ICES CM 2004/T:07

A preliminary analysis of longline fishing activity related to the bathymetry around South Georgia

R.C. Wakeford, M. Belchier and P. Morris

ABSTRACT

The Patagonian toothfish (*Dissostichus eleginoides*) is a large, predatory, nototheniid fish that is found around sub-antarctic islands and seamounts and in the cold temperate waters off Patagonia. Adult fish are usually found living close to the seabed at depths of 500 to 2,000 m whilst younger fish inhabit shallower waters. The fish, which can attain lengths in excess of 2 metres and weigh over 70 kg, are slow growing, taking between 6-10 years to reach sexual maturity and may live for more than 50 years. A longline fishery for toothfish has operated around the island of South Georgia since the early 1990's. Between 10 and 18 vessels are licensed to fish within the South Georgia maritime zone each year. Longlines of baited hooks are usually set in water depths of 1,000 m around the South Georgia shelf edge. However, fishing effort around the island is not uniform, as fishers have established which areas are the most productive. The available charts of the region are very incomplete and only give a poor idea of the form of the continental margin. In the past this made it difficult to establish any link between fishing success and the nature of the seafloor. Recent swath bathymetry surveys, however, now reveal the detailed bathymetry of the slope and allow us to relate the areas of greatest fishing activity to the nature of the seabed. Statistical models are developed to explore whether the new bathymetry data can improve the current level of understanding on biological and fisheries characteristics of toothfish around South Georgia. This provides a preliminary insight into preferred toothfish habitats, and the potential impact of the fishery on the ecosystem. Combined, this information will influence future strategies for fishery management and conservation.

Keywords: bathymetry, longline fishery, benthic mapping, South Georgia

R.C. Wakeford: MRAG Ltd, 18 Queen Street, London, W1J 5PN, UK [tel: ++44 (0) 20 7255 7771, fax: ++44 (0) 20 7499 5833, email: r.wakeford@mrag.co.uk]. M. Belchier and P. Morris: British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET [tel: +44 (0) 1223 221 600, fax. +44 (0) 1223 221259, email: markb@bas.ac.uk]

1. INTRODUCTION

South Georgia lies in the Southern Atlantic and is surrounded by a 200-mile maritime zone, which also includes the South Sandwich Islands (Fig.1). Created in 1993, it allows for greater control and regulation within the zone by the Government of South Georgia and the South Sandwich Islands (GSGSSI).

Patagonian toothfish (*Dissostichus eleginoides*) were first caught in the waters around South Georgia as by-catch by the Polish and Soviet bottom trawlers in the mid 1970's. It was not considered commercially viable as the majority of the larger fish were inaccessable to bottom trawls. It was not until the Soviet Union introduced longlining in 1988 that they began to be caught in any significant numbers. The fishery has developed since then, with the GSGSSI issuing between 10 and 18 licences to up to 6 different nations to fish within the zone each year.

The majority of the fishing takes place on the edge of the continental shelf at depths ranging between 500 and 2,000 m. Lines are set only at night to prevent bird mortalities and can extend up to 13 km in length, usually with between 5,000 and 9,000 hooks. Five statistical areas have been established around South Georgia and Shag Rocks to facilitate analysis of the fishery (cf. Fig. 1).

It has been found that the distribution of fishing effort around the island is not uniform, as fishers have established which areas are the most productive. These are believed to coincide with specific bathymetric characteristics but until now detailed analysis of the fishery with associated bathymetry features has been limited to poor/low resolution charts. Recent swath bathymetry surveys have now enabled a more thorough examination of the relationship between the fishery and the seafloor.

This study forms part of a preliminary analysis of both biological and fisheries characteristics obtained from research survey and commercial fishing data. A number of statistical models are developed to help describe these relationships.

