution of micronekton over the mid-slope region off southern Tasmania, Australia. Marine Biology 130: 259-276.

Young, J. W. and Blaber, S. J. M. (1986). Feeding ecology of three species of midwater fishes associated with the continental slope of eastern Tasmania, Australia. Marine Biology 93: 147-156.

Young, J. W. (1991). 'Biology of lanternfishes (Pisces: Family Myctophidae); an overview, with reference to species of the waters of the Pasminco-EZ jarosite dumpsite'. CSIRO Division of Fisheries Industry Report 1.91. 13 pp.

Zhivov, V. V. and Krivoruchko, V. M. (1990). On the biology of the Patagonian toothfish, *Dissostichus eliginoides*, of the Antarctic part of the Atlantic. Journal of Ichthyology 30: 142-146.

Table 15.1 Prey category by lowest possible taxonomic level and aggregated prey groups for toothfish caught around Macquarie Island.

Prey groups		Prey category by lowest taxonomic level
Fish	Bathylagidae	*Bathylagus antarcticus*
	Myctophidae	*Electrona subaspera, E. carlsbergi*
		Gymnoscopelus braueri, G. fraseri, G. microlampas, G. nichols
		Krefftichthys anderssoni
		Lampanyctus achirus
	Macrouridae	*Coryphaenoides* sp.
		Cynomacrurus piriei
	Moridae	*Halargyreus johnsonii*
		Lepidion sp.
	Nototheniidae	*Dissostichus eleganoides*
		Lepidonotothen squamifrons
		Paranotothenia magellanica
	Other Fish	Squalidae
		Nemichthyidae, *Labichthys yanoi*
		Microstomatidae, *Nansenia* sp.
		Astronesthidae, *Astronethes* sp.
		Stomiidae, *Stomias* sp., *Borostomias* sp.
		Chauliodus danae
		Idicanthidae, *Idiacanthus atlanticus*
		Scopelarchidae, *Scopelarchoides* sp.
		Melanonus gracilis
		Melamphaidae, *Poromitra* sp.
		Psychrolutidae
		Rosenblattia, Epigonus sp.
		Gempylidae, *Paradiplospinus antarcticus*
		Bothidae
Cephalopoda	*Chiroteuthis*	*Chiroteuthis* sp.
	Cirroteuthis	Cirroteuthis
	Gonatus	*Gonatus antarcticus*
	Mastigoteuthis	*Mastigoteuthis* sp.
	Moroteuthis	*Moroteuthis ingens, M. knipovitchi*
	Oceph	Unidentified Octopod
		Brachioteuthis
		Galiteuthis glacialis
		Histioteuthis eltaninae
		Histioteuthis macrohista
		Stoloteuthis sp.
		Vampyromorpha
		Taonius sp.
Crustacea	*Lithodes* sp.	*Lithodes murrayi*
	Prawns	Caridea
		Nematocarcinidae
		Euphausiidae, *Gnathophausia* sp.
		Mysid
		Sergestes
	OCrust	Amphipoda
		Ostracoda
		Barnacles
		Isopoda

THE DIET OF TOOTHFISH AND PELAGIC FISH AROUND MACQUARIE ISLAND

Table 15.2 Number of toothfish sampled for diet analysis around Macquarie Island in the 1996/96, 1997/98 and 1998/99 fishing seasons. Numbers and percentage for each season and ground, the mean total length of fish and the depth at which they were caught are also listed. *Sd*=standard deviation, *n*=number of samples used to calculate standard deviation.

Season	Ground	Number of stomach samples	Number with contents	Mean total length in mm (*sd*, *n*)	Mean depth in m (*sd*, *n*)
1995/96	Aurora Trough	495	424 (86%)	1006.7 (214.5, 11)	895 (83, 404)
1997/98	Northern Valleys	372	124 (33%)	689.2 (114.3, 371)	1167 (92, 372)
	Aurora Trough	37	32 (86%)	628.3 (72.3, 37)	902 (39, 37)
1998/99	Northern Valleys	350	166 (47%)	639.4 (121.1, 350)	1136 (131, 350)
	Aurora Trough	169	117 (69%)	604.2 (176.4, 158)	822 (144, 169)

THE DIET OF TOOTHFISH AND PELAGIC FISH AROUND MACQUARIE ISLAND

Table 15.3 Occurrence of prey groups and major prey types (fish, cephalopods, crustaceans) in the stomachs of toothfish from Macquarie Island. (Samples from all seasons and fishing grounds are pooled in this table.) The contribution of various prey items in the diet is expressed as the percentage frequency of occurrence (%F), percentage frequency by number (%N), percentage frequency by mass (%M) and index of relative importance (IRI).

Prey groups		%F	%N	%M	IRI
Fish	Bathylagidae	14.4	15.6	13.9	13.6
	Myctophidae	10.0	7.3	3.2	3.4
	Macrouridae	4.2	2.0	7.6	1.3
	Moridae	3.0	4.4	4.8	0.9
	Nototheniidae	2.4	1.2	8.7	0.8
	Ofish	3.7	4.2	5.4	1.1
	Unidentified Fish	36.0	20.4	14.6	40.3
Cephalopods	*Gonatus*	8.0	5.0	16.2	5.4
	Mastigoteuthis	5.0	3.3	1.9	0.8
	Moroteuthis	1.6	0.8	4.3	0.3
	Chiroteuthis	1.3	0.6	1.6	0.1
	Cirroteuthis	4.5	2.4	0.7	0.5
	OCeph	3.6	1.8	2.2	0.5
	Unidentified Cephalopods	13.7	7.9	4.6	5.5
Crustaceans	Prawns	28.0	19.2	9.0	25.3
	Lithodes	1.6	0.8	1.0	0.1
	OCrust	2.0	2.2	0.0	0.1
	Unidentified Crustaceans	2.1	1.0	0.3	0.1
Fish		64.9	55.0	58.1	71.4
Cephalopods		34.6	21.9	31.6	18.0
Crustaceans		32.7	23.1	10.3	10.6

THE DIET OF TOOTHFISH AND PELAGIC FISH AROUND MACQUARIE ISLAND

Table 15.4 Occurrence of prey groups and major prey types in the stomachs of toothfish from the Aurora Trough fishing ground at Macquarie Island over three fishing seasons. The contribution of various prey items in the diet is expressed as the percentage frequency of occurrence (%F), percentage frequency by number (%N), percentage frequency by mass (%M) and index of relative importance (IRI).

Prey groups		Season 1995/96				Season 1997/98				Season 1998/99			
		%F	%N	%M	IRI	%F	%N	%M	IRI	%F	%N	%M	IRI
Fish	Bathylagidae	12.7	10.4	6.7	4.7	37.5	23.9	27.9	37.4	7.7	6.0	8.5	3.9
	Myctophidae	4.7	5.6	2.4	0.8	18.8	9.8	4.8	5.3	24.8	16.8	8.6	22.1
	Macrouridae	1.2	0.6	2.0	0.1	21.9	7.6	25.5	13.9	2.6	1.2	3.1	0.4
	Moridae	0.5	0.4	1.4	0.0	0.0	0.0	0.0	0.0	1.7	1.2	1.4	0.2
	Nototheniidae	1.2	0.6	8.1	0.2	0.0	0.0	0.0	0.0	6.8	3.2	17.9	5.1
	Ofish	2.1	1.1	6.0	0.3	0.0	0.0	0.0	0.0	2.6	1.2	4.8	0.5
	Unidentified Fish	38.2	25.5	19.8	37.6	28.1	9.8	6.2	8.7	32.5	16.0	7.7	27.0
Cephalopods	*Gonatus*	8.3	4.9	22.9	5.0	25.0	13.0	15.3	13.6	12.8	10.4	25.5	16.2
	Mastigoteuthis	1.2	0.6	0.9	0.0	18.8	12.0	3.5	5.6	9.4	5.6	0.2	1.9
	Moroteuthis	1.2	0.6	2.8	0.1	3.1	1.1	10.8	0.7	2.6	1.6	12.7	1.3
	Chiroteuthis	0.5	0.2	1.1	0.0	0.0	0.0	0.0	0.0	2.6	1.2	2.0	0.3
	Cirroteuthis	1.2	0.7	0.1	0.0	9.4	4.3	1.4	1.0	1.7	1.2	0.2	0.1
	OCeph	1.4	0.9	2.3	0.1	3.1	1.1	2.2	0.2	6.0	3.2	0.4	0.8
	Unidentified Cephalopods	19.6	12.9	6.9	8.4	3.1	1.1	0.0	0.1	6.0	3.6	0.5	0.9
Crustaceans	Prawns	40.6	32.3	16.0	42.5	37.5	16.3	2.4	13.5	23.9	15.6	4.2	16.6
	Lithodes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	1.6	2.1	0.4
	OCrust	1.2	1.7	0.0	0.0	0.0	0.0	0.0	0.0	6.8	8.8	0.1	2.1
	Unidentified Crustaceans	1.9	1.0	0.4	0.1	0.0	0.0	0.0	0.0	3.4	1.6	0.1	0.2
Fish		55.4	44.2	46.5	56.2	81.3	51.1	64.3	69.1	74.4	45.6	52.1	66.8
Cephalopods		30.4	20.8	37.1	19.7	53.1	32.6	33.2	25.8	35.0	26.8	41.4	22.0
Crustaceans		42.0	35.0	16.5	24.1	37.5	16.3	2.4	5.2	35.9	27.6	6.5	11.2

THE DIET OF TOOTHFISH AND PELAGIC FISH AROUND MACQUARIE ISLAND

Table 15.5 Occurrence of prey groups and major prey types in the stomachs of toothfish from the Northern Valleys fishing ground at Macquarie Island over two fishing seasons. The contribution of various prey items in the diet is expressed as the percentage frequency of occurrence (%F), percentage frequency by number (%N), percentage frequency by mass (%M) and index of relative importance (IRI).

Prey groups		Season 97/98				Season 98/99			
		%F	%N	%M	IRI	%F	%N	%M	IRI
Fish	Bathylagidae	4.8	10.0	8.2	4.0	25.9	29.7	35.8	49.0
	Myctophidae	13.7	10.4	4.3	9.1	8.4	4.0	2.2	1.5
	Macrouridae	7.3	4.3	22.6	8.9	7.2	2.4	8.7	2.3
	Moridae	10.5	6.1	16.9	10.9	5.4	11.9	6.6	2.9
	Nototheniidae	2.4	1.3	6.9	0.9	3.0	1.2	8.7	0.9
	Ofish	6.5	3.5	5.7	2.7	7.2	11.2	4.6	3.3
	Unidentified Fish	29.8	19.9	9.6	40.0	39.2	15.6	9.7	28.6
Cephalopods	*Gonatus*	0.8	4.3	1.4	0.2	6.0	2.6	6.9	1.6
	Mastigoteuthis	2.4	4.8	2.8	0.8	10.8	5.3	4.3	3.0
	Moroteuthis	1.6	0.9	5.0	0.4	1.8	0.6	2.8	0.2
	Chiroteuthis	2.4	1.3	5.4	0.7	1.8	0.6	0.3	0.0
	Cirroteuthis	18.5	11.7	3.5	12.8	3.6	1.6	0.3	0.2
	OCeph	5.6	3.9	1.7	1.4	6.0	2.0	3.3	0.9
	Unidentified Cephalopods	4.8	3.0	0.1	0.7	12.7	5.0	4.2	3.3
Crustaceans	Prawns	8.1	10.0	0.7	3.9	12.0	4.6	1.0	1.9
	Lithodes	5.6	3.0	5.0	2.1	1.8	0.6	0.4	0.1
	OCrust	0.0	0.0	0.0	0.0	2.4	0.8	0.0	0.1
	Unidentified Crustaceans	3.2	1.7	0.1	0.3	1.2	0.4	0.2	0.0
Fish		78.2	55.4	74.3	78.5	79.5	76.0	76.3	87.4
Cephalopods		46.0	29.9	20.0	17.7	40.4	17.6	22.1	11.6
Crustaceans		24.2	14.7	5.8	3.8	17.5	6.3	1.6	1.0

THE DIET OF TOOTHFISH AND PELAGIC FISH AROUND MACQUARIE ISLAND

Table 15.6 The stomach contents of 23 species of meso- and bathypelagic fishes from near Macquarie Island, Australia. (Symbols are: *n* = number of stomachs dissected, no. full = number of stomachs containing prey.)

Family	Species	n	no. full	amphipod	copepod	euphausiid	decapod	ostracod	mysid	crustacean	fish	cephalopod	chaetognath	cnidarian	gastropod	unknown
Bathylagidae	*Bathylagus antarcticus*	24	4	100.0	-	-	-	-	-	-	-	-	-	-	-	-
Carapidae	*Echiodon cryomargerites*	2	1	-	-	-	-	-	-	-	100.0	-	-	-	-	-
Macrouridae	*Coryphaenoides subserrulatus*	6	4	29.4	24.1	5.5	-	-	-	15.4	-	-	11.3	-	-	14.3
	Cynomacrurus pirei	2	1	-	-	100.0	-	-	-	-	-	-	-	-	-	-
Myctophidae	*Electrona antarctica*	25	23	8.3	50.2	19.7	-	-	1.0	19.0	0.0	-	-	-	-	1.9
	E. carlsbergi	9	7	1.3	4.2	58.3	-	-	-	11.0	12.3	-	9.7	-	-	2.7
	E. subaspera	8	8	67.6	8.1	-	-	0.0	0.8	13.6	0.2	-	2.6	-	-	7.2
	Gymnoscopelus bolini	16	15	0.4	0.0	5.6	1.8	-	-	0.7	87.2	4.3	-	-	-	0.3
	G. braueri	36	18	35.1	31.5	8.2	-	-	-	22.9	-	-	-	-	-	2.3
	G. fraseri	22	22	16.9	10.1	13.7	4.5	0.9	-	43.0	-	-	1.3	-	0.19	9.4
	G. microlampas	19	19	21.2	11.1	27.7	8.3	0.2	-	19.5	6.0	-	-	-	-	6.0
	G. nicholsi	2	2	-	24.8	19.5	-	-	-	55.7	-	-	-	-	-	-
	G. piabilis	9	9	42.7	0.8	23.3	15.8	0.1	-	16.0	-	-	1.0	-	0.32	-
	Krefftichthys anderssoni	25	25	3.3	57.9	12.8	-	0.9	-	25.1	-	-	-	-	-	-
	Lampanyctus achirus	18	11	70.9	10.7	1.6	2.3	0.1	-	-	-	-	-	-	-	14.5
	Protomyctophum andriashevi	18	17	9.6	6.8	66.2	-	1.0	-	10.5	-	-	-	-	-	6.0
	P. bolini	26	26	7.8	31.8	56.9	-	0.1	-	3.5	-	-	-	-	-	-
	P. parallelum	4	4	75.0	25.0	-	-	-	-	-	-	-	-	-	-	-
	P. tenisoni	30	24	12.3	64.5	18.4	-	2.1	-	1.0	-	-	-	-	0.18	1.5
Phosichthyidae	*Phosichthys argenteus*	6	4	12.9	0.2	5.3	-	-	-	-	81.7	-	-	-	-	-
Stomiidae	*Borostomias antarcticus*	10	3	-	-	-	-	-	-	-	71.8	-	-	28.2	-	-
	Stomias gracilis	25	3	-	-	-	-	-	-	-	100.0	-	-	-	-	-
Zoarcidae	*Melanostigma gelatinosum*	4	3	91.4	-	-	-	6.5	-	2.1	-	-	-	-	-	-

Table 15.7 Kendall's coefficient of concordance between the diets of individuals of 13 myctophids from near Macquarie Island. Note that p value < 0.05 indicates no significant difference between diets of individuals in that species. (Symbols are: n = number of stomachs containing prey, W = Kendall's coefficient of concordance, df = number of prey items − 1)

Fish species	n	W	df	p value
E. antarctica	23	0.166	4	0.004 *
E. carlsbergi	7	0.067	4	0.809
E. subaspera	8	0.249	5	0.076
G. bolini	15	0.114	6	0.113
G. braueri	18	0.113	2	0.130
G. fraseri	22	0.180	6	0.001 *
G. microlampas	19	0.200	5	0.002 *
G. piabilis	9	0.075	6	0.673
K. anderssoni	25	0.518	3	<0.001 *
L. achirus	11	0.282	4	0.014*
P. andriashevi	17	0.178	3	0.029*
P. bolini	26	0.376	3	<0.001 *
P. tenisoni	24	0.351	4	<0.001 *

Table 15.8 Comparison of the diets of toothfish from five locations throughout the southern Atlantic (Argentine Shelf and South Georgia), southern Indian (Iles Crozet and Kerguelen) and southern Pacific Oceans (Macquarie Island), as indicated by percentage frequency of occurrence.

Prey Groups		Argentine shelf/slope[1]	South Georgia <300m[1]	South Georgia >1000m[1]	Iles Crozet[2]	Iles Kerguelen[3]	Macquarie Island[4]
	n	231	155	3272	74	1514	1423
	% stomach content	58.4	83.1	6.9	41.9	50.8	60.6
Fish	Bathylagidae						14.4
	Myctophidae	0.7	1.9		11.5	27.2	10.0
	Macrouridae	2.1		0.9			4.2
	Moridae	2.1		1.3			3.0
	Merluccidae	3.5					
	Gadidae	4.9					
	Zoarcidae	5.6		2.2			
	Nototheniidae	25.7	37.8	0.5	19.2	13.0	2.4
	Channichthyidae		39.5	0.5		26.1	
	Bathydraconidae			0.9			
	Ofish					0.3	3.8
	Unidentified fish	50.7	7.6	54.0	5.8	23.0	36.1
Cephalopods	*Gonatus*						8.0
	Mastigoteuthis						5.0
	Moroteuthis						1.6
	Loligo	2.8					
	Illex	2.8					
	Semirossia	0.7					
	Kondakovia			14.7			0.1
	Chiroteuthis						1.3
	Octopus	0.7					
	Cirroteuthis						4.5
	Unident. octopod						1.3
	Oceph						2.0
	Unidentified Cephalopods		0.8		7.7	1.0	13.7
Crustaceans	Prawns			2.7	3.8	0.1	28.1
	Euphausia		20.1		7.7	3.2	
	Lithodes			7.1			1.6
	Amphipods				23.1	1.4	
	Isopods				1.9		
	Ocrust						4.2
	Unidentified Crustaceans		2.9	12.1			
Fish		95.1	86.5	60.3	na	na	65.0
Cephalopods		6.9	0.8	14.7	7.7	1.0	34.7
Crustaceans		0.0	22.7	21.8	na	na	32.8

[1]García de la Rosa *et al.*, (1997); [2]Duhamel and Pletikosic (1983); [3]Duhamel (1981); [4]This study.

Table 15.9 Comparison of the diets of toothfish from three studies of fish collected at South Georgia and Shag Rocks in the south-west Atlantic, as indicated by percentage frequency of occurrence. Prey groups marked by an * represents cases where the percentage frequency of occurrence of more than one prey item were summed. In such cases the values presented may represent overestimates.

Prey groups		South Georgia[1]	Shag Rocks[2] 200–400m	Shag Rocks[2] 400–600m	South Georgia[2] 600–100m	South Georgia[2] 1000–1400m	South Georgia[3] <300m	South Georgia[3] >1000m
	n	52	2340	1144	673	1460	155	3272
	% stomach contents	90.4	10.6	14.0	36.3	14.9	83.1	6.9
Fish	Myctophidae		2.0*	3.8*	13.1*	13.4*	1.9	
	Macrouridae				1.2*	1.8*		0.9
	Moridae							1.3
	Zoarcidae							2.2
	Nototheniidae	17.1*	23.3*	1.98*	4.4*	1.0*	37.8	0.5
	Channichthyidae	6.4*	5.2*	3.7*	6.1*		39.5	0.5
	Bathydraconidae	2.1						0.9
	Gempylidae			3.1				
	Ofish	2.1	0.8		1.2			
	Unident. fish	66.0	47.4	43.1	51.2	27.7	7.6	54.0
Cephalopods	*Kondakovia*							14.7
	Unident. octopod		1.2	1.9	2.1	1.8		
	Oceph		4.0	10.0	5.3	9.7		
	Unident. Ceph.						0.8	
Crustaceans	Crabs		6.4	12.5	5.3	6.0		7.1
	Lobsters			5.0	3.7	24.0		
	Prawns	6.4						2.7
	Shrimps	29.8	0.4	1.9	3.3	2.3		
	Euphausia		4.8	4.4	0.4	2.3	20.1	
	Amphipods		0.4					
	Isopods		3.2	0.6	1.2	7.4		
	Unident. Crust						2.9	12.1
Echinoderms	Seastars			0.6				
	Sea Urchins			0.6				
Cnidarians	Medusae					1.8		
	Corals			0.6				
Stones			4.8	4.4	0.4			
Trash from fishing vessels				31.9	0.8	0.9		
Fish	Fish	87.2	na	na	na	na	86.5	60.3
Cephalopods	Cephalopods	na	na	na	na	na	0.8	14.7
Crustaceans	Crustaceans	na	na	na	na	na	22.7	21.8

[1]Tarverdiyeva, M. I. (1972); [2]Zhivov and Krivoruchko (1990); [3]García de la Rosa *et al.*, (1997).
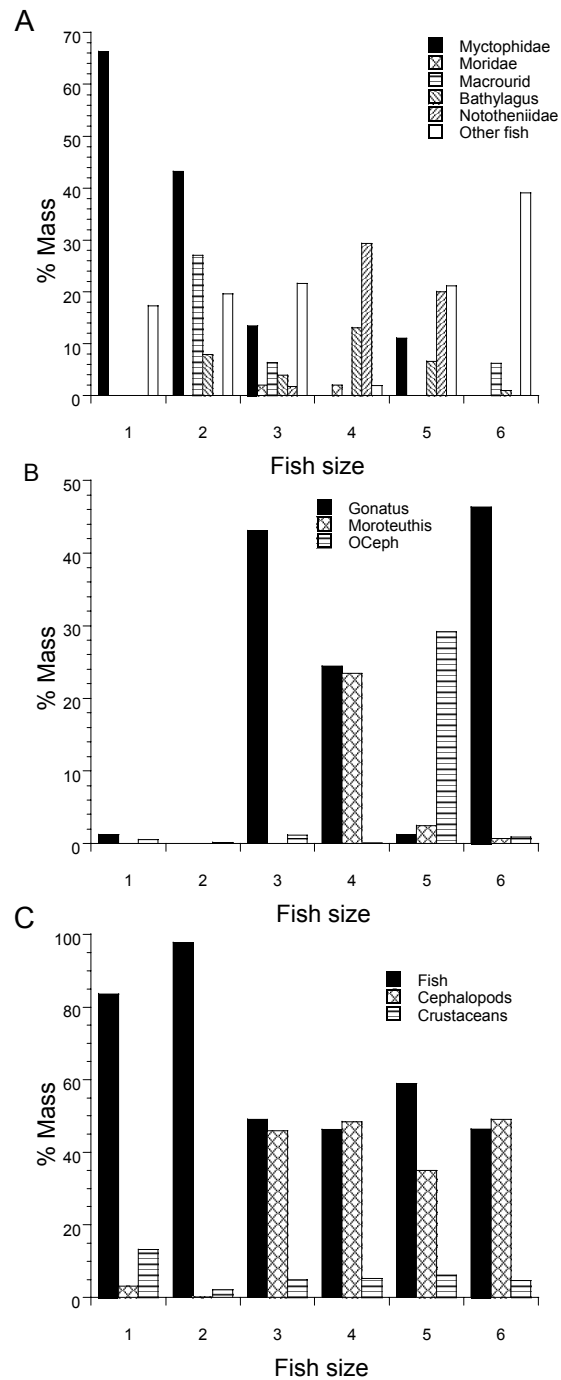
Figure 15.1 Changes in prey composition to toothfish size (1 = <450, 2 = 450-550, 3 = 550-650, 4 = 650-750, 5 = 750-850, 6 =>850 mm) in the Aurora Trough fishing ground at Macquarie Island in the 1998/99 fishing season. **A**=between six fish prey; **B**=between three cephalopod prey; **C**=between three broad prey categories.
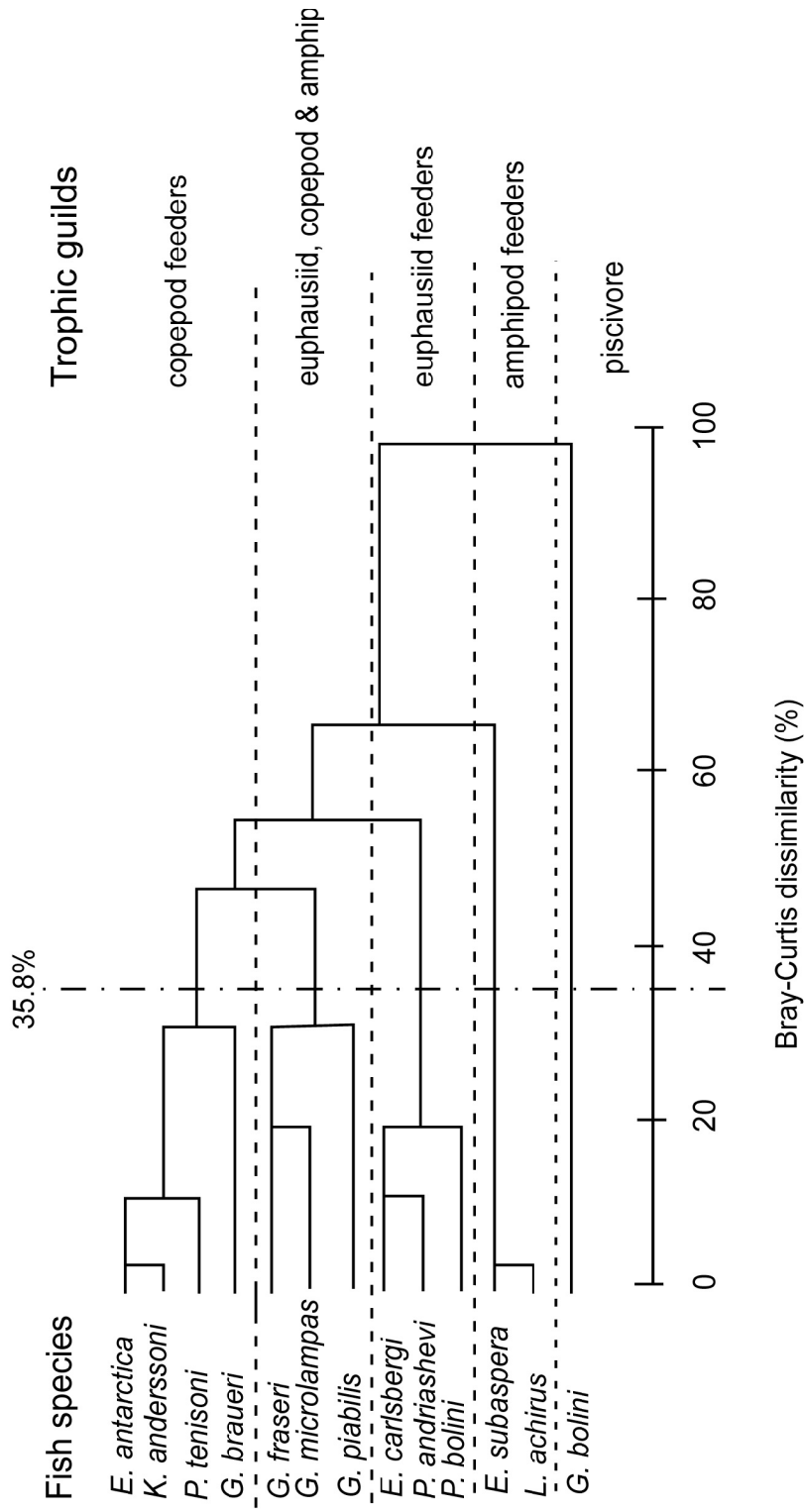
Figure 15.2 Cluster dendrogram based on Bray-Curtis dissimilarity for the diets of 13 species of myctophid fish. Species are separated by horizontal dashed lines into 5 trophic guilds identified at the significant level of dissimilarity of 35.8%.

16. Fatty acid analysis of toothfish

Gareth Wilson and Peter Nichol

Summary
Recent commercial interest in the toothfish in the Macquarie Island region has heightened the need for a better understanding of the life history of this species in order to ensure it's future sustainability. Of particular interest are dietary considerations. However, despite the importance of toothfish in the food web of the region, relatively little is known of their diet. Current knowledge is based upon the examination of stomach contents, a technique that fails to identify with any certainty long-term dietary composition. Many higher order species are thought to deposit dietary derived fatty acids into storage with little or no modification. These constituent fatty acids may therefore represent a temporal integration of diet. Analysis of fatty acid composition may therefore provide an alternate, simple and effective means of determining the diet of toothfish. A comparison of lipid content, lipid class and fatty acid composition was performed for toothfish (*n*=90) and potential prey over a range of sizes, fishing grounds and between sexes. Results indicate a significant difference in the diet of toothfish of different sizes, particularly in the southern ground, and between northern and southern fishing regions (but not between sex) based upon fatty acid composition. The exact reasons for these differences are open to conjecture, however the observed difference between fishing grounds may be due to a generally greater reliance on squid in toothfish from the northern fishing ground. Similarly the differences between size classes in the southern ground may be a consequence of greater predation on myctophids in smaller sized toothfish.

Introduction
Little is known of the long-term diet of toothfish, a component of toothfish biology essential to attaining an understanding of trophic structures within regional food webs and consequently insuring the proper management of the fishery. Current dietary information available for toothfish is based upon the examination of stomach contents, a technique that has a number of inherent problems (Antonelis *et al.* 1987, Harwood & Croxall 1988, Chou *et al.* 1995). Amongst these is a failure to identify with any certainty long-term dietary composition and bias due to differential digestion of prey items.

The use of alternate and complementary methods can overcome the disadvantages of the examination of stomach contents. One alternate method to stomach contents analysis is the use of biological markers (also termed "signature lipids") including fatty acids. Analysis of the fatty acid composition of toothfish may provide a simple and effective means of determining diet. Many fatty acids are readily transferred within the food web from prey to predator. In many higher order species, dietary derived fatty acids are thought to be incorporated into storage with little or no modification (e.g. Iverson 1993). These constituent fatty acids may therefore represent, to some extent, a temporal integration of diet. Observed differences in fatty acid composition between individuals of the same species are consequently due, in part, to differences in diet.

Whilst many fatty acids can be synthesized *de novo*, a large number can only have arisen from dietary sources and are termed 'essential'. Essential fatty acids are therefore potentially useful as 'signatures'. Signature lipids are combinations of fatty acids preserved as they pass up the food chain. They can be used as stand-alone tools or in combination with other procedures in the identification of dietary sources. In particular, many long-chain polyunsaturated fatty acids are synthesised exclusively by primary producers at the base of the food chain (e.g. Nichols *et al.* 1994, Graeve *et al.* 1994). The presence of these polyunsaturated fatty acids in the flesh of species higher up the food chain is therefore indicative of trophic interaction.

The complexity of intermediary trophic interactions for sub-Antarctic species has limited dietary determination in the majority of fish and squid species to traditional techniques. At the present time the fatty acid compositions of relatively few marine species from sub-Antarctic regions have been determined (Piatkowski & Hagen 1994). Previous studies into the use of fatty acids as dietary tracers in Southern Ocean ecosystems have so far been restricted primarily to either top-level marine predators (namely seals and whales) (e.g. Raclot *et al.* 1998, Brown *et al.* 1999), primary producers (phytoplankton, bacteria) (e.g. Graeve *et al.* 1994, Nichols *et al.* 1993) and lower-end consumers (zooplankton) (e.g. Kattner & Hagen 1995, Kattner *et al.* 1994). Despite these advances no truly inclusive dietary study, incorporating traditional methods in addition to fatty acids, has been attempted in the Southern Ocean.

More recently, heightened interest in the health benefits of fish and the increasing commercialisation of previously marginal marine species has combined to provide some lipid compositional information (e.g. Dunstan *et al.* 1999, Nichols *et al.* 1994, Sinclair *et al.* 1992). However, the vast majority of commercial species are from temperate, inshore environments and their use in dietary studies is limited to these regions. Reinhardt & Van Vleet (1986) and Friedrich & Hagen (1994) have studied a number of non-commercial Antarctic fish species, emphasising the possible influence of diet on lipid composition, but these studies were hampered by the lack of lipid data available for prey species.

The use of fatty acids as signature lipids may therefore contribute to an expansion in current understanding of toothfish diet in the Macquarie Island region. The main objectives of this study are: (1) to determine the fatty acid profile of toothfish in the Macquarie Island region and to compare these profiles over a range of sizes and ages, locations and between sexes; (2) to determine the fatty acid profile of the main prey items of toothfish, including fish and squid, as identified from stomach content analysis; and (3) to assess dietary interactions and the long-term diet of toothfish based on a comparison of the fatty acid profiles of toothfish and prey including the use of statistical analysis.

Materials, Methods and Terminology
Toothfish sampling
Toothfish samples were collected as part of the commercial fishing activities of the *Austral Leader*, a deep-sea trawler operated by Austral Fisheries Pty. Ltd. Fishing took place over the southern hemisphere summer of 1998/99 in fishing grounds of the Macquarie Island region. Fish were collected at random from 25 trawls over a range of trawl depths (622m-1,855m), location and time. Biological data including sex, stomach fullness, length and weight were recorded before samples from the lower tail section were removed for lipid analysis and frozen at -20°C.

A total of 90 toothfish were analysed, representing 53 females and 37 males. Fish ranged in size from a minimum of 310mm/300g to a maximum of 1051mm/12450g (Figure 16.1). A total of 54 samples from the northern fishing ground (Northern Valley fisheries, north of Macquarie Island) and 36 from the southern fishing ground (Aurora Trough, west of Macquarie Island) were processed. Analysis was performed on a small sample (1-2g) of flesh taken from the tail section of each fish. An initial trial was performed to examine possible variations in oil content and lipid composition of various body parts (gut and skin) and flesh regions (head, tail mid-section) of the toothfish.

Potential prey sampling
The potential prey species analysed were selected upon the basis of data obtained from stomach content analyses (Goldsworthy *et al.* In press, Chapter 15) and observations made during fishing operations. The species selected represent, where available, major prey items. A total of 7 fish and 4 squid species are included in this study (Table 16.1). *Bathylagus antarcticus* has been

divided into "small" and "large" size classes due to the greater number of samples available for this species. Analysis was performed on sub-samples taken after whole animals were blended.

Lipid extraction and class determination
Total lipids were extracted using the one-phase Bligh and Dyer (1959). After phase separation, total lipids were recovered from the lower chloroform phase and concentrated *in vacuo* (rotary evaporator, 40°C). Samples were stored at -20°C prior to analysis. Lipid class profiles were determined by TLC-FID using an Iatroscan MkV TH10 analyser (Volkman and Nichols 1991). Wax ester (WE), triacylglycerol (TAG), free fatty acid (FFA), sterol (ST) and polar lipid (PL) components were resolved in a polar solvent system consisting of hexane-diethyl ether-acetic acid (60:17:0.2 v/v/v). The presence of WE and diacylglyceryl ethers (DAGE) was confirmed by the use of a non-polar solvent system (hexane-diethyl ether; 96:4 v/v). Peak areas were quantified using commercially available chromatography software (DAPA Scientific Software, Kalamunda).

Fatty acid, fatty alcohols and glyceryl ether diol determination
Fatty acid methyl esters (FAME) were prepared by addition of MeOH/HCl/CHCl$_3$ (3mL 10:1:1, v/v/v, 80°C/2hr) to an aliquot of the total lipid. After the addition of 1mL of water, resulting FAME was extracted (3x) with 4:1 v/v hexane/CHCl$_3$. Chloroform containing C-19 FAME internal standard was then added. FAME fractions were treated with *N,O*-bis-(trimethylsilyl) trifluoroacetamide (BSTFA 50μL, 60°C, 2hr) to convert sterols, alcohols (derived from WE) and glyceryl ether diols (derived from DAGE) to their corresponding trimethylsilyl (TMS) ethers.

Gas chromatographic (GC) analysis was performed on a Hewlett Packard 5890A GC equipped with a flame ionisation detector, fitted with a cross-linked methyl silicone (HP1) fused silica capillary column (50 m length × 0.32 μm internal diameter), employing hydrogen as the carrier gas. Samples were injected (HP7673A auto-injector) at 50°C in the splitless mode, with a 2-min. venting time (Nichols *et al.* 1993). The injector and detector were maintained at 290°C and 310°C respectively. After 1 min. the oven was raised to 150°C at 30°C min^{-1}, then to 250°C at 2°C min^{-1} and finally to 300°C at 5°C min^{-1} (Nichols *et al.* 1993). Peak areas were quantified using Millennium 32 Chromatography Manager (Waters Corporation, Milford, Massachusetts). Identification of individual fatty acids, fatty alcohols, sterols and glyceryl ether diols was based upon a comparison of relative retention times with those obtained from previous studies in addition to laboratory standards. GC-mass spectrometry (FISONS MD800 system) was used for confirmation of components from representative samples (Nichols *et al.* 1993).

Statistical treatment: Multiple response permutation procedure
To test if toothfish fatty acid compositions were different between sex and fishing ground, a non-parametric statistical testing method (multiple response permutation procedure, MRPP) was used (Zimmerman *et al.* 1985, McCune and Mefford 1999). MRPP tests the hypothesis of no difference between two or more groups of multivariate data. The grouping must be *a priori*. In our analysis, groups were defined as fishing grounds and sex. Euclidean dissimilarities were used in the MRPP as distance measures. Probability values (*P* values) of the MRPP test greater than 0.05 indicate no significant differences in fatty acid composition between fishing grounds or sex.

Statistical treatment: Mantel's test
Differences in the fatty acid composition of toothfish between fish weight were tested using the Mantel's test (Mantel 1967, Manly 1991). The Mantel's test is a randomized statistical method and its test statistic is the correlation between two matrices. The significance of the test statistic is determined by comparing the test statistic with the distribution of the statistics obtained from randomly reallocating the order of the elements in one of the matrices. For testing differences in

fatty acid composition of toothfish between fish weight, the first matrix, *A*, was defined as the dissimilarity matrix of fatty acid compositions between all pairs of individual fish. The second matrix, *B*, was defined as the difference matrix of fish weight between all pairs of individual fish. That is, for *m* individual fish:

$$
A = \begin{bmatrix} 0 & & & \\ a_{21} & 0 & & \\ \dots & \dots & \dots & \\ a_{m1} & a_{m2} & & 0 \end{bmatrix} \text{ and } B = \begin{bmatrix} 0 & & & \\ b_{21} & 0 & & \\ \dots & \dots & \dots & \\ b_{m1} & b_{m2} & & 0 \end{bmatrix}
$$

where a_{ij} is the Euclidean dissimilarity between two samples,

$$
a_{ij} = \sqrt{\sum_{h=1}^{n} \left(P_{ih} - P_{jh} \right)^2} ,
$$

P_{ih} and P_{ih} are amounts of fatty acid *h* for individual fish *i* and *j*, *n* is the total number of fatty acids, and

$$
b_{ij} = | w_i - w_j | ,
$$

where w_i and w_j are the total lengths of fish *i* and *j*. For testing differences in the fatty acid compositions of toothfish between fish weights, the first matrix, *A*, was the same as the previously defined matrix. The second matrix, *B*, had b_{ij} values of 1 if $i = j$ and 0 if $i \neq j$.

Because both matrices are symmetric, the correlation between all the off-diagonal elements in two matrices is the same as the correlation between the *m(m-1)/2* elements in the lower triangular diagonal parts. The correlation between two matrices was compared to the distribution of the correlation calculated from randomly reallocating the elements of the *B* matrix 5,000 times. The null hypothesis that there was no difference in fatty acid compositions between fish weight was rejected if the test statistic was smaller or greater than 5% of values in the distribution.

Lipid nomenclature: lipid classes
Lipids are a chemically diverse group of compounds that perform a range of roles in biological systems. The major lipid classes present in biota may include triacylglycerols (TAG), wax esters (WE), polar lipids (PL), sterols (ST) and diacylglyceryl ethers (DAGE). All contain varying numbers of fatty acids as integral parts of their structures with the exception of sterols. Liberation of a FFA from TAG, which occurs during TAG metabolism, results in the formation of diacylglycerol (DG).

TAG consists of three fatty acids bound to a glycerol molecule and function as energy stores and, to a lesser extent, buoyancy regulators. WE consist of a fatty acid attached to a long-chain fatty alcohol and function similar to TAG. PL usually refers to phospholipids and contains two fatty acids and a highly polar phosphate group bound to a glycerol molecule. PL are integral structural components of biological membranes. ST are a structurally complex class of lipids and function as precursors to steroid hormones and structural components of biological membranes. Cholesterol is the most common ST in animal tissue. DAGE are similar to TAG, containing 2 fatty acids with one ether-linked alkyl side-chain. The primary roles of DAGE are thought to be buoyancy regulation and energy storage (Phleger 1998).

Lipid nomenclature: fatty acids

Fatty acids are the primary building blocks of lipids (oils or fats). The major roles of fatty acids are as an energy source for cellular metabolism (e.g. triacylglycerol) or as structural constituents within the cell membrane (e.g. phospholipids). Fatty acids in nature are found in complex lipid structures and are generally only released as free fatty acids (FFA) when required for energy.

Fatty acids consist of a carbon chain "backbone" of varying chain length that may also contain double bonds. One end of the carbon chain terminates in a carboxylic acid group, the other in a methyl group (Figure 16.2). Fatty acids can be separated into three groups based upon the number of double bonds present in the backbone: saturated fatty acids (SFA, no double bonds), monounsaturated fatty acids (MUFA, one double bond) and polyunsaturated fatty acids (PUFA, two or more double bonds). Less common are branched fatty acids that contain side chains attached to the carbon backbone.

Fatty acid nomenclature designates the carbon chain length, the number of double bonds and the position of the first double bond within the carbon chain from the terminal methyl end (labelled "ω"). For example, 18:1ω9c describes a fatty acid with an 18-carbon backbone containing 1 double bond that is located 9 carbons from the terminal methyl group. The suffix "c" denotes *cis* geometry of the double bond.

Results

Total lipid content and lipid class composition: toothfish

The total lipid content of toothfish (average percent total lipid {wet weight}=9%) was highly variable, particularly in larger sized fish. In spite of this variation, a marked increase in oil content with increasing weight and length was observed (Figure 16.3). The highest and lowest quantities of lipid were observed in fish measuring 648mm/2850g (22%) and 328mm/300g (1%) respectively (Table 16.2). In contrast, little variation in lipid class composition was detected. TAG dominated the oil composition (mean=96%, range 92-98%), accompanied by smaller amounts of FFA, ST/DG and PL. The relatively low level of FFA (mean=2%) indicates minimal deterioration of lipid in toothfish samples post collection.

Total lipid content and lipid class composition: potential fish prey

Total lipid content for potential fish prey varied considerably between species, as well as between individuals within certain species (notably *Bathylagus antarcticus* and *Gymnoscopelus fraseri*) (Table 16.2). *Electrona carlsbergi* (mean=10% wet weight) and *Promitra sp.* (mean=1%) contained the highest and lowest lipid contents respectively. *B. antarcticus* also exhibited a large difference in total lipid content between the "small" and "large" samples analysed (2% and 6% respectively).

Lipid class composition of potential prey fishes was similarly diverse. TAG represented the major lipid class detected in 5 of the 8 fish species. However, it's relative importance ranged from an average low of 6% ("small" *B. antarcticus)* to a high of 92% (*Stomias sp.).* TAG levels were relatively consistent within each species analysed with the exception of *G. fraseri* (15-89%). Major differences were also detected in "small" and "large" *B. antarcticus* (6% and 83% respectively). PL levels were high in a number of species and represented the major lipid class in "small" *B. antarcticus* (45%) and *Promitra sp. (*81%). The elevated FFA levels of many prey fishes, particularly "small" *B. antarcticus* (mean=36%) and *Gymnoscopelus fraseri* (mean=18%), suggest a degree of lipid degradation in these species may have occurred. WE and ST/DG were present as minor components in most species, although *G. fraseri,* "small" *B. antarcticus* and *Promitra sp.* contained substantial amounts of ST/DG (4-11%). WE were also present in "small" *B. antarcticus,* whilst they were absent in "large" *B. antarcticus*.

Total lipid content and lipid class composition: potential prey squid
Total lipid levels were highly variable for the squid species analysed, ranging from a low of 3% in *Mastigoteuthis sp.* to a high of 18% in *Gonatus antarcticus* (Table 16.2). Lipid levels were consistent for most squid species with the exception of *G. antarcticus* (range=8-28%).

Lipid class composition varied considerably between species, as well as between individuals of the same species. TAG represented the major lipid class in only one species, *Moroteuthis ingens* (mean=41% as percent total lipid) and was an important component (between 14-32%) in the three other squid species. PL dominated the composition of both *Histioteuthis eltaninae* (mean=38%) and *Mastigoteuthis sp.* (mean=67%) and was a major component of *M. ingens* (mean=26%). The lipid composition of *G. antarcticus* by contrast was dominated by DAGE (mean=61%), a lipid class present in significant levels in no other species (fish and squid) analysed. Free fatty acid levels were relatively high (range=12-26%) in all species with the exception of *Mastigoteuthis sp.*, possibly due to sample degradation post collection or high lipase activity in the digestive gland. WE (range=0-2%), and ST/DG (range=5-8%), were present in lower quantities.

Fatty acid composition: toothfish
Preliminary investigation, involving the analysis of flesh from various body regions, confirmed that tail flesh was representative of the fatty acid and lipid class composition and total lipid content of the entire toothfish (Table 16.3). MUFA dominated the fatty acid composition of all body regions (range=31-66%) with the exception of the gut, which contained higher levels of SFA (38%). SFA (range=22-38%) and PUFA (range=9-28%) represented smaller components, and branched fatty acids minor components (range=2-3%).

A total of 48 fatty acids were detected in the toothfish flesh samples analysed and were separated into 4 fatty acid classes (Table 16.4). MUFA accounted for the majority of constituent fatty acids (mean=61%, 21 fatty acids), followed by SFA (mean=23%, 7 fatty acids), PUFA (mean=15%, 14 fatty acids) and minor amounts of branched fatty acids (mean=1%, 6 fatty acids).

A total of 12 fatty acids contributed, individually, more than 1% to the total fatty acid composition (Table 16.5). Together they represented an average of 88% of the total fatty acid composition. The single most prevalent fatty acid detected in toothfish was 18:1ω9c (oleic acid, mean=30%, range=12-40%).

Saturated and branched fatty acids showed little variation over the range of toothfish sizes (weight and length) analysed. The predominant SFA was 16:0 (palmitic acid, mean=15%, range=12-19%).

The majority of variation in fatty acid composition was due to differences in MUFA and PUFA levels. These fatty acid classes combined account for an average of 76% of the overall fatty acid composition.

A major trend observed in fatty acid profiles was a decrease in PUFA and concomitant increase in MUFA levels with increasing toothfish size (illustrated by weight) (Figures 16.4 & 16.5). Both PUFA and MUFA levels varied with size until fish reached approximately 1,000g (500mm total length), at which point the fatty acid composition stabilises.

MUFA levels were highest (73%) and lowest (28%) in individual fish measuring 1950g (587mm) and 300g (323mm) respectively. The majority of the observed variation in MUFA levels can be attributed to three fatty acids, 16:1ω7c (range=2-17%), 18:1ω9c (12-40%) and

20:1ω9c (3-10%) (Table 16.5). These three fatty acids combined account for an average of 74% of total MUFA and 45% of total fatty acid composition.

PUFA levels were highest (48%) and lowest (5%) in individual fish measuring 300g (323mm) and 1750g (544mm) respectively. Two fatty acids, eicosapentaenoic acid (EPA, 20:5ω3, range=1-11%) and docosahexaenoic acid (DHA, 22:6ω3, range=1-31%) account for the majority of observed variation in PUFA, an average of 76% of PUFA composition and 11% of overall fatty acid composition (Table 16.5).

These five fatty acids; 16:1ω7c, 18:1ω9c, 20:1ω9c, EPA and DHA, account for over 50% of total fatty acid composition and the majority of observed variation in fatty acid composition.

Fatty acid composition of toothfish in relation to sex
Statistical analysis by MRPP (*P*=0.1995) revealed no significant difference in the fatty acid composition of toothfish with respect to sex (Table 16.6).

Fatty acid composition of toothfish in relation to fishing ground
Statistical analysis, by MRPP (*P*=0.0000) reveals significant differences in fatty acid composition between toothfish from northern and southern grounds (Table16.6). Comparison of the composition of the 5 major fatty acids in fish from southern and northern grounds is seen in Table 16.7. Fish from southern grounds were higher in EPA and DHA than those from northern grounds. Conversely, 16:1ω7c, 18:1ω9c and 20:1ω9c constituted a greater proportion of fatty acids in fish from the northern compared to the southern ground. Large standard deviations were recorded for major fatty acids from both grounds.

Fatty acid composition of toothfish in relation to size class: southern and northern fishing grounds
Levels of major MUFA (16:1ω7c, 18:1ω9c & 20:1ω9c) increased with increasing size class (weight) of toothfish from both southern and northern fishing grounds (Tables 16.8 & 16.9). The results of statistical analysis (Mantel's test) are shown in Table 16.6. This was accompanied by a concomitant decrease in levels of the major PUFA for toothfish from both grounds (EPA & DHA). Levels of DHA decreased by approximately 20% and 12% in southern and northern fish respectively, from the smallest to the largest size class. A large variation was also observed for 18:1ω9c, which doubled in its relative level in southern fish (mean=17% to 33%) from the smallest to the largest size class (Table 16.8). Levels of 18:1ω9c in northern fish increased from 21% to 35% (smallest to largest class) (Table 16.9). Levels of EPA decreased and 16:1ω7c and 20:1ω9c levels increased by smaller amounts than the other major fatty acids in toothfish from both fishing grounds. Standard deviations were generally higher in the smaller sized fish for all 5 major fatty acids at both grounds.

Fatty acid composition: potential prey fish
MUFA dominated the fatty acid composition of all fish species with the exception of "small" *B. antarcticus* and *Promitra sp.* which both contained higher levels of PUFA (Table 16.4). SFA and branched fatty acids contributed major and minor components respectively. Standard deviation values were generally low, suggesting reasonably uniform fatty acid composition within each species. The exception was the substantial difference in composition for a number of fatty acids, including DHA and the long-chain MUFA 20:1ω9c, between the two size classes of *B. antarcticus*.

The 12 major fatty acids found in toothfish also accounted, on average, for over 80% of the fatty acid composition in all potential fish prey species analysed. The dominant fatty acid varied between species, ranging from DHA (*Promitra sp.* and "small" *B. antarcticus*), 20:1ω9c (*G. nicholsi*) and 18:1ω9c for the remaining species (Table 16.5).

Fatty acid composition: potential prey squid
MUFA represented the majority of fatty acids observed in the squid species analysed (Table 16.4). SFA and PUFA were also important constituents and branched fatty acids accounted for less than 1% of composition. Minimal variation in fatty acid composition was observed over all the classes.

The 12 major toothfish fatty acids represented an average of over 80% of composition for all squid species, with the exception of *H. eltanina,* which was slightly lower (mean=75%) (Table 16.5). The major fatty acids found in each species were DHA (*H. eltaninae,* mean=14%), 16:0 (*Mastigoteuthis sp.,* 16%) and 18:1ω9c (*G. antarcticus*, mean=30%; *M. ingens,* mean=19%).

Discussion
Total lipid content
Toothfish are likely to store lipid for a variety of reasons, including as an energy reserve for times of low food availability. The relatively constant year-round primary production of the Macquarie Island region, though, would seem to exclude the availability of food as a limiting factor in toothfish survival. Perhaps of more importance is the requirement of toothfish to maintain neutral buoyancy in the water column. Most fish achieve buoyancy by employing a swimbladder, a structure absent in toothfish (Eastman 1993). Toothfish consequently require an alternate means of maintaining neutral buoyancy, specifically an adaptation in one or more body systems (Eastman 1988). Previous studies have highlighted the use of lipid stores as buoyancy regulators in a number of Antarctic fish species (Eastman 1988, Phleger 1998, Friedrich & Hagen 1994). Accumulation of lipid stores may accordingly be the buoyancy mechanism utilised by toothfish.

Altering the amount of total lipid would allow toothfish to adjust and maintain a range of depths in the water column with minimal expenditure of energy (Friedrich & Hagen 1994). Accumulation of larger lipid stores would allow for the maintenance of neutral buoyancy at greater depths.

The type of lipid stored is also a significant factor in determining whether the lipid stores present in toothfish are involved in buoyancy regulation. Lipid class analysis reveals that TAG comprises almost all the lipid present in toothfish. TAG is a lipid class of sufficiently low density to provide static lift (Phleger 1998, Eastman 1988, Freidrich & Hagen 1994).

A number of previous studies into the depth distribution of toothfish from other populations have recorded an increase in fish size with depth (Gon & Heemstra 1990, Gacía de la Rose *et al.* 1997). Associated with this distribution is a shift in diet from pelagic to benthopelagic prey in small and large fish respectively. If this size segregation held true for fish from Macquarie Island then levels of total lipid would be expected to increase with increasing size.

However, the results of the current investigation into toothfish from Macquarie Island contrast with these expected observations. Stomach content data reveals minimal variation in toothfish diet with respect to size and depth of capture (Goldsworthy *et al.* In press, this report Chapter 15). Similarly total lipid contents, whilst tending upwards, are highly variable in larger fish. This would seem to support the notion that toothfish size distribution at Macquarie Island is relative homogenous regardless of depth amongst the fish analysed in this study.

Lipid class composition
Toothfish lipid class composition consists almost entirely of TAG (average >96% of total lipid class), suggesting that this lipid class is the preferred form of lipid storage for this species. However, unlike fatty acid composition, the lipid class composition of potential prey species is unlikely to be reflected in the lipid composition of toothfish. Toothfish most likely redistribute

the fatty acids found in various lipid classes in prey species to their preferred state of storage (i.e. TAG).

Lipid class composition can reveal how energetically "attractive" prey are to predators. "Attractive" in this context is a function of not only the amount of lipid they contain but also how much "energy" (in the form of fatty acids) they contain. For instance, TAG contains 3 fatty acids whilst PL and DAGE contain 2 fatty acids and WE contains 1 fatty acid and 1 fatty alcohol. Thus although *G. antarcticus* contains almost 18% lipid, the majority of this lipid is in the form of DAGE, a lipid class less energetically rewarding to a predator than TAG.

Fatty acid composition
Although toothfish contain 48 constituent fatty acids, comparatively few show any notable variation in composition regardless of size, sex or location. The fatty acids that do vary are represented by a handful of MUFA (16:1ω7c, 18:1ω9c & 20:1ω9c) and PUFA (EPA & DHA) and are considered potential signature fatty acids. These 5 fatty acids account for over 50% of total composition as well as the bulk of variation (evidenced by large standard deviations). The large variation in composition of the 5 major fatty acids suggests a significant variation in diet over the range of toothfish analysed in this study.

The presence and compositional variation of EPA and DHA is particularly significant given that both these fatty acids are essential and can accordingly only be of dietary origin. Whilst both 18:1ω9c and 20:1ω9c can be synthesised by toothfish, the high levels of these two MUFA and the large variation in their composition suggest a substantial dietary influence. By contrast, whilst 16:0 (palmitic acid) is found in high levels in all the fish analysed, it is one of the most easily synthesized of all fatty acids. Especially important is the fact that it can be synthesised from non-lipid sources such as protein and carbohydrate (Allen 1976). The consistently high levels of 16:0 observed are likely to be due more to synthesis by toothfish rather than dietary influences alone.

Notwithstanding, similarity in the fatty acid composition between predator and prey may not be indicative of a direct dietary relationship. It is possible that two species that share a common diet will express similar fatty acid compositions. In the same way, different combinations of prey species may produce the same fatty acid composition in predators. However, the degree of variation in fatty acid composition observed in toothfish over the range of sizes and fishing locations of this study is likely to be due, at least to some extent, to a dietary influence. The exact nature of the prey species responsible for this variation is open to greater conjecture and will need to be studied further.

Fatty acid composition and sex
Statistical analysis found no significant differences in fatty acid composition based on sex (Table 16.6). On this basis the diets of male and female do not differ significantly using fatty acid composition as the sole measure. This observation is consistent with our hypothesis that the diet of toothfish would not be expected to vary considerably between sexes. Biological factors that may potentially influence predatory ability, such as sexual dimorphism, are not pronounced in toothfish.

Fatty acid composition and fishing ground
Fatty acid composition varies markedly between toothfish from the northern and southern fishing grounds, suggesting a substantial difference in diet between the two fishing grounds. Statistical analysis reveals highly significant variation (Table 16.6). Of the 5 major fatty acids, the composition of 18:1ω9c and DHA varied the most between grounds (Table 16.7).

Stomach content analysis supports the finding that the diet of toothfish varied significantly in northern and southern fishing grounds in the 1998-1999 season, although this observation was atypical in relation to the other seasons studied (Goldsworthy *et al.* In press, this report Chapter 15). Fish accounted for a higher proportion of the diet in toothfish from the northern ground (especially *B. antarcticus*) whilst squid were more important in the diet of toothfish from the southern ground (particularly *G. antarcticus*).

Comparison of the fatty acid compositions of toothfish and their potential prey can be a complex exercise. However, plots of the main classes or individual components can be used to observe large-scale trends in fatty acid composition. Plotting levels of MUFA against PUFA can be used to develop a "snap-shot" of associations between toothfish and their potential prey (Figure 16.6). The closer the data points the closer the fatty acid composition. Figure 16.6 highlights the difference in MUFA and PUFA composition between southern and northern fishing grounds. It also emphasises the range of MUFA and PUFA compositions of potential prey.

Fatty acid composition in toothfish from the southern fishing ground
Toothfish from the southern ground cluster with the majority of potential fish and squid prey (Figure 16.6). This suggests that toothfish from the southern ground potentially interact with a more diverse range of potential prey than toothfish from the northern ground, an observation supported by stomach content analysis. The larger standard deviations for both MUFA and PUFA for southern over northern toothfish also support this observation.

However, the use of MUFA and PUFA in isolation for comparing the fatty acid compositions of predator and prey is problematic. It fails to take into account variations in both the levels and constitution of fatty acids with MUFA and PUFA classes. Comparing the composition of principle fatty acids, specifically DHA and 18:1ω9c, allows for a more resolute assessment of dietary interaction between toothfish and their potential prey based upon their fatty acid compositions. For example, plotting the levels of DHA against 18:1ω9c produces a more refined comparison and allows for further insight into possible dietary interactions (Figure 16.7). Southern ground fish cluster closely with a number of fish species, particularly two myctophid species (*L. archirus* and *E. carlsbergi*). In contrast to the plot of MUFA against PUFA, squid species are less closely related, with *M. ingens* showing the greatest similarity to toothfish from the southern ground.

Taking this comparison one further step, Figure 16.8 compares the composition of the 5 major fatty acids between southern ground toothfish and those potential prey which show the greatest similarity in DHA and 18:1ω9c composition. The two myctophid species, *L. archirus* and *E. carlsbergi* are most closely related in their composition of the 5 major fatty acids to toothfish. The remaining species, whilst similar, show major differences in composition compared to toothfish both in the absolute as well as the relative amount amounts of the 5 major fatty acids.

These results both agree and disagree with the results of stomach content analysis for fish from the southern fishing ground. Overall, squid may be less important and fish more important in the diet of southern toothfish than stomach content analysis indicates. For example *G. antarcticus,* identified by stomach content analysis as the single most important squid species in the diet of toothfish from the southern ground, shows a substantial difference in fatty acid composition compared to southern toothfish. By contrast, the similarity in fatty acid composition observed between toothfish and *L. archirus* and *E. carlsbergi* may be symptomatic of a closer dietary relationship with myctophids than is suggested by stomach content analysis.

Fatty acid composition of toothfish from the northern fishing ground
Comparison of MUFA and PUFA levels for toothfish from the northern fishing ground highlights major differences in fatty acid composition compared to toothfish from the southern fishing ground (Figure 16.6). Northern toothfish are well separated from the majority of potential prey species (Figure 16.6). Northern toothfish shows the greatest similarity in fatty acid composition with the fish *Stomias sp.*and, to a lesser extent, the squid *G. antarcticus* (Figures 16.7 and 16.9).

As with southern toothfish, the fatty acid results obtained for toothfish from the northern fishing ground differ with the observations of stomach content analysis. Although stomach content data identified *B. antarcticus* (large and small) as an important prey species in northern toothfish, fatty acid analysis reveals a substantial difference in composition (Figures 16.6. and 16.7). Similarly, comparison of fatty acid composition indicates the possibility of a closer dietary interaction with squid, principally *G. antarcticus,* than is determined by stomach content analysis.

Fatty acid composition and fish size
Fish size has a pronounced effect on the fatty acid composition of toothfish suggesting a possible difference in diet between the largest and smallest sized fish (Tables 16.8 and 16.9). Variation in fatty acid composition is more pronounced in toothfish from the southern fishing ground compared to the northern ground. These observed differences are supported by statistical analysis, using Mantel's test as the measure (Table 16.6). Fatty acids composition varies significantly in toothfish from the southern fishing ground. In contrast, no significant variation in fatty acid composition was detected in northern toothfish.

These observations agree with the results of stomach content analysis that concluded that toothfish diet does not vary significantly between size classes, regardless of fishing ground or season. The exception was in the southern fishing ground in the 1998/1999 season (corresponding with this study). In this season, myctophids were the principal prey of smaller toothfish but were absent from the diet of larger toothfish. Southern and northern fishing grounds will be discussed separately, and weight is used as the measure of fish size.

Fatty acid composition and fish size: southern fishing ground
Statistical analysis revealed a significant variation in fatty acid composition over the entire range of toothfish sizes from the southern fishing ground. Statistically significant variation was observed in the composition of all 48 fatty acids over the range of fish weights analysed (Mantel's test, $P=0.0030$). Similarly, the composition of the 5 major fatty acids (16:1ω7c, 18:1ω9c, 20:1ω9c, EPA and DHA) varied significantly ($P=0.0016$) with varying fish weight.

However, no significant differences in fatty acid composition were observed if fish from the largest size class (>1,000g, *n*=9) were considered alone. Fatty composition in this size class did not vary significantly with respect to either all 48 fatty acids ($P=0.0294$) or the 5 major fatty acids ($P=0.0332$). Thus the observed differences in fatty acid composition in toothfish from the southern fishing ground are due exclusively to variations in fish from the smaller size classes (fish weighing less than approximately 1,000g).

Plots of MUFA against PUFA and DHA against 18:1ω9c accentuate these differences (Figures 16.10 and 16.11). The general trend observed is enrichment in MUFA levels as fish increase in size, accompanied by reduction in PUFA. Figure 16.12 compares the composition of the 5 major fatty acids of various sized southern toothfish with those potential prey with which they most closely cluster. Most notably, only toothfish in the size class 800-999g show similarity in fatty acid composition with a squid species, *G. antarcticus*. Toothfish from the remaining size classes show greatest similarity with prey fish species exclusively. Of greatest interest is that

two of the smaller toothfish size classes (400-599g and 600-799g) are similar to the myctophid species *L. archirus* and *E. carlsbergi* respectively. This observation is consistent with the results of stomach content analysis, which found a greater reliance on myctophid species in the diet of smaller compared to larger toothfish in the southern fishing ground.

Fatty acid composition and fish size: northern fishing ground
The results of statistical analysis reveals no significant variation in fatty acid composition with fish size, with regards to all 48 constituent or 5 major fatty acids (Table 16.6). The exception to this is the significant variation in the composition of all 48 fatty acids in the largest size class (>1,000g).

Comparison of the fatty acid composition of toothfish from northern and southern fishing grounds reveals potential dietary differences between grounds. Whilst the fatty acid composition of fish from the northern fishing ground follow the same general pattern as those from the southern, absolute levels of the major fatty acids differed substantially between the small size classes of both grounds (Tables 16.8 and 16.9). Most notably, levels of MUFA (16:1ω7c, 18:1ω9c & 20:1ω9c) and PUFA (EPA & DHA) were substantially higher and lower in the two smallest size classes (0-399g & 400-599g) compared to the southern ground. Levels of the 5 major fatty acids for the remaining three size classes were approximately the same as those from the southern ground.

Whilst statistical analysis found very little difference in fatty acid composition with regards to toothfish size, analysis of MUFA and PUFA levels still reveal noticeable differences (Figures 16.13 and 16.14). The three larger size classes (600-799g, 800-999g and 1,000g+) tend to cluster together whilst the smaller sizes are separated. Comparison of the 5 major fatty acids suggests a closer relationship with squid species (*M. ingens* and *G. antarcticus*) than for toothfish from the southern ground. The myctophid *E. carlsbergi* also displays a similar fatty acid composition to one of the smaller toothfish size classes (400-599g).

Conclusions
Many of the observed differences in fatty acid composition are in agreement with the results of stomach content analyses. For instance the fatty acid results obtained support the notion of dietary differences in toothfish from southern and northern fishing grounds. However, the possible reasons for these differences may be contradictory based on a comparison of these two methods. Fatty acid analysis predicts that northern toothfish may be more reliant on squid than toothfish from the southern ground. In contrast stomach content analysis suggests that northern toothfish have a greater reliance on fish species in the diet (particularly *B. antarcticus*) relative to southern toothfish that depend more on squid (mainly *G. antarcticus*). Further treatment of the data and expanded analyses of toothfish and related potential prey species from other years and regions will enable a more complete understanding of toothfish diet to be obtained.

The results of this study would appear to support the notion of distinct northern and southern toothfish populations in the Macquarie Island region, at least in terms of dietary composition. It also points to a degree of divergence in toothfish diet relative to age, a finding consistent with the acknowledged life history of the species. Whilst the exact reasons for these differences are still open to conjecture, this study highlights several advantages of using the relative stable and temporally resolute technique of fatty acid composition over traditional techniques of determining diet.

References

Allen, W. (1976). Biochemical Aspects of Lipid Storage and Utilization in Animals. American Zoologist, 16: 631-647.

Antonelis, G. A., Lowry, M. S., Demaster, D. P. and Fiscus, C. H. (1987). Assessing Northern Elephant Seal feeding habits by stomach lavage. Marine Mammal Science, 3(4): 308-322.

Bligh, E. G. and Dyer, W. M. (1959). A rapid method of lipid extraction and purification. Canadian Journal of Biochemical Physiology, 35: 911-917.

Brown, D. J., Boyd, I. L., Cripps, G. C. and Butler, P. J. (1999). Fatty acid signature analysis from the milk of Antarctic fur seals and Southern elephant seals from South Geogia: implication for diet determination. Marine Ecology Progress Series, 187: 251-263.

Chou, L., Bright, A. and Yeh, S. (1995). Stomach contents of Dolphins (*Delphinus delphis* and *Lissodelphis borealis*) from the North Pacific Ocean. Zoological Studies, 3(4): 206-210.

Dunstan, G. A., Olley, J. and Ratkowsky, D. A. (1999). Major environmental and biological factors influencing the fatty acid composition of seafood from Indo-Pacific to Antarctic waters. Recent Research Developments in Lipid Research, 3: 63-86.

Eastman, J. T. (1993). Antarctic Fish Biology: Evolution in a Unique Environment. Academic Press.

Eastman, J. T. (1988). Lipid storage systems and the biology of two neutrally buoyant Antarctic notothenoid fishes. Comparitive Biochemistry and Physiology 90b(3): 529-537.

Friedrich, C. and Hagen, W. (1994). Lipid contents of five species of notothenoid fish from high-Antarctic waters and ecological implications. Polar Biology, 14: 359-369.

García de la Rosa, S. B., Sánchez, F. and Figueroa, D. (1997). Comparative feeding ecology of Patagonian toothfish (*Dissostichus eleginoides*) in the southwestern Atlantic. CCAMLR Science 4: 105-124.

Goldsworthy, S., Williams, D., Lewis, M., Young, J. and He, X. (In press). Diets of Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island, Tasmania, Australia. Marine and Freshwater Research.

Gon, O. and Heemstra P. C. (eds.) (1990). Fishes of the Southern Ocean. J.L.B. Smith Institute of Ichthyology, Grahamstown.

Graeve, M., Kattner, G. and Hagen, W. (1994). Diet-induced changes in the fatty acid composition of Arctic herbivorous copepods: Experimental evidence of trophic markers. Journal of Experimental Marine Biology and Ecology, 182: 97-110.

Harwood, J. and Croxall, J. P. (1988). The assessment of competition between seals and commercial fisheries in the North Sea and the Antarctic. Marine Mammal Science, 4(1): 13-33.

Iverson, S. J. (1993). Milk secretion in marine mammals in relation to foraging: can milk fatty acids predict diet? Symposium of the Zoological Society of London, 66: 263-291.

Kattner, G. and Hagen, W. (1995). Polar herbivorous copepods – different pathways in lipid biosynthesis. ICES Journal of Marine Science, 52: 329-335.

Kattner, G., Graeve, M. and Hagen, W. (1994). Ontogenetic and seasonal changes in lipid and fatty acid/alcohol compositions of the dominant Antarctic copepods *Calanus propinquus*, *Calanoides acutus* and *Rhincalanus gigas*. Marine Biology, 118: 637-644.

Manly, B. F. J. (1991). Randomization and Monte Carlo methods in biology. (Chapman and Hall. New York.). 281 pp.

Mantel, N. (1967). The detection of disease clustering and a generalized regression approach. Cancer Research, 27: 209-220.

McCune, B., and Mefford, M. J. (1999). PC-ORD. Multivariate analysis of ecological data, Version 4. MjM Software Design, Gleneden Beach, Oregon, USA.

Nichols, D. S., Williams, D., Dunstan, G. A., Nichols, P. D. and Volkman, J. K. (1994). Fatty acid composition of Antarctic and temperate fish of commercial interest. Comparitive Biochemistry and Physiology, 107B(2): 357-363.

Nichols, P. D., Leeming, R., Rayner, M. S., Latham, V., Ashbolt, N. J. and Turner, C. (1993). Comparison of the abundance of the fecal sterol coprostanol and fecal bacteria in inner-shelf waters and sediments near Sydney, Australia. Journal of Chromatography, 643: 195-198.

McCune, B. and Mefford, M. J. (1999). PC-ORD. Multivariate analysis of ecological data, Version 4. MjM Software Design, Gleneden Beach, Oregon, USA.

Phleger, C. F. (1998). Buoyancy in Marine Fishes: Direct and Indirect Role of Lipids. American Zoologist, 38: 321-330.

Piatkowski, U. and Hagen, W. (1994). Distribution and lipid composition of early life stages of the cranchiid squid *Galiteuthis glacialis* (Chun) in the Weddell Sea, Antarctica. Antarctic Science 6(2): 235-239.

Raclot, T., Groscolas, R. and Cherel, Y. (1998). Fatty acid evidence for the importance of myctophid fishes in the diet of the king penguins, *Aptenodytes patagonicus*. Marine Biology, 132: 523-533.

Reinhardt, S. B. and Van Vleet, E. S. (1986) Lipid composition of twenty-two species of Antarctic midwater zooplankton and fish. Marine Biology, 91: 149-159.

Sinclair, A., Dunstan, G. A., Naughton, J. M., Sanigorski, A. J. and O'Dea, K. (1992). The lipid content and fatty acid composition of commercial marine and freshwater fish and molluscs from temperate Australian waters. Australian Journal of Nutrition and Dietetics, 49(3): 77-83.

Volkman, J. K. and Nichols, P. D. (1991). Application of thin layer chromatography-flame ionization detection to the analysis of lipids and pollutants in marine and environmental samples. Journal of Planar Chromatography, 4: 19-26.

Zimmerman, G. M., Goetz, H. and Mielke Jr., P. W. (1985). Use of an improved statistical method for group comparisons to study effects of prairie fire. Ecology, 66: 606-611.

FATTY ACID ANALYSIS OF TOOTHFISH

Table 16.1 List of fish and squid prey analysed (n = number of samples, S = small, L = large)

	Family	Common Name	Scientific Name	n	Length (mm)	Weight (g)
Fish	Myctophidae	Myctophids	*Electrona carlsbergi*	3	100-110	9-10
			Gymnoscopelus nicholsi	2	140-150	19-21
			Gymnoscopelus fraseri	3	60-100	1-7
			Lampanyctus achirus	1	140	1
	Bathylagidae	Deep-sea smelts	*Bathylagus antarcticus*	6 (S)	58-98	0.5-5
				5 (L)	115-140	8-14
	Stomiidae	Scaly dragon-fish	*Stomias sp.*	2	230-270	25-34
	Melamphaidae	Bigscale fish	*Promitru sp.*	1	65	2
Squid	Gonatidae	Gonate Squid	*Gonatus antarcticus*	4	340-400	132-217
	Onychoteuthidae	Warty Squid	*Moroteuthis ingens*	5	325-1000	145-686
	Mastigoteuthidae		*Mastigoteuthis sp.*	1	-	37
	Histioteuthidae	Jewel Squid	*Histioteuthis eltaninae*	3	-	62-91

FATTY ACID ANALYSIS OF TOOTHFISH

Table 16.2 Total oil content and lipid class composition of toothfish and selected potential prey (average ± standard deviation) (n = number of specimens, WE = wax ester, DAGE = diacylglyceryl ether, TAG = triacylglycerol, FFA = free fatty acid, ST = sterol, DG = diacylglycerol, PL = polar lipid, n = number, S = small, L = large)

Prey	Species	n	Total Lipid (%)	WE	DAGE	TAG	FFA	ST/DG	PL
						Lipid class (Percent composition)			
Fish (myctophids)	Toothfish	90	8.8 ± 6.3	0.0	0.0	96.0±2.1	2.2±1.0	0.5±0.1	1.3±1.9
	E. carlsbergi	3	9.5±2.2	0.3±0.2	0.0	64.2±8.8	4.9±2.8	1.6±0.7	29.0±7.3
	G. nicholsi	2	7.1±2.0	0.0	0.0	80.7±6.2	10.4±3.0	1.1±0.4	7.8±2.8
	G. fraseri	3	7.6±4.4	1.0±2.0	0.0	53.6±26.7	17.6±11.3	4.0±2.5	23.8±15.4
	L. achirus	1	6.1	2.7	0.0	20.4	27.9	8.8	40.2
(other fish species)	B. antarcticus (S)	6	2.2±0.45	1.6±0.7	0.0	6.3±4.1	35.8±1.8	11.4±0.8	44.9±5.6
	B. antarcticus (L)	5	6.3±1.4	0.0	0.0	82.9±5.4	8.1±3.7	1.8±0.7	7.2±3.0
	Stomias sp.	2	10.2±2.6	0.0	0.0	91.9±1.5	4.0±1.2	0.8±0.5	3.3±2.2
	Promitra sp.	1	1.4	1.6	0.0	8.6	0.0	8.9	80.9
Squid	G. antarcticus	4	17.5±7.2	0.8±0.2	60.5±10.3	14.3±6.7	12.3±8.1	6.0±3.4	6.1±6.5
	M. ingens	5	8.4±2.9	2.2±0.8	0.0	41.1±18.5	26.1±10.6	4.7±2.6	25.9±11.3
	Mastigoteuthis sp.	1	3.4	0.0	0.0	21.4	5.2	6.4	67.0
	H. eltaninae	3	5.6±1.6	1.2±0.8	0.0	32.4±19.9	20.4±6.4	8.1±2.1	37.9±22.7

Table 16.3 Relative percent composition of fatty acid classes in relation to body region of toothfish (SFA = saturated fatty acids, MUFA = monounsaturated fatty acids,
PUFA = polyunsaturated fatty acids) *values for whole fish were determined by combining fatty acid composition based upon weight proportions of each body region.

Fatty acid class	Body region (Percent composition)					
	Head	Mid section	Tail	Gut	Skin	Whole fish
Total lipid (%)	10.4	5.7	5.1	6.1	13.4	7.8
SFA	23.1	22.3	22.6	38.3	29.6	24.1
Branched	2.1	2.0	2.1	2.8	2.8	2.2
MUFA	66.2	64.7	65.4	31.3	58.0	62.8
PUFA	8.6	11.0	9.9	27.6	9.5	10.7

Table 16.4 Relative percent composition of fatty acid classes for toothfish and selected potential prey (average ± standard deviation) (MUFA = monounsaturated fatty acid,
PUFA = polyunsaturated fatty acid, L = large, S = small)

Prey	Species	Fatty acid class (Percent composition)			
		Saturates	Branched	MUFA	PUFA
Fish	Toothfish	22.6±1.7	1.4±0.3	60.7±10.9	15.3±11.0
(myctophids)	*E. carlsbergi*	25.1±0.8	1.4±0.3	51.2±4.5	22.3±4.7
	G. nicholsi	17.9±0.3	0.8±0.3	69.6±0.3	11.7±0.2
	G. fraseri	24.4±3.9	1.5±0.1	48.9±3.4	25.2±1.4
	L. achirus	23.8	1.3	47.6	27.3
(other fish species)	*B. antarcticus (S)*	24.6±0.8	1.4±0.2	35.4±3.9	38.6±4.6
	B. antarcticus (L)	22.5±1.2	1.7±0.3	50.4±1.5	25.4±2.0
	Stomias sp.	16.1±5.9	1.4±0.3	72.0±3.7	10.5±2.6
	Promitra sp.	25.3	2.0	29.4	43.3
Squid	*G. antarcticus*	12.8±6.3	1.2±0.4	69.3±4.3	16.7±1.5
	M. ingens	26.8±2.5	0.6±0.1	45.6±5.3	27.0±3.0
	Mastigoteuthis sp.	22.5	0.8	48.5	28.2
	H. eltaninae	17.7±3.0	0.7±0.3	53.0±5.7	28.6±2.9

FATTY ACID ANALYSIS OF TOOTHFISH

Table 16.5 Comparison of relative percent composition of major fatty acids in toothfish (>1% of total composition) and selected potential prey (average ± standard deviation) (Other = sum of fatty acids representing <1% of total composition, EPA = eicosapentaenoic acid [20:5ω3c], DHA = docosahexaenoic acid [22:6ω3], L = large, S = small)

Prey	Species	Fatty acid (Percent composition)												
		14:0	16:0	18:0	16:1ω7c	18:1ω9c	18:1ω7c	20:1ω9c	22:1ω11c	22:1ω9c	18:2ω6c	EPA	DHA	Other
Fish	Toothfish	3.2±1.1	14.9±1.3	3.2±0.6	7.4±2.3	29.8±6.9	5.5±0.5	7.4±1.6	2.7±0.8	1.7±0.7	1.3±0.2	3.6±2.3	7.2±7.6	11.9±1.1
(myctophids)	E. carlsbergi	1.5±0.6	18.1±0.7	3.9±0.1	5.7±0.7	23.7±1.9	3.9±0.4	4.8±1.5	3.6±1.3	1.9±0.5	1.4±0.1	6.5±1.2	10.6±3.4	14.5±0.5
	G. nicholsi	1.7±0.3	10.4±0.3	4.8±0.3	2.5±0.1	20.7±0.4	8.2±0.3	22.7±0.7	5.4±0.0	2.5±0.3	3.3±0.2	2.2±0.1	4.4±0.1	11.3±0.7
	G. fraseri	1.5±1.0	17.3±3.1	4.3±0.2	3.3±0.9	17.6±1.4	5.8±0.5	11.0±3.0	2.3±1.1	1.3±0.5	2.0±0.2	7.1±0.5	11.4±1.0	15.0±1.5
	L. achirus	1.6	17.4	4.1	5.8	22.8	4.1	5.6	2.1	0.9	1.0	5.2	17.2	12.2
(other species)	B.antarcticus (s)	2.1±0.7	16.4±0.6	5.1±0.4	3.0±1.4	16.5±1.8	4.0±0.8	2.4±1.2	1.1±0.3	1.4±0.4	0.8±0.1	7.1±0.7	24.7±4.4	15.4±0.7
	B.antarcticus (l)	1.9±0.5	15.4±0.8	4.0±0.4	4.7±0.6	18.8±2.9	3.7±0.2	7.8±1.7	4.1±1.4	3.4±0.5	1.1±0.2	7.6±1.2	11.4±1.1	16.4±1.6
	Stomias sp.	1.3±0.6	11.4±5.7	2.2±0.1	7.0±0.1	39.9±3.0	5.8±0.2	8.3±0.4	3.1±0.4	1.4±0.1	1.7±0.2	2.2±0.5	3.7±1.2	12.0±1.4
	Promitra sp.	1.5	17.3	5.3	2.6	11.7	3.7	1.8	1.1	0.7	0.8	9.1	27.2	17.3
Squid	G. antarcticus	2.6±1.0	7.7±5.0	1.9±0.3	4.4±0.6	29.5±4.6	6.5±2.4	14.9±3.2	1.7±2.0	1.6±0.3	1.4±0.3	6.0±1.5	6.3±0.8	15.6±6.0
	M. ingens	3.1±0.6	19.1±2.2	3.6±0.5	4.1±0.9	19.2±2.1	4.0±0.7	7.9±1.2	2.4±0.5	1.6±0.3	1.0±0.2	8.6±1.4	13.2±2.2	12.3±1.2
	Mastigoteuthis sp.	0.7	16.4	4.3	2.1	13.0	3.9	11.9	3.0	4.3	0.7	10.1	13.5	16.1
	H. eltaninae	0.8±0.2	12.5±1.9	3.4±1.1	3.2±0.3	13.1±0.5	3.7±0.4	7.7±0.5	3.4±0.5	3.0±0.3	0.7±0.1	9.7±1.5	13.9±1.5	25.0±5.4

Table 16.6 Comparison of probability values (p) for sex, fishing ground and weight using MRPP and Mantel's test. P values <0.05 indicate significant differences. N/A = not applicable, n = number of fatty acids, MRPP = multiple response permutation procedure. Major fatty acids include 16:1ω7c, 18:1ω9c, 20:1ω9c, DHA [docosahexaenoic acid, 22:6ω3] & EPA [eicosapentaenoic acid, 20:5ω3c])

| Variable tested | Statistical test | All fish | | Large fish only (>1,000g) | |
		Entire fatty acid composition (*n*=48)	Major fatty acids only (*n*=5)	Entire fatty acid composition (*n*=48)	Major fatty acids only (*n*=5)
Sex	MRPP	0.1995	N/A	N/A	N/A
Fishing ground	MRPP	0.0000	N/A	N/A	N/A
Weight (southern fishing ground)	Mantel's	0.0030	0.0294	0.0016	0.0332
Weight (northern fishing ground)	Mantel's	0.1314	0.0276	0.1878	0.1301

Table 16.7 Comparison of relative percent composition of potential signature fatty acids in toothfish samples from Northern and Southern fishing grounds (average ± standard deviation) (*n* = number, EPA = eicosapentaenoic acid [20:5ω3]), DHA = docosahexaenoic acid [22:6ω3])

| Fishing ground | *n* | Percent composition | | | | | |
		16:1ω7c	18:1ω9c	20:1ω9c	EPA	DHA	Total
Southern	36	5.9±2.2	24.8±7.0	7.0±1.9	5.2±2.5	12.7±8.8	55.2±1.9
Northern	54	8.3±1.8	33.2±4.5	7.6±1.3	2.5±1.5	3.6±3.5	55.6±1.7

Table 16.8 Comparison of relative percent composition of major fatty acids in toothfish samples from southern fishing grounds over five weight classes (average ± standard deviation) (*n* = number of species, MUFA = monounsaturated, PUFA = polyunsaturated, EPA = eicosapentaenoic acid [20:5ω3], DHA = docosahexaenoic acid [22:6ω3])

| Weight class | *n* | Percent composition | | | | | |
		16:1ω7c	18:1ω9c	20:1ω9c	EPA	DHA	Total
0-399g	7	3.7±1.5	16.8±3.9	5.4±1.8	7.9±1.5	23.4±7.0	57.3±2.1
400-599g	12	5.0±1.2	21.7±3.9	6.8±1.9	6.2±1.5	16.5±5.5	56.2±1.2
600-799g	5	6.1±2.2	25.3±5.2	7.8±1.6	5.1±2.2	10.2±4.4	54.4±0.6
800-999g	3	8.4±1.8	29.8±4.1	6.1±1.2	3.8±1.3	6.8±2.2	54.8±1.8
1,000g+	9	8.0±1.2	33.3±1.9	8.4±1.6	2.3±0.6	2.7±0.9	54.6±0.9

Table 16.9 Comparison of relative percent composition of major fatty acids in toothfish samples from northern fishing grounds over five weight classes (average ± standard deviation) (*n* = number of species, MUFA = monounsaturated, PUFA = polyunsaturated, EPA = eicosapentaenoic acid [20:5ω3c], DHA = docosahexaenoic acid [22:6ω3])