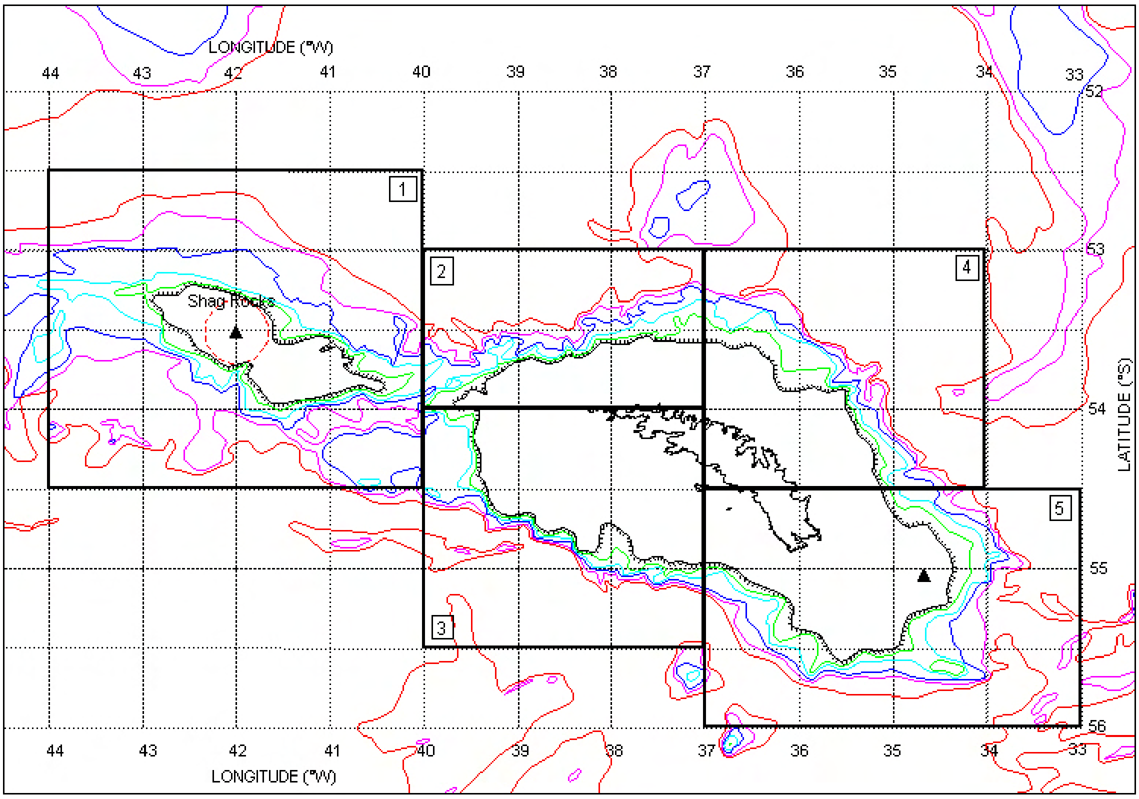

Figure 1. Location of South Georgia and Shag Rocks in the southern hemisphere showing depth contours between 500 and 2,500 m obtained from the GEBCO nautical atlas. Statistical fishing areas identify Shag Rocks (1), north South Georgia (2) west South Georgia (3) east South Georgia (4), and south South Georgia (5).

2. METHODS

2.1 Data collection

2.1.1 Acoustic information

Bathymetric data from South Georgia (Lat/Lon: 33°W, 53°S, 45°W, 56°S.) have been collected from a range of sources and aggregated to form a new high-resolution bathymetric map of the region. Existing UK Hydrographic Office and IHO/NOAA GEBCO data have been supplemented by finer scale echosounder data obtained from numerous commercial fishing and research vessels operating within the South Georgia region (Table 1). Swath bathymetry data, collected from the British Antarctic Survey's research vessel RRS James Clark Ross were also available from several cruises at South Georgia. Although to date the spatial coverage of the multibeam swath surveys at South Georgia has been low the resolution of the bathymetry data is extremely high with coverage increasing every year. These data were obtained using a hull-mounted Kongsberg Simrad multibeam swath-bathymetry system. The swath system was a deep-water EM120, with a 1° by 1° beam configuration.

Table 1. Summary of acoustic data used to develop new bathymetric chart of South Georgia region.

Data Source	Equipment	Datsets
Acoustic (*RRS James Clark Ross)*	SIMRAD EA500	1994- 2004
Acoustic (*FPRV Dorada*)	SIMRAD EK500	2002 - 2004
Acoustic (Commercial fishing vessels)	SIMRAD and FURUNO Commercial sounders	2000 - 2003
Acoustic (UKHO)	Various	
IHO/NOAA (GEODAS)	Various	1967-2003
Acoustic Swath Bathymetry (*RRS James Clark Ross*)	SIMRAD EM120 multibeam	2000-2003

Data from all sources were pooled and manipulated using GMT software. Median depth values found within cells measuring 0.002o (Lat.) by 0.004o (Long.) were gridded and contoured using a simiilar grid interval.

2.1.2 Biological data

Biological information on *D. eleginoides* and it's associated habitat is available from bottom trawl research surveys and Fisheries Observers sampling the commercial longline fishery.

Bottom trawl survey data collection

Since 1987 11 random depth-stratified bottom trawl surveys have been carried out at South Georgia in water depths ranging from 100 –500m. The primary objective has been to obtain estimates of biomass of all of the demersal finfish species within the South Georgia region (CCAMLR subarea 48.3) and in particular those that support a commercial fishery. Almost all surveys have taken place in the middle of the austral summer (1997 was an exception, taking place in late winter). Biological information including species composition, catch size, numbers caught, individual size, sex and sexual maturity has been recorded for all trawls (nearly 900 in total) and archived in a database with associated information on trawl location, net depth, trawl duration and net configuration.

Longline fishery data collection

Since the mid 1990's it has been mandatory for all toothfish longliners operating within CCAMLR waters to carry a scientific fisheries observer as part of the internationally agreed CCAMLR scheme of scientific fisheries observation. This has enabled high quality biological data to be collected from the commercial fishery at South Georgia which has included information on length frequency of catches, biological characteristics of the target species and information on bycatch species.

2.1 Data analysis

2.1.3 Biological characteristics

Toothfish size

Length frequency data, collected from the commercial longline fishery, were used to determine whether specific bathymetric characteristics are associated with the overall size of fish. Data were available from biological sampling by Fisheries Observers between 2001 and 2004 in depths between 150 and 2,000 m.

The average size of toothfish (total length, cm) was calculated for each longline set sampled. The location of each set is recorded in logbooks from a start/end position. Total catch and biological samples are recorded for the entire set, rather than specific lengths of line (i.e. every 1 km), which currently restricts the resolution of data available. The position of longline data was therefore calculated as the mid-point of the set. Additional information on the average fishing depth, year, fished area, vessel and general bathymetric features were also recorded. Commercial longline data were spatially resolved into five statistical regions (cf. Fig. 1). These have been selected arbitrarily to identify general geographic locations such as Shag Rocks. These data were used to develop both GAM and GLM statistical models within Splus.