| Weight class | *n* | Percent composition | | | | | |
		16:1ω7c	18:1ω9c	20:1ω9c	EPA	DHA	Total
0-399g	1	5.4	21.0	7.5	5.6	14.7	54.1
400-599g	6	7.7±4.7	26.8±6.3	6.5±2.1	4.9±3.1	9.7±5.8	55.6±2.5
600-799g	3	7.2±0.5	28.2±2.4	9.1±1.1	3.6±0.6	5.3±2.0	53.3±1.9
800-999g	3	7.7±1.0	31.9±3.6	7.6±0.8	3.3±1.2	4.4±2.4	54.9±1.7
1,000g+	41	8.6±0.8	34.9±2.5	7.7±1.2	2.0±0.5	2.2±0.9	55.4±1.8
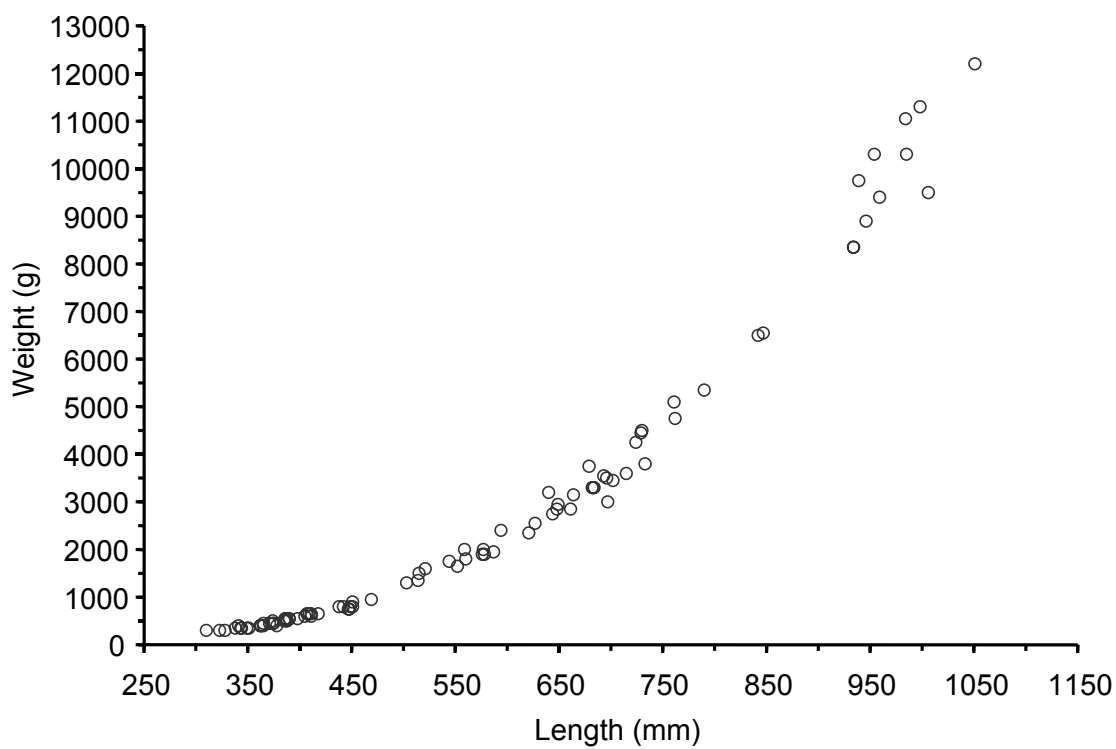
Figure 16.1 Length (total) and weight relationship of toothfish samples analysed (n=90).
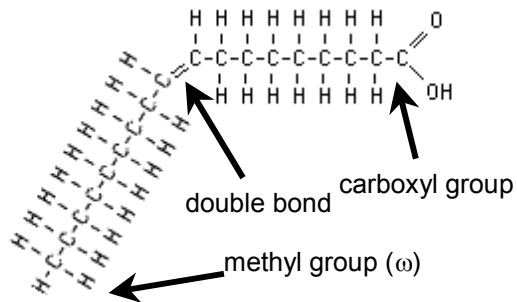
Figure 16.2 Example of a monounsaturated fatty acid (18:1ω9c, oleic acid).
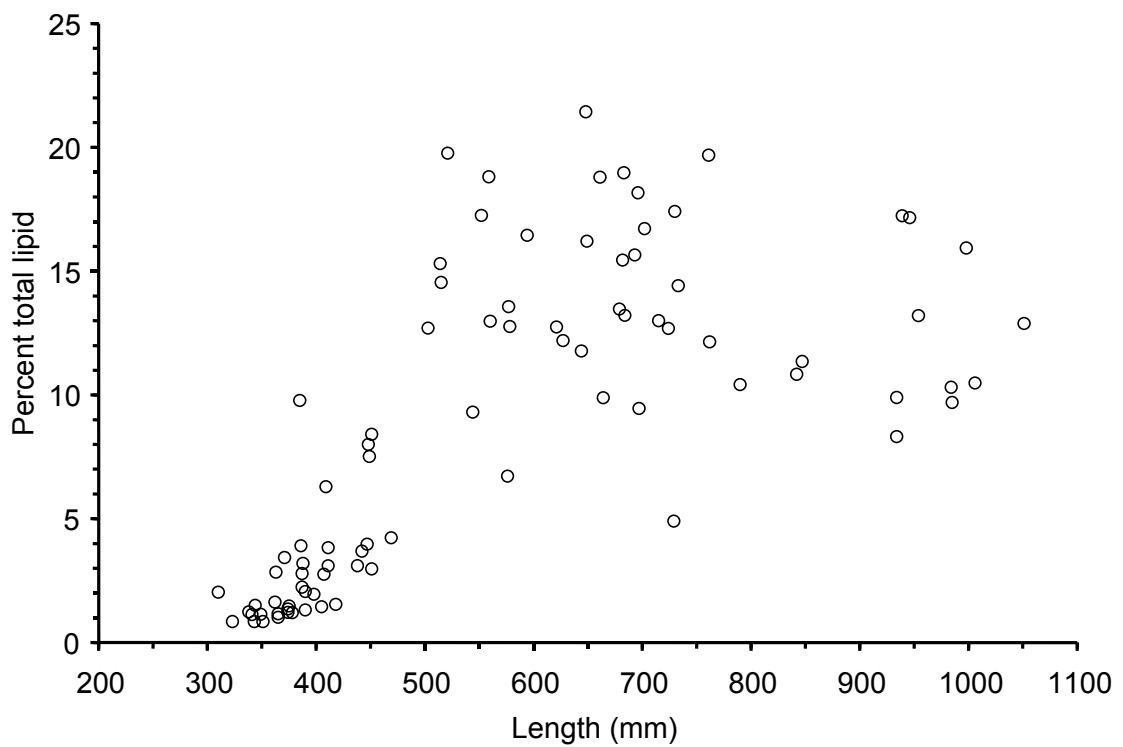
Figure 16.3 Percent total lipid content (wet weight) of toothfish in relation to total length.
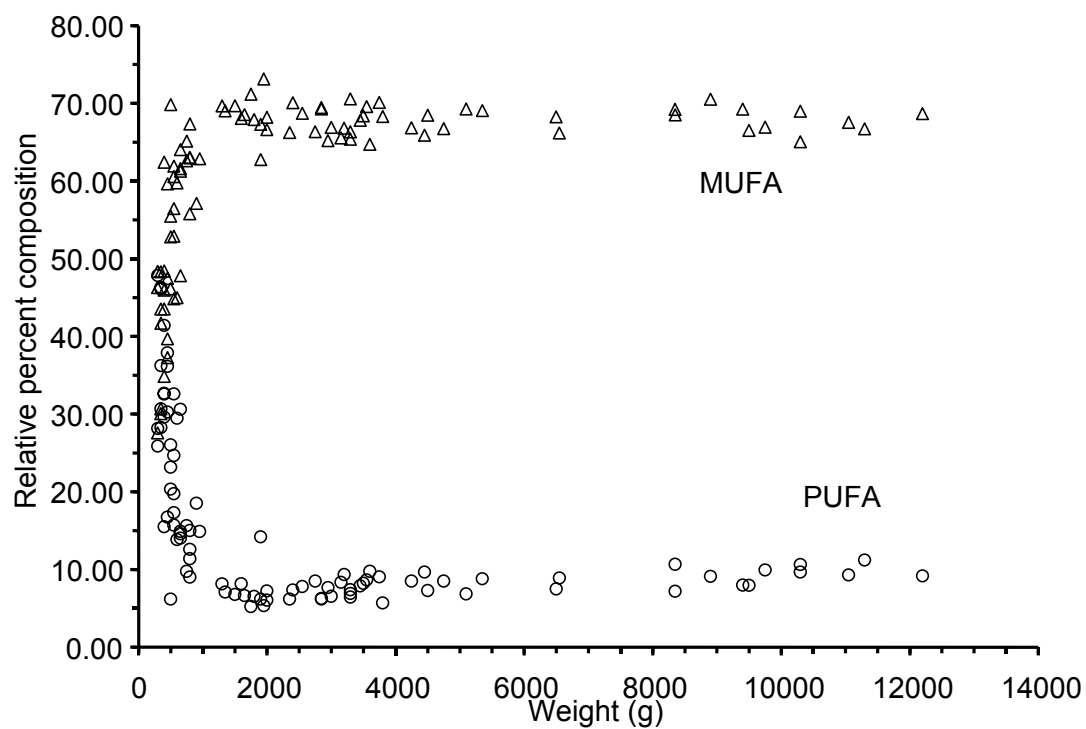
Figure 16.4 Relative polyunsaturated fatty acid (PUFA) and monounsaturated fatty acid (MUFA) composition (% of total fatty acids) in relation to toothfish fresh weight (*n*=90).
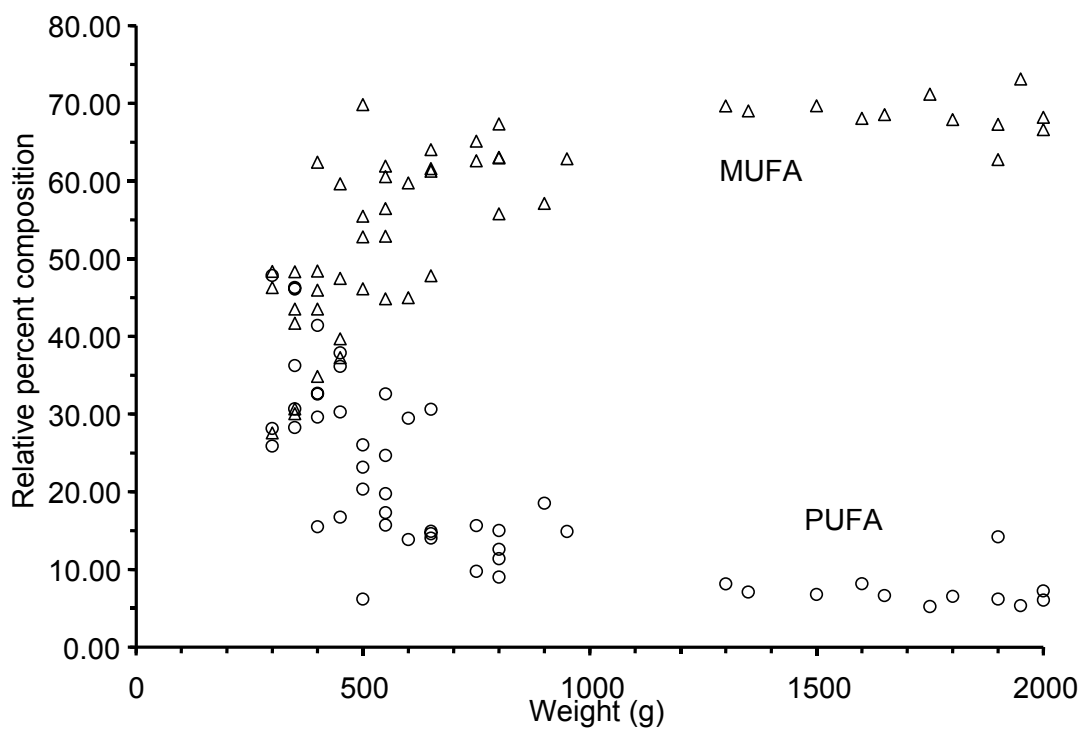
Figure 16.5 Relative polyunsaturated fatty acid (PUFA) and monounsaturated (MUFA) composition (% of total fatty acid) in relation to toothfish fresh weight (0-2,000g).
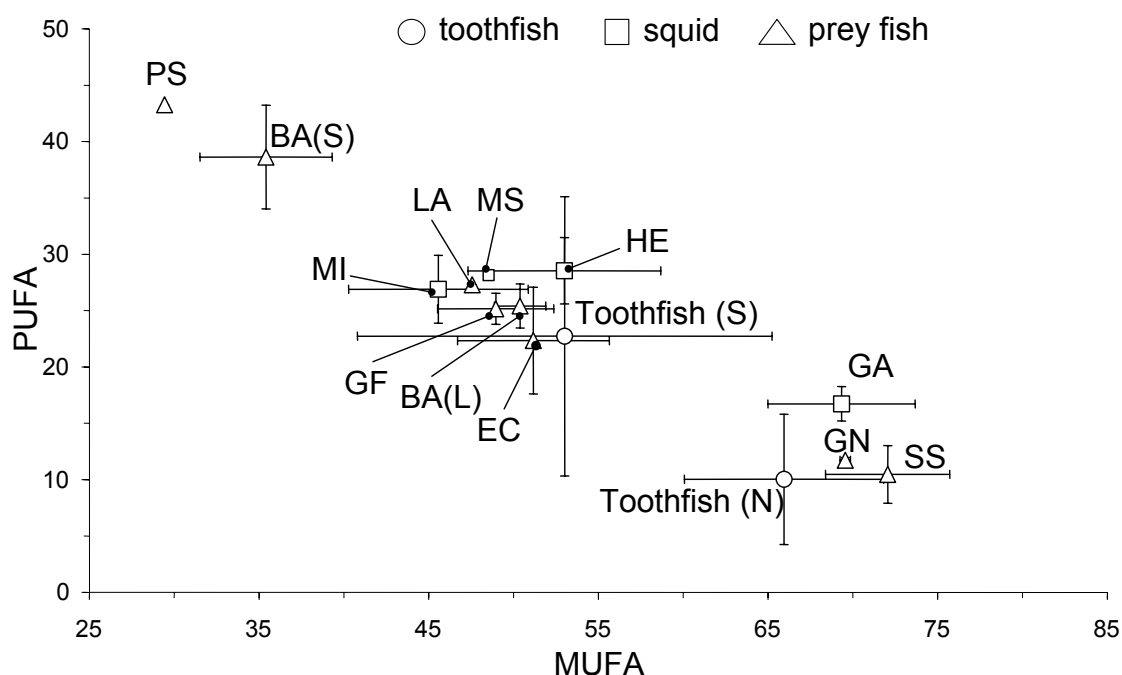
Figure 16.6 Comparison of relative percent composition of monounsaturates (MUFA) and polyunsaturates (PUFA) in toothfish from the southern and northern fishing grounds and potential prey (percent composition ± standard deviation). Toothfish (N)=toothfish from northern fishing ground, Toothfish (S)=toothfish from southern fishing ground, PS=*Promitra sp.*, BA(S)=small *B. antarcticus,* BA(L)=large *B. antarcticus,* LA=*L. archirus,* GF=*G. fraseri*, EC=*E. carlsbergi*, GN=*G. nicholsi*, SS=*Stomias sp.,* MI=*M. ingens,* HE=*H. eltaninae,* MS=*Mastigoteuthis sp.*, GA=*G .antarcticus.*
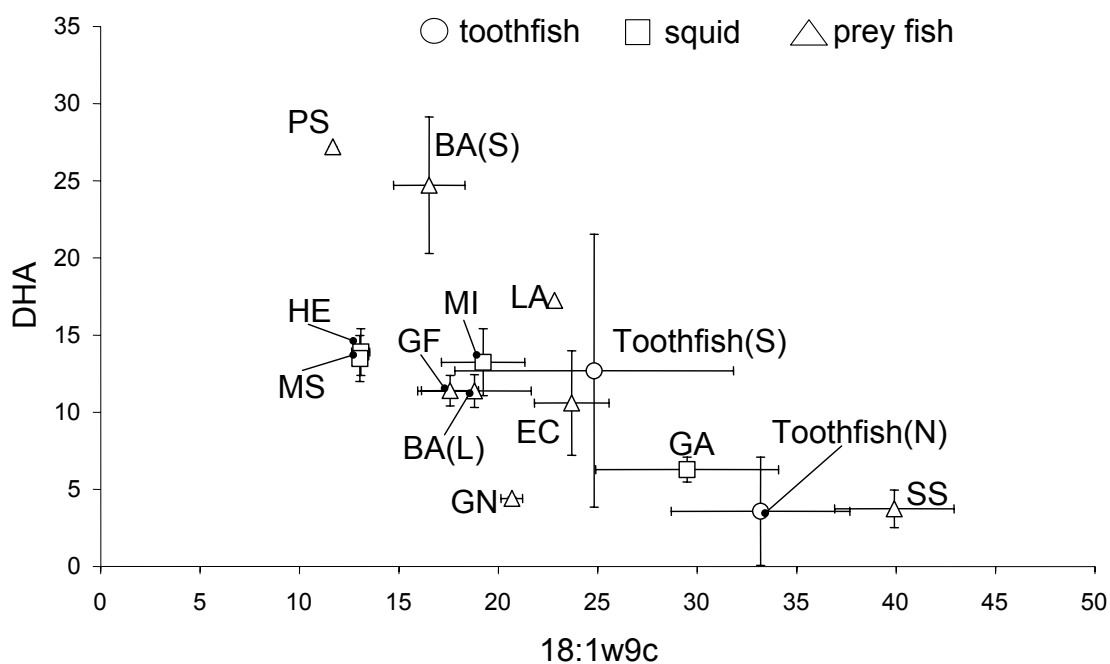
Figure 16.7 Comparison of relative percent composition of DHA and 18:1ω9c in toothfish from the southern and northern fishing grounds and potential prey (percent composition ± standard deviation). Toothfish (N)=toothfish from northern fishing ground, Toothfish (S)=toothfish from southern fishing ground, PS=*Promitra sp.*, BA(S)=small *B. antarcticus,* BA(L)=large *B. antarcticus,* LA=*L. archirus,* GF=*G. fraseri,* EC=*E. carlsbergi,* GN=*G. nicholsi,* SS=*Stomias sp.,* MI=*M. ingens,* HE=*H. eltaninae,* MS=*Mastigoteuthis sp.,* GA=*G .antarcticus,* DHA= *docosahexaenoic, 22:6ω3.*
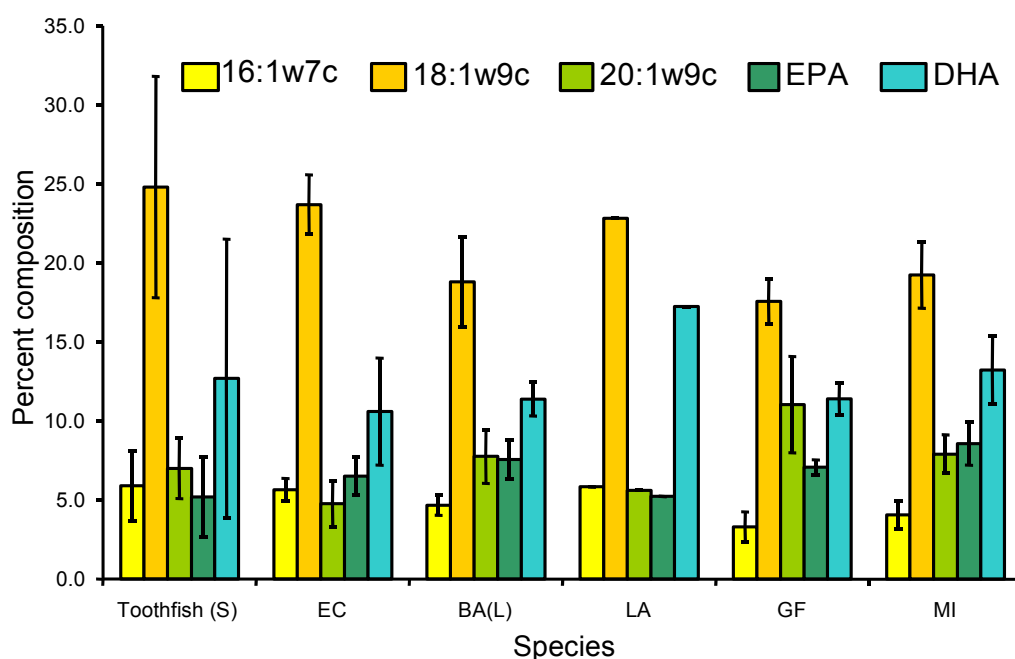
Figure 16.8 Comparison of relative percent composition of 5 major fatty acids for toothfish from the southern fishing ground and selected potential prey (percent composition ± standard deviation). Toothfish (S) = toothfish from southern fishing ground, EC = *E. carlsbergi*, BA(L) = large *B. antarcticus,* LA = *L. archirus*, GF = *G. fraseri,* MI = *M. ingens* EPA = *eicosapentaenoic acid (20:5ω3c)*, DHA = *docosahexaenoic acid (22:6ω3).*
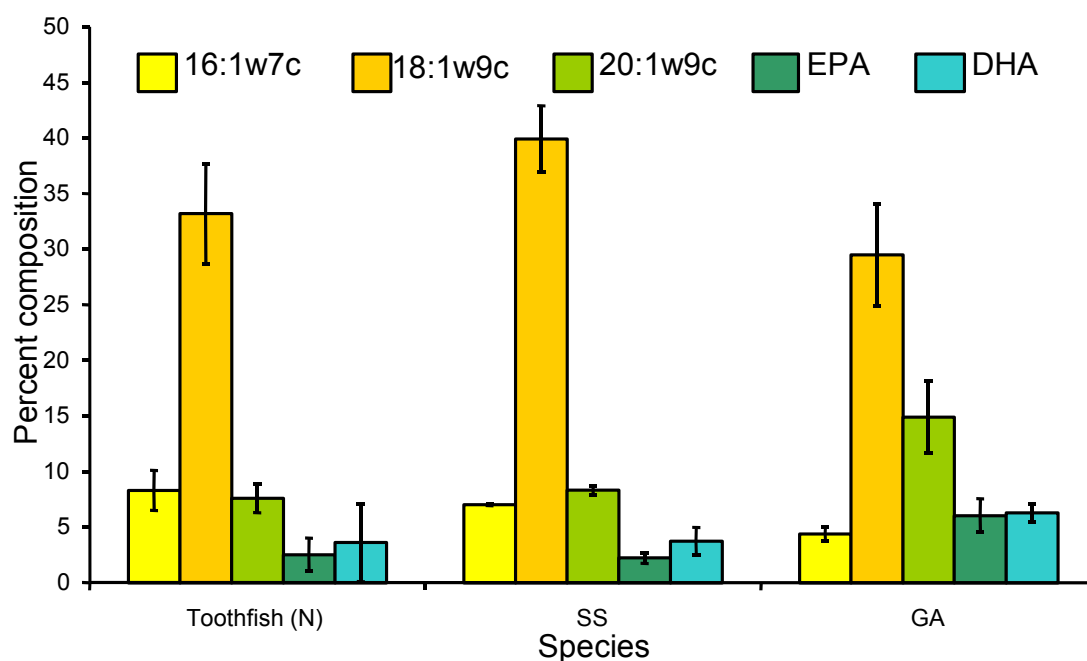
Figure 16.9 Comparison of relative percent composition of 5 major fatty acids for toothfish from the northern fishing ground and selected potential prey (percent composition ± standard deviation). Toothfish (N) = toothfish from northern fishing ground, SS = *Stomias sp.*, GA = *G. antarcticus,* EPA = *eicosapentaenoic acid (20:5ω3)*, DHA = *docosahexaenoic acid (22:6ω3).*
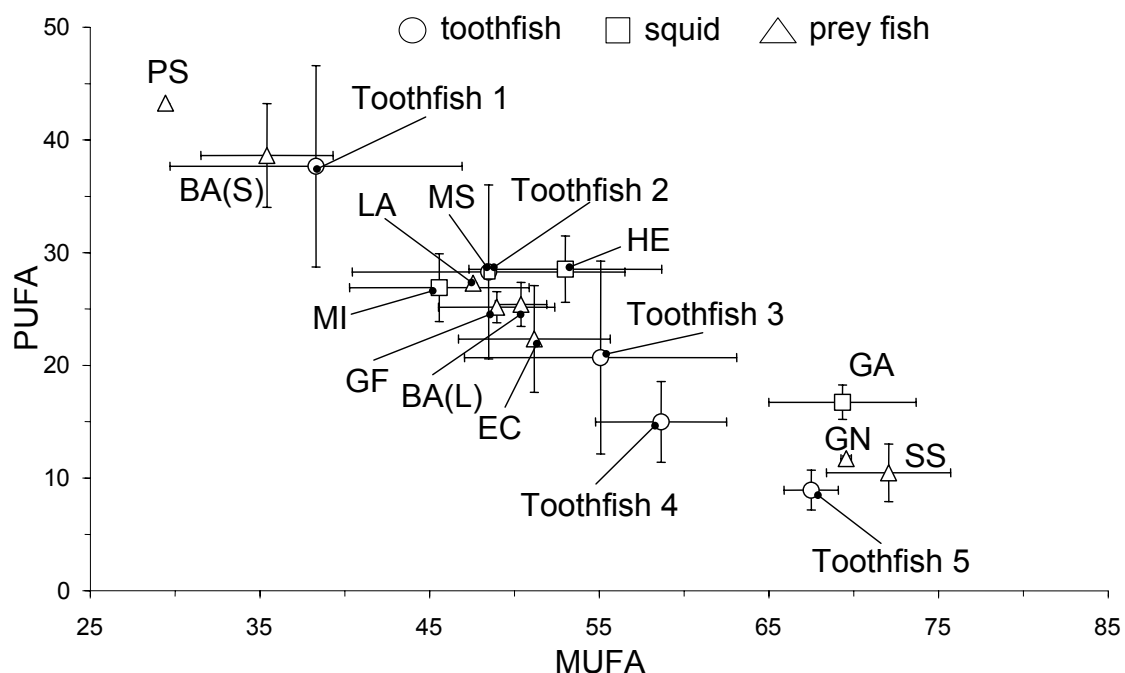
Figure 16.10 Comparison of relative percent composition of monounsaturates (MUFA) and polyunsaturates (PUFA) for toothfish various sizes (fresh weight) from the southern fishing ground and potential prey (percent composition ± standard deviation). Toothfish 1=*0-399g,* Toothfish 2=*400-599g,* Toothfish 3=*600-799g,* Toothfish 4=*800-999g,* Toothfish 5=*1,000g+,* PS=*Promitra sp.,* BA(S)=small *B. antarcticus,* BA(L)=large *B. antarcticus,* LA=*L. archirus,* GF=*G. fraseri,* EC=*E. carlsbergi,* GN=*G. nicholsi,* SS=*Stomias sp.,* MI=*M. ingens,* HE=*H. eltaninae,* MS=*Mastigoteuthis sp.,* GA=*G .antarcticus.*
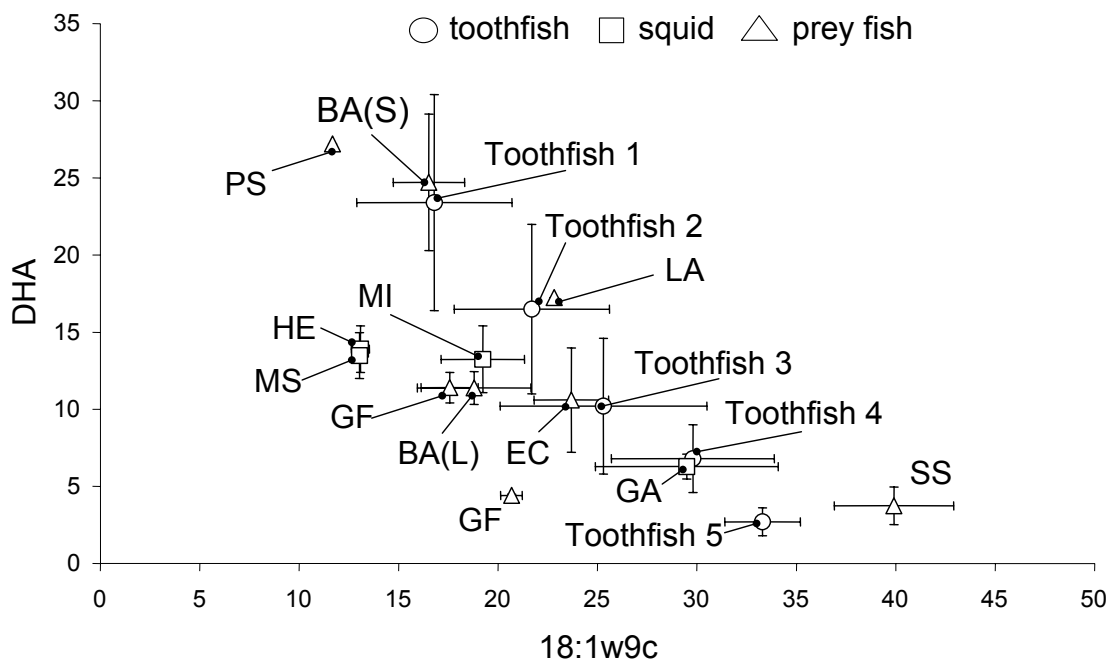
Figure 16.11 Comparison of relative percent composition of DHA and 18:1ω9c in toothfish of various sizes (fresh weight) from the southern fishing ground and potential prey (percent composition ± standard deviation). Toothfish 1=*0-399g,* Toothfish 2=*400-599g,* Toothfish 3=*600-799g,* Toothfish 4=*800-999g,* Toothfish 5=*1,000g+*, PS=*Promitra sp.*, BA(S)=small *B. antarcticus,* BA(L)=large *B. antarcticus,* LA=*L. archirus,* GF=*G. fraseri*, EC=*E. carlsbergi*, GN=*G. nicholsi*, SS=*Stomias sp.,* MI=*M. ingens,* HE=*H. eltaninae,* MS=*Mastigoteuthis sp.*, GA=*G .antarcticus,* DHA=*docosahexaenoic acid (22:6ω3).*
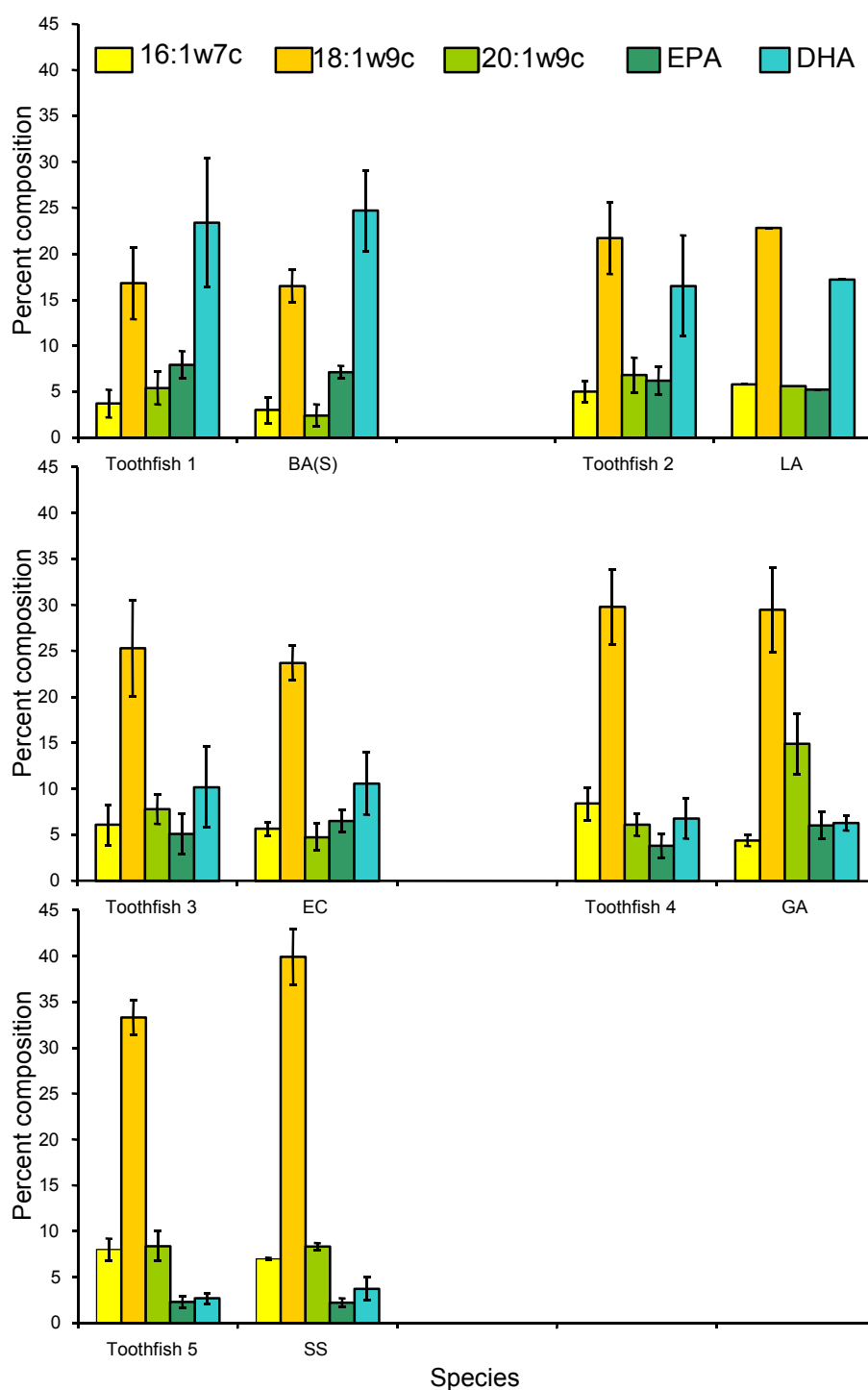
Figure 16.12 Comparison of relative percent composition of 5 major fatty acids for various toothfish size classes (fresh weight) from the southern fishing ground with selected potential prey (percent composition ± standard deviation). Toothfish 1=*0-399g,* Toothfish 2=*400-599g,* Toothfish 3=*600-799g,* Toothfish 4=*800-999g,* Toothfish 5=*1,000g+*, BA(S)=small *B. antarcticus,* LA=*L. archirus,* EC=*E. carlsbergi*, SS=*Stomias sp.,* GA=*G .antarcticus,* EPA = *eicosapentaenoic acid (20:5ω3)*, DHA=*docosahexaenoic acid (22:6ω3)*.
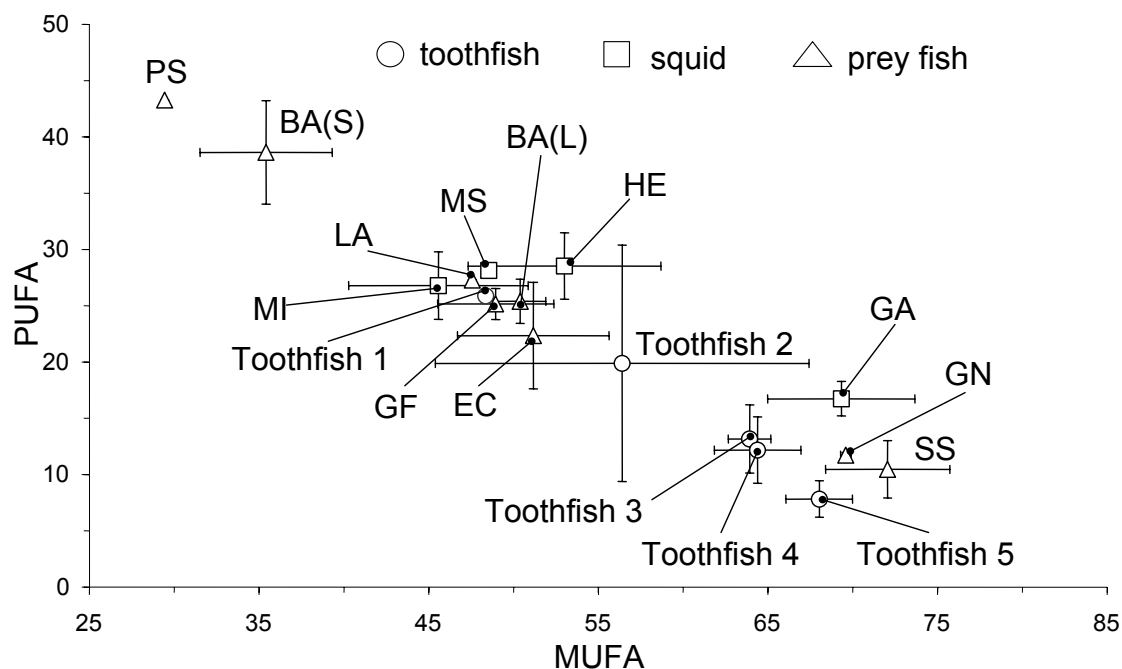
Figure 16.13 Comparison of relative percent composition of monounsaturates (MUFA) and polyunsaturates (PUFA) for various toothfish of various sizes (fresh weight) from the northern fishing ground and potential prey (percent composition ± standard deviation). Toothfish 1=*0-399g,* Toothfish 2=*400-599g,* Toothfish 3=*600-799g,* Toothfish 4=*800-999g,* Toothfish 5=*1,000g+*, PS=*Promitra sp*., BA(S)=small *B. antarcticus,* BA(L)=large *B. antarcticus,* LA=*L. archirus,* GF=*G. fraseri*, EC=*E. carlsbergi*, GN=*G. nicholsi*, SS=*Stomias sp.*, MI=*M. ingens,* HE=*H. eltaninae,* MS=*Mastigoteuthis sp.*, GA=*G. antarcticus*.
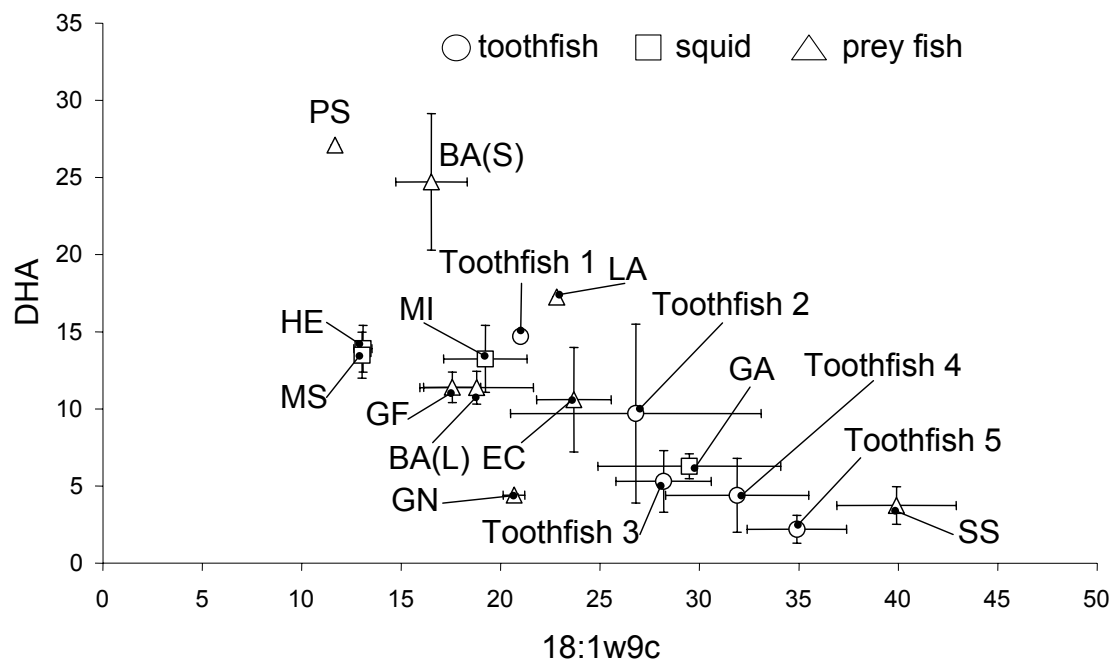
Figure 16.14 Comparison of relative percent composition of DHA and 18:1ω9c in toothfish of various sizes from the northern fishing ground and potential prey (percent composition ± standard deviation). Toothfish 1=*0-399g,* Toothfish 2=*400-599g,* Toothfish 3=*600-799g,* Toothfish 4=*800-999g,* Toothfish 5=*1,000g+,* PS=*Promitra sp.*, BA(S)=small *B. antarcticus,* BA(L)=large *B. antarcticus,* LA=*L. archirus,* GF=*G. fraseri*, EC=*E. carlsbergi*, GN=*G. nicholsi*, SS=*Stomias sp.,* MI=*M. ingens,* HE=*H. eltaninae,* MS=*Mastigoteuthis sp.*, GA=*G .antarcticus,* DHA=*docosahexaenoic acid (22:6ω3).*
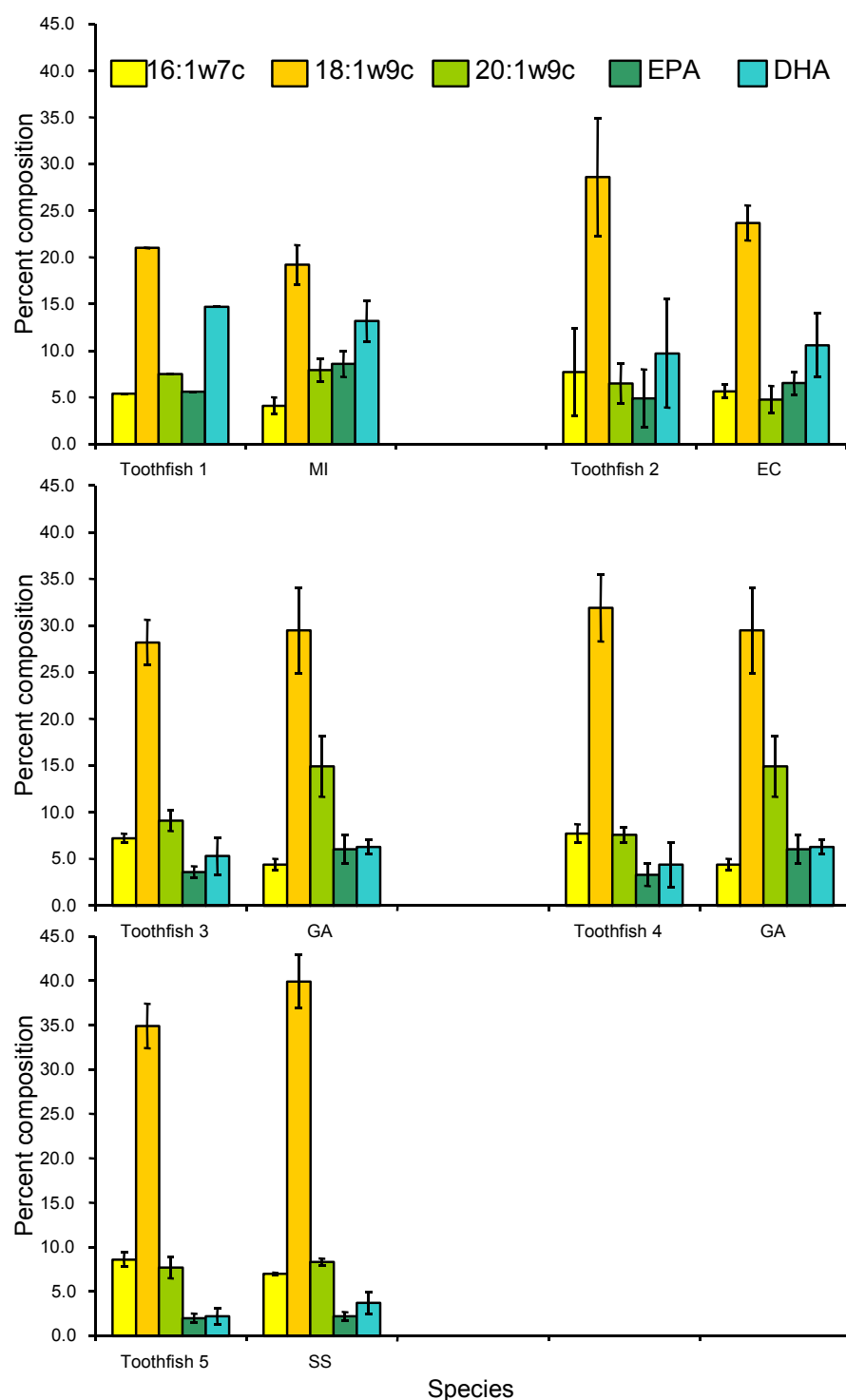
Figure 16.15 Comparison of relative percent composition of 5 major fatty acids for various toothfish size classes (fresh weight) from the northern fishing ground with selected potential prey (percent composition ± standard deviation). Toothfish 1=*0-399g,* Toothfish 2=*400-599g,* Toothfish 3=*600-799g,* Toothfish 4=*800-999g,* Toothfish 5=*1,000g+*, MI=*M. ingens,* LA=*L. archirus,* EC=*E. carlsbergi*, SS=*Stomias sp.,* GA=*G . antarcticus,* EPA = *eicosapentaenoic acid (20:5ω3)*, DHA=*docosahexaenoic acid (22:6ω3).*

17. Trophic interactions between toothfish, its fishery, seals and seabirds around Macquarie Island

Simon Goldsworthy, Xi He, Geoff Tuck, Mark Lewis and Dick Williams

Summary
For ecological sustainable development (ESD) of the fishery, this study investigated the trophic interactions based on diet composition and annual consumption between toothfish, its fishery, seals and seabirds, within the Macquarie Island Exclusive Economic Zone (MI-EEZ). Annual consumption rates for each predator were estimated from dietary data (mostly published sources), energetic budgets, prey energy content, and population size. Results indicated little predation on toothfish by seals or seabirds, or prey competition between toothfish and other marine predators. The greatest dietary overlap with toothfish was with gentoo penguins (21% dietary overlap) and southern elephant seals (19%). These overlaps in diet were small relative to those among fur seals (three species, ≥90%), giant petrels (84%), royal and rockhopper penguins (65%), and king and royal penguins and fur seals (>60%). The total annual prey biomass consumed by seabirds, seals, estimated available toothfish and the fishery within the MI-EEZ was estimated to be 419,774 t, with the greatest consumption in January at 2,779 t/d. Pelagic fish (61%, mostly myctophids), followed by pelagic crustaceans (28%, mostly euphausiids) and cephalopods (7%) were the major prey. Most prey biomass was consumed by penguins (88%), with comparatively small amounts by toothfish (8%), seals (3%) other seabirds (<1%) and the fishery (0.1%). These results indicate weak trophic linkages between toothfish, its fishery and seabirds and seals around Macquarie Island.

Introduction
General introduction
With major decreases in many of the world's fish stocks over the last few decades, and the concomitant development of more intensive fishing methods, there has been increased interest in the extent of competition for fish stocks between commercial fisheries and seabirds and marine mammals. Early investigations into this competition aimed at assessing the extent to which seals and seabirds consumed fish that could have potentially provided economic benefit to commercial fisheries (Davies 1958, Matthews 1961, Furness and Cooper 1982, Furness 1984). Many of these studies suggested that some seal and seabird populations consumed large quantities of commercially important fish species, and such information has been used to justify reductions in seal and seabird numbers (Davies 1958, Butterworth *et al*. 1988). More recently, with greater efforts to manage fisheries under the principles of Ecological Sustainable Development (ESD), the focus of studies has changed to examine how commercial fishing may affect the conservation status of seabird and marine mammal populations. Some research has suggested that commercial fisheries may be significant competitors with seabirds and marine mammals (Furness and Cooper 1982, Duffy 1983, Trites *et al*. 1997, Hammill *et al*. 1997, Stenson *et al*. 1997), and in cases of overfishing, cause major decreases in their populations (Anderson and Gress 1984, Burger and Cooper 1984, Trites *et al*. 1999).

The recent rapid expansion of toothfish commercial fishery in the Southern Ocean, has raised concerns over the sustainability of the fishery. In addition, the ecological consequences of over fishing especially on populations of seabirds and marine mammals, is unclear. The dependence of sea birds and marine mammal populations (primarily seals) on marine resources in Southern Ocean and Antarctic waters has been assessed by a number of studies, and some have also estimated the potential competition and impacts that commercial fisheries (mostly for Antarctic krill, *Euphausia superba)* may have on their populations (Abrams 1985, Adams *et al*. 1993, Brown 1989, Croll and Tershy 1998, Croxall and Prince 1982, Croxall *et al*. 1984, Croxall *et al*.

1985, Green *et al*. 1998, Hunt 1985, Ichii *et al*. 1996, Moore *et al*. 1998, Woehler and Green 1992). Studies investigating the consumption of marine resources by seals and seabirds in the South Atlantic Ocean have generally shown the importance of Antarctic krill in these food webs (Croll and Tershy 1998, Croxall and Prince 1982, Croxall *et al*. 1984, Croxall *et al*. 1985). However, in subantarctic regions of the South Indian and Pacific Oceans, fish appear to be more important prey than pelagic crustaceans, as such commercial fin-fisheries (eg. toothfish*, marbled rockcod, Notothenia rossii* and mackerel icefish*, Champsocephalus gunnari*) may place seabirds and seals at greater risk of competition for foods (Adams *et al*. 1993, Green *et al*. 1988, Moore *et al*. 1998, Woehler and Green 1992).

Macquarie Island is an important breeding site for large numbers of land-breeding marine predators, including 86,000 seals and over 3 million seabirds, most of which are penguins. In line with development and management of the fishery under the principles of ESD, it is essential to understand the potential interactions among the fishery, the toothfish population, and other marine predators, such as seabirds and seals.

A brief overview of food web interactions around Macquarie Island
In 1997, a workshop was held to examine predator-prey interactions at Heard Island and McDonald Islands and at Macquarie Island (Australian Antarctic Division, 1997). The aim of the Workshop was to report on the current state of knowledge on predator-prey relations in three island regions, to identify future research requirements, and to provide advice on the implications of predator-prey interactions for the development of management plans for fisheries. In particular, the focus of the Workshop was on ecological interactions, e.g. competition between fisheries and predators for the same prey species. Seals and seabirds (mainly penguins) had been identified as important components of the food webs, not only because they have high conservation values, but also it was believed that their consumption of prey species were high and will be increasing as their population sizes increase in the future. In addition, toothfish and their fisheries were identified as important components of the food webs, mainly because the fisheries could have potentially large impacts on the existing ecosystems. The workshop developed a "minimally realistic model" for the Macquarie Island food web, mostly based on limited data and knowledge available at that time. This food web model was then refined as more diet data on seals, seabirds, and toothfish became available (Chapter 15, 16, and this chapter). The updated model is presented in Figure 17.1.

The food web diagram presented in Figure 17.1 shows major trophic groups and interactions for the Macquarie Island EEZ. As indicated, seals, seabirds, and the fishery are top predators, which in turn are supported by squid, mesopelagic-, bathypelagic-, and benthopelagic-fishes. However, the trophic linkages shown in the food web only indicate qualitative interactions between major trophic groups. To assess the importance of competition between top predators, toothfish, and the fishery, and potential impacts of the fishery on the food web, quantitative methods are needed.

Aims of this chapter
This chapter aims to examine the trophic interactions based on the diet composition and relative consumption rates between the fishery, toothfish, seabirds and seals around Macquarie Island. Dietary overlaps among predators were estimated and used to assess potential food competition among predators. Annual consumption rates on all prey by these predators were also estimated and compared. These estimates will provide useful information to assess the relative importance of toothfish in the Macquarie Island ecosystem, and can be used to assess potential interactions between the toothfish fishery and other marine predators.

Methods

Area and species in study

The Macquarie Island Exclusive Economic Zone (MI-EEZ) extends from 3 – 200 nm (5.6 – 370 km) from the island (Figure 17.2). The north-eastern edge of the MI-EEZ is slightly less than 370 km, where it joins the Campbell and Auckland Islands EEZ (New Zealand, Figure 17.2). The area of ocean within the MI-EEZ is approximately 415,600 km^2. Only those species that undertake a significant portion of their foraging within the MI-EEZ, or have substantial biomass were included in this study. These includes the king (*Apenodytes patagonicus*), royal (*Eudyptes schlegeli*), and rockhopper (*E. chrysocome*) penguins, southern elephant seal (*Mirounga leonina*) and Antarctic (*Arctocephalus gazella*) and New Zealand (*A. forsteri*) fur seals, black-browed albatross (*Diomedea melanophrys*), northern (*Macronectes halli*) and southern (*M. giganteus*) giant petrel and Antarctic prion (*Pachyptila desolata*) that are present in the vicinity of the island during the breeding and moulting periods. Gentoo penguins (*Pygoscelis papua*) and Macquarie shags (*Phalacrocorax purpurascens*), are resident year round, while the subantarctic fur seal (*A. tropicalis*) is present on the island from December to October. Toothfish were assumed to be resident also.

Species, such as several of the small and large petrels (sooty shearwaters *Puffinus griseus*; white headed petrel *Pterodroma lessonii*; blue petrel *Halobaena caerulea*; light-mantled sooty albatross *Phoebetria palpebrata*; grey-headed albatross *Diomedea chrysostoma*; and wandering albatross *D. exulans*), other seabirds with very low abundance and biomass (fairy prion *Pachyptila turtur*; common diving petrel *Pelecanoides urinatrix*; South Georgian diving petrel *P. georgicus* and Wilson's storm petrel *Oceanites oceanicus)*, and species that feed mostly along the shoreline and inland (Antarctic terns *Sterna vittata*, kelp gulls *Larus dominicanus* and subantarctic skua *Catharacta lonnbergi*), were omitted from the study. Due to paucity of data, cetaceans were also excluded.

Population and biomass estimates

The population and biomass estimates of seabirds and seals at Macquarie Island used in this study are presented in Table 17.1. Population estimates for the southern elephant seal at Macquarie Island were based on an estimated annual pup production of 20,000 (D. Slip, Environment Australia, pers. comm.) and age-specific survival rate data from Heard Island and South Georgia (McCann 1985; Slip 1997). The biomass of each age class was estimated from the product of the number of individuals in an age class and their mean mass (Slip 1997). For fur seals, population and biomass estimates were based on pup production and mass data (Goldsworthy *et al*. 1998, Goldsworthy unpublished data), and hypothetical age-specific survival rates based on Antarctic and northern (*Callorhinus ursinus*) fur seal populations (Boyd *et al*. 1995, York 1987).

For king penguins, population estimates were based on data from Rounsevell (unpublished data in Scott 1994) extrapolated through to 1999 based on annual increases in chick production of 5-15%, the probable range of population growth based on other populations (E. J. Woehler pers. comm). A mean rate of 10% growth per year was used to calculate the population estimate in this study. Adult population size (individuals) was estimated by multiplying chick production by 3 [i.e. adult population = chick production x 2 (adults) x 1.5 (average of 2 chicks per 3 years)]. For royal, rockhopper, and gentoo penguins, population estimates were based on Copson and Rousevell (1987), Warham (1963), Rousevell and Brothers (1984), Copson (in Scott 1994), and Robinson and Hindell (1996). Biomass estimates for penguins were calculated by multiplying population size by average adult masses (Barrat 1976, Green and Gales 1990, Hull 1997, Reilly and Kerle 1981).

Estimates of the population size of black-browed albatrosses, southern and northern giant petrels and Antarctic prions were derived from Brothers (1984), Johnstone (1977) and Robinson and Scott (1999). Average mass data for these species were obtained from Johnstone (1977),

Voisin and Bester (1981), Weimerskirch *et al*. (1986, 1989), and Marchant and Higgins (1990). Population and mass data on the Macquarie shag were derived from Brothers (1985) and Brothers (unpublished data, in Scott 1994). The biomass of toothfish was based on estimates of the available abundance in mid-1995 (one year after the commencement of the fishery). The biomass of toothfish available to the fishery was estimated to be 62,474 (17,146 – 1,002,728) tonnes (Tuck *et al*. in press). For the purpose of this study, where a range of estimates for the population size of species was available, the mid-point of such estimates were used to calculate their energy and food requirements (Table 17.1).

Diet data sources and prey grouping
Data on the diets of seals and seabirds were obtained from published and unpublished sources, and are summarised in Table 17.2. With the exception of the Antarctic prion and the species composition of the diet of black-browed albatrosses (although percentage biomass of main prey groups were derived from Macquarie Island), all diet information used in this study came from samples collected at Macquarie Island (Table 17.2). Dietary composition of all predators was expressed as percentage of wet prey mass. In cases where data were expressed by the numerical abundance of prey, they were converted to mass by multiplying the number of prey items by the estimated mass of the prey items consumed. Data on the composition of the commercial catch at Macquarie Island was based on the mean annual catch of toothfish and bycatch species over a three-year period (1996/97 to 1998/99) (Williams unpublished data). Only major fish and invertebrate bycatch species were included. Corals and sponges were excluded.

Prey species were summarised into 35 groups based mostly on the lowest taxonomic level that could be identified from stomach or faecal data. For many diet studies the lowest taxonomic grouping of fish prey was to the family level (with the exception of toothfish), whereas for cephalopod prey this was generally to the genus level. However, where more detailed identification of fish prey to species level was available, this was used (eg. for fur seals, penguins and the fishery). Diet composition was also summarised into six main ecological prey categories, pelagic fish (Myctophidae, Bathylagidae, Paralepididae), demersal fish (Nototheniidae, Harpagiferidae, Congiopodidae, Moridae, Macrouridae, Bothidae, Squalidae), cephalopods, pelagic crustaceans (euphausiids, amphipods, copepods, and ostracods) and demersal crustaceans (prawns and crabs) and birds/carrion.

Diet overlaps
Diet overlaps between predators were examined using two methods. First, an overlap index was used to calculate diet similarities between two predators (*i* and *j*). This index, termed percentage similarity index (*%PSI*), was modified from Schoener (1970):

$$\% PSI_{ij} = 100 * (1.0 - 0.5\sum_{h=1}^{S} | P_{hi} - P_{hj} |) ,\qquad(1)$$

where P_{hi} is the proportion by mass of prey category *h* in predator *i*; P_{hj} the proportion by mass of prey category *h* in predator *j* , and *s* is the number of prey categories. This method produces a similarity matrix for all predator pairs being compared.

The second method applied a hierarchical cluster analysis to diet data in order to classify predator species into distinct trophic guilds. The Bray-Curtis dissimilarity coefficients were used along with the average linkage-clustering algorithm using the software package PRIMER (Plymouth Marine Laboratory, UK). Significant trophic guilds were determined following the methods of Jaksic and Medel (1990).

Energy requirements and food consumption estimates
The approach in this study was to estimate the daily energy requirements of individuals of each species while in the MI-EEZ based on estimates of activity and field metabolic rate (FMR). Daily energy requirements were then converted to food requirements by first transforming diet

data (expressed as proportion of biomass) to proportions of total energy intake using estimates of the energy density of various prey taxa consumed (Table 17.3). Daily food requirements were then calculated as the sum of the product of the daily energy requirements and prey energy frequencies. The total annual energy requirements and consumption were then estimated by multiplying the daily estimates by total days that animals were estimated to be within the MI-EEZ.

For a particular seabird or fur seal species *i*, the energy requirements *e* (KJ) on day *k* for animals of a given age-class and/or gender were estimated using the following equation, modified from Croll and Tershy (1998) (see Table 17.1):

$$e_i^k = \frac{(F_a P_a) + (F_r P_r)}{M} \tag{2}$$

where F_a is the field metabolic rate (KJ) of animals at sea (active) and F_r is the metabolic rate when animals are ashore (resting). The proportion of time spent at sea and on shore, on any given day, are given by P_a and P_r, respectively, *M* is the metabolic energy (assimilation efficiency) assumed to be 0.69 for petrels (Jackson 1986), and 0.74 for other species (Davis *et al*. 1989) (Table 17.1). Metabolic rate (*F*) values for fur seals were based on those determined for Antarctic fur seals at South Georgia (Costa *et al*. 1989). The active and resting metabolic rates for penguin and petrels were estimated from regression equations in Green and Gales (1990) and Warham (1996), respectively. The metabolic rate for the Macquarie Shag was estimated from allometric equations (Koteja 1991, Table 17.1).

The total number of days spent within the MI-EEZ by each species, and the proportion of time spent at sea and on shore during the various stages of the courting, incubation, brooding, chick feeding, lactation and moulting periods were estimated from accounts of the species annual cycle, breeding and attendance patterns (Brothers 1985, Davis *et al*. 1989; Goldsworthy 1999, and unpublished data; Hull 1997; Marchant and Higgins 1990 and references therein, Slip 1997, pers comm., Weimerskirch *et al*. 1986, and 1992; summarised in Table 17.1). For royal, rockhopper and king penguins undergoing long incubation and pre-moulting foraging trips, most of the foraging was estimated to occur outside of the MI-EEZ (Hull *et al*. 1977, Hull 1999a, B. Wienecke pers. comm). As such, the only foraging time included was that estimated to occur from the island to the edge of the MI-EEZ on leaving the island, and from the edge of the EEZ when returning to the island. Penguins were estimated to travel at an average horizontal speed of 3.6 km/hr, and take about 4.3 days to travel 370 km, assuming continuous swimming at that speed.

Average activity and attendance patterns relative to the mean laying or pupping dates, were used to estimate the daily activity (proportion of time ashore and at sea) of seabird pairs or lactating seals, respectively. However, as not all pairs or animals lay or pup on the same day, data on the timing and spread (standard deviation) of laying and pupping dates were used to calculate a normal distribution around their means. From these, the proportion of pairs or animals undertaking activities on the days either side of the means were calculated in order to provide a more realistic representation of the daily-energy expenditure and consumption patterns among populations of seabirds and seals.

The total annual energy requirements of predator *i* (E_i) was thus estimated as,

$$E_i = \sum_{k=1}^{d} \sum_{\substack{age \\ class}} \sum_{sex} e_i^k \ , \tag{3}$$

where *d* is the numbers of days spent in the MI-EEZ each year by predator *i*.

The daily consumption c_{ij}^k (tonnes), of prey species j by predator i was estimated as

$$c_{ij}^k = e_i^k \frac{f_{ij}}{\sum_{p=1}^{s} f_{ip} d_p} , \qquad (4)$$

where f_{ij} is the proportion by mass of prey species j in the diet of predator i, d_j is the energy density (KJ kg^{-1}) of prey species j, and s is total number of prey taxa consumed. The total annual food consumption by predator i, C_i, was calculated as

$$C_i = \sum_{k=1}^{d} \sum_{j=1}^{s} c_{ij}^k \qquad (5)$$

For seabirds, published estimates of the energy requirement or total mass provisioned to chicks by adults were used to calculate the total amount of food fed to chicks from hatching to fledging. For penguins this was estimated to be 119.0, 25.6, 18.0, and 43.8 kg prey mass from hatching to fledging per chick for king, royal, rockhopper and gentoo penguins respectively (Green and Gales 1990, Moore *et al*. 1998). For the Antarctic prion this was 0.49 kg per chick (Prince 1980b).

Estimates of the annual energy requirements of southern elephant seals within the MI-EEZ were based on estimates for elephant seals breeding at Heard Island (17200 MJ/seal/year, Slip 1997). The annual energy requirements for southern elephant seals at Macquarie Island (E'_{es}) was estimated as follows:

$$E'_{es} = E_{es} N_{es} \frac{D_{es}}{365} , \qquad (6)$$

where N_{es} is the estimated population size at Macquarie Island, E_{es} is the average annual energy requirements of an elephant seal (17,200 MJ) and D_{es} is the number days annually spent by elephant seals in the MI-EEZ waters (excluding time hauled out on land).

Satellite and geolocation tracking of approximately 100 elephant seals (juveniles, adult females and males) from Macquarie Island has shown a similar pattern of seals traveling directly to and from the island from foraging grounds that are generally located well outside the MI-EEZ (Bradshaw *et al*. in press, Hindell *et al*. 1999, Slip *et al*. 1994, J. van den Hoff pers. comm). As such, the only foraging time within the MI-EEZ was assumed to occur when seals were traveling to or from the island. For southern elephant seals, this occurs twice per year, once during the winter for juvenile animals or during the breeding season for adults, and once for moulting (all seals). Transit times across the MI-EEZ were based on satellite tracking data from seven transits of five year-old male elephant seals, which traveled on average 4.3 km/hour (sd = 1.2) (J van den Hoff unpublished data). Assuming such horizontal swimming speeds, elephant seals were estimated to travel the 370 km to the edge of the EEZ in 3.6 days (2.8 – 4.9) and hence spend a total of 14.4 (11.2 – 19.6) days in the MI-EEZ each year (Table 17.1).

The two annual haul-outs of southern elephant seals are very predictable in their timing, and for each age and sex-class (yearlings, 2-3 year olds, sub-adults, breeding males and breeding females) can be described by normal curves (Hindell and Burton 1988, Slip 1997). The date of maximum haul-out for the moulting and non-moulting haul-out for the various age and sex-classes, and the standard deviation of these (Slip 1997) were used to estimate the number of seals from each gender and age-class in the MI-EEZ on any given day of the year. Total annual food consumption for southern elephants seals was calculated using equations 4-5 above, and the ratio of annual consumption per total biomass of the population was used to estimate the

annual consumption per age and sex class, and from these the daily food consumption of these classes throughout the course of a year within the MI-EEZ.

The food consumption of toothfish was estimated using the multiple regression equation developed by Palomares and Pauly (1989) to estimate the consumption per biomass (Q/B) of marine fish populations:

$$\ln Q/B = -0.1775 - 0.2018 \ln W_\infty + 0.6121 \ln T + 0.5156 \ln A + 1.26F , \qquad (7)$$

where Q/B is the daily food consumption by a fish population as a percentage of its biomass, W_∞ the mean asymptotic mass (g) of the fish, T is the mean habitat temperature (°C), A is the aspect ratio of the caudal fin of the fish species (as a measure of the average activity/and or metabolic rate of the fish), and F is the food type (0 in carnivores, 1 in herbivores). The aspect ratio ($A = h^2/s$) of the caudal fin is estimated using measurements of its height (h) and surface area (s). W_∞ was estimated to be 139,328 g, the water temperature at 400 m depth at Macquarie Island is approximately 2.5°C (unpublished CTD data, CSIRO Marine Research), and A was estimated to be 1.09. The total annual food consumption C_t of the toothfish population in the MI-EEZ was estimated as:

$$C_t = 365\overline{B}(Q/B) , \qquad (8)$$

where $\overline{B}$ is the estimated biomass of the toothfish population. Consumption by toothfish on each prey taxon (j) was calculated by determining:

$$C_{tj} = f_j C_t . \qquad (9)$$

Sensitivity analysis

A single parameter analysis of sensitivity was undertaken to evaluate the relative importance of input parameters to estimates of annual relative consumption. Parameters examined include population size and metabolic rate as other parameters such as residence times and predation rates would show the same response as adjusting population size. Each parameter was separately varied ±10% for the five major predators (royal, king, rockhopper penguins, elephant seals and toothfish) and consumption for each prey species were recalculated. The percentage sensitivity $S_{p,i}$ from the base model for parameter p and predators i was then calculated:

$$S_{p,i} = \frac{100\left(RC'_{p,i} - RC_{p,i}\right)}{RC_{p,i}} \qquad (10)$$

where $RC'_{p,i}$ is the recalculated relative consumption by predator i with parameter p being varied by 10% and $RC_{p,i}$ is relative consumption from the base model. Sensitivities $\left| S_{p,i} \right| > 10\%$ indicate high sensitivities, while $\left| S_{p,i} \right| < 10\%$ indicate low sensitivity. For example, an $S_{p,i} = 5\%$ means that a 10% change of input parameter p for predator i resulted in increasing the base model estimate of consumption for predator i by 5%.

Results

Diet composition

The diet composition of the seals, seabirds, toothfish and the fishery around Macquarie Island, are presented in Table 17.4 (35 prey groups), Table 17.5 (ecological prey groups) and Table 17.6 (to genus and species level for penguins, fur seals and fishery). Pelagic fish (mostly myctophids), were the primary prey (>50%) of fur seals, king, and royal penguins, while demersal fish (mostly nototheniids were important in the diets of the Macquarie shag, gentoo penguin and toothfish. Other important fish genera were *Bathylagus* (20% by mass in the diet of toothfish) and *Harpagifer* (15% by mass in the diet of Macquarie shags). Squid were a major

component of the diets of southern elephant seals and black-browed albatrosses, and accounted for 32% of the diets in toothfish (Table 17.3). Squid accounted for 24% of the diet of northern giant petrels, 14% of the diet of gentoo penguins, and 11% of the diets of southern giant petrels, and were a minor component (<5%) for all other species examined. Although *Moroteuthis* (Onychoteuthidae) was the most widely consumed squid genus (10 of 14 species), it only accounted for ≤8% of the diet in all the predatory species. Three genera of squid were dominant as prey species, *Kondakvia* in elephant seals (23%), and *Todarodes* (39%) and *Martialia* (27%) (family Ommastrephidae) in black-browed albatrosses. *Gonatus* (19%) (family Gonatidae) was the main squid taken by toothfish. All predators, with the exception of the Macquarie Shag, consumed some squid (i.e. >2%).

Pelagic crustaceans (mostly euphausiids and copepods) were the main prey for Antarctic prions and rockhopper penguins (> 70%), and were also important in the diet of royal penguins (37%). Demersal crustaceans (mostly prawns) accounted for 10% of the diet in toothfish. Carrion (mostly birds) accounted for most of the diet of northern (72%) and southern giant petrels (84%), and at sea carrion accounted for 15% of the diet of black-browed albatrosses. About 10% of the diets of New Zealand fur seals were live birds, mostly *Eudyptes* penguins The diet composition of the seals, seabirds, toothfish and the fishery around Macquarie Island, are presented in Table 17.4 (35 prey groups), Table 17.5 (ecological prey groups) and Table 17.6 (to genus and species level for penguins, fur seals and fishery). Pelagic fish (mostly myctophids), were the primary prey (>50%) of fur seals, king, and royal penguins, while demersal fish (mostly nototheniids were important in the diets of the Macquarie shag, gentoo penguin and toothfish. Other important fish genera were Bathylagidae (20 % by mass in the diet of toothfish) and Harpagiferidae (15% by mass in the diet of Macquarie shags). Squid were a major component of the diets of southern elephant seals and black-browed albatrosses, and accounted for 32% of the diets in toothfish (Table 17.3). Squid accounted for 24% of the diet of northern giant petrels, 14% of the diet of gentoo penguins, and 11% of the diets of southern giant petrels, and were a minor component (<5%) for all other species examined. Although *Moroteuthis* (Onychoteuthidae) was the most widely consumed squid genus (10 of 14 species), it only accounted for ≤8% of the diet in all the predatory species. Three genera of squid were dominant as prey species, *Kondakvia* in elephant seals (23%), and *Todarodes* (39%) and *Martialia* (27%) (family Ommastrephidae) in black-browed albatrosses. *Gonatus* (19%) (family Gonatidae) was the main squid taken by toothfish. All predators, with the exception of the Macquarie Shag, consumed some squid (i.e. >2%).

Pelagic crustaceans (mostly euphausiids and copepods) were the main prey for Antarctic prions and rockhopper penguins (> 70%), and were also important in the diet of royal penguins (37%). Demersal crustaceans (mostly prawns) accounted for 10% of the diet in toothfish. Carrion (mostly birds) accounted for most of the diet of northern (72%) and southern giant petrels (84%), and at sea carrion accounted for 15% of the diet of black-browed albatrosses. About 10% of the diets of New Zealand fur seals were live birds, mostly *Eudyptes* penguins.

Dietary overlap
The highest level of dietary overlap was among the three fur seal species (≥89%) and between fur seals and king penguins (≥87%) (Table 17.7). There were also high levels (>60%) of dietary overlap between royal and rockhopper penguins and between royal and king penguins (Table 17.7). Other major diet overlaps were between rockhopper penguins and Antarctic prions (>60%), and between northern and southern giant petrels (both >80%). The levels of dietary overlap among other species were generally below 45% (Table 17.7). There was little dietary overlap between toothfish and other species, the greatest being with the gentoo penguin (22%), and southern elephant seal (19%) (Table 17.7). There was little dietary overlap with the commercial fishery, the greatest being with its target species, toothfish (4%). Other than the

commercial fishery, the only other predator that preyed on toothfish was the gentoo penguin, however its occurrence in the diet was very low (0.1%) (Table 17.4).

Indices of dietary overlap were highly sensitive to the taxonomic resolution of prey species groups. For example, when myctophid fish, a principal component of the diet of several seals and penguins (Table 17.4), were subdivided to genus or species level (Table 17.6), diet overlap between Antarctic fur seals and king penguins decreased from 95.0% to 4.1% (Table 17.8). This was because although both predators consumed myctophids, the Antarctic fur seal consumed mostly *E. subaspera*, while king penguins consumed *E. carlsbergi* and *K. anderssoni* (Table 17.6). Similarly, the overlap in diets of Antarctic fur seals with royal, rockhopper and gentoo penguins decreased from 63 to 7%, 30 to 5% and 21 to 8%, respectively, when prey were grouped to genus or species levels (Table 17.8).

Cluster-analysis illustrated that, based on the 35 prey group, the 14 marine predators and the fishery could be grouped into seven significantly different trophic guilds (Figure 17.3). These included (1) a single species guild containing the black-browed albatross, (2) a guild containing the giant petrels, (3) a large guild containing the fur seals, king penguin, gentoo penguin and southern elephant seal, (4) a guild including the royal and rockhopper penguin and Antarctic prion, and single species guilds containing the Macquarie shag (5), toothfish (6) and the fishery (7) (Figure 17.3).

Annual prey consumption within the MI-EEZ
Estimates for the population sizes, biomasses, metabolic rates and the annual ER for the MI-EEZ are presented in Table 17.1. The estimated total annual consumption within the Macquarie Island EEZ by seals, seabirds, toothfish and the fishery is 419,774 t (Table 17.9). The majority is consumed by penguins (88.4%), followed by toothfish (7.6%), and seals (3.1%). Petrels and Macquarie shags consumed only 0.8%, and the commercial fishery 0.1% of the total prey biomass. Royal (51.5%) and king penguins (23.9%) consumed more than 75% of the total annual prey biomass. Of the total prey biomass consumed, 64% was fish, 29% crustaceans and 7% cephalopod, with <1% being seabirds or carrion (Table 17.9). Myctophids comprised most (91%) of the fish prey biomass, with the next most important groups being bathylagids (3%), nototheniids (2%) and paralepidids (2%) (Table 17.9). Euphausiids (85%) were the dominant crustacean prey by biomass, followed by amphipods (11%) and prawns (2%) (Table 17.9). Of the cephalopod prey biomass, squid from the genus *Moroteuthis* (44%), *Gonatus* (20%) and *Kondokvia* (11%) were the most important prey species (Table 17.9).

The sensitivity of the relative consumption (% of total biomass consumed) by the 14 predators and the fishery to changes (±10%) in population and metabolic parameters are presented in Table 17.10. The results indicate that relative consumption of the predators and the fishery are generally insensitive to changes in these parameters with most showing a change of <5% from the base model estimates. In general, the relative consumption was slightly more sensitive to changes in population parameters than in metabolic parameters (Table 17.10). Although the overall sensitivity is low, the results also show that the relative consumption of each predator is relatively sensitive to changes of those parameters associated with the same predator as compared to changes of those parameters associated with other predators. For example, the relative consumption by elephant seals had the highest sensitivity to changes of elephant seal population estimates and metabolic rates but not to changes of other parameters.

Seasonal variation in consumption rates
Seasonal variation in the estimated daily consumption rates of seals and seabirds feeding in the MI-EEZ are presented in Figure 17.4. Although the daily consumption rates varied considerably among species, the seasonal trends were similar, with estimated consumption being greatest from October to March (Figure 17.4a-f). For many species (royal and rockhopper penguins, Antarctic fur seals and the petrels) daily consumption within the MI-EEZ was zero for part of

the year (typically from May to September) when these species feed outside the MI-EEZ. However, when they return to the island in preparation for breeding in September and October, daily consumption rates increased rapidly (Figure 17.4f). In the absence of any data on seasonal variation in the consumption rates of toothfish, daily consumption rates were assumed to be constant at about 108 t/day. Total consumption within the MI-EEZ was lowest in August, when it averaged 176 t/d, but increased steadily from September (381 t/d) to January (2,779 t/d) and then declined rapidly through to March (1,307 t/d)(Figure 17.4f). The average daily consumption in the MI-EEZ from October to March was 1,880 t/day, and peaked at 3,045 t/day in late January (Figure 17.4f). Daily consumption rates of fish (91% myctophids) were lowest in August (192 t/d), and highest in January (1,646 t/d)(Figure 17.4f). Crustacean (85% euphausiids) and cephalopod consumption were also lowest in August (12 t/d, 37 t/d, respectively), and highest in January (981t/d, 146 t/d, respectively) (Figure 17.4f).

Discussion

Data limitations

As with previous studies that have estimated the prey consumption of seals and seabirds, there are many inherent sources of error that must be considered when interpreting our results. These include uncertainties in population estimates, particularly for king, royal and rockhopper penguins that are the major consumers of marine resources in the MI-EEZ. There are also large uncertainties in estimates of toothfish biomass at Macquarie Island, due to poor understanding of the spatial and temporal dynamics of the population (Tuck *et al*. in press). Further, the estimates used here reflect the biomass available to the fishery and not the total biomass of toothfish in the region.

Much of the diet composition data used have come from studies that were only undertaken over a single season, and sometimes only for part of one season. Therefore, we have little understanding of the inter-annual and seasonal variability in the diets of most of the marine predators around Macquarie Island. Furthermore, the taxonomic resolution of prey species for some predators is poor, and as demonstrated here, can significantly bias diet similarity analyses. There are also likely to be some errors in estimates of the energy requirements of seabirds and seals, as most of these were derived from allometric equations. Further, the calorific values for many of the prey species are unknown and were estimated from values of similar or closely related species.

Uncertainty in estimates of activity budgets (attendance patterns), and assumptions on how much time species spent feeding in the MI-EEZ are also potential sources of error. This may be particularly relevant for the southern elephant seal, where we assumed that seals feed while in transit through the MI-EEZ between their main feeding grounds and haul-out sites on Macquarie Island. It is possible that the seals are feeding at a much lower rate (or possibly not at all) during these transits.

Because of scant demographic data on all the seabirds, and the unknown number of juveniles feeding within the EEZ at any time, all breeding pairs were assumed to breed annually (with the exception of king penguins) and successfully raise chicks, and all non-breeding, pre-breeding and failed breeders were excluded. The assumption that all pairs breed successfully would inflate estimates of consumption, however, the exclusion of non-breeding birds could decrease actual consumption estimates by up to 40% (Croxall *et al*. 1985). We could have made some estimate on the numbers of juveniles that may return to the island during the breeding season, but because we have no data on this, or the duration that these animals remain in the vicinity of Macquarie Island, we have decided that it is better to omit them from our model. Our sensitivity analysis showed that relative consumption of predators and the fishery were generally insensitive to changes in population size, residence times and metabolic rates, with most showing a change of <5% from the base model estimates. As such, we believe that although the absolute estimates of consumption by predators may not be precise due to the uncertainties

described, such errors are unlikely to alter the trophic relationships we have described among predators and the fishery.

One of the strengths of this study is that it has confined estimates of consumption to the period when animals actually feed within the MI-EEZ, where information on the diet was obtained. Most other studies that have estimated the consumption of marine resources in other parts of the Southern Ocean have typically extended estimates of consumption to outside the period when animals are feeding near breeding islands, where information on their diet and spatial distribution are generally lacking.

Competition between commercial fisheries and other marine predators
An approach to evaluating the extent of prey overlap and competition between seabirds and commercial fisheries was developed by Duffy and Schneider (1994). Although developed specifically for seabirds, the model is also applicable to assessing competition between fisheries and marine mammals. It provides a hierarchical assessment of competition, based on ratios, specifically the 'Horn Ratio' (that is the same as the %PSI measure used in this study), 'Schaefer Ratio', 'Evans Ratio', 'Wiens Ratio' and the 'Bourne Ratio' (Duffy and Schneider 1994). Using this hierarchical approach, a decision is made on the extent of competition at each ratio test; if the competition is low at the first step ('Horn Ratio'), then no further analysis is needed. However, if competition is high, then each successive ratio is tested in order to examine the extent and type of competition.

In the case of the toothfish fishery at Macquarie Island, we found that the *%PSI* (or Horn Ratio) between the fishery and seabirds and seals to be very low (0.1% for gentoo penguins, ≤0.1% for all other seals and seabirds, Table 17.7 and 17.8), indicating almost no direct overlap between prey species consumed by major marine predators and taken by the commercial fishery. The Schaefer ratio comparing the catch of toothfish by gentoo penguins and the fishery is also very low (0.007). The largest dietary overlap with the commercial fishery was with the target species, Patagonian toothfish, but even this was small (<4%, Table 17.7).

The limited trophic interactions between toothfish, the fishery and seals and seabirds at Macquarie Island, primarily result from limited dietary overlap and the small percentage of total prey biomass consumed by toothfish and the fishery, relative to that consumed by seabirds and seals. This is in marked contrast to the fishery for Antarctic krill in the south-west Atlantic where there is nearly complete overlap in the diets of penguins, fur seals and the fishery, producing correspondingly high Horn and Schaefer Ratios (Croll and Tershy 1998).

A recent investigation into the diet of vagrant Hooker's sea-lions (*Phocarctos hookerii*) that haul-out periodically on Macquarie Island, found that toothfish are a common prey items (42% frequency of occurrence in scats, McMahon *et al*. 1999). Hooker's sea lions have the greatest diving capacity of all otariid seals and have been recorded to dive to about 500 m (Gales and Mattlin 1997). However, as only 5-15 individuals of this species haul-out annually at Macquarie Island, their consumption is insignificant compared to that of other seals and seabirds that breed on the island. Although cetaceans were not considered in this study due to the paucity of data, sperm (*Physeter macrocephalus*) and killer (*Orcinus orca*) whales have been reported taking toothfish from active fishing gear (Ashford *et al* 1996), and sperm and southern bottlenose (*Hyperoodon planifrons*) whales (if the latter occur in the MI-EEZ) have the diving capacity to act as natural predators of toothfish (Hooker and Baird 1999, Korabel`nikov 1959, Solyanik 1963, Yukov 1972). Greenland sharks (*Somniosus microcephalus*), which are occasionally caught as bycatch in the toothfish trawl fishery at Macquarie Island may also be a natural predator of toothfish, however, examination of the stomach contents of two caught as bycatch revealed mostly macrourid and southern elephant seal remains (R. Williams unpublished data).

The seal and seabird communities around Macquarie Island prey primarily on pelagic fish (myctophids) and pelagic crustaceans (94% of prey biomass), neither of which form important prey of toothfish or are a target or bycatch of the commercial fishery. For this reason, the ecological impacts of the fishery on seals and seabirds are likely to be minimal, and may in fact bring about the competitive release of some pelagic fish that could be consumed by seals and seabirds. More detailed ecological modelling would need to undertaken to examine this possibility. Although the fishery for toothfish is unlikely to compete for the prey of seals and seabirds, the development of new fisheries in the future may. During the 1980s, approximately 75,000 t of the myctophid *E. carlsbergi* were taken from the south-western Atlantic, and processed into meal and oil (Kock 1992). Interest in this fishery has increased in recent years, and in the 1999/2000 fishing season, the CCAMLR set a precautionary catch limit of 109,000 t for *E. carlsbergi* in the south-west Atlantic (CCAMLR Statistical subarea 48.3, CCAMLR 1999). The rapid development of intensive aquaculture fisheries around the world has meant that the demand for fish-meal has been increasing, and as such it is possible that this fishery may expand to other areas in the Southern Ocean in the future. The estimated annual consumption of *E. carlsbergi* in the MI-EEZ is about 66,000 t, most of which is consumed by king penguins. If such a fishery were to be developed around Macquarie Island, it would compete directly with seabirds and seals and would need to be carefully managed.

Diet overlaps between marine predators
The greatest diet overlap among predators within the MI-EZZ was between the myctophid predators, especially among fur seals, between fur seals and king penguins, and among king, royal and rockhopper penguins. However, closer examination revealed that although the same myctophid species dominated in the diets of all three species of fur seal, the penguins (king, royal and rockhopper) consumed different myctophid species (Table 17.6), and as such the perceived high level of overlap was in fact much lower. This highlights how sensitive such analyses are to the taxonomic resolution of the prey species. The likely reason why different myctophid species are taken by fur seals and penguins is that different species may be available near the surface at night when fur seals feed than during the day when penguins mostly feed (Goldsworthy *et al*. 1997, Robinson and Hindell 1996, Hull 1997). The extent of dietary overlap between penguin species at Macquarie Island was much lower (16-65%) than that reported between gentoo and macaroni penguins (91%) at South Georgia where crustaceans (mostly *Euphausia superba*) dominate in the diets of most seabirds (Croxall *et al*. 1997). With the exception of high levels of dietary overlap between northern and southern giant petrels and moderate overlap between Antarctic prions and rockhopper penguins, the diet overlap among other marine predators was generally low. In general, the extent of resource partitioning among predators was high within the MI-EEZ, relative to similar predator communities in the south-west Atlantic.

None of the seal or seabird species investigated had high diet overlaps with toothfish, with the greatest overlap being with gentoo penguins (22%) and southern elephant seals (19%). The real extent to which gentoo penguins actually compete with toothfish for nototheniid fish (their common prey), is probably even lower than indicated by the similarity matrix, as gentoo penguins feed predominantly close inshore and in depths <150 m (Robinson and Hindell 1996), while toothfish are found most abundantly at depths > 400 m. Most of the competition between toothfish and southern elephant seals was for squid, however the main squid species targeted by toothfish was *Gonatus antarcticus*, while for southern elephant seals at Macquarie Island this was *Kondakovia longimania* (Goldsworthy *et al*. in press, Green and Burton 1993) (Table 17.4).

Consumption of marine resources
The total annual consumption of marine resources within the MI-EEZ by seals, seabirds, toothfish and the fishery was estimated to be 419,774 t, with pelagic fish, almost entirely myctophids, being the most important prey by biomass (61%), followed by pelagic crustaceans (30%) and cephalopods (7%). Other prey categories, including demersal fish and crustaceans

and birds and carrion, were relatively minor contributors to the estimated annual prey consumption. The importance of fish in diets of seabirds and seals at Macquarie Island is in marked contrast to many locations south of the Antarctic Polar Front, particularly in the south Atlantic Ocean, where the diets of most seabirds and seals are primarily pelagic crustaceans (Croll and Tershy 1998, Croxall *et al.* 1984, 1985, 1997). At Heard Island just south of the Antarctic Polar Front in the southern Indian Ocean, seals and seabirds also consume mostly pelagic crustaceans (60%), with smaller quantities of fish (32%) and squid (8%) (Woehler and Green 1992). The consumption of 419,774 t of prey per annum equates to a consumption of approximately 1,010 kg/km^2/y from within the MI-EEZ. However, there is likely to be considerable spatial heterogeneity of this consumption.

Results from Macquarie Island are more similar to those found by Adams *et al.* (1993) at the Prince Edward Islands, also north of the Antarctic Polar Front where consumption by four species of penguin was mostly of pelagic fish (70%), with pelagic crustaceans only making up 18% and cephalopods 11% of total prey biomass. This compares with 65% pelagic fish, 31% pelagic crustacean and 3% cephalopod of total prey biomass consumed by the four species of penguin at Macquarie Island. At Heard Island, demersal fish species occurred in more than 25% of dietary samples obtained from king, macaroni and gentoo penguins, 14% of those from Antarctic fur seals, and accounted for most of the fish diet in southern elephant seals (Green and Burton 1993, Green *et al.* 1989, 1991, Woehler and Green 1992, Moore at al. 1998). This is in marked contrast to Macquarie Island where demersal fish were entirely absent in the diets of king and royal penguins, fur seals and the southern elephant seals, although they were present in gentoo penguins. Such differences in the diets likely reflect the very large area of continental shelf on the Kerguelen Plateau available to marine predators around Heard Island, relative to Macquarie Island.

The greatest consumers of marine resources within the MI-EEZ were penguins, which consumed an about 88% of the total prey consumed by seabirds, seals and toothfish, 76% of which was consumed by royal and king penguins. Toothfish were estimated to consume 8% of the total prey biomass, and southern elephants seals 3%, with remaining species consuming <1% of the total prey biomass each. Of the total prey biomass consumed by seabirds and seals around Macquarie Island, penguins consumed 96% (82% by royal and king penguins). These results are similar to estimates for Heard Island where seabirds (mostly penguins) consumed 81% (Woehler and Green 1992), and for the South Shetland Islands where consumption by chinstrap (*Pygoscelis antarctica*), Adelie (*P. adeliae*) and gentoo penguins was estimated to account for 99% of local seabird and seal consumption (Croll and Tershy 1998).

The demand for marine resources by seabirds and seals around Macquarie Island was highly seasonal (Figure 17.4). The greatest period of consumption was between October and March and peaked at over 3,045 t/d in late January. This peak coincides with the period of greatest demand and competition for resources (from December to March), when most seabirds are feeding chicks and fur seals are lactating. At this time, these species are dependant on prey biomass very near the island (<200 km), where they consume on average 2,129 t of prey per day. These daily consumption rates are similar to those reported for four penguin species breeding at the Prince Edward Islands where they range from 1,900 to 3,300 t/d (Adams *et al.* 1993).

Estimates of consumption of various prey groups presented here have assumed static population sizes of various predators. However, the populations of many of the species have changed markedly over the past 200 years, and for some species, large changes in population size may be expected in the near future. The indigenous population of fur seals was completely eliminated by sealers soon after the island's discovery in 1810, when approximately 193,300 seals were killed with fur seals only re-establishing a breeding population since the mid-1950s (Shaughnessy *et al.* 1987). Currently the breeding population only numbers about 600 with pup

production increasing at a rate of about 13.9% per year (Goldsworthy *et al*. 1998). Unlike fur seals, the southern elephant seal population has recovered from sealing, but has recently declined to about half that of the estimated population size of the 1960s (Hindell and Burton 1987). King and royal penguins were also taken for oil, but the current status of each species is not well known. The king penguin population is currently increasing, probably at 5-15% annually (E. Woehler pers. comm). The royal penguin population has probably recovered from exploitation, although its population may still be increasing (Scott 1994). Changes in the population size of the various predators will affect the composition, and quantity, of marine resources consumed around Macquarie Island, and potentially alter the extent of inter-specific competition among predators. Such competition may affect the population sizes of some species, and the recovery of others.

This study provides an initial assessment of the ecological linkages among marine predators and the commercial fishery within the MI-EEZ. Inevitably, data limitations, the exclusion of cetaceans, and potential errors in consumption estimates such as the unknown contribution of consumption within the MI-EEZ by non-breeding penguins, will lead to errors in estimates of the magnitude of trophic interaction. However, we believe that our main finding of weak trophic linkages between the commercial fishery and seabirds and seals, and between toothfish and other marine predators are unlikely to change. As more data are accumulated on population estimates, diet composition, predator foraging behavior, energy requirements and prey production, these uncertainties will be reduced. More accurate assessment of the ecological functions of toothfish, the commercial fishery, and other marine predators within the MI-EEZ will then be possible. This study provides an essential food web model for the region on which further dynamic and integrated models can be developed to assist regional marine management.

References
Abrams R. W. (1985). Energy and food requirements of pelagic aerial seabirds in different regions of the African sector of the Southern ocean. In: Siegfried, W. R., Condy, P. R. and Laws, R. M. (eds) Antarctic Nutrient Cycles and foodwebs. Proc 4th SCAR Biol Symp. Berlin: Springer-Verlag. 466-472.

Adams, N. J., Moloney, C. and Navarro, R. (1993). Estimated food consumption by penguins at the Prince Edward Islands. Antarc. Sci. 5: 245-252.

Anderson, D. W. and Gress, F. (1984). Brown Pelicans and the anchovy fishery off southern California. In: Nettleship, D. N., Sanger, A., Springer, P. F. (eds) Marine birds: their feeding ecology and commercial fisheries relationships. Ottawa: Canadian Wildlife Service special publication. 128-135.

Adams, N. J., Moloney, C. and Navarro, R. (1993). Estimated food consumption by penguins at the Prince Edward Islands. Antarc. Sci. 5: 245-252.

Ashford, J. R., Rubilar, P. S. and Martin, A. R. (1996). Interactions between cetaceans and longline fishery operations around South Georgia. Mar. Mamm. Sci. 12: 452-457.

Barrat, A. (1976). Quelques aspects de la biologie et de l'ecologie du manchot royal (Aptenodytes patagonicus) des iles Crozet. Com Natl Franc Rech Antarct 40: 9-52.

Boyd, I. L., Croxall, J. P., Lunn, N. J. and Reid, K. (1995). Population demography of Antarctic fur seals - the costs of reproduction and implications for life-histories. J Anim Ecol 64: 505-518.

Bradshaw, C. J. A., Hindell, M. A., Littnan, C. and Harcourt, R. G. (In press) Determining marine movements of Australasian pinnipeds. In: Merrick, J. R., Archer, M., Hickey, G. and Lee, M. (eds) Evolution and Biogeography of Australasian Vertebrates. Sydney: Australian Scientific Publications.

Brothers, N. P. (1985). Breeding biology, diet and morphometrics of the King Shag, *Phalacrocorax albiventer purpurascens*, at Macquarie Island. Aust. Wildl. Res. 12: 81-94.

Brothers, N. P. (1984). Breeding, distibution and status of burrow-nesting petrels at Macquarie Island. Aust Wildl Res 11: 113-131.

Brown, C. R. (1987). Energy requirements for growth and maintenance in macaroni and rockhopper penguins. Polar Biol 8: 95-102.

Brown, C. R. (1989). Energy requirements and food consumption of Eudyptes penguins at the Prince Edward Islands. Antarc Sci 1: 15-21.

Burger, A. E. and Cooper, J (1984). The effects of fisheries on seabirds in South Africa and Namibia In: Nettleship, D. N., Sanger, A. and Springer, P. F. (eds) Marine birds: their feeding ecology and commercial fisheries relationships Ottawa: Canadian Wildlife Service special publication. 150-161.

Butterworth, D. S., Duffy, D. C., Best, P. B. and Bergh, M. O. (1988). On the scientific basis for reducing the South African seal population. S Afr J Sci 84: 179-188.

Cherel, Y. and Weimerskirch, H. (1995). Sea birds as indicator of marine resources: black-browed albatrosses feeding on ommastrephid squids in Kerguelen waters. Mar Ecol Prog Ser 129: 295-300.

Clarke, A., Clarke, M. R., Holmes, L. J. and Waters, T. D. (1985). Calorific values and elemental analysis of eleven species of oceanic squid (Mollusca:Cephalopoda). J Mar Biol Assoc UK 65: 983-986.

Copson, G. R. and Rousevelle, D. E. (1987). The abundance of royal penguins (*Eudyptes schlegeli,* Finsch) breeding at Macquarie Island. ANARE Research Notes 41, 11 pp.

Costa, D. P., Croxall, J. P. and Duck, C. (1989). Foraging energetics of Antarctic fur seals, *Arctocephalus gazella*, in relation to changes in prey availability. Ecology 70: 596-606.

Croll, D. A. and Tershy, B. R. (1998). Penguins, fur seals, and fishing: prey requirements and potential competition in the South Shetland Islands, Antarctica. Polar Biol 19: 365-374.

Croxall, J. P. and Prince, P. A. (1982). A preliminary assessment of the impact of seabirds on the marine resources at South Georgia. Comite National Francais des Recherches Antarctiques 51: 501-509.

Croxall, J. P., Ricketts, C. and Prince, P. A. (1984). Impact of seabirds on marine resources, chiefly krill, of South Georgia waters. In: Whittow, G. C. and Rahn, H. (eds) Seabird energetics. New York: Plenum Publishing Corporation, 285-317.

Croxall, J. P., Prince, P. A. and Ricketts, C. (1985). Relationships between prey life-cycles and the extent, nature and timing of seal and seabird predation in the Scotia Sea. In: Siegfried, W. R., Condy, P. R., and Laws, R. M. (eds) Antartcic nutrient cycles and food webs. Springer, Berlin, 516-533.

Croxall, J. P., Prince, P. A. and Reid, K. (1997). Dietary segregation of krill-eating South Georgia seabirds. J Zool 242: 531-556.

Davies, D. H. (1958). The South African pilchard (*Sardinops ocellata*) and maasbanker (*Trachurus trachurus*). The predation of sea-birds in the commercial fishery. Union of S Afr Div Invest Rep 31: 1-16.

Davis, R. W., Croxall, J. P. and O'Connell, M. J. (1989). The reproductive energetics of gentoo (*Pygoscelis papua*) and macaroni (*Eudyptes chrysolophus*) penguins at South Georgia. J Anim Ecol 58: 59-74.

Duffy, D. C. (1983). Environmental uncertainty and commercial fishing: effects on Peruvian guano birds. Biol Conserv 26: 227-238.

Duffy, D. C. and Schneider, D. C. (1994). Sea bird-fishery interactions: a manager's guide. In: Nettleship, D. N., Buger, J. and Gochfeld, M. (eds) Seabirds on islands. Birdlife Conservation Series no 1. Birdlife International, Cambridge, 26-38.

Furness, R. W. and Cooper, J. (1982). Interactions between breeding seabirds and pelagic fish populations in the Southern Benguela Region. Mar Ecol Prog Ser 8: 243-2150.

Furness, R. W. (1984). Modelling relationships among fisheries, seabirds and marine mammals. In: Nettleship D. N., Sanger A , Springer P. F. (eds) Marine birds: their feeding ecology and commercial fisheries relationships. Ottawa: Canadian Wildlife Service special publication, 117-126.

Gales, N. J. and Mattlin, R. H. (1997). Summer diving behaviour of lactating New Zealand sea lions, Phocarctos hookeri. Can J Zool 75: 1695-1706.

Goldsworthy, S. D. (1999). Maternal attendance behaviour of sympatrically breeding Antarctic and subantarctic fur seals, *Arctocephalus spp.*, at Macquarie Island. Polar Biol. 21: 316-325.

Goldsworthy, S. D., Hindell, M. A. and Crowley, H. M. (1997). Diet and diving behaviour of sympatric fur seals, *Arctocephalus gazella* and *A. tropicalis*, at Macquarie Island. In: Hindell, M. A. and Kemper, C. (eds) Marine Mammal Research in the Southern Hemisphere Volume 1: Status, Ecology and Medicine. Surrey Beatty and Sons, Chipping Norton, 151-63.

Goldsworthy, S. D., Wynen, L., Robinson, S. and Shaughnessy, P. D. (1998). The population status and hybridisation of three sympatric fur seals (*Arctocephalus spp.*) at Macquarie Island. N.Z. Nat. Sci. 23, Supplement 68pp.

Goldsworthy, S. D., Williams, R., Lewis, M., Van den Hoff, J., Young, J. and He, X. (in press) Diets of the Patagonian toothfish (*Dissostichus eleganoides*) around Macquarie Island. Mar Freshwat Res.

Green, K., Burton, H. R. and Williams, R. (1989). Diet of Antarctic fur seals *Arctocephalus gazella* during the breeding season at Head Island. Antarc Sci 1: 317-24.

Green, K., Williams, R., Handasyde, K. A., Burton, H. R. and Shaughnessy, P. D. (1990). Interspecific and intraspecific diets of fur seals *Arctocephalus* species (Pinnipedia: Otariidea), at Macquarie Island. Aust Mammal 13: 193-200.

Green, K., Burton, H. R. and Williams, R. (1991). The diet of Antarctic fur seals during the late autumn and early winter around Head Island. Antarc Sci 3: 359-361.

Green, K. and Burton, H. R. (1993). Comparison of the stomach contents of southern elephant seals, *Mirounga leonina*, at Macquarie and Heard Islands. Mar Mamm Sci 9: 10-22.

Green, B. and Gales, R. P. (1990). Water, sodium, and energy turnover in free-living penguins. In: Davis, L. S. and Darby, J. T. (eds) Penguin Biology. Acedemic Press, San Diego pp 245-268.

Green, K, Slip, D. J. and Moore, G. J. (1998). The take of fish species by seabirds and marine mammals in the Australian Fisheries Zone around Heard Island: the potential for competition with a commercial fishery. Polar Biol 20: 273-280.

Hammill, M. O., Lydersen, C. L., Kovacs, K. M. and Sjare, B. (1997). Estimated fish consumption by hooded seals (*Cystophora cristata*), in the Gulf of St Lawence. J Northwest Atl Fish Sci 22: 249-258.

Hindell, M. A. (1988a). The diet of the king penguin *Aptenodytes patagonicus* at Macquarie Island. Ibis 130: 193-203.

Hindell, M. A. (1988b). The diet of the rockhopper penguin *Eudyptes chrysocome* at Macquarie Island. Emu 88: 227-233.

Hindell, M. A. (1988c). The diet of the royal penguin *Eudyptes schlegeli* at Macquarie Island. Emu 88: 219-226.

Hindell, M. A. (1989). The diet of the gentoo penguin *Pygoscelis papua* at Macquarie Island: winter and early breeding season. Emu 89: 71-78.

Hindell, M. A. and Burton, H. R. (1987). Past and present status of the southern elephant seal (*Mirounga leonina*) at Macquarie Island. J Zool 213: 365380.

Hindell, M. A. and Burton, H. R. (1988). Seasonal haul-out patterns of the southern elephant seal (*Mirounga leonina*) at Macquarie Island. J Mammal 69: 81-88.

Hindell, M. A., Mcconnell, B. J., Fedak, M. A., Slip, D. J., Burton, H. R., Reijnders, H. R. and Mcmahon, C. R. (1999). Environmental and physiological determinants of successful foraging by naive southern elephant seal pups during their first trip to sea. Can J Zool 77: 1807-1821.

Hooker, S. K. and Baird, R. W. (1999). Deep-diving behaviour of the northern bottlenose whale, *Hyperoodon ampullatus* (Cetacea : Ziphiidae). Proc R Soc Lon, Ser B: Biol Sci 266: 671-676.

Hull, C. L. (1997). The comparative foraging ecology of Royal *Eudyptes schlegeli* and Rockhopper *E. chrysocome* Penguins. PhD thesis. University of Tasmania, Australia.

Hull, C. L. (1999a). Comparison of the diets of breeding royal (*Eudyptes schlegeli*) and rockhopper (*Eudyptes chrysocome*) penguins on Macquarie Island over three years. J Zool 247: 507-529.

Hull, C. L. (1999b). The foraging zones of breeding royal (*Eudyptes schlegeli*) and rockhopper (E. chrysocome) penguins: an assessment of techniques and species comparisons. Wild Res 26: 789-803.

Hull, C. L., Hindell, M. A. and Michael, K. (1997). Foraging zones of royal penguins during the breeding season, and their association with oceanographic features. Mar Ecol Prog Ser 153: 217-228.

Hunt, J. R. (1985). A preliminary comparison of marine bird biomass and food consumption between the south eastern Berring Sea and parts of the Southern Ocean. In: Siegfried, W.R., Condy, P.R. and Laws, R.M. (eds) Antartcic nutrient cycles and food webs. Springer-Verlag, Berlin, 487-492.

Hunter, S. (1983). The food and feeding ecology of the giant petrels *Macronectes halli* and *M. giganteus* at South Georgia. J Zool Lond 203: 521-38.

Ichii, T., Naganobu, N. and Ogishima, T. (1996). Competition between the krill fishery and penguins in the South Shetland Islands. Polar Biol 16: 63-70.

Jackson, S. (1986). Assimilation efficiencies of White-chinned Petrels (*Procellaria aequinoctialis*) fed different prey. Comp Biochem Physiol 85A: 301-303.