Species diversity and evenness

A preliminary exploration of the diversity of the South Georgia bottom fish assemblage was expressed using the Shannon diversity index (*H*) and measure of equitability (E_H) (Zar, 1999). These measures attempt to account for both the abundance and evenness of the fish species present and assume that they are all equally vulnerable to the survey trawl net.

Both indices were calculated from the number of fish caught during a standardised bottom trawl from research surveys undertaken between 1987 and 2004. To avoid inclusion of pelagic species in the analysis, which may be caught during periods of setting and hauling, only known benthic species were used (Table 2).

Table 2. Abundance of fish species caught around South Georgia and Shag Rocks from standardised bottom trawl research surveys between 1987 and 2004.

Species	N	%
Patagonotothen guntheri	68,474	55.0%
Gobionotothen gibberifrons	20,757	16.7%
Chaenocephalus aceratus	11,016	8.9%
Lepidonotothen squamifrons	10,870	8.7%
Pseudochaenichthys georgianus	5,211	4.2%
Dissostichus eleginoides	2,990	2.4%
Lepidonotothen nudifrons	2,459	2.0%
Notothenia rossii	2,458	2.0%
Rajiformes spp.	228	0.2%

Diversity indices were calculated from each bottom trawl and for each research survey between 1987 and 2004. In total, 854 indices were calculated with associated information on average fishing depth and survey location. Similar to commercial longline data, research trawls were spatially resolved into five statistical regions (cf.

Fig. 1). In addition, fishing location was used to determine general bathymetric characteristics associated with the diversity indices (see section 3.2).

2.1.4 Fisheries characteristics

Toothfish catch rates

Catch per unit effort (CPUE) is currently used in the stock assessment of toothfish around South Georgia (CCAMLR, 2003). A marked change in standardised CPUE was observed between 1995 and 1996, which is thought to be mainly attributed to IUU fishing. Although there are currently a number of models being developed to help reconcile these observations (Agnew et al. 2004), catch rates might also vary with changes in the bathymetry.

A preliminary examination of the distribution of toothfish catch rates from the commercial fishery was explored using both GAM and GLM statistical models developed within Splus. Additional information on the area fished, average depth, year and vessel were also included in the analysis.

3. RESULTS

3.1 Revised bathymetry chart

The availability of acoustic data from both research surveys and commercial fishing, and the subsequent post-processing has greatly improved our current understanding of the bathymetry around Shag Rocks and South Georgia (Fig. 2). This is most obvious in waters less than 500 m, where deepwater canyons typical of previous glacial activity are observed extending out from South Georgia to the shelf break.

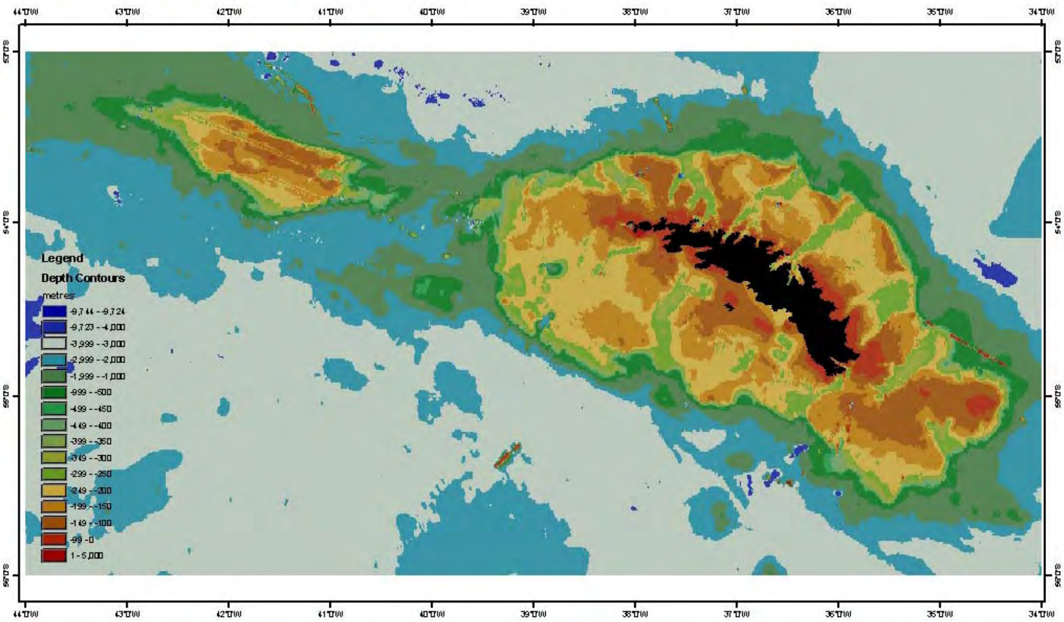

Figure 2. Preliminary new chart of South Georgia showing detailed bathymetric contours on shelf and surrounding areas obtained from acoustic data.

The preliminary analysis of the bathymetric data currently prohibits detailed classification such as slope characteristics to areas surrounding South Georgia. Instead, a broad-brush approach has been taken here to explore both biological and fisheries characteristics in relation to geographic areas (cf. Fig. 1) and large bathymetric features such as the observed canyons.