Jaksic, F. M. and Medel, R. G. (1990). Objective recognition of guilds: testing for statistically significant species clusters. Oecologia 82: 87-92.

Johnstone, G. W. (1977). Comparative feeding ecology of the giant petrels *Macronectes giganteus* (Gmelin) and *M. halli* (Mathews). In: Llana GA (ed) Adaptations within Antarctic Ecosystems. Proc 3rd SCAR Symposium on Antarctic Biology, 647-668.

Kato, A., Nishiumi, I. and Naito, Y. (1996). Sex differences in the diet of King Cormorants at Macquarie Island. Polar Biol 16: 75-77.

Kock, K-H. (1992). Antarctic fish and fisheries. Cambridge University Press, Cambridge. 359pp.

Korabel`nikov, L. V. (1959). The food of the sperm whale in the Antarctic seas. Priroda No 3.

Koteja, P. (1991). On the relation between basal and field metabolic rates in birds and mammals. Funct Ecol 5: 56-64.

Marchant, S. and Higgins, P. J. (1990). Handbook of Australian, New Zealand and Antarctic Birds. Melbourne, Oxford University Press Vol 1A 735 pp.

Matthews, J. P. (1961). The pilchard of South-West Africa (*Sardinops ocellata*) and maasbanker (*Trachurus trachurus*): bird predators, 1957–1958. SW Afr Res Lab Invest Rep Mar 3: 1-35.

McCann, T. S. (1985). Size, status and demography of southern elephant seal (*Mirounga leonina*) populations. In: Ling JK and Bryden MM (eds) Sea mammals in south

latitudes. Proceedings of a Symposium of the 52nd ANZAAS Congress, South Australian Museum, Adelaide, 1-17.

McMahon, C. R., Holly, D. and Robinson, S. (1999). The diet of itinerant male Hooker's sea lions, *Phocartos hookeri*, at sub-Antarctic Macquarie Island. Wildl Res 26: 839-846.

Moore, G. J., Robertson, G. and Wieneke, B. (1998). Food requirements of breeding king penguins at Heard Island and potential overlap with commercial fisheries. Polar Biol 20: 293-302.

Palomares, M. L. and Pauly, D. (1989). A multiple regression model for predicting the food consumption of marine fish populations. Aus J Mar Freshw Res 40: 259-73.

Prince, P. A. (1980a). The food and feeding ecology of grey-headed albtross *Diomedea chrysostoma* and black-browed albatross *D. melanophris*. Ibis 122: 476-488.

Prince, P. A. (1980b). The food and feeding ecology of blue petrel (*Halobaena caerulea*) and Dove prion (*Pachyptila desolata*). J Zool 190: 59-76.

Reilly, P. N. and Kerle, J. A. (1981). A study of the gentoo penguin *Pygoscelis papua*. Notornis 28: 189-202.

Reid, K., Croxall, J.P. and Edwards, T. M. (1997). Interannual variation in the diet of the Antarctic Prion *Pachyptila desolata* at South Georgia. Emu 97: 126-132.

Robinson, S. A. and Scott, J. J. (1999). Marine conservation at Macquarie Island. Tasmanian Parks and Wildlife Service 61 pp.

Robinson, S. A. and Hindell, M. A. (1996). Foraging ecology of gentoo penguins *Pygoscelis papua* at Macquarie Island during the period of chick care. Ibis 138: 722-731.

Rousevelle, D. E. and Brothers, N. P. (1984). The status and conservation of seabirds at Macquarie Island. In: Croxall, J. P. and Schreiber, P. G. H. (eds) Status and conservation of the world's seabirds. ICBP Tech Publ 2, Cambridge.

Schoener, T. W. (1970). Non-synchronous spatial overlap of lizards in patchy habitats. Ecology 51: 408-418.

Scott, J. J. (1994). Marine conservation at Macquarie Island. Tasmanian Parks and Wildlife Service and Ocean Rescue 2000. 141 pp.

Shaughnessy, P. D. and Fletcher, D. (1987). Fur seals, *Arctocephalus spp.*, at Macquarie Island. In: Croxall, J. P. and Gentry, R. L. (eds) Status, Biology and Ecology of Fur Seals. Proceedings of an International Symposium and Workshop, Cambridge, England, 177-188.

Slip, D. J. (1997). Foraging ecology of southern elephant seals from Heard Island. PhD thesis, University of Tasmania, Australia.

Slip, D. J., Hindell, M. A. and Burton, H. R. (1994). Diving behaviour of elephant seals from Macquarie Island: an overview. In: Le Boeuf, B.J. and Laws, R.M. (eds) Elephant seals: population ecology, behavior, and physiology. University of California Press, Berkeley, 253-270.

Stenson, G. B., Hammill, M. O. and Lawson, J. W. (1997). Predation by harp seals in Atlantic Canada: preliminary consumption estimates for Artcic cod, capelin and Atlantic cod. J Northwest Atl Fish Sci 22: 137-154.

Solyanik, G. A. (1963). An interesting ichthyological find. Inform Byul Sov Antarkt Eksped No. 42.

Trites, A. W., Christensen, V. and Pauly, D. (1997). Competition between fisheries and marine mammals for prey and primary production in the Pacific Ocean. J Northwest Atl Fish Scie 22: 173-187.

Trites, A. W., Livingstom, P. A., Mackinson, S., Vasconcellos, M. C., Springer, A. M. and Pauly, D. (1999). Ecosystem change and the decline of marine mammals in the eastern Bering sea: testing the ecosystem shift and commercial whaling hypothesis. Fisheries Centre Research Reports, Vol 7.

Tuck, G. N., Hearn, W. S., Williams, R., Smith, A. D. M., He, X., Constable, A. and de la Mare, W. K. (in press) An exact time of release and recapture assessment model with an application to abundance and recruitment estimation for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island.

Voisin, J. F. and Bester, M. N. (1981). The specific status of giant petrels *Macronectes* at Gough Island. In: Cooper J (ed) Proceedings of the Symposium on Birds of the sea and shore. African seabird Group, Cape Town, 215-22.

Warham, J. (1963). The rockhopper penguin, *Eudyptes chrysocome*, at Macquarie Island. Auk 80: 229-256.

Warham, J. (1996). The behaviour, population biology and physiology of the petrels. Acedemic Press, London, UK 613 pp.

Weimerskirch, H., Jouventin, P. and Stahl, J-C. (1986). Comparative ecology of the six albtross species on the Crozet Islands. Ibis 128: 195-213.

Weimerskirch, H., Zotier, H. and Jouventin, P. (1989). The avifauna of the Kerguelen Islands. Emu 89: 15-29.

Weimerskirch, H., Stahl, J-C. and Jouventin, P. (1992). The breeding biology and population dynamics of king penguins *Aptenodytes patagonica* on the Crozet Islands. Ibis 134: 107-117.

Woehler, E. J. and Green, K. (1992). Consumption of marine resources by seabirds and seal at Heard Island and the McDonald Islands. Polar Biol 12: 659-665.

York, A. (1987). Northern fur seal, *Callorhinus ursinus*, Eastern Pacific Population (Pribilof Islands, Alaska, and San Miguel, Island California). In 'Status, biology and ecology of fur seals' (eds J.P. Croxall and R.L. Gentry) NOAA Technical Report National Marine Fisheries Service No 51, pp 9-21.

Yukhov, V. L. (1972). The range of the genus Dissostichus (Family Nototheniidae) in the Antarctic waters of the Indian Ocean. J Ichthyol 12: 346-347.

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.1 Population and biomass estimates, mean individual mass, metabolic rates and estimated annual days and energy used for 13 marine predators in the Macquarie Island EEZ. Sources of data and estimates are given in the text. Abbreviations are: M=male, F=female, SAM=sub-adult males, FMR=field metabolic rate, ME=metabolic energy, ER=energy requirements.
[1] Annual pup production, [2] total animals, [3] breeding pairs

Predator	Estimated population range	Population Estimate used (individuals)	Estimated biomass (t)	Sex Age class	Mean individual mass (kg)	FMR sea (kJ/d)	FMR shore (kJ/d)	Days in EEZ	ME	Annual ER from EEZ (MJ)
Southern elephant seal	20,000[1]	86,150	39,283					14		809
Antarctic fur seal	106[1]	457	15	M	140.0	76,689	59,996	75	0.74	5,949
				F	33.8	33,411	14,483	134	0.74	3,847
				SAM	65.0	35,605	27,855	90	0.74	3,266
				Juv	16.0	8,810	6,892	90	0.74	808
Subantarctic fur seal	30[1]	129	4	M	140.0	76,689	59,996	75	0.74	5,949
				F	33.8	33,411	14,483	319	0.74	9,066
				SAM	65.0	35,605	27,855	90	0.74	3,266
				Juv	16.0	8,810	6,892	90	0.74	808
New Zealand fur seal	2-3,000[2]	2,500	150	AM-Juv	60.0	32,867	25,713	49	0.74	1,634
King penguin	131,863-299,019[3]	323,162		M	12.8	7,860	3,499	237	0.74	1,816
				F	11.5	7,275	3,256	247	0.74	1,704
Royal penguin	850,000[3]	1,700,000	9,435	M	5.7	4,035	1,883	216	0.74	776
				F	5.4	4,035	1,883	214	0.74	776
Rockhopper penguin	100,000-500,000[3]	600,000	2,190	M	3.6	2,843	1,360	199	0.74	437
				F	3.7	2,843	1,360	208	0.74	458
Gentoo penguin	4,700-6,800[3]	11,500	66	Breeding	5.7	4,383	2,033	150	0.74	574
				Winter	5.7	4,383	2,033	215	0.74	804
Black-browed albatross	180[3]	360		Adults	3.7	2,500	945	225	0.69	490
Northern giant petrel	1,000[3]	2,000		M	4.8	2,919	1,141	180	0.69	472
				F	3.6	2,469	931	180	0.69	403
Southern giant petrel	4,000[3]	8,000	19	M	5.1	3,040	1,199	280	0.69	757
				F	4.2	2,714	1,044	280	0.69	679
Antarctic prion	48,900[3]	97,800	7,188	Adults	0.15	393	99	156	0.69	52
Macquarie shag	768[3]	1,536		M	3.6	2,905	1,367	365	0.69	950
				F	2.6	2,366	1,113	365	0.69	773
Toothfish			62,473							

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.2 Details on the sources of diet information used in this study, and the type, number and timing when samples were collected. The form in which prey composition data were available (FM – frequency by mass, FN – frequency by number, FO – frequency of occurrence), and how data were converted to FM, where needed, are also presented.

Species	Type of samples	No. and location	Year	Months	Data form	Source
Southern elephant seal	Stomach contents from dead seals, stomach flushed	71- MI	1978-85 1987-88 1989-90	Spring-summer	FM – squid FN - fish [1,2]	Green & Burton 1993
Antarctic fur seal	Faecal	138- MI	1990-91	Dec-Mar	FN-fish, FO-squid [1,3]	Goldsworthy et al. 1997,
Subantarctic fur seal						Goldsworthy unpub. data
New Zealand fur seal	Faecal	371- MI	1988-89	Nov-Mar	FN-fish FO-squid, birds [1,4]	Green et al. 1990
King penguin	Stomach contents	144- MI	1984-85	Nov-Nov	FM	Hindell 1988a
Royal penguin	Stomach contents	258- MI	1984-85	Nov-Feb	FM	Hindell 1988c
	Stomach contents	304- MI	1993-96	Nov-Feb	FM	Hull 1997, 1999b
Rockhopper penguin	Stomach contents	104- MI	1984-85	Nov-Feb	FM	Hindell 1988b
	Stomach contents	236- MI	1984-85	Dec-Feb	FM	Hull 1997, 1999b
Gentoo penguin	Stomach contents	98- MI	1985	Apr-Nov	FM	Hindell 1989
	Stomach contents	82- MI	1993-94	Oct-Jan	FM	Robinson & Hindell 1996
Black-browed albatross	Regurgitations	Unknown- MI	1997-1999	Spring-autumn	FM [5]	A. Terauds pers. comm.

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.2 continued

Species	Type of samples	No. and location	Year	Months	Data form	Source
Northern giant petrel	Regurgitations	341- MI	1969-70 1970-71	Spring-autumn	FO [6]	Johnstone 1977
Southern giant petrel	Regurgitations	310- MI	1969-70 1970-71	Spring-autumn	FO [6]	Johnstone 1977
Antarctic prion	Regurgitations	90– South Georgia	1974/75	Dec-Mar	FM	Prince 1980a Reid *et al.* 1997
Macquarie shag	Regurgitations	77- MI	1975-79	Dec-Feb	FM	Kato *et al.* 1996
Patagonian toothfish	Stomach contents	1423- MI	1995-1999	Nov- Mar	FM	Goldsworthy *et al.* in press
Fishery	Commercial hauls	839 hauls	1996/97 – 1998/99	Nov – Feb	FM [7]	Chapters 6 and 13

1. Fish taxa numerical abundance (based on the presence as otoliths) converted to relative biomass using estimates of prey mass.
2. Biomass contribution of cephalopods (55%) and fish (45%) at Macquarie Island, based on the estimate by Slip (1997) for Heard Island southern elephant seals.
3. Estimated biomass contribution of fish (95%) and cephalopods (5%) (Goldsworthy unpublished data).
4. Estimated biomass contribution of fish (85%), cephalopods (5%) and birds (10%) (Goldsworthy unpublished data).
5. Estimates of fish (15%), cephalopods (65%), crustacean (5%) and carrion (15%) biomass in the diet from A. Terauds (pers. comm.). Cephalopod prey species and their relative contribution based on data from Iles Kerguelen (Cherel and Weimerskirch 1995). Fish component in the diet based on Prince 1980a).
6. Study used to determine prey composition. Mass contribution of prey items estimated using prey biomass data in Hunter (1983).
7. Excluding corals and sponges.

Table 17.3 Mean energy content (MJ/kg wet mass), available standard deviations (*SD*), and numbers of samples (*N*) of 16 prey taxa groups used in the analysis.

Prey taxon	Energy Content MJ/kg	*SD*	*N*	Source
Fish:				
Bathylagus antarcticus	3.93	1.17	18	M. Tierny unpublished data
Protomyctophum spp. [1]	7.54	2.97	42	M. Tierny unpublished data
Krefftichthys anderssoni	8.36	0.92	18	M. Tierny unpublished data
Electrona antarctica	8.77	2.40	20	M. Tierny unpublished data
E. carlsbergi	5.37	1.65	6	M. Tierny unpublished data
E. subaspera	7.42	0.59	6	M. Tierny unpublished data
Gymnoscopelus spp. [2]	9.05	2.79	42	M. Tierny unpublished data
Anitmora rostrata (Moridae)	1.26	0.11	2	M. Tierny unpublished data
Lepidonotothen squamifrons	5.00			G. Robinson unpublished data
Cephalopods:				
Todarodes sp.	4.01		2	Clarke *et al.* 1985
Moroteuthis sp.	1.84		1	Clarke *et al.* 1985
Gonatus sp.	3.78		4	Clarke *et al.* 1985
Histioteuthis sp.	2.65		5	Clarke *et al.* 1985
Mastigoteuthis sp.	1.82		3	Clarke *et al.* 1985
Crustaceans	4.68			Brown 1987

[1]Includes: 12 *P. andreashevii*, 18 *P. bolini*, 6 *P. parellelum*, 6 *P. tennisoni*.

[2]Includes: 18. *G. fraseri*, 18 *G. braueri*, 6 *G. microlampus*.

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.4 Percentages of prey biomass for 35 prey groups in the diets of 14 marine predators and the fishery in the Macquarie Island EEZ. The 35 prey groups are further aggregated into four major groups: fish, Cephalopods, Crustaceans, and birds/carrion (bottom panel, over page).

	Prey groups	Southern elephant seal	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Black-browed albatross	Northern giant petrel	Southern giant petrel	Antarctic prion	Macquarie Shag	Toothfish	Fishery
Fish	Myctophids	37.3	95.0	95.0	84.9	92.7	59.0	27.2	40.7	0	0	0	1.8	0	4.5	0
	Bathylagids	7.7	0	0	0	0	0	0	0	0	0	0	0	0	19.5	0
	Nototheniids	0	0	0	0.1	0	0	0	2.6	15.0	2.0	1.0	0	85.1	12.1	0.1
	Dissostichus	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	96.4
	Harpagiferidae	0	0	0	0	0	0	0	0.3	0	0	0	0	14.9	0	0
	Congiopodidae	0	0	0	0	0	0	0	9.0	0	0	0	0	0	0	0
	Moridae	0	0	0	0	0	0	0	0	0	0	0	0	0	6.7	0.5
	Macrouridae	0	0	0	0	0	0	0	0	0	0	0	0	0	10.6	2.7
	Paralepididae	0	0	0	0	5.0	0	0	0.2	0	0	0	0	0	0	0
	Bothidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0
	Shark	0	0	0	0	0	0	0	0	0	0	0	0	0	4.2	0
Cephalopods	*Alluroteuthis*	4.4	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0
	Brachioteuthis	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Chiroteuthis	0.2	0	0	0	0	0	0	0	0	0.8	0	0	0	1.9	0
	Cirroteuthis	0	1.3	1.3	1.3	0	0	0	0	0	0	0	0	0	0.8	0
	Galiteuthis	0.3	0	0	0	0	0	0	0	0	3.2	3.0	0	0	0.6	0
	Gonatus	0.5	0	0	0	0	0	0	0	0	1.2	0	0	0	19.0	0
	Histioteuthis	8.2	0	0	0	0	0	0	0	0	2.0	0	0	0	1.0	0
	Kondakovia	23.4	0	0	0	0	0.2	0	0	0	0	2.0	0	0	0	0

Continued next page…

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.4 continued

	Prey groups	Southern elephant seal	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Black-browed albatross	Northern giant petrel	Southern giant petrel	Antarctic prion	Macquarie Shag	Toothfish	Fishery
Cephalopods	*Martialia*	1.4	0	0	0	0.1	0.2	0.1	6.3	26.5	15.2	6.0	0	0	0	0
	Mastigoteuthis.	0	0	0	0	0	0	0	0	0	0.4	0	0	0	2.2	0
	Moroteuthis	5.6	3.8	3.8	3.8	2.1	3.4	2.2	7.9	0	0.8	0	0	0	5.0	0
	Octopoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0
	Taonius	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0.2	0
	Todarodes	10.9	0	0	0	0	0.1	0	0	38.5	0	0	0	0	0	0
	Vampryoteuthis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crustaceans	Euphausiids	0	0	0	0	0	31.9	67.0	0	0	0	0	57.6	0	0	0
	Prawns	0	0	0	0	0	0	0	0	0	0	0	0	0	9.3	0
	Crabs	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0.3
	Amphipods	0	0	0	0	0	5.2	3.4	0	0	0	0	8.1	0	0	0
	Ostracods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Copepods	0	0	0	0	0	0	0	0	0	0	0	31.9	0	0	0
	Other Crustacea	0	0	0	0	0	0	0	0	5.0	2.0	4.0	0	0	0	0
	Birds	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
	Carrion	0	0	0	0	0	0	0	0	15.0	72.0	84.0	0	0	0	0
	Fish	45.0	95.0	95.0	85.0	97.8	59.0	27.2	85.9	15.0	2.0	1.0	1.8	100	58.1	99.7
	Cephalopods	55.0	5.0	5.0	5.0	2.2	3.9	2.4	14.1	65.0	24.0	11.0	0.6	0	31.6	0
	Crustaceans	0	0	0	0	0	37.1	70.3	0	5.0	2.0	4.0	97.6	0	10.3	0.3
	Birds/Carrion	0	0	0	10	0	0	0	0	15.0	72.0	84.0	0	0	0	0

Predators

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.5 Percentages of prey biomass combined into six ecological prey groups, in the diets of 14 marine predators and the fishery in the Macquarie Island EEZ.

Prey groups	Southern elephant seal	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Black-browed albatross	Northern giant petrel	Southern giant petrel	Antarctic prion	Macquarie Shag	Toothfish	Fishery
Pelagic fish	45.0	95.0	95.0	84.9	97.8	59.0	27.2	40.8	0.0	0.0	0.0	1.8	0.0	24.0	0.0
Demersal fish	0	0	0	0.1	0	0	0	45.0	15.0	2.0	1.0	0	100	34.2	99.7
Cephalopods	55.0	5.0	5.0	5.0	2.2	3.9	2.4	14.1	65.0	24.0	11.0	0.6	0	31.6	0
Pelagic crustaceans	0	0	0	0	0	37.1	70.3	0	5.0	2.0	4.0	97.6	0	0	0
Demersal crustaceans	0	0	0	0	0	0	0	0	0	0	0	0	0	10.3	0.3
Birds & carrion	0	0	0	10	0	0	0	0	15.0	72.0	84.0	0	0	0	0

Table 17.6 Percentages of prey biomass in the diets of the major myctophid-consuming predators and the fishery (including bycatch species) in the Macquarie Island EEZ. The taxonomic grouping of prey is to genus or species.

Prey species	Predators							
	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Fishery
Fish								
Magnisudis prionosa	0	0	0	4.5	0	0	0.2	0
Notolepis sp.	0	0	0	0.5	0	0	0	0
Krefftichthys anderssoni	0	0	4.0	38.0	51.8	23.2	9.2	0
Protomyctophum spp.	0	0	0	0.9	0	0	0.4	0
Electrona antarctica	0	0	0.1	0	0	0	0	0
E. carlsbergi	1.6	0.2	0.5	53.6	4.8	2.8	15.0	0
E. subaspera	92.0	86.7	55.1	0	2.4	1.3	1.2	0
Gymnoscopelus spp.	1.3	8.1	25.3	0.3	0	0	14.7	0
Zanclorhynchus spinifer	0	0	0	0	0	0	9.0	0
Harpagifer georgianus	0	0	0	0	0	0	0.3	0
Macrourus carinatus	0	0	0	0	0	0	0	1.5
Other Macrourids	0	0	0	0	0	0	0	1.1
Antimora rostata	0	0	0	0	0	0	0	0.3
Halargyreus johnsonii	0	0	0	0	0	0	0	0.2
Dissostichus eleginoides	0	0	0	0	0	0	0.1	96.4
Lepidonotothen squamifrons	0	0	0	0	0	0	11.1	0.1
Notothenia rossii	0	0	0	0	0	0	1.0	0
Paranotothenia magellanica	0	0	0.1	0	0	0	23.6	0
Cephalopods:								
Kondakovia longimana	0	0	0	0	0.2	0	0	0
Martialia hyadesi	0	0	0	0.1	0.2	0.1	6.3	0
Chiroteuthis spp.	1.3	1.3	1.3	0	0	0	0	0
Moroteuthis spp.	3.8	3.8	3.8	2.1	3.4	2.2	7.9	0
Todarodes spp.	0	0	0	0	0.1	0	0	0
Crustacea:								
Lithodes sp.	0	0	0	0	0	0	0	
Euphausia spp.	0	0	0	0	31.9	67.0	0	0
Themisto gaudichaudii	0	0	0	0	5.2	3.4	0	0
Birds (*Eudyptes* sp.)	0	0	10	0	0	0	0	0

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.7 Diet overlaps between 14 marine predators and the fishery in the Macquarie Island EEZ, based on the 35 prey groups presented in Table 17.3. Diet overlap is expressed as percentage similarity index (%PSI).

	Predator													
	Southern elephant seal	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Black-browed albatross	Northern giant petrel	Southern giant petrel	Antarctic prion	Macquarie Shag	Toothfish
Antarctic fur seal	41.0													
Subantarctic fur seal	41.0	100												
New Zealand fur seal	41.0	89.9	89.9											
King penguin	39.5	94.9	94.9	87.0										
Royal penguin	41.1	62.5	62.5	62.5	61.2									
Rockhopper penguin	29.7	29.5	29.5	29.5	29.4	64.9								
Gentoo penguin	44.3	44.4	44.4	44.5	43.0	44.3	29.6							
Black-browed albatross	12.4	0	0	0.1	0.1	0.3	0.1	21.3						
Northern giant petrel	5.2	0.8	0.8	0.9	0.9	1.0	0.9	9.1	34.2					
Southern giant petrel	3.7	0	0	0.1	0.1	0.4	0.2	7.0	26.0	84.0				
Antarctic prion	2.4	1.8	1.8	1.8	1.8	38.9	62.8	1.8	0	0	0			
Macquarie Shag	0	0	0	0.1	0	0	0	36.0	15.0	2.0	1.0	0		
Toothfish	19.2	9.1	9.1	9.1	6.6	7.9	6.7	21.6	12.1	7.0	1.6	1.8	12.1	
Fishery	0	0	0	0.1	0	0	0	0.2	0.1	0.1	0.1	0	0.1	3.6

Table 17.8 Diet overlap between predators (fur seals and penguins) and the fishery in the Macquarie Island EEZ based taxonomic grouping to genus and species level as presented in Table 17.5. Diet overlap is expressed as percentage similarity index (%PSI).

	Predator						
	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin
Subantarctic fur seal	93.3						
New Zealand fur seal	62.0	68.4					
King penguin	4.1	2.6	6.8				
Royal penguin	7.4	6.0	10.2	45.0			
Rockhopper penguin	5.1	3.7	7.9	28.2	64.9		
Gentoo penguin	8.0	13.3	24.2	27.4	18.9	15.6	
Fishery	0	0	0	0	0	0	0.1

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.9 The estimated annual prey consumption (t) of 14 marine predators and the fishery in the Macquarie Island EEZ on the 35 prey groups (top panel), on six aggregated prey groups (middle panel), and on all prey combined (bottom panel).

	Prey	Southern elephant seal	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Black-browed albatross	Northern giant petrel	Southern giant petrel	Antarctic prion	Macquarie shag	Toothfish	Fishery	Total
Pelagic fish	Bathylagidae	932	0	0	0	0	0	0	0	0	0	0	0	0	6,255	0	7,187
	Paralepididae	0	0	0	0	5,059	0	0	6	0	0	0	0	0	0	0	5,065
	Myctophidae	4,486	151	75	610	93,184	127,657	13,709	1,564	0	0	0	25	0	1,432	0	242,891
Demersal fish	Squalidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1,357	0	1,357
	Macrouridae	0	0	0	0	0	0	0	0	0	0	0	0	0	3,401	15	3,416
	Moridae	0	0	0	0	0	0	0	0	0	0	0	0	0	2,149	3	2,152
	Congiopodidae	0	0	0	0	0	0	0	345	0	0	0	0	0	0	0	345
	Harpagiferidae	0	0	0	0	0	0	0	10	0	0	0	0	36	0	0	45
	Dissosticus	0	0	0	0	0	0	0	4	0	0	0	0	0	0	550	553
	Other Nototheniidae	0	0	0	1	0	0	0	1,373	7	4	11	0	359	3,884	1	5,641
	Bothidae	0	0	0	0	0	0	0	0	0	0	0	0	0	170	0	170
Cephalopods	*Alluroteuthis*	535	0	0	0	0	0	0	0	0	0	0	8	0	0	0	543
	Brachioteuthis	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
	Chiroteuthis	25	0	0	0	0	0	0	0	0	2	0	0	0	606	0	633
	Cirroteuthis	0	2	0	9	0	0	0	0	0	0	0	0	0	271	0	282
	Galiteuthis	36	0	0	0	0	0	0	0	0	7	34	0	0	195	0	272
	Gonatus	58	0	0	0	0	0	0	0	0	3	0	0	0	6,098	0	6,158
	Histioteuthis	981	0	0	0	0	0	0	0	0	4	0	0	0	317	0	1,302

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.9 continued.

Group	Prey	Southern elephant seal	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Black-browed albatross	Northern giant petrel	Southern giant petrel	Antarctic prion	Macquarie shag	Toothfish	Fishery	Total
Cephalopods	Kondakovia	2,813	0	0	0	0	426	23	0	0	0	23	0	0	0	0	3,285
	Martialia	173	0	0	0	101	420	71	242	13	32	69	0	0	0	0	1,222
	Mastigoteuthis	0	0	0	0	0	0	0	0	0	0	1	0	0	707	0	708
	Moroteuthis	677	6	3	27	2,125	7,423	1,127	302	0	2	0	0	0	1,618	0	13,310
	Taonius	0	0	0	0	0	0	0	0	0	1	0	0	0	71	0	72
	Todarodes	1,317	0	0	0	0	126	0	0	19	0	0	0	0	0	0	1,462
	Vampryoteuthis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Octopoda	0	0	0	0	0	0	0	0	0	0	0	0	0	245	0	245
Crustacea	Euphausiids	0	0	0	0	0	68,895	33,719	0	0	0	0	788	0	0	0	103,402
	Prawns	0	0	0	0	0	0	0	0	0	0	0	0	0	2,976	0	2,976
	Crabs	0	0	0	0	0	0	0	0	0	0	0	0	0	328	2	330
	Amphipods	0	0	0	0	0	11,353	1,692	0	0	0	0	111	0	0	0	13,156
	Ostracods	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	8
	Copepods	0	0	0	0	0	0	0	0	0	0	0	436	0	0	0	436
	Other Crustaceans	0	0	0	0	0	0	0	0	2	4	46	0	0	0	0	52
	Birds	0	0	0	72	0	0	0	0	0	0	0	0	0	0	0	72
	Carrion	0	0	0	0	0	0	0	0	7	152	961	0	0	0	0	1120
	Pelagic fish	5,418	151	75	610	98,242	127,657	13,709	1,569	0	0	0	25	0	7,687	0	255,143
	Demersal fish	0	0	0	1	0	0	0	1,728	7	4	11	0	395	10,961	19	13,126
	Cephalopods	6,622	8	4	36	2,226	8,395	1,221	544	32	51	126	8	0	10,128	0	29,400
	Pelagic crustaceans	0	0	0	0	0	80,248	35,411	0	2	4	46	1,335	0	8	0	117,054
	Demersal crustaceans	0	0	0	0	0	0	0	0	0	0	0	0	0	3,304	2	3,306
	Bird & carrion	0	0	0	72	0	0	0	0	7	152	961	0	0	0	0	1,192
	Total consumption	12,040	158	79	718	100,468	216,300	50,341	3845	49	211	1,144	1,368	395	32,088	570	419,774
	Total consumption (%)	2.87	0.04	0.02	0.17	23.93	51.53	11.99	0.92	0.01	0.05	0.27	0.33	0.09	7.64	0.14	

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS

Table 17.10. Sensitivities of relative consumption estimates of the 14 predators and the fishery to 10% changes in population size and metabolic rate estimates of the five main consumers of marine resources in the MI-EEZ used in this study.

Parameter and species	% change in parameter	Sensitivity - Percentage (%) change in consumption														
		Southern elephant seal	Antarctic fur seal	Subantarctic fur seal	New Zealand fur seal	King penguin	Royal penguin	Rockhopper penguin	Gentoo penguin	Black-browed albatross	Northern giant petrel	Southern giant petrel	Antarctic prion	Macquarie shag	Toothfish	Fishery
Population size																
Southern elephant seal	10	9.7	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
	-10	-9.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
King penguin	10	-2.3	-2.3	-2.3	-2.3	7.4	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3
	-10	2.5	2.5	2.5	2.5	-7.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Royal penguin	10	-4.9	-4.9	-4.9	-4.9	-4.9	4.6	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9
	-10	5.4	5.4	5.4	5.4	5.4	-5.1	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Rockhopper penguin	10	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	8.7	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2
	-10	1.2	1.2	1.2	1.2	1.2	1.2	-8.9	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Toothfish	10	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	9.2	-0.8
	-10	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	-9.3	0.8
Metabolic rate																
Southern elephant seal	10	9.7	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
	-10	-9.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
King penguin	10	-2.0	-2.0	-2.0	-2.0	6.5	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
	-10	2.1	2.1	2.1	2.1	-6.8	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Royal penguin	10	-4.4	-4.4	-4.4	-4.4	-4.4	4.2	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4
	-10	4.9	4.9	4.9	4.9	4.9	-4.6	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
Rockhopper penguin	10	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	7.8	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1
	-10	1.1	1.1	1.1	1.1	1.1	1.1	-7.9	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Toothfish	10	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	4.6	-0.4
	-10	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	-4.9	0.4

Figure 17.1 Food web diagram showing major trophic groups and interactions for the Macquarie Island EEZ. The diagram was based on a preliminary model developed in the Predator-prey Workshop (AAD 1997) and available diet data from seals, seabirds and toothfish (Chapter 16 and this chapter). Arrows represent major interactions (>10% of diet) between groups where data are available.
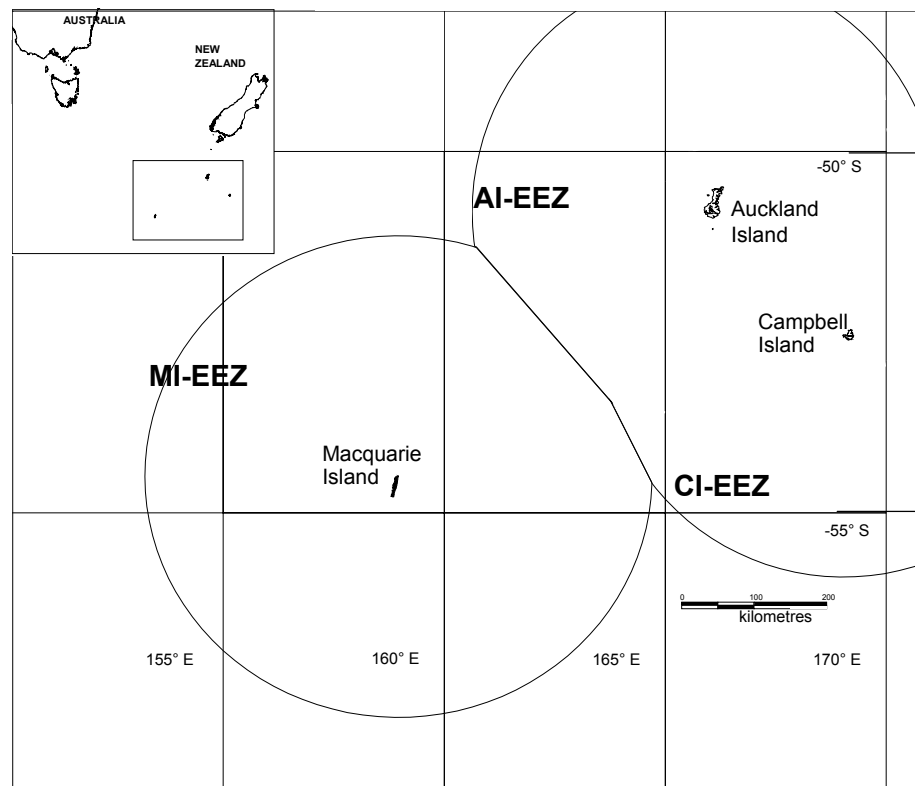
Figure 17.2 The location of Macquarie Island Exclusive Economic Zone (MI-EEZ), relative to the Campbell Island Exclusive Economic Zone (CI-EEZ) and the Auckland Island Exclusive Economic Zone (AI-EEZ).
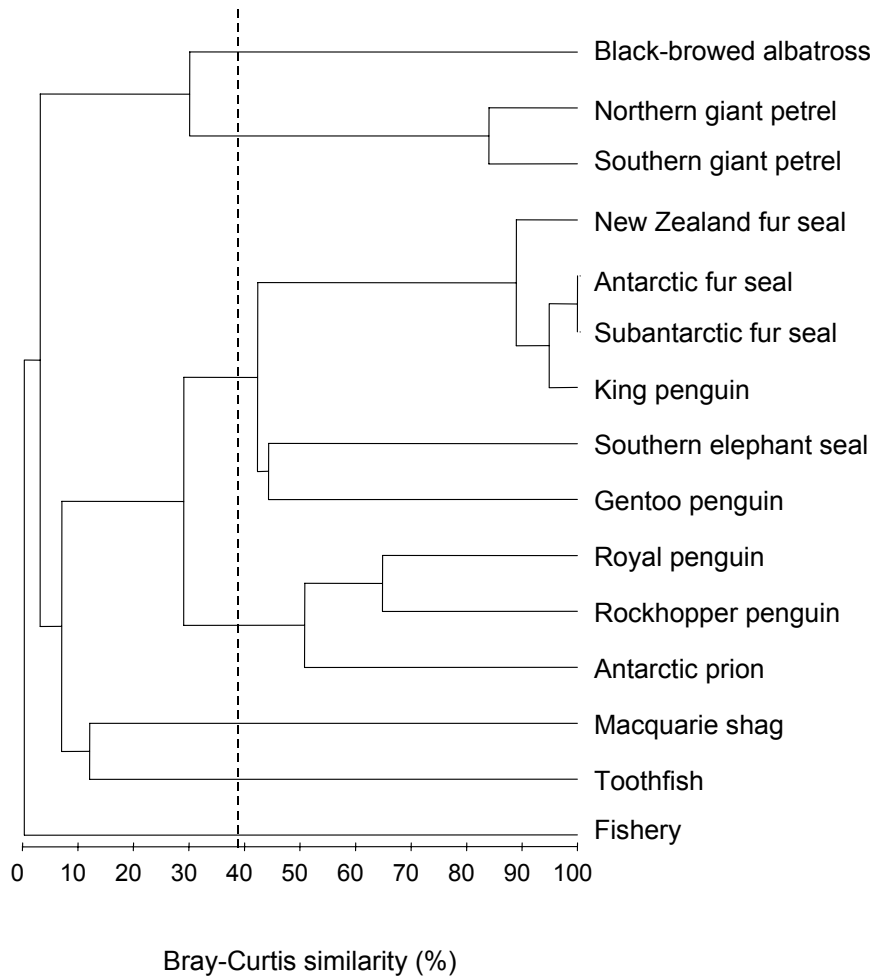
Figure 17.3 Cluster dendogram on seabirds, seals, toothfish and the fishery around Macquarie Island, based on the diet composition by mass of the 35 prey groups. Significant trophic guilds were determined following the methods of Jaksic and Medel (1990), using 5000 randomisations. The broken line at 38.9% diet similarity indicates that seven trophic guilds are significant at *P*<0.05

TROPHIC INTERACTIONS BETWEEN TOOTHFISH, FISHERY, SEALS AND SEA BIRDS
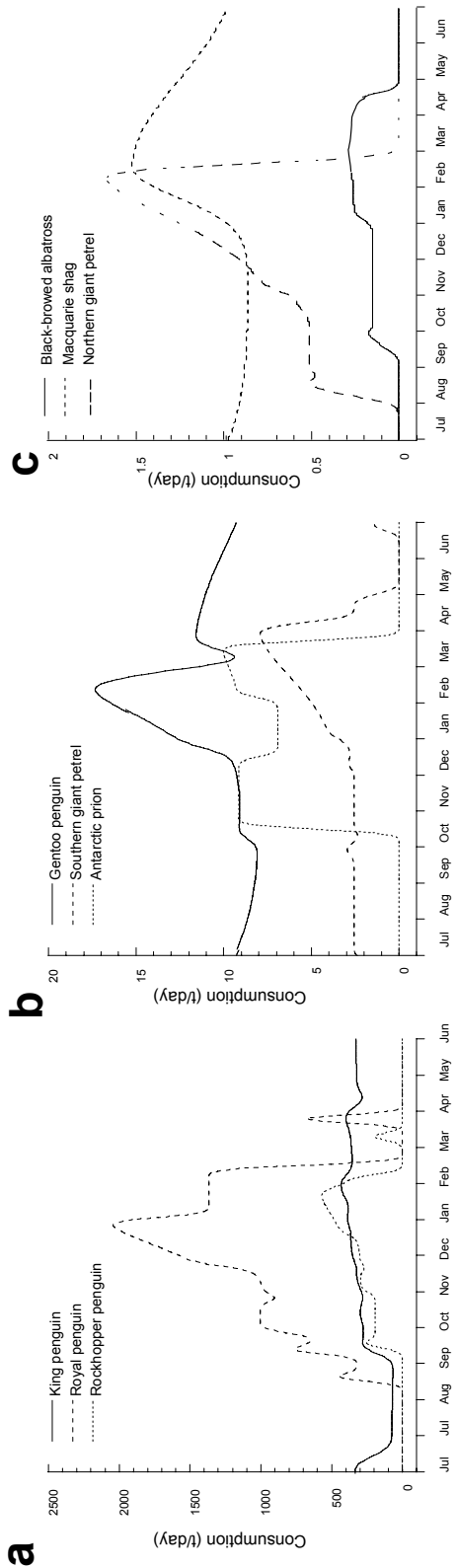
Figure 17.4 Seasonal variation in the estimated daily consumption rates of marine resources by seabirds and seals within the MI-EEZ (a-e) (continued next page). The estimated total daily consumption, and consumption of fish, crustaceans and cephalopods by seabirds, seals and toothfish within the MI-EEZ are also presented (f).
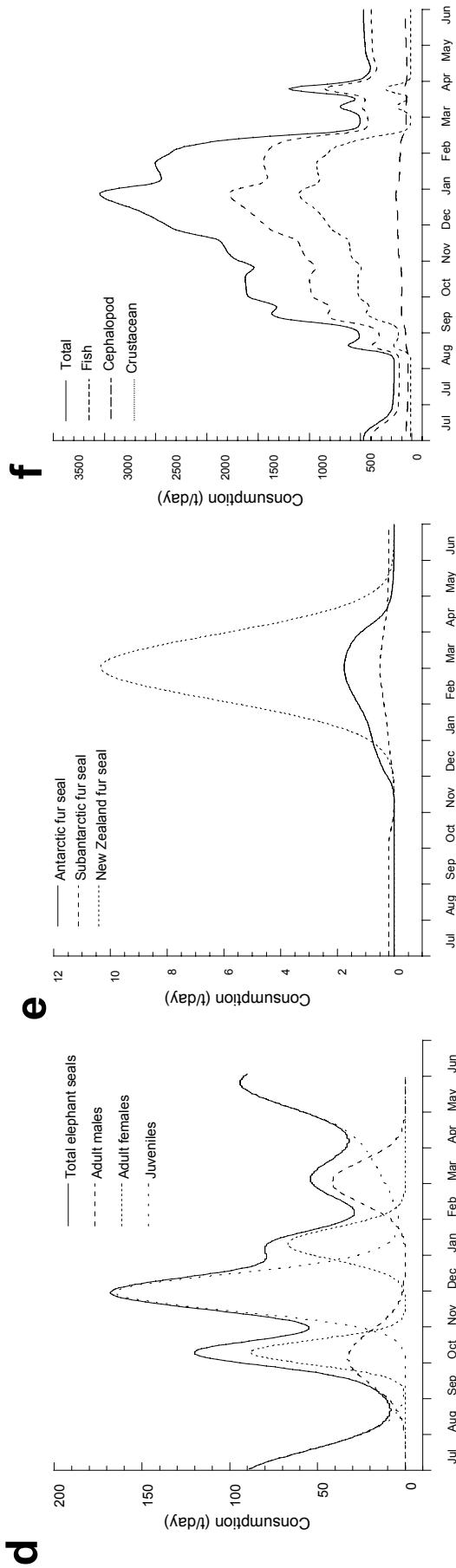
Figure 17.4 continued Seasonal variation in the estimated daily consumption rates of marine resources by seabirds and seals within the MI-EEZ (a-e). The estimated total daily consumption, and consumption of fish, crustaceans and cephalopods by seabirds, seals and toothfish within the MI-EEZ are also presented (f).

18. Conclusions

1. Before this project, there was very limited knowledge on biological oceanography, toothfish biology, and ecological interactions between toothfish, seals, seabirds, and other pelagic resources, for the Macquarie Island pelagic and benthic ecosystems. The multi-disciplinary research approach and close multi-organisation collaborations undertaken by this project have greatly increased our understanding of these ecosystems. The first ever research voyage around Macquarie Island by the *FRV Southern Surveyor* of the CSIRO Marine Research, collected valuable information on biological oceanography, and tested applications of combined acoustic and trawl surveys for estimating toothfish abundance and spatial distributions. Intensive data and specimen collection from FV *Austral Leader* during fishing operations allowed a detailed history of fishery trends to be established and provided much material for research projects undertaken during this study. This multi-disciplinary research approach proved to have many advantages over more traditional single-disciplinary approaches. The approach allowed a variety of technologies and ecological methods to be applied ranging from tagging, retrieval of satellite oceanographic data, genetic stock structure assessment, fatty acid analysis of toothfish diet, acoustic assessment of toothfish distribution and abundance, to community and diet analysis of pelagic prey fishes, tag release-recapture assessment models, management strategy evaluation, and food web models. As a result, the project was able to provide scientific advice not only on understanding toothfish population dynamics and managing the fishery, but also on assessing ecological interactions between toothfish, the fishery, seals, and seabirds, and potential impacts of the fishery on the ecosystems. The latter is particularly important for the toothfish fishery since it is a developmental fishery, and Macquarie Island supports vulnerable seal and seabird species.

2. Macquarie Island has a relatively small continental shelf, but it is influenced by several large-scale oceanographic phenomena, including the Antarctic Circumpolar Current (ACC), the Antarctic Polar Front (APF), and the Subantarctic Front (SAF). The mean sea surface temperature (SST) around the island is about 6.6˚C and varies by about 3˚C over the course of a year. Mean summer SSTs around the island have varied by about 2˚C over the past 20 years, with some warmer years in the late 1980s and some colder years in the early 1990s. Three years of ocean colour (surface chlorophyll a concentration) data for the region show marked annual differences in the primary production around Macquarie Island. Although the record is very short, the ocean colour data suggest that cooler SSTs are associated with increased phytoplankton biomass. Biomass and community structure of mid-water necton (zooplankton and mid-water fishes) vary among sample sites around the island with generally higher biomass near the island and on the west side of the island than the other sites. However, influences of the large-scale oceanographic phenomena on benthic production, toothfish behavior, and toothfish catchability are mostly unknown. This is limited by lack of long-term fishery catch data and regional oceanographic models capable of predicting production and water mass in deep waters. Thus, development of regional oceanographic models is urgently needed for understanding the dynamics of mid-water and benthic production and relating them to toothfish behaviour and the fishery catchability.

3. Toothfish is a long-lived fish, growing to over 2m in length and living between 35 and 50 years. The current fishery catches predominantly juvenile fish aged between 5-8 years old. Fishery catch data and stock assessment indicate that the length composition of fish in the catches varies significantly with fishing seasons and as a result of negative recruitment (fish moving out of fishing grounds). Diet analyses also show that toothfish is an opportunistic predator capable of preying on both mid-water and benthic prey. This suggests that fish may move up the water column to feed and are therefore not available to fishing. Whether there

exists a length specific movement of toothfish between bottom and water column, and/or between depths, is uncertain. This uncertainty has led to difficulties in specifying length structure and availability in the stock assessment models and in estimating gear selectivity for the fishery. It has been proposed that understanding the length specific movement of toothfish be a high priority research project, including uses of archival tags with sensors of depth, temperature, and possibly light in addition to the conventional tagging program already under way. This will provide vital information on behavior and local and long-distance movement of toothfish. The information on long-distance movement of toothfish will also help in defining stock structure of toothfish around Macquarie Island.

4. The pilot genetic study of toothfish stock structure suggests the possibility of separate toothfish stocks between the two fishing grounds. This is supported by very low exchange rates of tagged fish between the two fishing grounds. A current research project to further study toothfish stock structure, supported by the FRDC and conducted by the CSIRO Marine Research, is underway. It is using additional genetic markers on many more fish samples, and will provide more definitive conclusions concerning the stock structure of toothfish.