3.2 Bathymetric classification in fishing areas

The commercial longline fishery around South Georgia currently operates near the shelf break in deep water, between 500 and 2 000 m. There is anecdotal evidence to suggest that longline vessels which target toothfish favour locations situated at or close to canyon features.

Deepwater canyons identified on the shelf using the latest acoustic data, have been extended to encompass the area available to longline fishing. Until more sophisticated techniques can be employed, this has been undertaken in a subjective manner simply by extending the width of the canyon observed on the shelf outwards to the 2 000 m contour (Fig. 3).

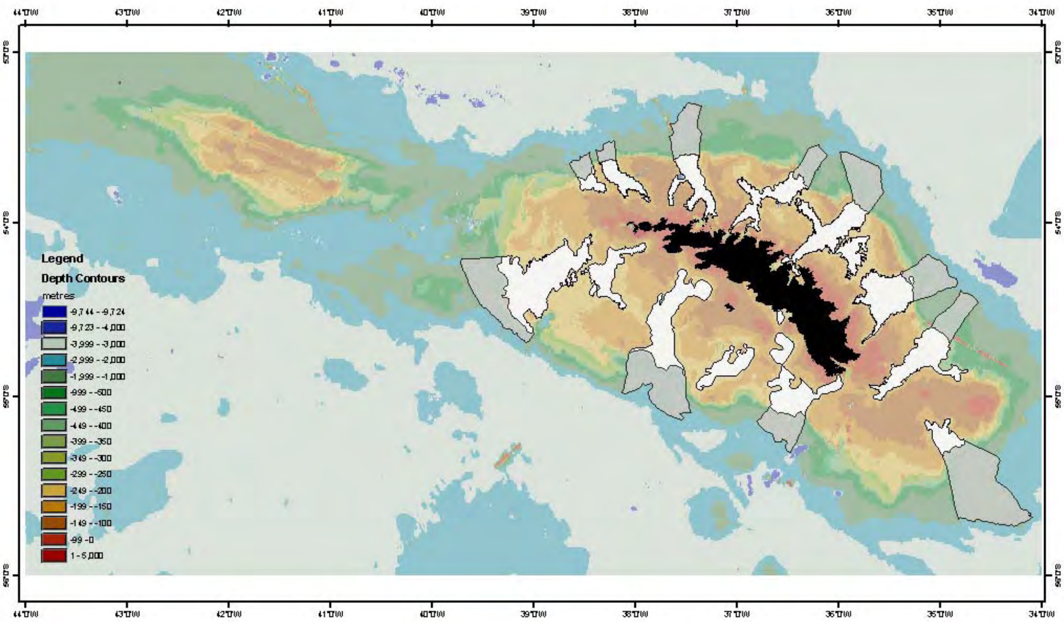

Figure 3. Chart showing location of deepwater canyons on the South Georgia shelf region (white region) and their extension into deeper water to encompass the commercial longline fishery in depths between 500 and 2 000 m (grey region).

3.3 Size distribution of toothfish

Commercial longline data, sampled as part of an ongoing Scientific Observer Programme, has been used to investigate the average size of toothfish in relation to year, area, vessel, canyon and depth. With exception to depth, all variables were treated as factors. An exploratory analysis of the data has been undertaken using a general additive model with a smoothing function on depth (Fig. 4).

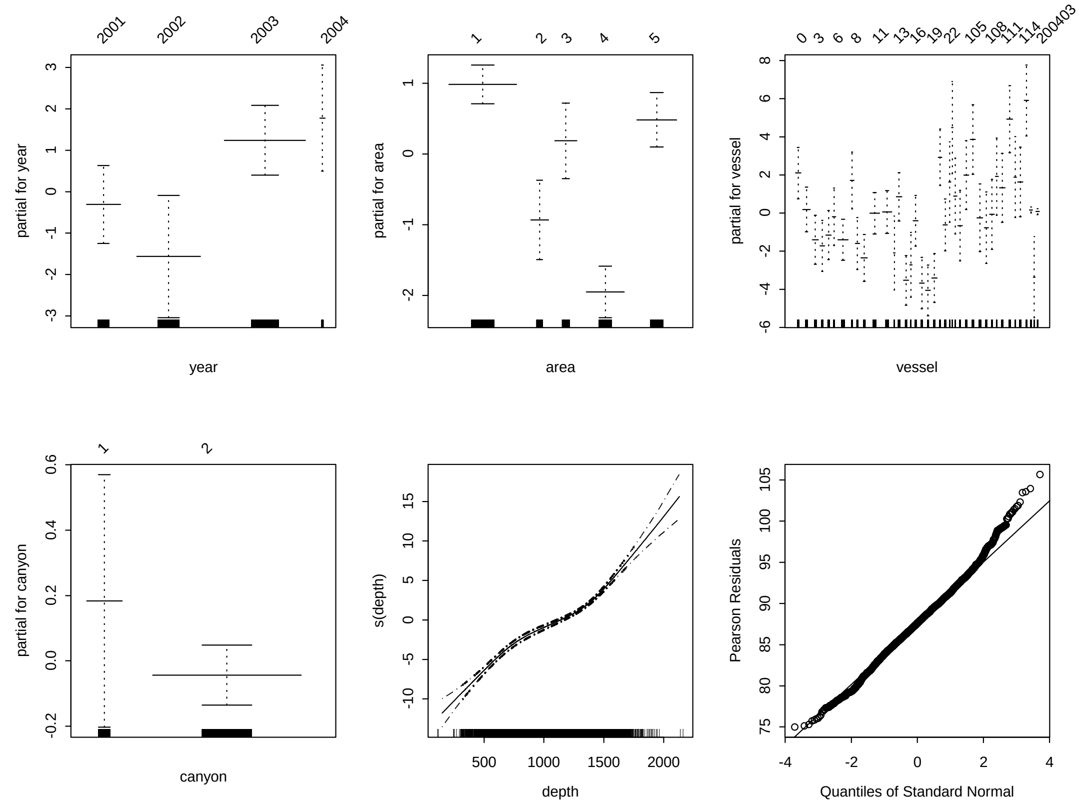

Figure 4. Results of a GAM model to show the relationship between the average size of toothfish caught in the longline fishery between 2001 – 2004 and area, vessel, canyon and depth.

The results of the GAM show that there is notable variation in the average size of toothfish caught between 2001 and 2004. Overall, larger fish have been landed more recently in comparison to either 2001 or 2002. Size also varies according to area fished. On average, catches around Shag Rocks (area 1) contain larger fish than South Georgia (areas 2 – 5). Not surprisingly, individual vessels show considerable variation and size is closely related to fishing depth. Interestingly however, the average size of toothfish is greater within canyons than outside. This is mainly due to an observed increase in depth within canyon features.

A generalised linear model (GLM) has been fitted in Splus to the same data, but has included an interaction term for canyon and depth, based on the results of the GAM:

```
topsize1.glm<-glm((size)~year+area+vessel+canyon*depth,data=topsize,
   family=gaussian, na.action=na.omit)
```

	Df	Deviance	Resid. Df	Resid. Dev	F Value	Pr(F)
NULL			4864	241094.4		
year	3	1130.76	4861	239963.6	10.970	0.000
area	4	1976.52	4857	237987.1	14.381	0.000
vessel	37	29684.78	4820	208302.3	23.349	0.000
canyon	1	94.50	4819	208207.8	2.750	0.097
depth	1	42398.06	4818	165809.8	1233.923	0.000
canyon:depth	1	295.84	4817	165513.9	8.610	0.003

The results of the GLM explains 34.4% of the observed variation in the data, with depth (20.4%) and vessel (12.5%) having the greatest importance. With exception to canyon, all other factors are significant ($p<0.05$). There is however, a significant relationship between deepwater canyon and depth between approximately 500 and 2,000 m.

3.4 Toothfish habitat

Shannon-Wiener diversity and evenness indices have been calculated from bottom trawl research surveys. Unlike the commercial toothfish fishery, research surveys have the potential to cover a larger area, but are mainly restricted to the shelf region around South Georgia and Shag Rocks to the west.

3.4.1 Finfish species diversity

Analysis of the distribution of finfish diversity indices was modelled using an exploratory GAM and GLM in Splus. Greater understanding of toothfish distribution and abundance may be gained via knowledge of their potential habitat and species assemblage. The following GAM was fitted using a smoothing function on fishing depth:

```
fish.gam<-gam((h)~year+area+canyon+s(depth),data=fish04, family=gaussian,
    na.action=na.omit)
```

The results indicate no decline in fish diversity has occurred between 1987 and 2004 (Fig. 5). Observed differences were reported between fishing areas (1-5), depth and regions associated with canyons. Low fish diversity was observed around Shag Rocks (area 1), which increases further to the east of South Georgia. Higher fish diversity was also reported within canyons, and in deeper water above 200 m on the shelf region.