5. Bycatch of the fishery and contacts between seabirds, seals, and fishing gear are generally low. Fishery observers were present on every fishing voyage during the period covered by this study and aimed to monitor 60% of shots and hauls for seabird and seal interactions with fishing gears. Weather conditions, however, permitted 42% of shots and 55% of hauls being observed. Contacts between seabirds and fishing gear were noted during 22% and 36% of observed shots and hauls, respectively. Of all observed contacts, none appeared to result in any injuries. Two seals were encountered. One fur seal was seen swimming around the net but it did not touch it. One juvenile male southern elephant seal was discovered dead in the net, probably by drowning after it had been caught in the net. Bycatch of fish and invertebrates averaged 8.5% of total catch in all observed hauls, and was relatively low in the established fishing grounds of Aurora Trough (2.2%) and Northern Valleys (12.0%) compared to the exploratory hauls in other locations (52.9%). The percentages of bycatch of fish and invertebrates have risen from the 1998/99 season onwards, which are coincident with declines in toothfish catches. The vast majority of fish bycatch is of common and widespread species and is not considered a threat to their population either locally or globally.

6. The stock assessment models provide estimates of the abundance of toothfish accessible to the fishery. This measure is known as the available (or fishable) abundance. Gear type, oceanographic conditions and fish movements all can influence the daily available abundance of fish. The available abundance is a proportion of the total abundance of the population, which is not estimated by these assessment models. Depending on model assumptions, point estimates of pre-tagging available numbers of fish were between 0.5 and 1 million fish in Aurora Trough, and between 4 and 10 million fish in the Northern Valleys region. For Aurora Trough, the estimated current available number of fish is 50% to 60% of the estimated pre-tagging number of fish, and between 30% and 40% in terms of available biomass. For the Northern Valleys region, the models indicated a substantial decline in available abundance. The estimated current available number of fish is 11% to 14% of the estimated pre-tagging number of fish, and between 6% and 8% in terms of available biomass. However, the estimated decline in available abundance is much greater than can be explained by the fishery catches, even in the absence of recruitment. In addition, while catches were large in the first season in the Northern Valleys, only 3 tagged fish were recaptured, leading to very imprecise estimates of pre-tagging available abundance. Dynamic spatial behaviour could account for these large changes in available abundance. Hypotheses being explored to explain the dynamics include (i) that the population is composed of a small resident population, but that most fish are part of a broader transient

population, and (ii) that the fish have remained in the area but their availability fluctuates greatly over space and time (due to dispersion in the water column, moving to untrawlable ground or escaping detection). This uncertainty, which then feeds into management decisions, re-iterates the importance of understanding the fishes' behaviour and, in particular, its movement dynamics. The assessments use an exact-time of release and recapture population model, which relied upon the early implementation, and continuation, of the tagging experiment. The continued support of the fishing industry in this regard has been of great benefit to the assessment process.

7. Initial results from an evaluation of potential management strategies for the toothfish fishery appear to suggest that fishing operations have a smaller impact on the resource than one might expect. In addition, economic constraints, which force operators to abandon fishing during unfavourable catch conditions, may be the most important factor conserving the resource. However, this result is conditional on several key factors. These are that (a) selection applies to a narrow range of ages, (b) spawning fish contribute to local recruitment only, (c) economic constraints (through leaving triggers) lead the vessel to abandon fishing in poor catch conditions, (d) effort is limited, and (e) assessment estimates of key biological parameters are reasonable. If any of these factors are false, then results show that the impact on the stock may be substantial.

8. An evaluation of management strategies showed that a range of policies, with appropriately chosen parameters, can satisfy sustainability criteria and maintain catch levels under most of the scenarios considered. Some management strategies considered can dramatically impact the stock when effort is limited to the current levels in the fishery. Future work should carefully consider the modelling of catch rates, and spatial models of the population as these have a strong influence on results. Alternative management strategies could be considered, such as the potential for longlining or spatial closures. The inability to catch the full TAC appears to be the controlling factor in the current fishery indicating that the current rules for establishing TAC's need to be refined so that they are an effective management tool should they ever be reached routinely. This is most pertinent for protecting the resident fish in a two stocks resource scenario if effort is increased substantially from present levels. The development of the management strategy evaluation software now provides a flexible tool to evaluate harvest strategies when applied to complex dynamical resource models for situations similar to Macquarie Island.

9. The food web linkages between toothfish, the fishery, seals, and seabirds, are weak. This is based on combined diet analysis and consumption models. Midwater fishes feed mostly on zooplankton. Toothfish feed on a broad range of foods, including benthic and mesopelagic fish, squid and crustaceans, suggesting that toothfish are opportunistic predators. Available data indicate that toothfish are not food sources for seabirds or seals. Consumption models estimated that seabirds (mostly penguins) consume most (88%) of food resources in terms of prey biomass around the Macquarie Island, followed by toothfish (8%), seals (3%), and other seabirds (<1%).

References

Abrams R. W. (1985). Energy and food requirements of pelagic aerial seabirds in different regions of the African sector of the Southern ocean. In: Siegfried, W. R., Condy, P. R. and Laws, R. M. (eds) Antarctic Nutrient Cycles and foodwebs. Proc 4th SCAR Biol Symp. Berlin: Springer-Verlag. 466-472.

Adams, N. J., Moloney, C. and Navarro, R. (1993). Estimated food consumption by penguins at the Prince Edward Islands. Antarctic Science 5: 245-252.

Agnew, D. J., Heaps, L., Jones, C., Watson, A., Berkieta, K. and Pearce, J. (1999). Depth distribution and spawning pattern of *Dissostichus eleginoides* at South Georgia. CCAMLR Science, 6: 19-36.

Allen, W. (1976). Biochemical Aspects of Lipid Storage and Utilization in Animals. American Zoologist, 16: 631-647.

Anderson, D. W. and Gress, F. (1984). Brown Pelicans and the anchovy fishery off southern California. In: Nettleship, D. N., Sanger, A., Springer, P. F. (eds) Marine birds: their feeding ecology and commercial fisheries relationships. Ottawa: Canadian Wildlife Service special publication. 128-135.

Anon. (1999). Hooker's sea lions: victims of squid fishing. http://www.nzwwa.com/education/conservation/forest-bird/brochure/hooker/sealion.htm

Antonelis, G. A., Lowry, M. S., Demaster, D. P. and Fiscus, C. H. (1987). Assessing Northern Elephant Seal feeding habits by stomach lavage. Marine Mammal Science, 3(4): 308-322.

Ashford, J. R., Rubilar, P. S. and Martin, A. R. (1996). Interactions between cetaceans and longline fishery operations around South Georgia. Mar. Mamm. Sci. 12: 452-457.

Barndorff-Nielsen, O. E., James, I. R. and Leigh, G. M. (1989). A note on a semi-parametric estimator of mortality. Biometrika 76: 803-805.

Barrat, A. (1976). Quelques aspects de la biologie et de l'ecologie du manchot royal (Aptenodytes patagonicus) des iles Crozet. Com Natl Franc Rech Antarct 40: 9-52.

BIOMASS Working Party on Bird Ecology. (1984). Recording observations of birds at sea (rev. edn). BIOMASS Handbook 18.

Bligh, E. G. and Dyer, W. M. (1959). A rapid method of lipid extraction and purification. Canadian Journal of Biochemical Physiology, 35: 911-917.

Boehringer Mannheim (1995). The DIG System User's Guide for Filter Hybridization. Boehringer Mannheim GmbH Biochemica, Mannheim, Germany.

Botnikov, V. N. (1963). Geophysical position of the Antarctic convergence zone in the Pacific Ocean. Soviet Antarctic Information Bulletin 4: 324-327.

Boyd, I. L. (1993). Tooth growth in male Antarctic fur seals (*Arctocephalus gazella*) from South Georgia: an indicator of long term growth history. Journal of Zoology, London. 229: 177-190.

Boyd, I. L., Croxall, J. P., Lunn, N. J. and Reid, K. (1995). Population demography of Antarctic fur seals - the costs of reproduction and implications for life-histories. J Anim Ecol 64: 505-518.

Bradshaw, C. J. A., Hindell, M. A., Littnan, C. and Harcourt, R. G. (In press) Determining marine movements of Australasian pinnipeds. In: Merrick, J. R., Archer, M., Hickey, G. and Lee, M. (eds) Evolution and Biogeography of Australasian Vertebrates. Sydney: Australian Scientific Publications.

Brothers, N. (1991). Albatross mortality and associated bait loss in the Japanese longline fishery in the Southern Ocean. Biological Conservation, 55, 255-268.

Brothers, N. P. (1984). Breeding, distibution and status of burrow-nesting petrels at Macquarie Island. Aust Wildl Res 11: 113-131.

Brothers, N. P. (1985). Breeding biology, diet and morphometrics of the King Shag, *Phalacrocorax albiventer purpurascens*, at Macquarie Island. Aust. Wildl. Res. 12: 81-94.

Brown, C. R. (1987). Energy requirements for growth and maintenance in macaroni and rockhopper penguins. Polar Biol 8: 95-102.

Brown, C. R. (1989). Energy requirements and food consumption of Eudyptes penguins at the Prince Edward Islands. Antarc Sci 1: 15-21.

Brown, D. J., Boyd, I. L., Cripps, G. C. and Butler, P. J. (1999). Fatty acid signature analysis from the milk of Antarctic fur seals and Southern elephant seals from South Geogia: implication for diet determination. Marine Ecology Progress Series, 187: 251-263.

Burger, A. E. and Cooper, J (1984). The effects of fisheries on seabirds in South Africa and Namibia In: Nettleship, D. N., Sanger, A. and Springer, P. F. (eds) Marine birds: their feeding ecology and commercial fisheries relationships Ottawa: Canadian Wildlife Service special publication. 150-161.

Butler, A., Williams, A., Koslow, J. A., Gowlett-Holmes, K., Barker, B., Lewis, M. and Reid, R. (2000). A study of the Conservation Significance of the Benthic Fauna Around Macquarie Island and the Potential Impact of the Patagonian Toothfish Trawl Fishery. CSIRO, Hobart.

Butterworth, D. S., Duffy, D. C., Best, P. B. and Bergh, M. O. (1988). On the scientific basis for reducing the South African seal population. S Afr J Sci 84: 179-188.

Callahan, J. E. (1972). The structure and circulation of Deep Water in the Antarctic. Deep-Sea Research 19: 563-575.

Chastel, O., Weimerskirch, H. and Jouventin, P. (1993). High annual variability in reproductive success and survival of an Antarctic seabird, the snow petrel *Pagodroma nivea*. Oecologica 94: 278-285.

Cherel, Y. and Weimerskirch, H. (1995). Sea birds as indicator of marine resources: black-browed albatrosses feeding on ommastrephid squids in Kerguelen waters. Mar Ecol Prog Ser 129: 295-300.

Chou, L., Bright, A. and Yeh, S. (1995). Stomach contents of Dolphins (*Delphinus delphis* and *Lissodelphis borealis*) from the North Pacific Ocean. Zoological Studies, 3(4): 206-210.

Christoph, M., Barnett, T. P. and Roeckner, E. (1998). The Antarctic circumpolar wave in a coupled ocean-atmosphere GCM. Journal of Climate 11: 1659-1672.

Clarke, A., Clarke, M. R., Holmes, L. J. and Waters, T. D. (1985). Calorific values and elemental analysis of eleven species of oceanic squid (Mollusca:Cephalopoda). J Mar Biol Assoc UK 65: 983-986.

Clarke, T. A. (1980). Diets of fourteen species of vertically migrating mesopelagic fishes in Hawaiian waters. Fishery Bulletin 78(3): 619-640.

Constable, A. J. and Ball, I. R. (in review). A method for estimating recruitment and mortality from time series of length-density data. CCAMLR Science.

Constable, A. J., de la Mare, W. K., Agnew, D. J., Everson, I. and Miller, D. (2000). Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). Ices Journal of Marine Science, 57: 778-791.

Constable, A. J., Williams, R., Lamb, T. and van Wijk, E. (1999). Revision of biological and population parameters for Dissostichus eleginoides on the Heard Island Plateau (Division 58.5.2) based on a comprehensive survey of fishing grounds and recruitment areas in the region. Report to the SC-CAMLR Working Group on Fish Stock Assessment.

Copson, G. R. and Rousevelle, D. E. (1987). The abundance of royal penguins (*Eudyptes schlegeli,* Finsch) breeding at Macquarie Island. ANARE Research Notes 41, 11 pp.

Cortés, E. (1997). A critical review of methods of studying fish feeding based on analysis of stomach contents: application to elasmobranch fishes. Canadian Journal of Fisheries and Aquatic Sciences 54: 726-738.

Costa, D. P., Croxall, J. P. and Duck, C. (1989). Foraging energetics of Antarctic fur seals, *Arctocephalus gazella*, in relation to changes in prey availability. Ecology 70: 596-606.

Croll, D. A. and Tershy, B. R. (1998). Penguins, fur seals, and fishing: prey requirements and potential competition in the South Shetland Islands, Antarctica. Polar Biol 19: 365-374.

Croxall, J. P. and Prince, P. A. (1982). A preliminary assessment of the impact of seabirds on the marine resources at South Georgia. Comite National Francais des Recherches Antarctiques 51: 501-509.

Croxall, J. P., Prince, P. A. and Reid, K. (1997). Dietary segregation of krill-eating South Georgia seabirds. J Zool 242: 531-556.

Croxall, J. P., Prince, P. A. and Ricketts, C. (1985). Relationships between prey life-cycles and the extent, nature and timing of seal and seabird predation in the Scotia Sea. In: Siegfried, W. R., Condy, P. R., and Laws, R. M. (eds) Antartcic nutrient cycles and food webs. Springer, Berlin, 516-533.

Croxall, J. P., Ricketts, C. and Prince, P. A. (1984). Impact of seabirds on marine resources, chiefly krill, of South Georgia waters. In: Whittow, G. C. and Rahn, H. (eds) Seabird energetics. New York: Plenum Publishing Corporation, 285-317.

Croxall, J.P. (1992). Southern Ocean environmental changes: effects on seabirds, seal and whale populations. Philosophical Transactions of the Royal Society London, B 338: 319-328.

Davies, D. H. (1958). The South African pilchard (*Sardinops ocellata*) and maasbanker (*Trachurus trachurus*). The predation of sea-birds in the commercial fishery. Union of S Afr Div Invest Rep 31: 1-16.

Davis, R. W., Croxall, J. P. and O'Connell, M. J. (1989). The reproductive energetics of gentoo (*Pygoscelis papua*) and macaroni (*Eudyptes chrysolophus*) penguins at South Georgia. J Anim Ecol 58: 59-74.

Dayton, P. K. (1998). Reversal of the burden of proof in fisheries management. Science, 279: 821-822.

de la Mare, W. K. and Williams, R. (1997). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies. Sub-Antarctic Fisheries Assessment Group document. SAFAG-97/6. Australian Fisheries Management Authority, Canberra.

Duffy, D. C. (1983). Environmental uncertainty and commercial fishing: effects on Peruvian guano birds. Biol Conserv 26: 227-238.

Duffy, D. C. and Schneider, D. C. (1994). Sea bird-fishery interactions: a manager's guide. In: Nettleship, D. N., Buger, J. and Gochfeld, M. (eds) Seabirds on islands. Birdlife Conservation Series no 1. Birdlife International, Cambridge, 26-38.

Duhamel, G. (1981). Caracteristiques biologiques des principales especes de poissons du plateau continental des Iles Kerguelen. Cybium 5: 19-32.

Duhamel, G. (1991). Biologie et exploitation de *Dissostichus eleginoides* autour des iles Kerguelen (Division 58.5.1). Selected Scientific Papers, 1991 (SC-CAMLR-SSP/8). CCAMLR, Hobart. pp. 85-106.

Duhamel, G. and Pletikosic, M. (1983). Donnes biologiques sur les Nototheniidae des Ilse Crozet. Cybium 7: 43-57.

Duhamel, G., Koubbi, P. and Ravier, C. (2000). Day and night mesopelagic assemblages off the Kerguelen Islands (Southern Ocean). Polar Biology, 23: 106-112.

Dunstan, G. A., Olley, J. and Ratkowsky, D. A. (1999). Major environmental and biological factors influencing the fatty acid composition of seafood from Indo-Pacific to Antarctic waters. Recent Research Developments in Lipid Research, 3: 63-86.

Eastman, J. T. (1988). Lipid storage systems and the biology of two neutrally buoyant Antarctic notothenoid fishes. Comparitive Biochemistry and Physiology 90b(3): 529-537.

Eastman, J. T. (1993). Antarctic Fish Biology: Evolution in a Unique Environment. Academic Press.

Everson, I. and Murray, A. (1999). Size at sexual maturity of Patagonian toothfish(*Dissostichus eleginoides*). CCAMLR Science, 6: 37-46.

Fischler, K. J. (1965). The use of catch-effort, catch sampling and tagging data to estimate a population of blue crabs. Trans. Amer. Fish. Soc. 94: 287-310.

Foote, K. G. (1982). Optimizing copper spheres for precision calibration of hydroacoustic equipment. Journal of the Acoustical Society of America 71: 742-747.

Francois, R. E. and Garrison, G. R. (1982). Sound absorption based on ocean measurements. II. Boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America 72: 896-907.

Freese, L., Auster, P. J., Heifetz, J. and Wing, B. L. (1999). Effects of trawling on seafloor habitat and associated invertebrate taxa in the Gulf of Alaska. Marine Ecology Progress Series, 182: 119-126.

Friedrich, C. and Hagen, W. (1994). Lipid contents of five species of notothenoid fish from high-Antarctic waters and ecological implications. Polar Biology, 14: 359-369.

Furlani, D., He, X., Williams, R., Lamb, T. and Tuck, G. N. (2000). Analysis of length frequency for the Patagonian toothfish fishery of Macquarie Island: implications of fish movement in and out of fishing grounds. Manuscript.

Furness, R. W. (1984). Modelling relationships among fisheries, seabirds and marine mammals. In: Nettleship D. N., Sanger A , Springer P. F. (eds) Marine birds: their feeding ecology and commercial fisheries relationships. Ottawa: Canadian Wildlife Service special publication, 117-126.

Furness, R. W. and Cooper, J. (1982). Interactions between breeding seabirds and pelagic fish populations in the Southern Benguela Region. Mar Ecol Prog Ser 8: 243-2150.

Gales, N. J. and Mattlin, R. H. (1997). Summer diving behaviour of lactating New Zealand sea lions, Phocarctos hookeri. Can J Zool 75: 1695-1706.

Gales, R. (1998). Albatross populations: status and threats. Albatross biology and conservation (eds G. Robertson and R. Gales), pp. 20-45. Surrey Beatty and Sons, Chipping Norton, New South Wales.

García de la Rosa, S. B., Sánchez, F. and Figueroa, D. (1997). Comparative feeding ecology of Pategonian toothfish (*Dissostichus eleginoides*) in the southwestern Atlantic. CCAMLR Science 4: 105-124.

George, E. L. and Hadley, W. F. (1979). Food and habitat partitioning between rock bass (*Ambloplites rupestris*) and smallmouth bass (*Micropterus dolomieui*) young of the year. Transactions of the American Fisheries Society 108: 253-261.

Goldsworthy, S. D. (1999). Maternal attendance behaviour of sympatrically breeding Antarctic and subantarctic fur seals, *Arctocephalus spp*., at Macquarie Island. Polar Biol. 21: 316-325.

Goldsworthy, S. D., He, X., Lewis, M., Williams, R., and Tuck, G. (2001). Trophic interactions between Patagonian Toothfish, its fishery and seals and seabirds around Macquarie Island. Marine Ecology Progress Series, 218: 283-302.

Goldsworthy, S. D., Hindell, M. A. and Crowley, H. M. (1997). Diet and diving behaviour of sympatric fur seals, *Arctocephalus gazella* and *A. tropicalis*, at Macquarie Island. In: Hindell, M. A., Kemper, C (eds) Marine Mammal Research in the Southern Hemisphere Volume 1: Status, Ecology and Medicine. Surrey Beatty and Sons, Chipping Norton, 151-63

Goldsworthy, S. D., Williams, R., Lewis, M., Van den Hoff, J., Young, J. and He, X. (in press) Diets of the Patagonian toothfish (*Dissostichus eleganoides*) around Macquarie Island. Mar Freshwat Res.

Goldsworthy, S. D., Wynen, L., Robinson, S. and Shaughnessy, P. D. (1998). The population status and hybridisation of three sympatric fur seals (*Arctocephalus spp.*) at Macquarie Island. N.Z. Nat. Sci. 23, Supplement 68pp.

Gon, O. (1990). Bathylagidae: Deep sea smelts. In 'Fishes of the Southern Ocean'. (Eds O. Gon and P. C. Heemstra.) pp.107-110. (J.L.B. Smith Institute of Ichthyology: Grahamstown, South Africa).

Gon, O. and Heemstra P. C. (eds.) (1990). Fishes of the Southern Ocean. J.L.B. Smith Institute of Ichthyology, Grahamstown,462pp.

Gordon, J. D. M., Merrett, N. R. and Haedrich, R. L. (1995). Environmental and biological aspects of slope-dwelling fishes of the North Atlantic. In 'Deep-Water Fisheries of the North Atlantic Oceanic Slope'. (Ed A. G. Hopper.) pp.1-26. (Kluwer Academic Publishers: Dordrecht, The Netherlands).

Gorelova, T. A. and Kobyliansky, S. G. (1985). Feeding of deepsea fishes of the family Bathylagidae. Voprosy Ikhtiologii 2: 264-274.

Gorelova, T. A. and Efremenko, V. N. (1989). On the food composition of the larvae of Lantern Anchovies (Myctophidae) from the Scotia Sea. Journal of Ichthyology 29(5): 106-109.

Graeve, M., Kattner, G. and Hagen, W. (1994). Diet-induced changes in the fatty acid composition of Arctic herbivorous copepods: Experimental evidence of trophic markers. Journal of Experimental Marine Biology and Ecology, 182: 97-110.

Green, B. and Gales, R. P. (1990). Water, sodium, and energy turnover in free-living penguins. In: Davis, L. S. and Darby, J. T. (eds) Penguin Biology. Acedemic Press, San Diego pp 245-268.

Green, K. and Burton, H. R. (1993). Comparison of the stomach contents of southern elephant seals, *Mirounga leonina*, at Macquarie and Heard Islands. Mar Mamm Sci 9: 10-22.

Green, K., Burton, H. R. and Williams, R. (1989). Diet of Antarctic fur seals *Arctocephalus gazella* during the breeding season at Head Island. Antarc Sci 1: 317-24.

Green, K., Burton, H. R. and Williams, R. (1991). The diet of Antarctic fur seals during the late autumn and early winter around Head Island. Antarc Sci 3: 359-361.

Green, K, Slip, D. J. and Moore, G. J. (1998). The take of fish species by seabirds and marine mammals in the Australian Fisheries Zone around Heard Island: the potential for competition with a commercial fishery. Polar Biol 20: 273-280.

Green, K., Williams, R., Handasyde, K. A., Burton, H. R. and Shaughnessy, P. D. (1990). Interspecific and intraspecific diets of fur seals *Arctocephalus* species (Pinnipedia: Otariidea), at Macquarie Island. Aust Mammal 13: 193-200.

Greene, W. H. (1993). Econometric Analysis. Macmillan, New York.

Guinet, C., Chastel, O., Koudil, M., Durbec, J-P. and Jouventin, P. (1998). Effects of warm sea-surface temperature anomalies on the blue petrel at the Kerguelen Islands. Proceedings of the Royal Society, London B. 265: 1001-1006.

Guinet, C. Cherel, Y., Ridoux, V. and Jouventin, P. (1996). Consumption of marine resources by seabirds and seals in Crozet and Kerguelen waters: changes in relation to consumer biomass 1962-85. Antarctic Science 8: 22-30.

Guinet, C., Jouventin, P. and Georges, J-Y. (1994). Long term population changes of fur seals *Arctocephalus gazella* and *Arctocephalus tropicalis* on subantarctic (Crozet) and subtropical (Amsterdam) islands and their possible relationship to El Niño Southern Oscillation. Antarctic Science 6: 473-478.

Gulland, J. A. (1965). Estimation of mortality rates. Annex to Arctic Fisheries Working Paper Group Report. Paper presented to ICES Annual Meeting, 1965 (mimeo).

Hammill, M. O., Lydersen, C. L., Kovacs, K. M. and Sjare, B. (1997). Estimated fish consumption by hooded seals (*Cystophora cristata*), in the Gulf of St Lawence. J Northwest Atl Fish Sci 22: 249-258.

Hannson, S. (1998). Methods of studying fish feeding: a comment. Canadian Journal of Fisheries and Aquatic Sciences 55: 2706-2707.

Harrison, P. (1988). Seabirds, an identification guide. Croom Helm, London.

Harwood, J. and Croxall, J. P. (1988). The assessment of competition between seals and commercial fisheries in the North Sea and the Antarctic. Marine Mammal Science, 4(1): 13-33.

He, X., Bulman, C., Goldsworthy, S. and Williams, A. (in prep.) Using Mantel test to detect changes of diet composition in fish length.

Hearn, W. S. (1986). Mathematical methods for evaluating marine fisheries. PhD thesis. University of New South Wales. 195p.

Hearn, W. S., Sandland, R. L. and Hampton, J. (1987). Robust estimation of the natural mortality rate in a completed tagging experiment with variable fishing intensity. J. Cons. Int. Explor. Mer. 43: 107-117.

Hilborn, R. and Walters, C. J. (1995). Biomass dynamic models: users manual. FAO Computerised Information Series (Fisheries) No. 10. Rome, FAO. 62p.

Hilborn, R. and Walters, C.J. (1992). Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Hindell, M. A. (1988a). The diet of the king penguin *Aptenodytes patagonicus* at Macquarie Island. Ibis 130: 193-203.

Hindell, M. A. (1988b). The diet of the rockhopper penguin *Eudyptes chrysocome* at Macquarie Island. Emu 88: 227-233.

Hindell, M. A. (1988c). The diet of the royal penguin *Eudyptes schlegeli* at Macquarie Island. Emu 88: 219-226.

Hindell, M. A. (1989). The diet of the gentoo penguin *Pygoscelis papua* at Macquarie Island: winter and early breeding season. Emu 89: 71-78.

Hindell, M. A. and Burton, H. R. (1987). Past and present status of the southern elephant seal (*Mirounga leonina*) at Macquarie Island. J Zool 213: 365380.

Hindell, M. A. and Burton, H. R. (1988). Seasonal haul-out patterns of the southern elephant seal (*Mirounga leonina*) at Macquarie Island. J Mammal 69: 81-88.

Hindell, M. A., Mcconnell, B. J., Fedak, M. A., Slip, D. J., Burton, H. R., Reijnders, H. R. and Mcmahon, C. R. (1999). Environmental and physiological determinants of successful foraging by naive southern elephant seal pups during their first trip to sea. Can J Zool 77: 1807-1821.

Hoenig, J. M., Barrowman, N. J., Pollock, K. H., Brooks, E. N., Hearn, W. S. and Polacheck, T. (1998). Models for tagging data that allow for incomplete mixing of newly tagged animals. Can. J. Fish. Aquat. Sci. 55: 1477-1483.

Hooker, S. K. and Baird, R. W. (1999). Deep-diving behaviour of the northern bottlenose whale, *Hyperoodon ampullatus* (Cetacea : Ziphiidae). Proc R Soc Lon, Ser B: Biol Sci 266: 671-676.

Hull, C. L. (1997). The comparative foraging ecology of Royal *Eudyptes schlegeli* and Rockhopper *E. chrysocome* Penguins. PhD thesis. University of Tasmania, Australia.

Hull, C. L. (1999). Comparison of the diets of breeding royal (*Eudyptes schlegeli*) and rockhopper (*Eudyptes chrysocome*) penguins on Macquarie Island over three years. Journal of Zoology 247:507-529.

Hull, C. L. (1999). The foraging zones of breeding royal (*Eudyptes schlegeli*) and rockhopper (E. chrysocome) penguins: an assessment of techniques and species comparisons. Wild Res 26: 789-803.

Hull, C. L., Hindell, M. A. and Michael, K. (1997). Foraging zones of royal penguins during the breeding season, and their association with oceanographic features. Mar Ecol Prog Ser 153: 217-228.

Hulley, P. A. (1990). Myctophidae: Lanternfishes. In 'Fishes of the Southern Ocean'. (Eds O. Gon and P. C. Heemstra.) pp.146-178. (J.L.B. Smith Institute of Ichthyology: Grahamstown, South Africa).

Hunt, J. R. (1985). A preliminary comparison of marine bird biomass and food consumption between the south eastern Berring Sea and parts of the Southern Ocean. In: Siegfried, W.R., Condy, P.R. and Laws, R.M. (eds) Antartcic nutrient cycles and food webs. Springer-Verlag, Berlin, 487-492.

Hunter, S. (1983). The food and feeding ecology of the giant petrels *Macronectes halli* and *M. giganteus* at South Georgia. J Zool Lond 203: 521-38.

Ichii, T., Naganobu, N. and Ogishima, T. (1996). Competition between the krill fishery and penguins in the South Shetland Islands. Polar Biol 16: 63-70.

Iverson, S. J. (1993). Milk secretion in marine mammals in relation to foraging: can milk fatty acids predict diet? Symposium of the Zoological Society of London, 66: 263-291.

Iwamoto, T. (1990). Macrouridae: Grenadiers. In 'Fishes of the Southern Ocean'. (Eds O. Gon and P. C. Heemstra.) pp.195-206. (J.L.B. Smith Institute of Ichthyology: Grahamstown, South Africa).

Jackson, S. (1986). Assimilation efficiencies of White-chinned Petrels (*Procellaria aequinoctialis*) fed different prey. Comp Biochem Physiol 85A: 301-303.

Jaksic, F. M. and Medel, R. G. (1990). Objective recognition of guilds: testing for statistically significant species clusters. Oecologia 82: 87-92.

Johnstone, G. W. (1977). Comparative feeding ecology of the giant petrels *Macronectes giganteus* (Gmelin) and *M. halli* (Mathews). In: Llana GA (ed) Adaptations within Antarctic Ecosystems. Proc 3rd SCAR Symposium on Antarctic Biology, 647-668.

Jolly, G. M. (1965). Explicit estimates from capture-recapture data with both death and immigration-stochastic models. Biometrika 52: 225-247.

Kalish, J. M., Timmiss, T. A., Pritchard, J. C. and Johnston, J. M. (1999). Validated age and growth of Patagonian toothfish *Dissostichus eleginoides* determined from otoliths. Report to the AFMA Subantarctic Fisheries Assessment Group, November 1999.

Kalish, J. M., Timmiss, T. A., Pritchard, J. C., Johnston, J. M. and Duhamel, G. (1999). Validation and direct estimation of age and growth of Patagonian toothfish *Dissostichus eleginoides* based on otoliths. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/2. Australian Fisheries Management Authority, Canberra.

Kato, A., Nishiumi, I. and Naito, Y. (1996). Sex differences in the diet of King Cormorants at Macquarie Island. Polar Biol 16: 75-77.

Kattner, G., Graeve, M. and Hagen, W. (1994). Ontogenetic and seasonal changes in lipid and fatty acid/alcohol compositions of the dominant Antarctic copepods *Calanus propinquus*, *Calanoides acutus* and *Rhincalanus gigas*. Marine Biology, 118: 637-644.

Kattner, G. and Hagen, W. (1995). Polar herbivorous copepods – different pathways in lipid biosynthesis. ICES Journal of Marine Science, 52: 329-335.

King, W. (1984). Incidental mortality of seabirds in gillnets in the North Pacific. Status and Conservation of the world's seabirds. (eds J. P. Croxall, P. G. H. Evans, and R. W. Schreiber), pp. 709-716. ICBP Technical Publication No 2, Paston Press, Norwich.

Kloser, R. J. (1996). Improved precision of acoustic surveys of benthopelagic fish by means of a deep-towed transducer. ICES Journal of Marine Science 53: 407-13.

Kloser, R. J., Koslow, J. A. and Williams, A. (1996). Acoustic assessment of the biomass of a spawning aggregation of orange roughy (*Hoplostethus atlanticus*, Collett) off southeastern Australia 1990-93. Marine and Freshwater Research 47: 1015-1024.

Kloser, R. J., Koslow, J. A., Ryan, T. and Sakov, P. (1998) Species identification in the deep-water orange roughy fishery using multiple frequencies. ICES Fisheries Acoustic Science and Technology working group.

Kloser, R. J., Ryan, T. E., Williams, A. and Soule, M. (1999). Development and implementation of an acoustic survey of orange roughy in the Chatham Rise spawning box from an Industry Vessel, CSIRO report for the Orange Roughy Management Company.

Kloser, R. J., Williams, A. and Koslow, J. A. (1997). Problems with acoustic target strength measurements of a deep water fish, Orange Roughy. ICES Journal of Marine Science 54: 60-73.

Kock, K-H. (1992). Antarctic fish and fisheries. Cambridge University Press, Cambridge. 359pp.

Korabel`nikov, L. V. (1959). The food of the sperm whale in the Antarctic seas. Priroda No 3.

Koslow, J. A. (1997). Seamounts and the ecology of deep-sea fisheries. American Scientist 85: 168-176.

Koslow, J. A. and Gowlett-Holmes, K. (1998). The seamount fauna off southern Tasmania: Benthic communities, their conservation and impacts of trawling. Final report to Environment Australia and the Fisheries Research Development Corporation. FRDC Project 95/058

Koteja, P. (1991). On the relation between basal and field metabolic rates in birds and mammals. Funct Ecol 5: 56-64.

Kozlov, A. N. (1995). A review of the trophic role of mesopelagic fish of the family Myctophidae in the Southern Ocean ecosystem. CCAMLR Science 2: 71-77.

Langenkamp, D. (2000). A bioeconomic study of the Macquarie Island Patagonian toothfish fishery. Thesis submitted as part requirement for the Bachelor of Economics (Honours) Degree, University of Queensland.

Leigh, G. M. (1988). A comparison of estimates of natural mortality from fish tagging experiments. Biometrika 75: 347-353.

Leigh, G. M., Hearn, W. S. and Pollock, K. H., Submitted. Time-dependent instantaneous mortality rates from multiple tagging experiments with exact times of release and recovery. Ecol. Environ. Stat.

Mace, P. M. and Doonan, I. J. (1988). A generalised bioeconomic simulation model for fish population dynamics. New Zealand Fisheries Assessment Research Document 88/4. December 1988, N.Z. Ministry of Agriculture and Fisheries.

MacKenzie, K. V. (1981). A nine-term equation for sound speed in the oceans. Journal of the Acoustical Society of America 70: 807-812.

MacLennan, D. N. and Simmonds, J. E. (1992). Fisheries Acoustics. Chapman and Hall.

Manly, B. F. J. (1991) Randomization and Monte Carlo methods in biology. (Chapman and Hall. New York.). 281 pp.

Mantel, N. (1967). The detection of disease clustering and a generalized regression approach. Cancer Research, 27: 209-220.

Marchant, S. and Higgins, P. J. (1990). Handbook of Australian, New Zealand and Antarctic Birds. Melbourne, Oxford University Press Vol 1A 735 pp.

Marr, J. C. (1951). On the use of the terms "Abundance", "Availability" and "Apparent Abundance" in fishery biology. Copeia, No. 2, pp. 163-169.

Matthews, J. P. (1961). The pilchard of South-West Africa (*Sardinops ocellata*) and maasbanker (*Trachurus trachurus*): bird predators, 1957–1958. SW Afr Res Lab Invest Rep Mar 3: 1-35.

McCann, T. S. (1985). Size, status and demography of southern elephant seal (*Mirounga leonina*) populations. In: Ling JK and Bryden MM (eds) Sea mammals in south latitudes. Proceedings of a Symposium of the 52nd ANZAAS Congress, South Australian Museum, Adelaide, 1-17.

McCullagh, P. and Nelder, J. A. (1983). *Generalized Linear Models*. Chapman and Hall, New York.

McCune, B. and Mefford, M. J. (1999). PC-ORD. Multivariate analysis of ecological data, Version 4. MjM Software Design, Gleneden Beach, Oregon, USA.

McMahon, C. R., Holly, D. and Robinson, S. (1999). The diet of itinerant male Hooker's sea lions, *Phocartos hookeri*, at sub-Antarctic Macquarie Island. Wildl Res 26: 839-846.

Methot, R.D. (1990). Synthesis model: an adaptive framework for analysis of diverse stock assessment data. Int. North Pac. Fish. Comm. Bull. 50: 259-277.

Miller, C. M., Oosthuizen, W. H. and Wickens, P. A. (1996). Cape fur seals trapped in trawling gear: age structure, sex ratio, seasonality and distribution. South African Journal of Marine Science, 17: 105-111.

Moore, G. J., Robertson, G. and Wieneke, B. (1998). Food requirements of breeding king penguins at Heard Island and potential overlap with commercial fisheries. Polar Biol 20: 293-302.

Murphy, G. I. (1965). A solution of the catch equation. J. Fish. Res. Board Can. 22, 191-202.

Nichols, D. S., Williams, D., Dunstan, G. A., Nichols, P. D. and Volkman, J. K. (1994). Fatty acid composition of Antarctic and temperate fish of commercial interest. Comparitive Biochemistry and Physiology, 107B(2): 357-363.

Nichols, P. D., Leeming, R., Rayner, M. S., Latham, V., Ashbolt, N. J. and Turner, C. (1993). Comparison of the abundance of the fecal sterol coprostanol and fecal bacteria in inner-shelf waters and sediments near Sydney, Australia. Journal of Chromatography, 643: 195-198.

Ogi, H. (1984). Seabird mortality incidental to the Japanese salmon gill-net fishery. Status and Conservation of the world's seabirds. (eds J. P. Croxall, P. G. H. Evans, and R. W. Schreiber), pp. 717-722. ICBP Technical Publication No 2, Paston Press, Norwich.

Onley, D. and Bartle, S. (1999). Identification of seabirds of the Southern Ocean: a guide for scientific observers aboard fishing vessels. Te Papa Press, Wellington.

Orsi, A. H., Whitworth III, T. W. and Nowlin, W. D. (1995). On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Research I 42: 642-673.

Oven, L. S., Konstantinova, M. P. and Shevenko, N. F. (1990). Aspects of reproduction and feeding of myctophids (Myctophidae) in the Southwest Atlantic. Journal of Ichthyology 30(2): 115-127.

Pakhomov, E. A. (1997). Feeding and exploitation of the food supply by demersal fishes in the Antarctic part of the Indian Ocean. Journal of Ichthyology 37(5): 360-380.

Pakhomov, E. A., Perissinotto, R. and McQuaid, C. D. (1996). Prey composition and daily rations of myctophid fishes in the Southern Ocean. Marine Ecology Progress Series 134: 1-14.

Palomares, M. L. and Pauly, D. (1989). A multiple regression model for predicting the food consumption of marine fish populations. Aus J Mar Freshw Res 40: 259-73.

Parkes, G., Moreno, C. A., Pilling, G. and Young, Z. (1996). Use of the Leslie stock depletion model for the assessment of local abundance of Patagonian toothfish (*Dissostichus eleginoides*). CCAMLR Science, 3: 55-77

Parslow, J. S., Boyd, P., Rintoul, S. R. and Griffiths, F. B. (submitted). A subsurface chlorophyll maximum in the Polar Frontal Zone south of Australia: seasonal evolution and implications for phytoplankton – light – nutrient interactions. Journal of Geophysical Research.

Perez, M. A. and Loughlin, T. R. (1991). Incidental catch of marine mammals by foreign and joint venture trawl vessels in the U.S. EEZ of the North Pacific, 1973-88. NOAA Technical Report NMFS 104.

Perissinotto, R. and McQuaid, C. D. (1992). Land-based predator impact on vertically migrating zooplankton and micronekton advected to a Southern Ocean archipelago. Marine Ecology Progress Series, 80: 15-27.

Phleger, C. F. (1998). Buoyancy in Marine Fishes: Direct and Indirect Role of Lipids. American Zoologist, 38: 321-330.

Piatkowski, U. and Hagen, W. (1994). Distribution and lipid composition of early life stages of the cranchiid squid *Galiteuthis glacialis* (Chun) in the Weddell Sea, Antarctica. Antarctic Science 6(2): 235-239.

Pierce, D. A. and Schafer, D. W. (1986). Residuals in generalised linear models. J. American Statistical Assoc. 81: 977-986.

Polacheck, T., Klaer, N. L., Millar C. and Preece, A. L. (1999). An initial evaluation of management strategies for the southern bluefin tuna fishery. ICES Journal of Marine Science, 56: 811-826.

Pope, J. G. (1972). An investigation of the accuracy of virtual population analysis using cohort analysis. ICNAF Res. Bull. 9: 65-74.

Press, W. H., Teukolsky, S. A., Vetterling, W. T. and Flannery, B. P. 1995. Numerical Recipes in C, the Art of Scientific Computing: 2nd Edition. Cambridge University Press. Cambridge, UK.

Prince, P. A. (1980a). The food and feeding ecology of grey-headed albtross *Diomedea chrysostoma* and black-browed albatross *D. melanophris*. Ibis 122: 476-488.

Prince, P. A. (1980b). The food and feeding ecology of blue petrel (*Halobaena caerulea*) and Dove prion (*Pachyptila desolata*). J Zool 190: 59-76.

Prince, P. A., Croxall, J. P., Trathan, P. N. and Wood, A. G. (1998). The pelagic distribution of South Georgia albatrosses and their relationships with fisheries. Albatross biology and conservation (eds G. Robertson and R. Gales), pp. 137-167. Surrey Beatty and Sons, Chipping Norton, New South Wales.

Punt, A. E. On estimating growth curves for coral trout making allowance for gear selectivity. Unpublished report for Ecologically sustainable effects of line fishing project, CRC Research Centre for Great Barrier Reef.

Quinn II, T.J. and Deriso, R.B. (1999). Quantitative fish dynamics. Oxford University Press, New York.

Raclot, T., Groscolas, R. and Cherel, Y. (1998). Fatty acid evidence for the importance of myctophid fishes in the diet of the king penguins, *Aptenodytes patagonicus*. Marine Biology, 132: 523-533.

Reid, K., Croxall, J.P. and Edwards, T. M. (1997). Interannual variation in the diet of the Antarctic Prion *Pachyptila desolata* at South Georgia. Emu 97: 126-132.

Reilly, A. and Ward, R. D. (1999). Microsatellite loci to determine stock structure of the Patagonian toothfish, *Dissostichus eleginoides*. Molecular Ecology, 8: 1753-1754.

Reilly, A., Ward, B. and Williams, R. (1998). Preliminary results of investigations into the stock structure of Patagonian toothfish around Macquarie Island. Sub-Antarctic Fisheries Assessment Group document. SAFAG-98/4/4. Australian Fisheries Management Authority, Canberra.

Reilly, P. N. and Kerle, J. A. (1981). A study of the gentoo penguin *Pygoscelis papua*. Notornis 28: 189-202.

Reinhardt, S. B. and Van Vleet, E. S. (1986) Lipid composition of twenty-two species of Antarctic midwater zooplankton and fish. Marine Biology, 91: 149-159.

Rintoul, S. R. and Bullister, J. L. (1999). A late winter hydrographic section from Tasmania to Antarctica. Deep-Sea Research I 46: 1417-1454.

Rintoul, S. R., Donguy, J. R. and Roemmich, D. (1997). Seasonal evolution of upper ocean thermal structure between Tasmania and Antarctica. Deep Sea Research I 44: 1185-1202.

Rintoul, S. R. and Trull, T. W. (submitted). Seasonal evolution of mixed layers in the Subantarctic Zone south of Australia. Journal of Geophysical Research.

Robinson, S. A. and Hindell, M. A. (1996). Foraging ecology of gentoo penguins *Pygoscelis papua* at Macquarie Island during the period of chick care. Ibis 138: 722-731.

Robinson, S. A. and Scott, J. J. (1999). Marine conservation at Macquarie Island. Tasmanian Parks and Wildlife Service 61 pp.

Roff, D. A. and Bentzen, P. (1989). The statistical analysis of mitochondrial DNA polymorphisms: χ^2 and the problem of small samples. Molecular Biology and Evolution, 6: 539-545.

Rousevelle, D. E. and Brothers, N. P. (1984). The status and conservation of seabirds at Macquarie Island. In: Croxall, J. P. and Schreiber, P. G. H. (eds) Status and conservation of the world's seabirds. ICBP Tech Publ 2, Cambridge.

Sabourenkov, E. N. (1990). Mesopelagic fish of the Southern Ocean – summary results of recent Soviet studies. Selected Scientific Papers. (Scientific Committee for CCAMLR: Hobart). 573 pp.

Sambrook, J., Fritsch, E. F. and Maniatis, T. (1989). Molecular Cloning: a Laboratory Manual, 2nd edn. Cold Spring Harbor Laboratory Press, New York.

SC-CAMLR-XIII (1994). Report of the Thirteenth Meeting of the Scientific Committee. Scientific Committee for the Conservation of Antarctic Marine Living resources, Hobart. Paragraphs 5.18 – 5.26.

SC-CAMLR-XVII (1998). Report of the 17th Meeting of the Scientific Committee. Scientific Committee for the Conservation of Antarctic Marine Living Resources, Hobart.

Schoener, T. W. (1970). Non-synchronous spatial overlap of lizards in patchy habitats. Ecology 51: 408-418.

Scott, J. J. (1994). Marine conservation at Macquarie Island. Tasmanian Parks and Wildlife Service and Ocean Rescue 2000. 141 pp.

Seber, G. A. F. (1965). A note on the multiple recapture census. Biometrika 52: 249-259.

Shaughnessy, P. D. and Fletcher, D. (1987). Fur seals, *Arctocephalus spp.*, at Macquarie Island. In: Croxall, J. P. and Gentry, R. L. (eds) Status, Biology and Ecology of Fur Seals. Proceedings of an International Symposium and Workshop, Cambridge, England, 177-188.

SIMRAD Fisheries Division. (1993). SIMRAD EK500 service and technical manual, SIMRAD, Horten Norway.

Sinclair, A., Dunstan, G. A., Naughton, J. M., Sanigorski, A. J. and O'Dea, K. (1992). The lipid content and fatty acid composition of commercial marine and freshwater fish and molluscs from temperate Australian waters. Australian Journal of Nutrition and Dietetics, 49(3): 77-83.

Slip, D. J. (1997). Foraging ecology of southern elephant seals from Heard Island. PhD thesis, University of Tasmania, Australia.

Slip, D. J., Hindell, M. A. and Burton, H. R. (1994). Diving behaviour of elephant seals from Macquarie Island: an overview. In: Le Boeuf, B.J. and Laws, R.M. (eds) Elephant seals:

population ecology, behavior, and physiology. University of California Press, Berkeley, 253-270.

Smith, A. D. M., Punt A. E., Wayte, S. E., and Klaer, N. L. (1996). Evaluation of harvest strategies for eastern gemfish (*Rexea solandri*) using Monte Carlo simulation. In, Smith A. D. M. Evaluation of harvesting strategies for Australian fisheries at different levels of risk from economic collapse. FRDC T93/238, pp 120-164.

Sokal, R. R. and Rohlf, F. J. (1981). Biometry, 2nd edn., WH Freeman and Co., USA, 770-782.

Sokal, R. R. and Rohlf, F. J. (1995). Biometry. W. H. Freeman and Company, New York.

Sokolov, S. and Rintoul, S. R. (submitted). The subsurface structure of Southern Ocean surface temperature anomalies. Geophysical Research Letters.

Solyanik, G. A. (1963). An interesting ichthyological find. Inform Byul Sov Antarkt Eksped No. 42.

Stenson, G. B., Hammill, M. O. and Lawson, J. W. (1997). Predation by harp seals in Atlantic Canada: preliminary consumption estimates for Artcic cod, capelin and Atlantic cod. J Northwest Atl Fish Sci 22: 137-154.

Sutton, T. T. and Hopkins, T. L. (1996). Species composition, abundance, and vertical distribution of the stomiid (Pisces: Stomiiformes) fish assemblage of the Gulf of Mexico. Bulletin of Marine Science 59(3): 530-542.

Tarverdiyeva, M. I. (1972). Daily food consumption and feeding patterns of the Georgian cod (*Notothenia rossi marmorata* Fisher) and the Patagonian toothfish (*Dissostichus eleigenoides* Smitt) (Fam. Nototheniidae) in the South Georgia area. Journal of Ichthyology. 12: 684-692.

Tirasin, E. M. and Jorgensen, T. (1999). An evaluation of the precision of diet description. Marine Ecology Progress Series 182: 243-252.

Trites, A. W., Christensen, V. and Pauly, D. (1997). Competition between fisheries and marine mammals for prey and primary production in the Pacific Ocean. J Northwest Atl Fish Scie 22: 173-187.

Trites, A. W., Livingstom, P. A., Mackinson, S., Vasconcellos, M. C., Springer, A. M. and Pauly, D. (1999). Ecosystem change and the decline of marine mammals in the eastern Bering sea: testing the ecosystem shift and commercial whaling hypothesis. Fisheries Centre Research Reports, Vol 7.

Tseitlin, V. B. (1985). Energetics of fish populations inhabiting seamounts. Oceanology 25(2): 237-239.

Tuck, G. N. (2000). Macquarie Island Patagonian Toothfish Management Strategy Evaluation Workshop: Outcomes. 3 April 2000, CSIRO, Hobart. SAFAG-00/9/. Australian Fisheries Management Authority, Canberra.

Tuck, G. N. and Campbell, R. A. (1999). Standardisation of Catch and Effort Data for the Patagonian Toothfish (*Dissostichus eleginoides*) Fishery of Macquarie Island: A Preliminary Analysis. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/5. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Hearn, W. S., Williams, R., Smith, A. D. M., He, X., Constable, A. and de la Mare, W. K. (in press) An exact time of release and recapture assessment model with an application to abundance and recruitment estimation for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island.

Tuck, G. N., Williams, R., Constable, A., Smith, A. D. M., He, X. and Hearn, W. S. (1998). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-1998. Sub-Antarctic Fisheries Assessment Group document. SAFAG-98/4/2. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Williams, R., He, X., Smith, A. D. M. and Constable, A., (2000). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-2000. Sub-Antarctic Fisheries Assessment Group document. SAFAG-00/10/4. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Williams, R., Smith, A. D. M., He, X. and Constable, A. (1999). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-1999. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/3. Australian Fisheries Management Authority, Canberra.

Tuck, I. D., Hall, S. J., Robertson, M. R., Armstrong, E. and Basford, D. J. (1998). Effects of physical trawling disturbance in a previously unfished Scottish sea loch. Marine Ecology Progress Series, 162: 227-242.

Tyler, H. R. Jnr. and Pearcy, W. G. (1975). The feeding habits of three species of Lanternfishes (Family Myctophidae) off Oregon, USA. Marine Biology 32: 7-11.

Voisin, J. F. and Bester, M. N. (1981). The specific status of giant petrels *Macronectes* at Gough Island. In: Cooper J (ed) Proceedings of the Symposium on Birds of the sea and shore. African seabird Group, Cape Town, 215-22.

Volkman, J. K. and Nichols, P. D. (1991). Application of thin layer chromatography-flame ionization detection to the analysis of lipids and pollutants in marine and environmental samples. Journal of Planar Chromatography, 4: 19-26.

Walker, T. I., Taylor, B. L., Hudson, R. and Cottier, J. P. (1998). The phenomenon of apparent change of growth rate in gummy shark (*Mustelus antarcticus*) harvested off southern Australia. Fish. Res. 39: 139-163.

Waluda, C. M., Trathan, P. N. and Rodhouse, P. G. (1999). Influence of oceanographic variability on recruitment in the *Illex argentinus* (Cephalopoda: Ommastrephidae) fishery in the South Atlantic. Marine Ecology Progress Series. 183: 159-167.

Warham, J. (1963). The rockhopper penguin, *Eudyptes chrysocome*, at Macquarie Island. Auk 80: 229-256.

Warham, J. (1996). The behaviour, population biology and physiology of the petrels. Acedemic Press, London, UK 613 pp.

Waring, J. R., Kloser, R. J. and Pauly, T. (1994). Echo – Managing Fisheries Acoustic Data. In 'Proceedings of the International Conference on Underwater Acoustics University of New South Wales, Dec. 1994'. pp.22-24. (Australian Acoustical Society: Darlinghurst Public School, NSW.)

Weimerskirch, H., Capdeville, D. and Duhamel, G. (2000). Factors affecting the number and mortality of seabirds attending trawlers and longliners in the Kerguelen area. Polar Biology, 23: 236-249.

Weimerskirch, H., Jouventin, P. and Stahl, J-C. (1986). Comparative ecology of the six albtross species on the Crozet Islands. Ibis 128: 195-213.

Weimerskirch, H., Stahl, J-C. and Jouventin, P. (1992). The breeding biology and population dynamics of king penguins *Aptenodytes patagonica* on the Crozet Islands. Ibis 134: 107-117.

Weimerskirch, H., Zotier, H. and Jouventin, P. (1989). The avifauna of the Kerguelen Islands. Emu 89: 15-29.

WG-FSA (1995). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

WG-FSA (1997). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

WG-FSA (1998). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

WG-FSA (1999). Report of the Scientific Committee Working Group on Fish Stock Assessment. CCAMLR, Hobart.

White, W. B. and Peterson, R. G. (1996). An Antarctic circumpolar wave in the surface pressure, wind, temperature and sea-ice extent. Nature 380: 699-702.

William, R. (1988). The nearshore fishes of Macquarie Island. Papers and Proceedings of the Royal Society of Tasmania 122: 233-245.

Williams, A. and Koslow, J. A. (1997). Species composition, biomass and vertical distribution of micronekton over the mid-slope region off southern Tasmania, Australia. Marine Biology 130: 259-276.

Williams, A. Koslow, J. A., Terauds, A. and Haskard, K. (In prep.). Feeding ecology of fishes from the mid-slope micronekton community off southern Tasmania, Australia.

Williams, R., Lamb, T., Constable, A. and Tuck, G. N. (1998). History of the Macquarie Island fishery: 1994-1998. Sub-Antarctic Fisheries Assessment Group document. SAFAG-98/4/6. Australian Fisheries Management Authority, Canberra.

Woehler, E. (1996). Concurrent decreases in five species of Southern Ocean seabirds in Prydz Bay. Polar Biology, 16: 379-382.

Woehler, E. J. and Green, K. (1992). Consumption of marine resources by seabirds and seal at Heard Island and the McDonald Islands. Polar Biol 12: 659-665.

York, A. (1987). Northern fur seal, *Callorhinus ursinus*, Eastern Pacific Population (Pribilof Islands, Alaska, and San Miguel, Island California). In 'Status, biology and ecology of fur seals' (eds J.P. Croxall and R.L. Gentry) NOAA Technical Report National Marine Fisheries Service No 51, pp 9-21.

Young, J. W. (1991). 'Biology of lanternfishes (Pisces: Family Myctophidae); an overview, with reference to species of the waters of the Pasminco-EZ jarosite dumpsite'. CSIRO Division of Fisheries Industry Report 1.91. 13 pp.

Young, J. W. and Blaber, S. J. M. (1986). Feeding ecology of three species of midwater fishes associated with the continental slope of eastern Tasmania, Australia. Marine Biology 93: 147-156.

Yukhov, V. L. (1972). The range of the genus Dissostichus (Family Nototheniidae) in the Antarctic waters of the Indian Ocean. J Ichthyol 12: 346-347.

Zaykin, D. V. and Pudovkin, A. I. (1993). Two programs to estimate significance of χ^2 values using pseudo-probability tests. Journal of Heredity, 84: 152pp.

Zhivov, V. V. and Krivoruchko, V. M. (1990). On the biology of the Patagonian toothfish, *Dissostichus eliginoides*, of the Antarctic part of the Atlantic. Journal of Ichthyology 30: 142-146.

Zimmerman, G. M., Goetz, H. and Mielke Jr., P. W. (1985). Use of an improved statistical method for group comparisons to study effects of prairie fire. Ecology, 66: 606-611.

Appendix 1: Reports, refereed publications, presentations and posters from this project

Fisheries Assessment Group (Major) Reports

Tuck, G. N., Williams, R., Constable, A., Smith, A. D. M., He, X. and Hearn, W. S. (1998). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-1998. Sub-Antarctic Fisheries Assessment Group document. SAFAG-98/4/2. Australian Fisheries Management Authority, Canberra.

Tuck, G. N. and Campbell, R. A. (1999). Standardisation of Catch and Effort Data for the Patagonian Toothfish (*Dissostichus eleginoides*) Fishery of Macquarie Island: A Preliminary Analysis. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/5. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Smith, A. D. M., He, X and Constable, A. (1999). Simulation testing of the Patagonian toothfish (*Dissostichus eleginoides*) stock assessment: progress report and preliminary results. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/6. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Williams, R., Smith, A. D. M., He, X. and Constable, A. (1999). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-1999. Sub-Antarctic Fisheries Assessment Group document. SAFAG-99/7/3. Australian Fisheries Management Authority, Canberra.

Tuck, G. N. (2000). Standardisation of Catch and Effort Data for the Patagonian Toothfish (*Dissostichus eleginoides*) Fishery of Macquarie Island: 1995 to 2000. Sub-Antarctic Fisheries Assessment Group document. SAFAG-00/10/3. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Williams, R., He, X., Smith, A. D. M. and Constable, A. (2000). Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies: 1995-2000. Sub-Antarctic Fisheries Assessment Group document. SAFAG-00/10/4. Australian Fisheries Management Authority, Canberra.

Tuck, G. N., Smith, A. D. M., Klaer, N. L., He, X. and Constable, A. (2000). An initial evaluation of management strategies for the Macquarie Island Patagonian toothfish (*Dissostichus eleginoides*) fishery. Sub-Antarctic Fisheries Assessment Group document. SAFAG-00/10/5. Australian Fisheries Management Authority, Canberra.

Williams, R., Lamb, T. Constable, A. and Tuck, G. (1998). History of the Macquarie Island fishery, 1994 to 1998. SAFAG November 1998 meeting.

Williams, R., Lamb, T. and Wijk, E. (2000). Bycatch in the Macquarie Island and HIMI fishery. SAFAG February 2000 meeting.

Journal articles

Gaskett, A. C., Bulman, C., He, X. and Goldsworthy, S. D. (2001) Diet composition and guild structure of mesopelagic and bathypelagic fishes near Macquarie Island, Australia. New Zealand Journal of Marine and Freshwater Research, 35: 469-476.

Goldsworthy, S. D., He, X., Lewis, M., Williams, R. and Tuck, G. (2001). Trophic interactions between Patagonian toothfish, its fishery and seals and seabirds around Macquarie Island. Marine Ecology Progress Series, 218: 283-302.

Goldsworthy, S. D., Lewis, M., Williams, R., He, X., Young, J. and van den Hoff, J. (in press). The diet of Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island, South Pacific Ocean. Marine and Freshwater Research.

Kuikka, S., Tuck, G., Smith, A. D. M. and He, X. (2001). Using simulation results and Bayesian belief network to assist fisheries planning: a case study of Patagonian toothfish fishery. Submitted to ICES Journal of Marine Science.

Reilly, A. and Ward, R. D. (1999). Microsatellite loci to determine stock structure of the Patagonian toothfish, *Dissostichus eleginoides*. Molecular Ecology, 8: 1753-1754.

Tuck, G. N., de la Mare, W. K., Hearn, W. S., Williams, R., Smith, A. D. M., He, X. and Constable, A. An exact time of release and recapture stock assessment model applied to Macquarie Island Patagonian toothfish (*Dissostichus eleginoides).* Submitted to Fisheries Research.

Presentations:
Tuck, G. N, de la Mare, W. K., Williams, R., He, X., Smith, A. D. M. and Klaer, N. (2000). Abundance estimation and management strategy evaluation for Macquarie Island Patagonian toothfish. Talk presented to the Australian Society for Fish Biology, Albury, NSW, 10-12 August 2000.

Tuck, G. N., Williams, R., Hearn, W. S., Smith, A. D. M. and He, X. (1999). Abundance of Patagonian toothfish at Macquarie Island: estimates from tagging studies 1995-1998. Talk presented to the SCFA Research Committee Minisymposium of Stock Assessment Experts, Queenscliff, Victoria, 19-21 July 1999.

Tuck, G. N., Williams, R., Hearn, W. S., Smith, A. D. M. and He, X. (1999). Abundance of Patagonian toothfish at Macquarie Island: estimates from tagging studies 1995-1999. Talk presented to the Statistics in Ecology and Environmental Monitoring conference, Dunedin, NZ, 6-10 December 1999.

Wilson, G. and Nichols, P. "Fatty acid analysis of the Patagonian toothfish around Macquarie Island: implications for the determination of long-term diet" Australian Marine Sciences Association (AMSA) Annual Conference, University of New South Wales, Kensington, Sydney, July 11-14 2000.

Wilson, G. and Nichols, P. "Signature lipids of the Patagonian toothfish: preliminary findings" American Oil Chemists Society (AOCS) Australasian Section Workshop, Food Science Australia, Werribee, Melbourne, October 11-12 2000.

Posters:
Furlani, D. M. and He, X. (2000). "Zooplankton abundance and community structure around Macquarie Island" Australian Society for Fish Biology, Albury, NSW, 10-12 August 2000.

Wilson, G., Nichols, P. and Burton, H. (1999). "Fatty Acids as Indicators of Southern Elephant Seal Diet" Australian Marine Sciences Association (AMSA) Annual Conference, University of Melbourne, Parkville, Melbourne, July 11-14 1999.

Wilson, G., Nichols, P. and Burton, H. (1999). "Fatty Acids as Indicators of Southern Elephant Seal Diet" Thirteenth Biennial Meeting of the Society for Marine Mammalogy, Outrigger Resort, Maui, Hawaii, USA, November 28-December 3 1999.

Wilson, G., Nichols, P. and Burton, H. (2000) "Fatty Acids as Indicators of Southern Elephant Seal Diet" American Oil Chemists Society (AOCS) Australasian Section Workshop, Food Science Australia, Werribee, Melbourne, October 11-12 2000.

Appendix 2: Staff and affiliation

Andrew Constable	AAD
Dianne Furlani	CSIRO
Simon Goldsworthy	CSIRO
Karen gowlett-Holmes	CSIRO
Xi He	CSIRO
Rudy Kloser	CSIRO
Tony Koslow	CSIRO
Tim Lamb	AAD
Mark Lewis	CSIRO
William de la Mare	AAD
Peter Nichols	CSIRO
Tim Ryan	CSIRO
Keith Sainsbury	CSIRO
Geoff Tuck	CSIRO
Bob Ward	CSIRO
Alan Williams	CSIRO
Dick Williams	AAD
Gareth Wilson	CSIRO
Jock Young	CSIRO

AAD	Australian Antarctic Division
CSIRO	Commonwealth Scientific and Industrial Research Organisation

Appendix 3: Intellectual property

The intellectual property arising from this work is the joint property of FRDC, CSIRO, AAD and Austral Fisheries Pty. Ltd.

Appendix 4: Voyage report

**VOYAGE
REPORT
SS01/99**

10 January–4 February, 1999
CSIRO Division of Marine Research
Marine Laboratories
Headquarters
Telephone (03) 62325 222
Telex AA 57-812
Facsimile (03) 62325 000
GPO Box 1538
Hobart Tasmania 7001
Australia

ISSN 1039-2041

ITINERARY

Departed: Hobart 0900 Sunday, 10 January 1999
Arrived: Hobart 1930 Wednesday, 3 February 1999

AREA OF OPERATION

The voyage was carried out in waters in the vicinity of Macquarie Island and the Macquarie Ridge between 53°S - 56° 17'S and 158° 30'E - 159° 25' E.

RESEARCH BACKGROUND

The voyage is designed to provide the scientific basis for management of the Macquarie Island Patagonian toothfish (*Dissostichus eleginoides*) fishery, based upon, on the one hand, an assessment of population size and hence sustainable yield, and on the other hand, additional information on ecological interactions of the fishery with marine mammal and seabird populations that breed on the State Reserve of Macquarie Island. A benthic survey will contribute to the planning and development of a Commonwealth Marine Protected Area within Australia's EEZ around Macquarie Island.

VOYAGE OBJECTIVES:

1. Conduct an acoustic/trawl survey around Macquarie Is. and along the Macquarie Ridge to 1500 m to assess the distribution and relative abundance of Patagonian toothfish and, so far as possible, an assessment of absolute abundance. To complete this objective the following sub-objectives will be achieved:

- Obtain *in situ* target strength measurements of Patagonian toothfish and other dominant species.

- Test use of the acoustic multi-frequency system to discriminate between species in the survey area.

2. Assess the diet of Patagonian toothfish and dominant nekton species in order to establish a food web for the nekton and higher predators and assess predatory and competitive interactions.

3. Describe the abundance and community structure of the nekton in the upper 1500 m of the water column in relation to oceanographic conditions, i.e. across the sub-Antarctic Front, on Macquarie Ridge (Patagonian toothfish habitat) and in deepwater based upon depth-stratified sampling.

4. Assess the abundance of zooplankton in the upper 200 m of the water column in relation to ocean conditions in the same habitats as Objective 3.

5. Undertake systematic observations of the seabirds and sea mammals in relation to physical and biological ocean conditions across the sub-Antarctic Front along the Macquarie Ridge and off Macquarie Is.

6. Obtain data for a baseline description of the benthic invertebrate community within and around the area of a potential MPA and assess the impact of trawling on it based on broad-scale acoustic mapping and detailed habitat assessments from camera/video transects and dredge sampling from 200-1500 m.

7. Collect genetic material from Patagonian toothfish for stock discrimination studies.

RESULTS

The voyage consisted of the following components: an acoustic/trawl survey of Patagonian toothfish; oceanographic sampling of the water column with Bongo and surface nets for zooplankton and with the Midwater Opening/Closing net system (MIDOC) for nekton, and with the CTD to measure physical and chemical properties and chlorophyll concentration in the upper water column; and benthic sampling with a deepwater video and dredge. Results are presented under those headings. A complete list of stations is found in Appendix 4A.

Acoustic survey of Patagonian toothfish
Intensive acoustic surveys with the deep water multi-frequency towed body (MUFTI) were undertaken in the following regions on the Macquarie Ridge from 53.5° S to S56.3°S (see Appendix 4A for positions):

Aurora Trough
Beer Garden, Grand Canyon, Colgate Valley
East Macquarie
West Macquarie
Southern Ridge

The towed system was deployed at 100-400m below the surface and towed at speeds of 6-9 knots. Acoustic fish marks observed during the survey were recorded and relayed to the *Austral Leader* for trawling. Several acoustic marks that were observed within the 3 NM limit of Macquarie Island were trawled by the *Southern Surveyor*. The vessel mounted and towed acoustic systems were calibrated at the start of the voyage and the deep water system was calibrated to a depth of 500m at the completion of the acoustic work. Measurements of the water column temperature and salinity were conducted to estimate the sound speed and absorption profiles for the various frequencies. The cold 6 °C surface water that declined to around 2 °C at 800m increased the absorption of our 38kHz system to 9.8dB whilst reducing the

120kHz absorption to 36dB. Independent experiments were carried out to estimate the absolute absorption at 38kHz for these waters.

Along with the multi-frequency towed system, the vessel's 12kHz, 38kHz and 28kHz echosounders were also digitally recorded during the survey. In general the hull mounted acoustic systems (12, 28 kHz) were of poor quality and could not be used for identification of acoustic marks. The weather conditions on the western side of Macquarie Island were generally 30-35 knot westerly winds. These conditions soon rendered the vessel hull-mounted acoustic systems useless. However a 38kHz transducer mounted on a pole that extends 3m below the ships hull was operable for 80 % of the survey and proved to be a useful backup to the towed system. The towed acoustic system produced acoustic echograms of high data quality in all weather conditions encountered during the survey.

Initial catch results indicate that whilst low to moderate catches of Patagonian toothfish were caught in most trawls there were also significant catches of species with gas-filled swim bladders: namely morids and whiptails. As Patagonian toothfish do not have a gas-filled swim bladder their reflectance is expected to be significantly less than the gas-bladdered species, as is the case with orange roughy. No acoustic mark identified during the broad acoustic survey could be definitely and uniquely attributed to Patagonian toothfish.

The largest catches of Patagonian toothfish during this survey originated from a region in Aurora Trough known as the Golden Mile. Extra acoustic surveying took place in this region with the deepwater multi-frequency towed system deployed 50-100m off bottom to measure *in-situ* target strengths. Several marks observed with our multi-frequency system as being typical of non-gas-bladdered fish were target trawled by the *Austral Leader*. Catches were higher on these marks and after further analysis will assist in our acoustic identification of Patagonian Toothfish. Unfortunately these marks were very small, 5 –10m high and 0.2 NM long and would be difficult to resolve and identify with vessel- or shallow-towed acoustic systems. Another area that contained significant quantities of juvenile toothfish was located near the 3 NM boundary and deep water multi-frequency acoustic signatures complemented the trawl catches obtained.

Given the lack of any significant acoustic mark that could be attributed to Patagonian toothfish and the low catches during the survey with a high proportion of gas-bladdered species such as the morids and whiptails, an acoustic assessment of biomass will not be possible.

Midwater Trawl Sampling
The mesopelagic fauna was sampled at five sites with a pelagic trawl fitted with a MIDOC multiple cod-end. This allowed sampling in four depth strata: 1,000-750, 750-500m, 500-250 and 250m-surface. Two samples during the daytime and two at night were attempted at each station, but at most stations it was only possible to obtain one night-time sample because of the shortness of the night.

The following stations were sampled.

STATION	Number of samples
Macquarie offshore - deep water to west of Ridge	2 day, 2 night
Aurora Trough - on Macquarie Ridge	2 day, 1 night
Beer Garden - on Macquarie Ridge	2 day, 1 night
Ridge Gap - gap in Macquarie Ridge north of island	2 day, 1 night
North Site - north of Ridge Gap, close to Subantarctic Front	1 day

Despite the differences in submarine topography and a latitude range of 140 NM, there was little difference in the species composition between sites. Species composition by both number and weight was dominated by a range of species of myctophid fish from the genera *Protomyctophum*, *Krefftichthys*, *Electrona*, *Gymnoscopelus* and *Lampanyctus*, and other fish such as *Bathylagus* sp. *Stomias* sp. and *Borostomias* sp. Among invertebrates, coronate medusae, the ostracod *Gigantocypris mulleri*, the hyperiid amphipod *Themisto gaudichaudi*, *Euphausia triacantha* and *E. vallentini* and the decapod crustaceans *Pasiphaea* sp. and 'red carid' were typical of all stations.

Some small differences were apparent, however. The sites on Macquarie Ridge, Beer Garden and in particular Aurora Trough, produced a number of benthopelagic shelf-dwelling species in the deepest net, eg. *Halargyreus johnsoni*, *Coryphaenoides subserrulatus* and *Melanostigma gelatinosum*. In these locations, the deepest net would have been within 100-200m of the bottom. The more northerly stations at Ridge Gap and North Ridge also contained a few individuals characteristic of the Subantarctic Front and waters to the north, such as *Electrona subaspera*, *Phosichthyus argenteus*, *Polymetme* sp and *Protomyctophum* (*Hierops*) sp. Additionally, the North Ridge station produced other species characteristic of waters north of the Subantarctic Front such as *Diaphus hudsoni*, *Persparsia kopua*, *Woodsia meyerwaardeni* and *Rosenblattia robusta*.

There were marked differences in species composition and abundance with depth. In the daytime hauls, net 2 (1,000-750m) had by far the largest catches, particularly of medusae, *Bathylagus* sp. and the myctophids *Lampanyctus* sp and *Gymnoscopelus braueri*. Net 3 (750-500m) generally had the next largest catch, with a similar species composition to net 2, and the other nets at shallower depths generally produced low catches containing few species.

There was some evidence of diurnal vertical migration, but in few cases was this strongly evident. *Protomyctophum* sp. was usually found over the whole depth range sampled during the day, but at night was concentrated in the top 500m. *Gymnoscopelus braueri*, *Lampanyctus* spp. and *Bathylagus* spp were mostly found in the lower nets by day, but spread more evenly through the depths at night.

Catches of all fish species per net, expressed as crude grams per haul without correction for volume filtered, are given in the following table.

Station	DAY				NIGHT			
	1000-750	750-500	500-250	250-0	1000-750	750-500	500-250	250-0
MO	767.1	149.9	11.9	231.6	169	0	531.1	144.9
AT	2309.7	469.6	78.4	73.5	1287.1	466.8	173	196.6
BG	720.2	214.4	57.7	127.8	1080.5	559.7	132	462.6
RG	1146.4	585.8	72.6	578.4	959.3	476.8	772.4	715.8
NR	269	589.5	13.6	20.6				

For most sites, catches in the deeper nets were greater by day than by night, and the reverse was generally true for the shallower nets, which presumably reflects the diurnal vertical migration of some species. Differences between sites are also evident. By day, Aurora Trough (AT) and Ridge Gap (RG) have the greatest biomass at most depths, and at night Beer Garden (BG) has a comparable biomass with AT and RG for most depths. The Macquarie Offshore (MO) site had considerably less biomass than the three sites on or near Macquarie Ridge, except for the shallowest stratum by day and the 500-250m stratum at night. This supports the theory of there being some concentrating effect by the Macquarie Ridge on the mesopelagic fauna, especially at depths greater than 500m where the toothfish is thought to feed.

For each MIDOC trawl, vessel pole-mounted acoustics were recorded to estimate the biomass in each 250m depth layer associated with the MIDOC trawl depths and times. In general the daytime echograms on or near the ridge at 38kHz showed distinct layers, typically at 0-30m, 100 – 150m, 400 – 550m, and 600 – 900m depth. The acoustic layer at 100 - 150m during the day was of the highest intensity and its structure typical of a tightly schooling small gas-bladdered fish (eg. a myctophid). Additionally the deep water towed system was deployed to ca 900m depth and slowly brought to the surface to obtain the target strengths of the dominate species as a function of depth. The multi-frequency echograms from the deep towed system showed distinct layering of species in each depth layer that will be compared to the species caught in the individual depth layers.

Benthic survey
On the ridge sites both north and south of Macquarie Island, stony coral was collected mainly on the top of the ridges, with very little if any in the deeper samples (ie on the slope or base). While live coral was collected only on the site at the north end of the Gap, this may reflect a sampling artefact, not a lack of live coral at the other sites. The shallowest samples on these ridge sites also had the largest quantities and greatest diversity of gorgonacean-type octocorals. The octocorals decreased markedly both in diversity and abundance further down the slope at all these sites. Both stony coral (live or dead) and octocorals were virtually absent from the sites directly east and west of Macquarie Island. Generally, the ridge sites also had more sponges and a greater variety of crustaceans and echinoderms than the sites east and west of Macquarie Island.

The shallow sites east and west of Macquarie Island had very large quantities of brachiopods, mostly attached to dead bivalve shells. Two species of solitary ascidians were also present in very large numbers and attached to dead bivalve shells. The dead shells were predominantly from a species of Chlamys and a small venerid, both of which were also collected live. The quantities of dead shell and its associated fauna decreased markedly with depth, particularly on the east side. None of these species were collected from the ridge sites. The east side samples also had far more sediment and sediment-related fauna, such as sea pens, than the west side samples, because the west side is much more exposed to heavy weather conditions.

Deeper samples at all sites tended to have more rocks and rubble than the shallowest samples, indicating that the slopes in all the areas have significant amounts of rock scree present. Unstable scree is not a suitable substrate for the development of communities of large fixed invertebrates, and may be one reason why they are not present in the deeper water.

Little can be said about biogeographic affinities until more of the material has been positively identified. However, the fauna appears substantially different from that found on the seamounts south of Tasmania.

Survey of the sea birds and mammals
David Eades (Birds Australia) carried out hourly, standardised observations of sea birds and mammals at all sites. The relatively shallow waters of the main part of the Macquarie Ridge appear to be an important foraging area for most seabird species with significant breeding populations at Macquarie Island. The same areas may also represent a significant foraging site for some seabird species breeding at the New Zealand subantarctic islands to the north, particularly for Southern Royal Albatrosses from Campbell Island and Shy Albatrosses from the Auckland Islands. Numbers of birds per count were generally highest around Macquarie Island and along the ridge toward the south. Counts decreased north of the island and offshore. A total of 30 species of seabird were recorded on counts made at the nine main sites. Six species breeding locally at Macquarie Island accounted for the bulk of seabird abundance: Antarctic Prion, Rockhopper Penguin, Royal Penguin, Northern Giant-Petrel, Black-browed Albatross

and King Penguin. No sea mammals were recorded during the standardised observations. See Appendix 4B for a full report of the sea bird observations

VOYAGE NARRATIVE

The vessel departed Hobart at 0900 on 10 January and proceeded initially to a sheltered anchorage off Port Arthur to calibrate the towed body, hull and pole-mounted acoustic systems. Several difficulties were encountered, due to brisk winds. To obtain additional stability, the trawl doors were lowered, but these crossed and confounded the calibration, and also tangled upon retrieval. There was also difficulty lowering the pole in the vessel's moonpool.

The vessel departed Port Arthur at about midnight for the passage to Macquarie Island. The trip was uncomfortable but uneventful except for an accident during a test deployment of the towed body, which resulted in Matt Sherlock losing the end of the middle finger on his left hand, when it was crushed between the towed body and cradle. The end of the finger was retrieved, he sewed it back on and he was put on antibiotics. Matt received further medical attention subsequently at Macquarie Island, and the finger seems to be healing well. Within the shelter of Buckles Bay off the northeast corner of Macquarie Island, Dick Williams and Tim Lamb were trans-shipped to the fishing vessel, *Austral Leader*, for the duration of the acoustic survey, and the voyage leader and Rudy Kloser went aboard *Austral Leader* to discuss the acoustic survey with Mr. Halli Stefansson, skipper of the *Austral Leader*. Halli kindly provided *Southern Surveyor* with his vessel's digital bathymetric data for Macquarie Ridge, which was to prove invaluable throughout the voyage.

The acoustic survey of Patagonian toothfish was carried out from 14 through 18 January. The first area surveyed was the Aurora Trough, just west of Macquarie Island, where the fishery has centred since its inception. The first transect was across an area where juvenile toothfish have been found northwest of the island, followed by a series of six transects laid systematically across the trough to cover all the ground at depths greater than 500 m with transect spacing of 2° longitude (2.15km). Because of the unevenness of the ground, two passes were generally made with the towed body: first, at a depth of about 200 – 300m, and then ~100-150m above bottom for target strength (TS) measurement. There were few acoustic marks, and most of these were small. *Austral Leader* carried out 15 trawls in the area, covering much of the transects. Typical catches were several hundred kg of toothfish, sometimes up to a ton or so and sometimes less than 100kg. Intermittent problems with the towed body transducer and the onset of a gale caused *Southern Surveyor* to take shelter behind Macquarie Island late on the 14th. Repair of the towed body required retermination of the cable, which requires ~12 hours to perform. In the interim, *Southern Surveyor* carried out three tows on acoustic marks observed on the innermost transect, which were inside State waters and where only *Southern Surveyor* had permission to trawl. The tows yielded relatively few toothfish along with whiptails (the small *Coryphaenoides subserrulatus* and the large *Macrourus carinatus*), carapid eels, and a variety of small 'feed' fishes (e.g. myctophids and Bathylagus).

After completion of a CTD cast in the trough area, *Southern Surveyor* undertook a series of zig-zag transects on the 17th January between 500 and 1,000m depth along the edge of the Ridge, en route to the northern toothfish grounds. Acoustic transects were carried out in the northern complex of fishing grounds: again, few marks were observed, but those observed were passed along and fished by *Austral Leader*. Catches of toothfish remained poor. Conditions were marginal with winds of 30-40 knots throughout the day. The acoustic survey of the northern fishing grounds was completed on the 18th. Several further marks were passed on to *Austral Leader*. Although some of the marks were substantial, there was no evidence from either vessel of the major aggregation that was fished several years ago.

After completing this portion of the survey, *Southern Surveyor* proceeded south, carrying out zig-zag acoustic transects along the slope on the eastern side of the ridge. The vessel then continued south of Macquarie Island, surveying the Caroline Trough, south of Aurora Trough, zig-zagging between the 500m depth contour on the ridges to either side of the trough. The trough extends about 20 NM. Two significant acoustic marks were seen, which were passed on to *Austral Leader*.

The vessel then continued south, surveying a series of banks en route to the first benthic survey site at 56° S. However, the bank indicated on the chart of the NZ Oceanographic Institute did not exist, not the first time that this chart proved grossly inaccurate, even in areas where its 'reliability scale' indicated there were adequate soundings. A site somewhat to the south was therefore selected. A CTD cast was made to ~1,000m, which indicated that the surface water was significantly colder (4 °C cf 6 °C) and fresher than in Aurora Trough. Temperatures at depths >500m were between 2 °C and 3 °C.

Four benthic sled tows were carried out: one on top of the ridge at 500-600m and three on the slope between 600 and 1300 m. Only one of the latter tows was successful. The tow on top of the hill yielded a number of gold and black corals and about 20kg of dead colonial coral, but a different genus and species than that found on the seamounts south of Tasmania; rather it appeared to be the coral found in New Zealand waters. There were considerable quantities of sponge as well and some prawns but no squat lobsters, brisingid seastars, urchins, and virtually no starfish, as found around Tasmania. However there was a Paralaemonema and a muraenolepid. The tow on the slope yielded about a tonne of rock and a few sponges and bits of coral. One of the other tows on the slope yielded two rocks only, so it appears that there is in fact little life on the slope (at least the west-facing slope).

Having completed the acoustic survey portion of the voyage, we steamed back to Macquarie Island. A deepwater calibration of the acoustic system was carried out in the early morning of 20 January in the lee of the island. At 0900, the Voyage Leader and Rudy Kloser went ashore to review the project with Simon Goldsworthy, who reported that the fur seals were foraging in the approximate region of the northern toothfish fishing ground, though more in the lee of the ridge. Most crew and scientists also went ashore for a mid-voyage break for the morning. Halli Stefansson later came aboard Southern Surveyor to review the acoustic survey. There was general agreement that there was little sign of any concentration of toothfish and that the data were too inconclusive to establish the appearance of toothfish acoustically.

Southern Surveyor weighed anchor at 1300, and an acoustic experiment was carried out to measure sound absorption in seawater. The deepwater video pressure housings were then successfully pressure tested by lowering and retrieving them from 1500m. The following morning, the camera system was first used at 100m depth in the vicinity of Buckles Bay. The camera and lights needed adjustment, and there were electronic problems communicating with the camera. These problems were corrected later that day.

The vessel proceeded to Aurora Trough, where, during 21st and 22 January it carried out oceanographic and benthic sampling of this key site in the toothfish fishery. The water column down to ~1,000 m was sampled in four 250m depth horizons with the MIDOC trawl system. Replicate samples were obtained in daytime but only one sample from the night period, due to the short length of the night, which at this latitude and time of year is only about 6.5 hours from sunset to sunrise; sampling of the water column required 3 hours, exclusive of turnaround time on deck, and it was desirable not to sample within an hour of sunrise and sunset. Zooplankton sampling of the upper 200 m of the water column with the Bongo net and a surface net was aborted due to problems with the block, which, in combination with deteriorating weather conditions (winds of ~30 knots) caused the tow cable to repeatedly jump out of the block. Benthic sampling was carried out at three depth horizons: 200-500m, 500-700m and 700-900m.

The shallow dredge sample yielded a large number of bivalve shells, to which were attached numerous brachiopods and ascidians. The mid-depth sample, however, which came from the steep portion of the slope, had to be repeated four times to obtain a reasonable sample, which consisted mostly of cobbles with their attached fauna. There was little in the dredge sample from the base of the trough, consistent with observations from the fishery, from which there has been little benthic invertebrate bycatch.

Southern Surveyor proceeded to the offshore sampling site, 25 NM west of Macquarie Island on 23 January. Two day and two night MIDOC sets of samples were obtained, although the second night MIDOC series came up somewhat late (0345) and apparently experienced a twist in the net, causing the samples from the first four nets to be deposited together in the fourth codend. The following day (24 January), a CTD cast was carried out to 1500 m, and six replicate Bongo net samples were obtained, following modification of the block to minimise the risk of the cable jumping the block. Acoustic sampling of the water column was carried out, following the transect used for MIDOC sampling, by lowering the towed body to about 900m and gradually raising it to measure both nekton abundance with three acoustic frequencies (12, 38 and 120kHz) and their target strength distribution for comparison with the midwater trawl sampling. The vessel then returned to Aurora Trough to obtain Bongo zooplankton samples from that site.

On 25 January, the camera system was successfully deployed on the leeward, east side of Macquarie Island, initially at 200-400m depth, then at 400m and finally from 400 to about 1400m depth. Through this series of deployments, various teething problems were worked out. Because the footage cannot be viewed 'live' and there is little control over the tilt of the system, much of the footage is imperfect. Nonetheless the quality is impressive, much of it of professional 'broadcast' standard, in addition to being of immense value scientifically. While the dredge is able to obtain samples of specimens for study in hand, the video footage, supplemented by a laser-based positioning and measurement system, can provide quantitative data on abundance, community composition, size distribution, and spatial distribution in relation to habitat structure. These deployments showed what was only suggested from the dredge sampling: an exceptionally rugged slope with rubble fields, steep overhangs where suspension feeders (*e.g.* sponges, gorgonians, psolid holothurians, anemones and hydrocorals) were most abundant, and generally a moderate abundance of lithodid crabs (relatives of the Alaskan king crab and equally tasty), the occasional toothfish, while crustaceans, carapid eels and other fishes were patchily abundant over the bottom. There was relatively little life on the cobble fields, which may be due to instability of this environment. Three samples were obtained the following day with the dredge over this depth horizon at the east Macquarie site, which generally confirmed the picture obtained from the video system.

The vessel then proceeded to the Beer Garden fishing ground. The weather was exceptionally fine initially, so the camera system was deployed first. However a tangle in the towlines during deployment ended with the electrical cable between the depth pinger and camera going under the vessel, being caught in the propeller and severed. Unfortunately, the fine conditions required for deployment of the system were never again obtained while at a suitable site.

Four benthic dredge shots were then carried out. The first covered the top of the eastern ridge that defined the ground, from about 400 to 600m. The sample contained a number of gorgonian coral species, as well as sponges and other suspension feeders. The second shot, aimed at the steep portion of the slope, failed to obtain a sample, but the succeeding one brought up the codend full of rocks, indicative of the rubble seen on the steep portion of the slope in the video from the east side of Macquarie Island. Mixed in were a number of sponges, occasional corals, some fish and lithodid crabs, all reminiscent of the fauna seen on the video of the slope. The final sled sample from the base of the slope along the flat trawlable floor of the valley yielded very little, consistent with the sampling carried out in Aurora Trough.

On 27 January, two day and one night set of depth-stratified samples of the nekton were obtained of the water column with the MIDOC gear. Sea conditions then rose with winds to over 40 knots (Beaufort scale 8/9). The vessel suspended sampling for the night. In the morning, the wind had dropped considerably but sea conditions were still too rough to safely deploy gear, so the vessel proceeded north to a site within the gap between two sections of the ridge, where the sub-Antarctic Front is generally positioned (S. Rintoul, pers. comm.). Two midwater trawls with the MIDOC gear were carried out in the day, followed by a CTD cast and night deployment of the MIDOC. The CTD indicated an intrusion of extremely cold water (~1.5 °C) below about 100 m. There was a strong westward set, which caused the gear to veer substantially from its intended course. The daytime midwater trawl samples were highly consistent, with small catches with low diversity near surface (the hyperiid amphipod, *Parathemisto gaudichaudi*, a myctophid, *Krefftichthys anderssoni*, and *Stomias* sp in the upper 250 m and little more between 250 and 500 m) but large quantities (10-35 kg) of jellyfish (Coronatae and *Atolla*) and large numbers of a fairly diverse fish fauna in the deeper layers. An acoustic transect was carried out in the night, followed by six Bongo and surface net samples on the morning of the 29th, after which an acoustic transect was carried out in daylight conditions.

The vessel then returned to the Beer Garden site, where a night-time acoustic transect was conducted. Benthic sampling with the dredge was carried out at the northern edge of the Macquarie Ridge from about 0100 on the 30th of January through most of the morning. Small samples were obtained from the 'flat' portion on top of the ridge at about 1,000m depth; from the upper portion of the slope at 1,000-1,200m and a deeper sample from about 1,200 – 1,500m depth. Two attempts were required to obtain the last sample, with extensive damage to the tow bridle and net on the last tow. The vessel then returned to the Beer Garden to complete the daytime sampling: acoustic sampling of the water column and the replicate Bongo tows. Only five Bongo tows could be completed, before rising sea conditions and the dusk tipped the balance between the potential risk and gain of further sampling.

The vessel proceeded to the extension of Macquarie Ridge north of the gap. The last day of sampling began poorly with steerage being lost at about 0200. This was corrected after 2-3 hours. Three benthic dredge samples were then obtained on the edge of the northern extension of the ridge system. There were a number of corals in the samples. By the time the benthic sampling had been completed, sea conditions had increased to force 7/8 with winds over 35 knots, and the vessel hove to. Sea surface temperature remained at about 7 °C, indicating the vessel had not passed through the Sub-Antarctic Front (SAF). A CTD cast (carried out without bottles to minimize the risk of damage) indicated a single layer at about 4 °C below the near-surface mixed layer. The vessel then steamed north to locate the SAF, which unfortunately proved somewhat elusive. By 1600, with the day coming to an end and needing to head back to Hobart, a last midwater trawl was carried out with the MIDOC on the western flank of an extension of the Macquarie Ridge, followed by a CTD cast to 1,000 m. The vessel then headed for Hobart at 2,000, 31 January. The vessel arrived alongside CSIRO at 1930, 3 February 1999.

SUMMARY

The achievements of the present voyage need to be assessed with the perspective that this was the first voyage by CSIRO to these waters, that it was the first attempt by any group to survey Patagonian toothfish acoustically, and it was the first trial of the newly-designed and constructed deepwater video system. Sea conditions were often difficult and the benthic ground was generally exceptionally steep and rough. Despite these conditions, virtually all objectives were achieved, at least so far as was possible.

Despite the efforts of the commercial fishing vessel and the CSIRO acoustic survey, no substantial concentrations of Patagonian toothfish were found. Bycatch species were sufficiently abundant to confound any attempt to obtain an acoustic estimation of toothfish biomass, particularly since most bycatch species contained gas-filled swimbladders and therefore presented acoustic targets at least as large or larger than that of the toothfish.

Oceanographic sampling of the water column structure, zooplankton, and nekton abundance, distribution and day-night movements through the water column were carried out over the major toothfish fishing grounds and at control sites offshore to the west and in the vicinity of the Sub-Antarctic Front to the north. An initial assessment of the nekton data suggests that the dominant prey of toothfish and of fur seals and penguins are restricted to the deep and upper waters, respectively, and that there is relatively little food web interaction between them.

The benthic survey indicates considerable heterogeneity in benthic habitat along Macquarie Ridge. Suspension feeders seemed diverse and abundant along the tops of the ridges and on overhangs and ledges. Steep portions of the slope were likely unstable and were relatively depauperate, given the low growth and recruitment rates typical of the mid-slope fauna. The flat ground at the base of troughs and canyons, where most toothfish trawling has been concentrated, contained a typical soft-bottom fauna.

The seabird fauna varied considerably on and off the ridge, being substantially more abundant on the Ridge. Dominant species, such as the black-browed albatross, appeared to be largely restricted to the ridge environment, suggesting that the ridge significantly influences the biological oceanography of the region in ways that are not yet understood.

PERSONNEL

(Note: unless otherwise indicated, all personnel are staff of CSIRO Marine Research.)

LEG 1:
Dr Tony Koslow (Voyage Leader)
Mr Rudy Kloser
Mr Mark Lewis
Ms Karen Gowlett-Holmes
Mr Matt Sherlock
Mr Jeff Cordell
Ms Val Latham
Mr Miroslaw Ryba
Mr Tim Ryan
Mr David Eades (Birds Australia)
Mr Tim Lamb (Australian Antarctic Division)
Mr Dick Williams (Australian Antarctic Division)

SHIP'S COMPANY
Mr. P. Dunbar	Master
Mr. R. Pepper	Chief Mate
Mr. J. Boyes	2nd Mate
Mr. I. Murray	Chief Engineer
Mr. E. Peters	2nd Engineer
Mr. J. Hinchliffe	3rd Engineer
Mr. T. Condon	Chief Cook
Mr. W. Hatton	2nd Cook
Ms. B. Sherriff	Steward
Mr. M. McDougall	Bosun
Mr. G. McDougall	IR
Mr. L. Jacomos	IR
Mr. S. O'Doherty	IR
Mr. G. Murtagh	IR
Mr. A. Hearne	IR
Mr. P. Wallace	Greaser
Mr. N. Irvine	IR

ACKNOWLEDGEMENTS

We thank the Master, Peter Dunbar, the Mates, Roger Pepper and John Boyes, and the crew of *Southern Surveyor* for their skills and help during the voyage. We thank the captain of the *Austral Leader,* Mr. Halli Stefansson, for his cooperation and assistance. Thanks are also extended to Ian Helmond and the staff from the CSIRO Workshop for their assistance with building the deepwater video and their extensive work in preparing the other gear for the voyage. Lastly, sincere thanks to all voyage participants for their effort during the time at sea. Your efforts and company combined to make SS 1/99 a successful and pleasant scientific voyage.

Tony Koslow
Voyage Leader

Nan Bray
Chief, CSIRO Marine Research

CONTACTS

For further information about this voyage contact:

Dr Tony Koslow
Mr Rudy Kloser
CSIRO Marine Research
GPO Box 1538
Hobart Tasmania 7001
Phone (03) 62325 5389
Fax (61) (3) 62325 000

Appendix 4A. List of stations showing activity, area, and date, time and position at the start of sampling. (The position of fishing grounds are commercial in confidence and, as such, are not specified here.)

Not included.