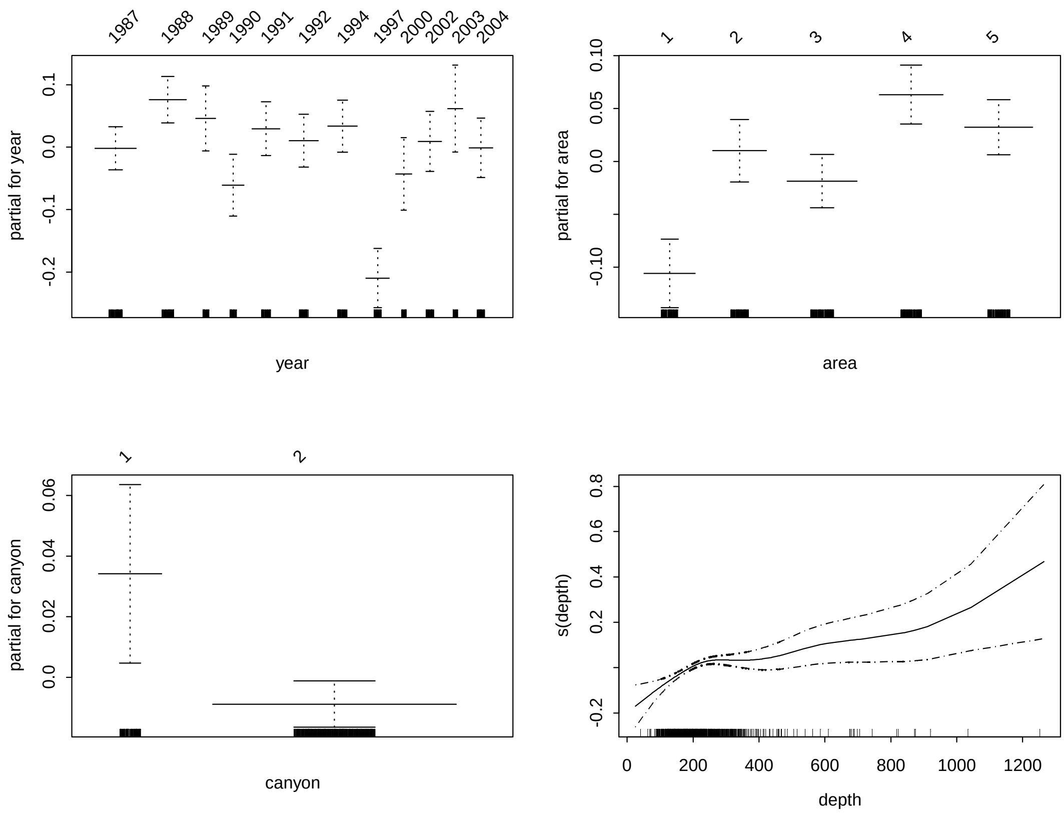

Figure 5. Diagnostics from GAM model to show the relationship between finfish species diversity from bottom trawl research surveys between 1987 and 2004 and area, canyon and depth effects.

A GLM was fitted to the same fish diversity data, but included an interaction term between canyon and depth, which had previously been identified as being a significant factor (see section 3.3).

```
fish.glm<-glm((h)~year+area+canyon*depth,data=fish04, family=gaussian,
   na.action=na.omit)

             Df Deviance Resid. Df Resid. Dev  F Value     Pr(F)
        NULL                   883   45.518
        year 11 4.530170       872   40.988  9.98           0.000
        area  4 3.341329       868   37.646 20.25           0.000
      canyon  1 0.828631       867   36.818 20.09           0.000
       depth  1 1.069280       866   35.749 25.92           0.000
canyon:depth  1 0.066925       865   35.682  1.62           0.203
```

The results show that trends observed in the exploratory GAM above are significant, although the model currently explains relatively little of the observed variation in the data (22%). Annual species diversities explained the majority of the variation in the model (10.0%), and although this was significant no trend was apparent. Interestingly however, the interaction between depth and canyons was not significant.

3.5.2 Finfish species evenness (*E*)

In addition to finfish species diversity, an index of fish evenness was calculated to determine the relative abundance of one or more species within an area. The following species evenness was modelled using an exploratory GAM within Splus:

```
fish2.gam<-gam((e)~year+area+canyon+s(depth),data=fish04, family=gaussian,
   na.action=na.omit)
```

The diagnostics of the model show that it is comparatively similar to the diversity index (Fig. 6). An important distinction, however, can be observed by the low species evenness around west South Georgia (fishing areas 2 and 3), which is more similar to Shag Rocks than to east South Georgia.

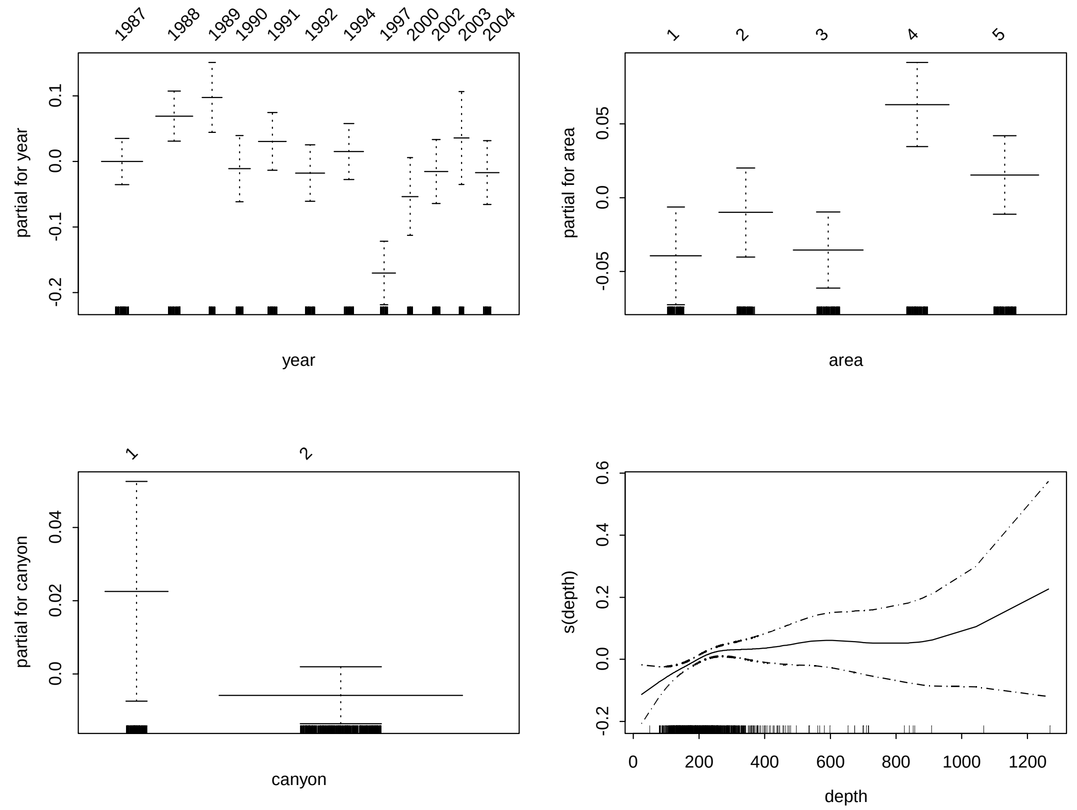

Figure 6. Diagnostics from GAM to show the relationship between finfish species evenness from bottom trawl research surveys between 1987 and 2004 and area, canyon and depth effects.

Species evenness was modelled using the following GLM within Splus that included an interaction term for canyon and depth:

```
fish3.glm<-glm((e)~year+area+canyon*depth,data=fish04, family=gaussian,
   na.action=na.omit)
```

Similar to fish diversity, the model explains relatively little of the variation observed in the data (approx. 14%). The results confirm that year, area, depth and canyon are significant factors in describing the distribution of species evenness around South Georgia.

	Df	Deviance	Resid. Df	Resid. Dev	F Value	Pr(F)
NULL			883	42.69814		
year	11	3.343993	872	39.35415	7.14559	0.000
area	4	1.636283	868	37.71787	9.61533	0.000
canyon	1	0.438943	867	37.27893	10.31748	0.001
depth	1	0.406824	866	36.87210	9.56251	0.002
canyon:depth	1	0.071866	865	36.80024	1.68923	0.194

Looking at both fish species diversity and evenness analyses together it has been shown that Shag Rocks has comparatively fewer species within the fish assemblage than South Georgia and the habitat is dominated by fewer species, namely toothfish.

3.5 Toothfish catch rates

The distribution of toothfish catch rates was explored with the addition of new bathymetric data. The following GAM was fitted in Splus using a smoothing function on depth to determine whether the inclusion of deepwater canyons could explain any of the variation observed in the catch rates of toothfish:

```
top1.gam<-gam((ln_cpue)~year+area+vessel+canyon+s(depth),data=top04,
    family=gaussian, na.action=na.omit)
```

Individual vessels were modelled as a factor, rather than including other specific characteristics such as Gross Registered Tonnage (GRT).

Although the model did not fit the data particularly well, higher CPUE values were associated within canyons. This result was already expected since higher average sizes (and therefore weight) of toothfish has already been shown to be associated within canyons (cf. section 3.3). The results of the following GLM however, showed that catch rates did not differ significantly with canyons:

```
top1.glm<-glm((ln_cpue)~year+area+vessel+canyon*depth,data=top04,
    family=gaussian, na.action=na.omit)
```

4. DISCUSSION

Analysis of acoustic data, collated from both research and commercial fishing vessels operating around South Georgia and Shag Rocks, has advanced our knowledge of the bathymetry within the region. A series of new depth contours now facilitate finer scale analyses of bathymetric features such as deepwater canyons which extend outwards from South Georgia to the shelf break.

There currently exist a number of constraints that have restricted a full analysis of the data. First, bathymetric features have been identified in a rather subjective manner in relation to the latest depth contours. Second, biological data collected from the commercial longline fishery has been used with a number of underlying assumptions about the distribution and abundance of fish. Due to the length of longline sets, a mid-point has had to be used in the analysis which represents the average fishing position, even though both bathymetric and species characteristics may vary along the line.

Within these constraints, the results have shown that the average size of toothfish are larger around Shag Rocks than South Georgia. No relationship was found, however, between size of toothfish and deepwater canyon features, although not surprisingly, larger individuals were caught in deeper water.

Examination of the survey data has shown that there was no overall decline in fish diversity between 1987 and 2004 although there was evidence of annual variation. However, significantly lower fish diversity was reported around Shag Rocks, which increased further to the east around South Georgia. Higher fish diversity was also reported within deepwater canyons and increasing water depth. Furthermore, indices of fish evenness were similar to those reported for fish diversity. However, it was noted that a few species tended to dominate around Shag Rocks and to the west of South Georgia.

The lower diversity in fish species observed by trawl sampling at Shag Rocks compared to South Georgia is likely to have a number of underlying causes. Although the two shelf regions are less than 50 miles apart, a deep channel with depths greater than 1,500 m through which flows a strong current, separates them. This may provide a barrier to movement between regions for both adults and eggs/larvae particularly for fish that live at shallower depths. The Shag Rocks shelf is not ‘scarred’ by underwater canyons and gullies to the same degree as South Georgia which is likely to reduce the number of available habitats. The deep fjords and canyons around the island of South Georgia are known to be spawning grounds and nursery areas for a number of the dominant notothenid fish species such as *Notothenia rossi* and members of the Channichthyidae (icefishes). The lack of these features at Shag Rocks is also likely to influence the number of species that occur there. The shelf waters of South Georgia have a number of abundant fish species that are rarely, if ever, caught at Shag Rocks including an endemic icefish species *Pseudochaenicthys georgianus.* The presence of the magallanic notothenid species *Patagonotothen guntheri* at Shag Rocks and its absencence at South Georgia suggests that the fish assemblage is more closely associated with the Patagonian region than with that found at South Georgia and other sub-Antarctic islands.