Appendix 4B. Observations of seabirds in Macquarie Island waters

by D.W.Eades
Birds Australia
415 Riversdale Rd
Hawthorn East VIC 3123

1.   Introduction

Although the biology of the seabird species breeding on Macquarie Island is fairly well-known from land-based studies, comparatively little is known about their distribution at sea in surrounding waters, nor of the non-breeding species that also frequent these waters (Scott 1994). The present survey is a first attempt at determining the distribution and relative abundance of all seabird species occurring in Macquarie Island waters, especially in relation to the main bathymetric and oceanographic features of the study area, namely the Macquarie Ridge and Subantarctic Front, respectively. To this end, observations of seabirds were made by the author from aboard the CSIRO Research Vessel *Southern Surveyor* while it conducted acoustic, trawling and benthic surveys in the waters immediately round Macquarie Island and northwards along the Macquarie Ridge during 14-31 January 1999.

2.   Study area

The nine main sites within the study area and the distribution of seabird counts at each site are shown in Figure 1. Most observations were made over the relatively shallow waters of the main part of the Macquarie Ridge i.e. close inshore off the east and west coasts of the island and northward along the ridge to the southern edge of the Subantartic Front Gap (sites 2-5). Additional observations were made in shallow waters well south of the island at the southernmost part of the ridge (site 7), and at two other ridge sites north of the Subantarctic Front Gap (sites 8 and 9). Observations were also carried out at two deep-water (pelagic) sites: at site 6 in waters c.25 miles west of Aurora Trough, and at the Subantarctic Front Gap (site 1) immediately north of the main north-south ridge through the island.

3.   Count methods

Depending on the ship's activities and operations, two standard count methods (BIOMASS Working Party on Bird Ecology 1984) were variously employed to census seabird numbers. While in transit between sites (at ship-speeds of 6 knots), one 10-minute 90 forward quadrant 300-m wide Transect count was conducted every thirty minutes to determine relative abundance (no. birds/count) and density (no. birds/km2). When ship-speeds were 5 knots eg. when on station or while conducting trawling and acoustic surveys, one 10-minute 360 Station count was made of all seabirds visible round the ship to determine relative abundance. No counts were made when visibility was <300m. All observations were conducted from the bridge deck; for both count methods a pair of 10x42 magnification binoculars were used to detect birds.

4. Results

Counts: For the 9 main sites in study area a total of 67 Transect and 74 Station counts were made, giving a grand total of 131 counts. Count effort by site is summarised in Table 1.

Appendix 4B. Table 1

Summary by site of count effort, no. of birds and mean abundance of seabirds (all species combined).

SITE	NO. COUNTS	NO. BIRDS	MEAN NO. BIRDS/COUNT
1	16	173	10.8
2	9	148	16.4
3	21	1563	74.4
4	14	455	32.5
5	39	1712	43.9
6	11	189	17.2
7	13	518	39.8
8	5	82	16.4
9	3	42	14.0

4.1   Analysis of count data

Data from both count-types were combined to give a rough index of relative abundance (mean no. birds/count) for each of the nine sites in the study area; a more rigorous analysis of the count data will appear elsewhere (Eades and Koslow in prep.). The mean abundance for all species, subspecies and birds identified only to species-group level is given for each site in Tables 3-11, which also summarise the main environmental parameters (depth, sea surface temperature and salinity) that broadly characterise the habitat (ridge or pelagic) of each site. From these data the following main trends and broad conclusions can be drawn.

4.2   Patterns of distribution and relative abundance

The mean number of birds/count for all species combined is summarised for each site in Table 1, and their relative abundance shown in Figure 2. For all sites combined, the mean no. of birds/count by species is given in Table 2. Total abundance (all species combined) was highest over the relatively shallow waters of the main part of the ridge (sites 3-5, 32.5--74.4/count), similar at the southernmost ridge (site 7, 39.8/count), but was markedly lower at the northern end of the ridge (site 2, 16.4/count). Total abundance decreased markedly at the two ridge sites north of the main ridge (sites 8 and 9, 14.0-16.4/count), reflecting a general trend of decreasing abundance with increasing distance from the island northwards along the ridge and into deeper waters. Compared to the relatively high abundance of seabirds over the main part of the ridge, total abundance of seabirds at the two pelagic sites (1 and 6, 10.8-17.2/count) was markedly lower and comparable to that at the northernmost two ridge sites (sites 8 and 9).

A total of 30 species of seabird were recorded on counts made at the nine main sites (Table 2; total excludes those birds not identified to species, and subspecies are lumped). Taking all sites together, six species breeding locally at Macquarie Island accounted for the bulk of seabird abundance (2.7-12.0 birds/count) - Antarctic Prion, Rockhopper Penguin, Royal Penguin, Northern Giant-Petrel, Black-browed Albatross (nominate *melanophrys*) and King Penguin. Mean abundance for all other species was <2.0 birds/count. Broad patterns of distribution for the six most abundant species across all sites are briefly described below.

Antarctic Prion
Antarctic Prions occurred at all sites but were most abundant over the northern part of the main ridge (8.1-51.5/count) and at the southernmost ridge site (27.8/count). Abundance was lower in

eastern and western ridge waters (6.9/count) and lowest at the two northernmost ridge sites and the two pelagic sites (1.4-3.9/count), suggesting that prions were foraging mainly over ridge waters close to the island.

Penguins
Rockhopper Penguins were recorded at all main and southernmost ridge sites but were not seen at the two northernmost sites farthest from the island. Abundance of Rockhoppers was low at most ridge and one pelagic site (0.1-0.3/count) and was highest at Aurora Trough (site 5), closest to the breeding colonies [CHECK]. Royal Penguins were recorded at all sites except the northernmost two ridge sites. Abundance was highest (9.6/count) in eastern waters just offshore from breeding colonies but was also relatively high in western waters over the ridge at Aurora Trough (3.4/count) and farther offshore in pelagic waters at the Western site (2.6/count); numbers were lower at the northern and southern parts of the main ridge and over deep waters at the Subantarctic Front Gap (0.1-1.2/count). King Penguins were recorded only in eastern waters in close proximity to their breeding colonies (1.4/count).

Northern Giant-Petrel
Northern Giant-Petrels were recorded at all sites but abundance was greatest (10.3/count) over the ridge at Aurora Trough and in eastern waters (4.9/count). Numbers were lower elsewhere along the main and southern ridge sites (0.1-3.8/count) and at the two pelagic sites (0.3-2.6/count).

*Black-browed Albatross (*nominate *melanophrys)*
The distribution and relative abundance of Black-browed Albatrosses is shown in Figure 3. Black-brows were concentrated over ridge waters, with highest abundances recorded over the Mid Northern Ridge (8.9/count) and in Aurora Trough (4.9/count). Abundance at other ridge sites was markedly lower (0.3-1.5/count), similar to rates recorded for the two pelagic sites (0.2-1.4/count). There were fourteen sightings of breeding adult birds colour-marked by researchers on Macquarie Island. Except for two sightings at the pelagic site west of Aurora trough, all others were concentrated over ridge waters at Aurora Trough and over the northern part of the main ridge, suggesting that breeding birds are mainly foraging over relatively shallow waters close to their breeding colonies at the northern and southern tips of the island.

Other species
The following main points of interest were noted:

Grey-headed and Wandering Albatrosses tended to be most abundant in pelagic waters and least abundant over the shallow waters of the ridge, a pattern reflecting their preference for foraging over deep waters at greater distances from the island than does the Black-browed Albatross, a ridge specialist.

Significant numbers of Southern Royal and Shy Albatrosses and Sooty Shearwaters were noted over the ridge areas, suggesting that the Macquarie Ridge may be a regular foraging area for these New Zealand subantarctic breeding species.

Small numbers of Mottled Petrels were regularly sighted moving through the more open and pelagic waters of the study area, suggesting that this species regularly passes through Macquarie I. waters while in transit to and from it's southern New Zealand breeding areas and it's favoured foraging grounds in antarctic waters to the south and south-west of Macquarie Island.

Two sightings of vagrant birds were made while in the study area. An adult Chinstrap Penguin was noted swimming with Royal Penguins at the Southern Ridge on [DATE], an area where sea surface temperatures and salinities were markedly lower than those over the main ridge area immediately round the island. An Antarctic Petrel was also reported from Aurora Trough by Dick Williams [DATE]. Both sightings of these antarctic-breeding species are far north of their normal distribution during summer.

5.   Conclusions

The relatively shallow waters of the main part of the Macquarie Ridge appear to be an important foraging area for most seabird species with significant breeding populations at Macquarie Island. The same areas may also represent a significant foraging site for some seabird species breeding at the New Zealand subantarctic islands to the north, particularly for Southern Royal Albatrosses from Campbell Island and Shy Albatrosses from the Auckland Islands.

6.   References

BIOMASS Working Party on Bird Ecology. (1984). Recording observations of birds at sea (rev. edn). BIOMASS Handbook 18.

Scott, J. (1994). Marine Conservation at Macquarie Island. Tas. Parks & Wildlife 141 pp.

Appendix 4B. Table 2

List of seabird species and their relative abundance (mean no./count)
for all sites (1-9) combined.

SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO. BIRDS/COUNT
42	Antarctic Prion	1971	12.0
60	Rockhopper Penguin	206	6.1
61	Macaroni/Royal Penguin	341	5.8
6	giant-petrel sp.	259	5.5
5	Northern Giant-Petrel	645	4.0
91	Crested Penguin sp.	109	3.9
84	Black-browed Albatross (melanophrys)	434	3.6
56	King Penguin	19	2.7
37	penguin sp.	14	2.0
29	petrel sp.	14	1.8
4	Southern Giant-Petrel	131	1.6
44	Sooty Shearwater	92	1.5
9	Black-browed Albatross	41	1.5
43	Short-tailed Shearwater	3	1.5
46	Southern Royal Albatross	132	1.3
12	Shy Albatross (cauta/steadi)	77	1.3
72	Kelp Gull	12	1.3
101	Short-tailed/Sooty Shearwater	5	1.3
25	Mottled Petrel	46	1.2
20	White-headed Petrel	63	1.1
13	Light-mantled Sooty Albatross	59	1.1
34	Great Skua	20	1.1
85	Black-browed Albatross (impavida)	17	1.1
21	Black-bellied Storm-Petrel	16	1.1
7	Wandering Albatross	73	1.0
8	Grey-headed Albatross	37	1.0
17	White-chinned Petrel	10	1.0
71	'great' albatross sp.	5	1.0
23	Wilson's Storm-Petrel	4	1.0
15	Cape Petrel (australe)	3	1.0
45	diving-petrel sp.	3	1.0
68	Common Diving-Petrel	3	1.0
83	'mollymawk' sp.	3	1.0
48	Grey-backed Storm-Petrel	3	1.0
10	Buller's Albatross	2	1.0
14	albatross sp.	2	1.0
24	storm-petrel sp.	1	1.0
75	Antarctic Tern [check]	1	1.0
70	Blue-eyed Cormorant	1	1.0
62	Northern Royal Albatross	1	1.0
52	Soft-plumaged Petrel	1	1.0
49	Salvin's Albatross	1	1.0
47	Chinstrap Penguin	1	1.0
28	Grey Petrel	1	1.0

Appendix 4B. Table 3

Site 1: Subantarctic Front Gap	
Habitat	Pelagic
Number of Station Counts	11
Number Transect Counts	5
Depth Range	146-1586
Sea Surface Temp Range	7.2-7.8
Salinity Range	33.76-33.86

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
1	42	Antarctic Prion	34	2.1
1	7	Wandering Albatross	27	1.7
1	84	Black-browed Albatross (melanophrys)	22	1.4
1	20	White-headed Petrel	18	1.1
1	25	Mottled Petrel	12	0.8
1	12	Shy Albatross (cauta/steadi)	9	0.6
1	44	Sooty Shearwater	8	0.5
1	8	Grey-headed Albatross	7	0.4
1	46	Southern Royal Albatross	6	0.4
1	5	Northern Giant-Petrel	4	0.3
1	13	Light-mantled Sooty Albatross	4	0.3
1	61	Macaroni/Royal Penguin	3	0.2
1	85	Black-browed Albatross (impavida)	3	0.2
1	4	Southern Giant-Petrel	2	0.1
1	6	giant-petrel sp.	2	0.1
1	29	petrel sp.	2	0.1
1	9	Black-browed Albatross	2	0.1
1	10	Buller's Albatross	1	0.1
1	48	Grey-backed Storm-Petrel	1	0.1
1	71	'great' albatross sp.	1	0.1
1	68	Common Diving-Petrel	1	0.1
1	45	diving-petrel sp.	1	0.1
1	34	Great Skua	1	0.1
1	17	White-chinned Petrel	1	0.1
1	28	Grey Petrel	1	0.1

Appendix 4B. Table 4

Site 2: Northern Edge	
Habitat	Ridge
Number of Station Counts	4
Number Transect Counts	5
Depth Range	988-2141
Sea Surface Temp Range	7.4-7.7
Salinity Range	33.80-33.84

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
2	42	Antarctic Prion	73	8.1
2	12	Shy Albatross (cauta/steadi)	15	1.7
2	84	Black-browed Albatross (melanophrys)	13	1.4
2	7	Wandering Albatross	11	1.2
2	20	White-headed Petrel	6	0.7
2	44	Sooty Shearwater	5	0.6
2	25	Mottled Petrel	4	0.4
2	46	Southern Royal Albatross	4	0.4
2	13	Light-mantled Sooty Albatross	3	0.3
2	17	White-chinned Petrel	3	0.3
2	60	Rockhopper Penguin	2	0.2
2	5	Northern Giant-Petrel	1	0.1
2	8	Grey-headed Albatross	1	0.1
2	9	Black-browed Albatross	1	0.1
2	91	Crested Penguin sp.	1	0.1
2	61	Macaroni/Royal Penguin	1	0.1
2	48	Grey-backed Storm-Petrel	1	0.1
2	21	Black-bellied Storm-Petrel	1	0.1
2	14	albatross sp.	1	0.1
2	10	Buller's Albatross	1	0.1

Appendix 4B. Table 5

Site 3: Mid Northern Ridge	
Habitat	Ridge
Number of Station Counts	17
Number Transect Counts	4
Depth Range	392-1528
Sea Surface Temp Range	7.2-8.0
Salinity Range	33.84-34.04

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
3	42	Antarctic Prion	1082	51.5
3	84	Black-browed Albatross (melanophrys)	175	8.3
3	5	Northern Giant-Petrel	80	3.8
3	46	Southern Royal Albatross	34	1.6
3	61	Macaroni/Royal Penguin	25	1.2
3	8	Grey-headed Albatross	23	1.1
3	44	Sooty Shearwater	22	1.0
3	12	Shy Albatross (cauta/steadi)	19	0.9
3	6	giant-petrel sp.	15	0.7
3	4	Southern Giant-Petrel	14	0.7
3	7	Wandering Albatross	14	0.7
3	13	Light-mantled Sooty Albatross	12	0.6
3	20	White-headed Petrel	10	0.5
3	9	Black-browed Albatross	6	0.3
3	21	Black-bellied Storm-Petrel	6	0.3
3	85	Black-browed Albatross (impavida)	6	0.3
3	34	Great Skua	4	0.2
3	25	Mottled Petrel	3	0.1
3	17	White-chinned Petrel	2	0.1
3	60	Rockhopper Penguin	2	0.1
3	43	Short-tailed Shearwater	2	0.1
3	37	penguin sp.	2	0.1
3	68	Common Diving-Petrel	1	0.0
3	71	'great' albatross sp.	1	0.0
3	72	Kelp Gull	1	0.0
3	75	Identified but not listed	1	0.0
3	83	'mollymawk' sp.	1	0.0

Appendix 4B. Table 6

Site 4: East Macquarie I.	
Habitat	Ridge
Number of Station Counts	3
Number Transect Counts	11
Depth Range	103-2197
Sea Surface Temp Range	6.8-7.8
Salinity Range	33.86-34.01

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
4	61	Macaroni/Royal Penguin	135	9.6
4	42	Antarctic Prion	97	6.9
4	5	Northern Giant-Petrel	69	4.9
4	6	giant-petrel sp.	37	2.6
4	4	Southern Giant-Petrel	21	1.5
4	56	King Penguin	19	1.4
4	13	Light-mantled Sooty Albatross	13	0.9
4	44	Sooty Shearwater	13	0.9
4	84	Black-browed Albatross (melanophrys)	10	0.7
4	91	Crested Penguin sp.	9	0.6
4	37	penguin sp.	8	0.6
4	9	Black-browed Albatross	5	0.4
4	46	Southern Royal Albatross	5	0.4
4	60	Rockhopper Penguin	4	0.3
4	20	White-headed Petrel	3	0.2
4	34	Great Skua	3	0.2
4	8	Grey-headed Albatross	1	0.1
4	17	White-chinned Petrel	1	0.1
4	72	Kelp Gull	1	0.1
4	25	Mottled Petrel	1	0.1

Appendix 4B. Table 7

Site 5: Aurora Trough	
Habitat	Ridge
Number of Station Counts	15
Number Transect Counts	24
Depth Range	131-989
Sea Surface Temp Range	7.0-7.6
Salinity Range	33.83-34.09

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
5	5	Northern Giant-Petrel	402	10.3
5	42	Antarctic Prion	269	6.9
5	60	Rockhopper Penguin	195	5.0
5	84	Black-browed Albatross (melanophrys)	191	4.9
5	6	giant-petrel sp.	184	4.7
5	61	Macaroni/Royal Penguin	132	3.4
5	91	Crested Penguin sp.	96	2.5
5	4	Southern Giant-Petrel	76	1.9
5	46	Southern Royal Albatross	40	1.0
5	9	Black-browed Albatross	24	0.6
5	44	Sooty Shearwater	23	0.6
5	13	Light-mantled Sooty Albatross	16	0.4
5	7	Wandering Albatross	10	0.3
5	72	Kelp Gull	10	0.3
5	34	Great Skua	9	0.2
5	12	Shy Albatross (cauta/steadi)	6	0.2
5	29	petrel sp.	6	0.2
5	23	Wilson's Storm-Petrel	4	0.1
5	15	Cape Petrel (australe)	3	0.1
5	20	White-headed Petrel	3	0.1
5	37	penguin sp.	3	0.1
5	8	Grey-headed Albatross	2	0.1
5	71	'great' albatross sp.	2	0.1
5	25	Mottled Petrel	1	0.0
5	85	Black-browed Albatross (impavida)	1	0.0
5	101	Short-tailed/Sooty Shearwater	1	0.0
5	49	Salvin's Albatross	1	0.0
5	62	Northern Royal Albatross	1	0.0
5	70	Blue-eyed Cormorant	1	0.0

Appendix 4B. Table 8

Site 6: Western site	
Habitat	Pelagic
Number of Station Counts	8
Number Transect Counts	3
Depth Range	462-4220
Sea Surface Temp Range	6.3-6.7
Salinity Range	33.78-33.86

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
6	42	Antarctic Prion	43	3.9
6	5	Northern Giant-Petrel	41	3.7
6	61	Macaroni/Royal Penguin	29	2.6
6	25	Mottled Petrel	17	1.5
6	44	Sooty Shearwater	14	1.3
6	6	giant-petrel sp.	12	1.1
6	4	Southern Giant-Petrel	7	0.6
6	7	Wandering Albatross	6	0.5
6	20	White-headed Petrel	3	0.3
6	17	White-chinned Petrel	2	0.2
6	84	Black-browed Albatross (melanophrys)	2	0.2
6	91	Crested Penguin sp.	2	0.2
6	8	Grey-headed Albatross	1	0.1
6	12	Shy Albatross (cauta/steadi)	1	0.1
6	13	Light-mantled Sooty Albatross	1	0.1
6	101	Short-tailed/Sooty Shearwater	1	0.1
6	83	'mollymawk' sp.	1	0.1
6	71	'great' albatross sp.	1	0.1
6	60	Rockhopper Penguin	1	0.1
6	52	Soft-plumaged Petrel	1	0.1
6	45	diving-petrel sp.	1	0.1
6	34	Great Skua	1	0.1
6	21	Black-bellied Storm-Petrel	1	0.1

Appendix 4B. Table 9

Site 7: Southern Ridge	
Habitat	Ridge
Number of Station Counts	9
Number Transect Counts	4
Depth Range	518-1911
Sea Surface Temp Range	5.3-5.9
Salinity Range	33.70-33.96

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
7	42	Antarctic Prion	361	27.8
7	5	Northern Giant-Petrel	35	2.7
7	46	Southern Royal Albatross	30	2.3
7	84	Black-browed Albatross (melanophrys)	19	1.5
7	61	Macaroni/Royal Penguin	16	1.2
7	4	Southern Giant-Petrel	10	0.8
7	6	giant-petrel sp.	6	0.5
7	25	Mottled Petrel	6	0.5
7	12	Shy Albatross (cauta/steadi)	5	0.4
7	13	Light-mantled Sooty Albatross	5	0.4
7	85	Black-browed Albatross (impavida)	5	0.4
7	44	Sooty Shearwater	3	0.2
7	9	Black-browed Albatross	2	0.2
7	60	Rockhopper Penguin	2	0.2
7	34	Great Skua	2	0.2
7	101	Short-tailed/Sooty Shearwater	2	0.2
7	29	petrel sp.	2	0.2
7	21	Black-bellied Storm-Petrel	1	0.1
7	91	Crested Penguin sp.	1	0.1
7	68	Common Diving-Petrel	1	0.1
7	47	Chinstrap Penguin	1	0.1
7	43	Short-tailed Shearwater	1	0.1
7	37	penguin sp.	1	0.1
7	24	storm-petrel sp.	1	0.1

Appendix 4B. Table 10

Site 8: Northern Ridge	
Habitat	Ridge
Number of Station Counts	4
Number Transect Counts	1
Depth Range	362-1724
Sea Surface Temp Range	7.4-7.5
Salinity Range	33.91-33.95

SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
8	12	Shy Albatross (cauta/steadi)	17	3.4
8	20	White-headed Petrel	15	3.0
8	5	Northern Giant-Petrel	10	2.0
8	42	Antarctic Prion	7	1.4
8	46	Southern Royal Albatross	7	1.4
8	21	Black-bellied Storm-Petrel	4	0.8
8	44	Sooty Shearwater	4	0.8
8	6	giant-petrel sp.	3	0.6
8	7	Wandering Albatross	3	0.6
8	13	Light-mantled Sooty Albatross	2	0.4
8	85	Black-browed Albatross (impavida)	2	0.4
8	29	petrel sp.	2	0.4
8	4	Southern Giant-Petrel	1	0.2
8	48	Grey-backed Storm-Petrel	1	0.2
8	101	Short-tailed/Sooty Shearwater	1	0.2
8	84	Black-browed Albatross (melanophrys)	1	0.2
8	9	Black-browed Albatross	1	0.2
8	14	albatross sp.	1	0.2

Appendix 4B. Table 11

Site 9: Northernmost site	
Habitat	Ridge
Number of Station Counts	3
Number Transect Counts	0
Depth Range	1714-1722
Sea Surface Temp Range	8.2
Salinity Range	34.02-34.03

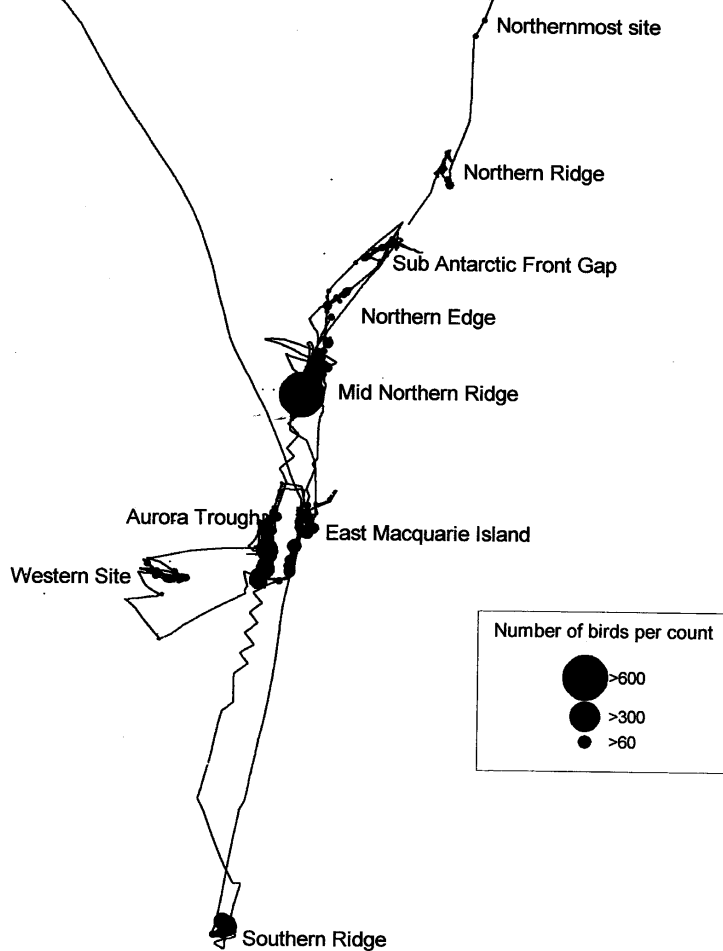| SITE	SPECIES CODE	SPECIES NAME	NO. BIRDS	MEAN NO./COUNT
9	46	Southern Royal Albatross	6	2.0
9	12	Shy Albatross (cauta/steadi)	5	1.7
9	42	Antarctic Prion	5	1.7
9	20	White-headed Petrel	5	1.7
9	5	Northern Giant-Petrel	3	1.0
9	13	Light-mantled Sooty Albatross	3	1.0
9	21	Black-bellied Storm-Petrel	3	1.0
9	7	Wandering Albatross	2	0.7
9	8	Grey-headed Albatross	2	0.7
9	25	Mottled Petrel	2	0.7
9	29	petrel sp.	2	0.7
9	17	White-chinned Petrel	1	0.3
9	45	diving-petrel sp.	1	0.3
9	83	'mollymawk' sp.	1	0.3
9	84	Black-browed Albatross (melanophrys)	1	0.3

Cruise Report SS 01/99

Figure 1. SS9901. Distribution of 10-minute seabird counts in waters around Macquarie Island.

Northernmost site

Northern Ridge

Sub Antarctic Front Gap

Northern Edge

Mid Northern Ridge

Aurora Trough
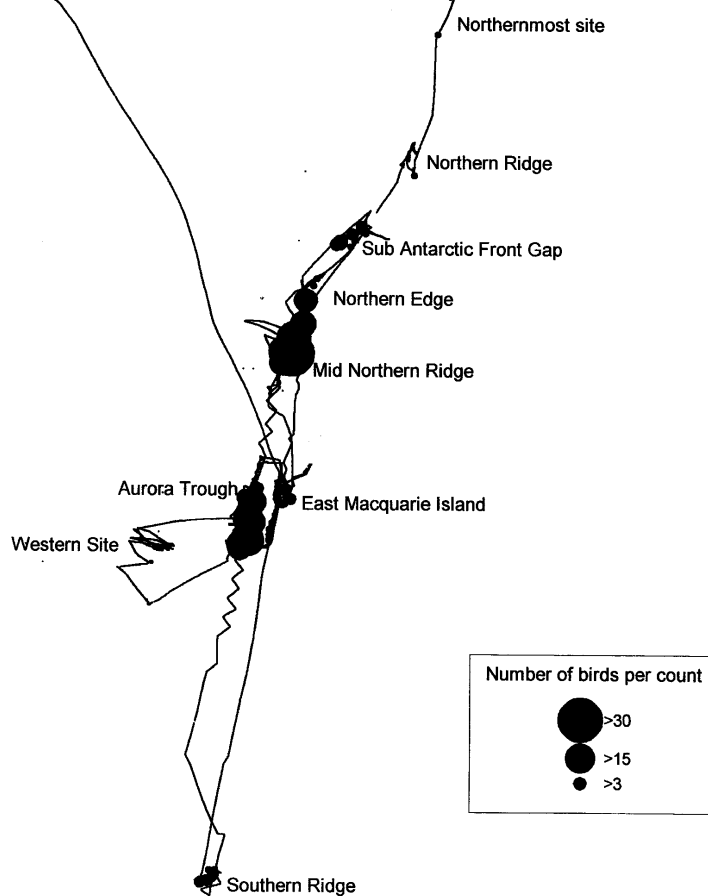
Western Site

East Macquarie Island

Southern Ridge
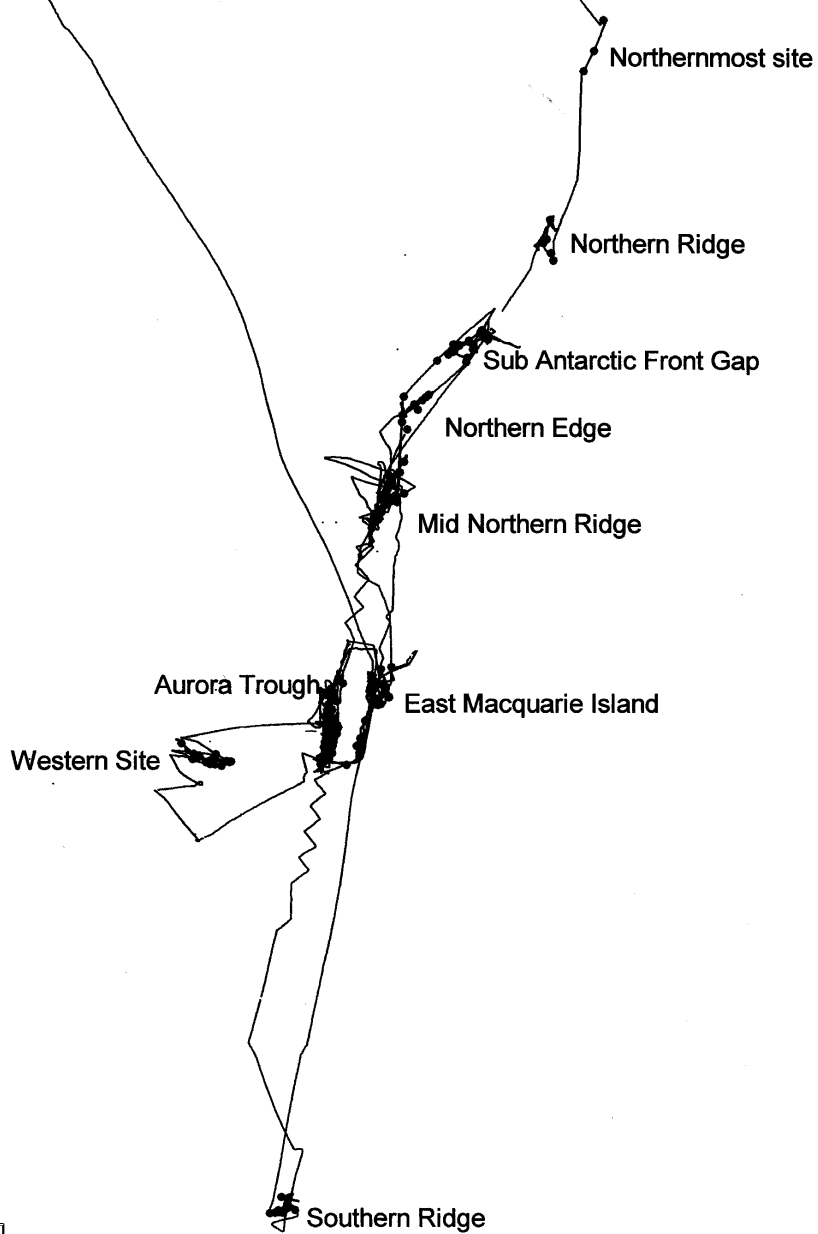
Cruise Report SS 01/99

Figure 2. SS9901.Relative abundance of seabirds
(number of seabirds per count, all species combined)
in waters around Macquarie Island.

Northernmost site

Northern Ridge

Sub Antarctic Front Gap

Northern Edge

Mid Northern Ridge

Aurora Trough

East Macquarie Island

Western Site

Southern Ridge

Number of birds per count

>600

>300

>60

Figure 3. SS9901.Relative abundance Black-browed Albatross Diomedea m. melanophrys in waters around Macquarie Island.

Northernmost site

Northern Ridge

Sub Antarctic Front Gap

Northern Edge

Mid Northern Ridge

Aurora Trough

East Macquarie Island

Western Site

Number of birds per count
>30
>15
>3

Southern Ridge

Appendix 5. A preliminary checklist of trawl bycatch fishes

Spikey Riddoch, Peter Last and Dick Williams

Summary
The toothfish fishery off Macquarie Island is exceptional in that data for the bycatch has been obtained continuously since the first exploratory surveys of the region. Rarely has the composition and structure of the fauna been known before the commencement of formal commercial fishing operations.

Prior to these surveys little was known of the Macquarie Island fish fauna. Waite (1916) described fishes collected from Macquarie Island during the first Australian Antarctic Expedition (1914-16). Williams (1988) reviewed previous work and listed 12 benthic (mainly inshore) and 21 pelagic species. The preliminary checklist includes at least 153 species and 103 genera from 52 families (Appendix 5 Table 1), of which 133 species and 89 genera were not previously known from the region. The most speciose families were the Myctophidae (11 genera, 29 species), Macrouridae (8 genera, 16 species) and Stomiidae (9 genera, 9 species).

The identification of species from the region often proved difficult and the identities of some of these are provisional. Fishing observers are trained to identify common animals but their task becomes increasingly difficult in an unexplored region such as Macquarie where many of the animals are unique or poorly known. Some field identifications, later vetted back in the laboratory, proved questionable for diverse and taxonomically difficult groups such as morid cods (Moridae) and whiptails (Macrouridae). This situation improved after 1999 when the first draft of a bycatch guide became available (Last *et al*, In prep.).

Many of the fishes found at Macquarie Island are from groups that are not well known taxonomically in the Southern Hemisphere. These include the spiny eels (Notacanthidae), halosaurs (Halosauridae), deep-sea smelts (Bathylagidae), slickheads (Alepocephalidae), eel cods (Muraenolepididae), crustheads (Melamphaidae), snailfishes (Liparidae), and southern flounders (Achiropsettidae). Many of their species are not covered by the major identification guide to fishes of the Southern Ocean (Gon and Heemstra, 1990). The Macquarie Ridge fauna contains elements derived from the continental slope of Antarctica and temperate regions further to the north of the ridge, as well as a pelagic fish fauna distributed widely in the Southern Ocean.

Most of the material collected during this project has been deposited in the Australian National Fish Collection (CSIRO). Photographs and voucher specimens have been retained for all bycatch species. Surplus material has been dispersed to state museums (ie Australian Museum, Museum Victoria). Data from this study will be used to produced more detailed technical reports and guides to the fauna including a treatment of its biogeographical structure.

References
Waite, E. R. (1916). Fishes. *In*: Australasian Antarctic expedition 1911–1914. Science Report Series C, Zoology & Botany, Adelaide. Science Report, Australian Antarctic Expedition 3 (pt 1): 1–92, Pls. 1–5, 2 maps.

Williams, R. (1988). The nearshore fishes of Macquarie Island. Papers and Proceedings of the Royal Society of Tasmania. 122(1): 233–245.

Gon, 0. & Heemstra, P. C. (eds). (1990). Fishes of the Southern Ocean. J.L.B. Smith Institute of Ichthyology, Grahamstown, South Africa, 462 pp. 12 pls.

Nelson, J. S. (1994). Fishes of the world. 3rd edition. John Wiley & Sons. i–xvii + 1–600.

Last, P. R. and Riddoch, S. G. K. (1999). Fishes of Macquarie Island. CSIRO Unpublished field guide.

Appendix 5. Table 1. A list of fish, by family and species name, taken as bycatch in the Macquarie Island toothfish trawl fishery (ordered according to Nelson, 1994).

Family - common name *Species, authority*	**Family - common name** *Species, authority*
Chimaeridae - shortnose chimaeras *Chimaera sp.*	**Stomiidae - barbeled dragonfishes** *Astronesthes psychrolutes (Gibbs & Weitzman, 1965)* *Borostomias antarcticus (Lönnberg, 1905)*
Dalatiidae - sleeper sharks *Somniosus antarcticus Whitley, 1939*	*Chauliodus danae Regan & Trewavas, 1929* *Idiacanthus atlanticus Brauer, 1906* *Malacosteus sp.*
Squalidae - dogfish sharks *Etmopterus sp.*	*Melanostomias niger Gilchrist & von Bonde, 1924* *Opostomias micripnus (Günther, 1878)* *Stomias gracilis Garman, 1899* *Trigonolampa miriceps Regan & Trewavas, 1930*
Halosauridae - halosaurs *Aldrovandia sp.* *Halosauropsis macrochir (Günther, 1878)*	**Scopelarchidae - pearleyes** *Benthalbella elongata (Norman, 1937)* *Benthalbella macropinna Bussing & Bussing, 1966*
Notacanthidae - spiny eels *Notacanthus chemnitzii Bloch, 1788* *Polyacanthonotus cf. rissoanus (De Filippi & Verany, 1857)*	*Benthalbella sp.* *Scopelarchoides kreffti Johnson, 1972* *Scopelarchoides sp.*
Synaphobranchidae - cutthroat eels *Diastobranchus capensis Barnard, 1923*	**Notosudidae - waryfishes** *Luciosudis normani Fraser-Brunner, 1931* *Scopelosaurus hamiltoni (Waite, 1916)*
Derichthyidae - longneck eels *Derichthys serpentinus Gill, 1884*	*Scopelosaurus sp.*
Nemichthyidae - snipe eels *Labichthys yanoi (Mead & Rubinoff, 1966)*	**Paralepididae - barracudinas** *Magnisudis prionosa (Rofen, 1963)* *Notolepis coatsi Dollo, 1908*
Serrivomeridae - sawtooth eels *Serrivomer sp. 1* *Serrivomer sp. 2*	**Anotopteridae - daggertooth** *Anotopterus pharao Zugmayer, 1911*
Microstomatidae - microstomatids *Nansenia antarctica Kawaguchi & Butler, 1984*	**Evermannellidae - sabertooth fishes** *Evermannella balbo (Risso, 1820)*
Bathylagidae - deep-sea smelts *Bathylagichthys australis Kobyliansky, 1990* *Bathylagichthys longipinnis (Kobyliansky, 1985)* *Bahtylagichthys sp.* *Bathylagus gracilis Lönnberg, 1905* *Bathylagus cf. antarcticus Günther, 1878* *Bathylagus tenuis Kobyliansky, 1986*	**Myctophidae - lanternfishes** *Diaphus danae Tåning, 1932* *Diaphus hudsoni Zurbrig & Scott, 1976* *Diaphus ostenfeldi Tåning, 1932* *Electrona carlsbergi (Tåning, 1932)* *Electrona paucirastra Bolin in Andriashev, 1962* *Electrona subaspera (Günther, 1864)* *Gymnoscopelus bolini Andriashev, 1962*
Opisthoproctidae - barreleyes *Dolichopteryx sp.*	*Gymnoscopelus braueri (Lönnberg, 1905)* *Gymnoscopelus fraseri (Fraser-Brunner, 1931)* *Gymnoscopelus hintonoides Hulley, 1981*

Continued

Family - common name *Species, authority*	Family - common name *Species, authority*
Alepocephalidae - slickheads	**Myctophidae - lanternfishes** continued
Alepocephalus cf antipodiana (Parrott, 1948)	*Gymnoscopelus microlampas Hulley, 1981*
Alepocephalus sp.	*Gymnoscopelus nicholsi (Gilbert, 1911)*
Rouleina squamilatera (Alcock, 1898)	*Gymnoscopelus opisthopterus Fraser-Brunner, 1949*
	Gymnoscopelus piabilis (Whitley, 1931)
Platytroctidae - tubeshoulders	*Hintonia candens Fraser-Brunner, 1949*
Persparsia kopua (Phillipps, 1942)	*Krefftichthys anderssoni (Lönnberg, 1905)*
	Lampadena notialis Nafpaktitis & Paxton 1968
Gonostomatidae - bristlemouths	*Lampadena speculigera Goode & Bean, 1896*
Diplophos rebainsi Krefft & Parin, 1972	*Lampanyctus achirus Andriashev, 1962*
Gonostoma bathyphilum (Vaillant in Fihol, 1884)	*Lampanyctus intracarius Tåning, 1928*
	Lampanyctus sp.
Sternoptychidae - hatchetfishes	*Lampichthys procerus (Brauer, 1904)*
Argyropelecus gigas Norman, 1930	*Metelectrona ventralis (Becker, 1963)*
Argyropelecus hemigymnus Cocco, 1829	*Protomyctophum andriashevi Becker, 1963*
Sternoptyx pseudodiaphana Borodulina, 1977	*Protomyctophum gemmatum Hulley, 1981*
	Protomyctophum normani (Tåning, 1932)
Phosichthyidae - lightfishes	*Protomyctophum parallelum (Lönnberg, 1905)*
Phosichthys argenteus Hutton, 1872	*Protomyctophum tenisoni (Norman, 1930)*
Woodsia meyerwaardeni Krefft, 1973	*Symbolophorus boops (Richardson, 1845)*
Lamprididae - opahs	**Barbourisiidae - red whalefish**
Lampris immaculatus Gilchrist, 1904	*Barbourisia rufa Parr, 1945*
Carapidae - carapids	**Anoplogastridae - fangtooths**
Echiodon cryomargarites Markle, Williams & Olney, 1983	*Anoplogaster cornuta (Valenciennes, 1833)*
Macrouridae - grenadiers	**Diretmidae - spinyfins**
Caelorinchus innotabilis McCulloch, 1907	*Diretmus argenteus Johnson, 1864*
Caelorinchus kaiyomaru Arai & Iwamoto, 1979	
Caelorinchus kermadecus Jordan & Gilbert in Jordan & Starks, 1904	**Trachichthyidae - roughies**
Coryphaenoides murrayi Günther, 1878	*Hoplostethus atlanticus Collett, 1889*
Coryphaenoides serrulatus Günther, 1878	
Coryphaenoides sp. 1	**Zeidae - dories**
Coryphaenoides sp. 2	*Cyttus sp. (juvenile)*
Coryphaenoides sp. 3	
Coryphaenoides striaturus Barnard, 1925	**Oreosomatidae - oreos**
Coryphaenoides subserrulatus Makushok, 1976	*Pseudocyttus maculatus Gilchrist, 1906*
Cynomacrurus piriei Dollo, 1909	
Idiolophorhynchus andriashevi Sasanov, 1981	**Congiopodidae - racehorses**
Macrourus carinatus (Günther, 1878)	*Zanclorhynchus spinifer Günther, 1880*
Nezumia sp. 1	
Nezumia sp. 2	**Psychrolutidae - fathead sculpins**
Trachonurus gagates Iwamoto & McMillan, 1997	*Ambophthalmos magnicirrus (Nelson, 1977)*
	Ebinania macquariensis Nelson, 1982
	Ebinania sp.

Continued

Family - common name *Species, authority*	Family - common name *Species, authority*
Moridae - morid cods	
Antimora rostrata (Günther, 1878)	**Liparidae - snailfishes**
Guttigadus globiceps (Gilchrist, 1906)	*Careproctus sp.*
Halargyreus johnsonii Günther, 1862	*Paraliparis sp.*
Lepidion sp. 1	*Paraliparis thalassobathyalis Andriashev, 1982*
Lepidion sp. 2	
Paralaemonema sp. 1	**Epigonidae - deepwater cardinalfishes**
Paralaemonema sp. 2	*Epigonus cf. robustus (Barnard, 1927)*
	Rosenblattia robusta Mead & De Falla , 1965
Melanonidae - pelagic cods	
Melanonus gracilis Günther, 1878	**Caristiidae - manefishes**
Melanonus zugmayeri Norman, 1930	*Caristiidae*
	Platyberx sp.
Muraenolepididae - eel cods	
Muraenolepis marmoratus Günther, 1880	**Zoarcidae - eelpouts**
Muraenolepis sp.	*Melanostigma gelatinosum Günther, 1881*
Himantolophidae - footballfishes	**Nototheniidae - cod icefishes**
Himantolophus appelii (Clarke, 1878)	*Dissostichus eleginoides Smitt, 1898*
Himantolophus sp.	*Lepidonotothen squamifrons (Günther, 1880)*
Oneirodidae - oneirodids	**Chiasmodontidae - swallowers**
Oneirodes sp. 1	*Kali sp.*
Oneirodes sp. 2	*Pseudoscopelus sp.*
Ceratiidae - seadevils	**Gempylidae - snake mackerals**
Ceratias sp.	*Paradiplospinus antarcticus (Andriashev, 1960)*
Ceratias tentaculatus (Norman, 1930)	
Cryptopsaras couesii Gill, 1883	**Centrolophidae - medusafishes**
	Icichthys australis Haedrich, 1966
Gigantactinidae - slender anglerfishes	*Schedophilus maculatus Günther, 1860*
Gigantactis sp.	*Tubbia tasmanica Whitley, 1943*
Rhynchactis sp.	
	Achiropsettidae - southern flounders
Linophrynidae - linophrynids	*Achiropsetta sp. 1*
Linophrynidae	*Mancopsetta maculata (Günther, 1880)*
	Neoachiropsetta milfordi (Penrith, 1965)
Melamphaidae - bigscale fishes	
Poromitra crassiceps (Günther, 1878)	
Poromitra sp. 1	
Poromitra sp. 2	
Sio nordenskjoldii (Lönnberg, 1905)	

Distribution list of final report 97/122

FRDC (10 copies)

CSIRO Library, (2 copies)
Dennis Abbott
CSIRO Marine Research
Castray Esplanade
Hobart Tas 7001

AAD Library, (2 copies)
Andie Smithies
Australian Antarctic Division
Channel Highway,
Kingston Tas 7050

National Library
Legal Deposit Unit
National Library of Australia
Canberra ACT 2600

State Library of Tasmania
K. Andrews, Legal Deposit Officer
Technical Services
State Library of Tasmania
91 Murray St.
Hobart, Tas 7000

SAFAG, (15 copies)
Sarah Scott (requested to provide distribution details for members)
AFMA
PO BOX 7051
Canberra Mail Centre
ACT 2610

SouthMAC, (12 copies)
Sarah Scott (requested to provide distribution details for members)

Environment Australia (2 copy)
Conall O'Connel, Alex Wells
Marine Protected Areas
Marine and Water Division
Environment Australia
GPO Box 787
Canberra

National Oceans Office (2 copies)
Campbell Davies, Meredith Hall
GPO Box 2139
Hobart, Tas, 7001

Key Industry Members, (2 copies)
         Martin Exel (covered by SAFAG)
         Halli Stefansson, *Austral Leader*

CSIRO (15 copies)
         Cathy Bulman, Dianne Furlani, Simon Goldsworthy, Karen Gowlett-Holmes, Rudy
         Kloser, Tony Koslow, Peter Last, Mark Lewis, Peter Nichols, Spikey Riddoch, Tim
         Ryan, Geoff Tuck (covered by SAFAG), Bob Ward, Gareth Wilson, Alan Williams,
         Jock Young, (1 copy each)
         CSIRO Marine Research
         Castray Esplanade
         Hobart, Tas 7001

AAD (1 Copies)
         Tim Lamb, Dick Williams (covered by SAFAG)
         Australian Antarctic Division
         Channel Highway
         Kingston, Tas 7050

AMC Library (1 Copy)
         PO Box 986
         Launceston Tas 7250

John Kalish (BRS)
         PO. Box E11
         Edmund Barton Bldg.
         Kingston, ACT 2604

Authors, (1 copy)
         Xi He, Keith Sainsbury, Andrew Constable (each covered by SAFAG), William de la
         Mare