Large, deep-water species such as toothfish are less likely to find the deep channel and strong current between Shag Rocks and South Georgia a significant barrier to movement. Consequently adult fish are taken by the fishery at both locations at depths of 500 –2000m. Trawl surveys however, indicate that juvenile toothfish less than 50 cm TL, which are generally found at depths less than 350 m are far more abundant at Shag Rocks than at South Georgia. It is not known to what extent this is driven by topography but it is likely that the high abundance of their preferred food item, *P. guntheri,* at Shag Rocks and its absence at South Georgia may be an important factor.

High resolution swath bathymetric data is currently available for a limited number of areas of the South Georgia slope and shelf as the majority of swath surveys have been carried out in water depths > 2000 m. Areas of overlap with the commercial longline fishery for toothfish are currently restricted to a few regions to the South and South East of South Georgia and a small region to the North West of Shag Rocks. However it is intended to continue the collection of swath bathymetry data from the zones in which the fishery operates. Detailed acoustic outputs, such as that shown below, will soon be available for fisheries analyses. It is clear from this fine scale output that the fishery does not operate in a uniform manner around the 1,000 m depth contour but that fine scale undersea topographic features are important in determining the location at which longlines are set.

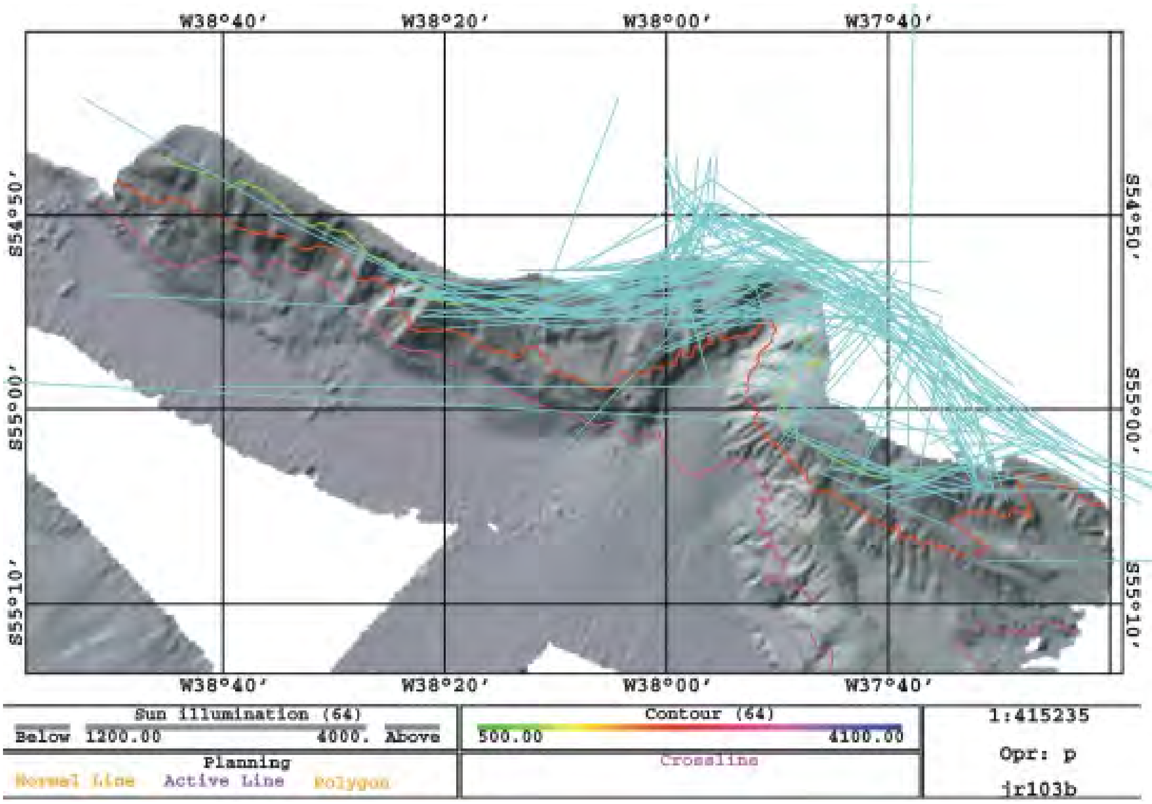

Figure 7. Longline fishing activity on the shelf break to the south-east of South Georgia (blue lines) in relation to revised bathymetric contours and underlying acoustic data.

The current analysis of the new bathymetric data has been very broad-brush, and only very large features such as deepwater canyons have been identified. In future it will be possible to apply algorithms to the 'xyz' data to determine more specific slope characteristics. However, to make best use of this fine-scale mapping, the spatial resolution of the biological data collected from the commercial longline fishery must also be increased. A new sampling strategy has recently been instigated within the Fisheries Observer Programme to help resolve this issue.

5. REFERENCES

Agnew D.J., Payne A. and G.P. Kirkwood. Alternative assessment methods for toothfish at South Georgia. WG-FSA-SAM-04/07. 14pp.

CCAMLR (2003). Report of the working group on fish stock assessment. Hobart, Australia, October 2003.

GEBCO digital nautical atlas. http://www.ngdc.noaa.gov/mgg/gebco/gebco.html

Zar, J.H. 1999. *Biostatistical analysis*. [4th Ed]. Pretence Hall. 663 p.

ACKNOWLEDGEMENTS

We thank the UK Hydrographic Office and commercial longline operators for providing additional bathymetric data within the region. Biological information was collected by Fisheries Observers within the commercial longline fishery and masters, officers and crew on board both RRS James Clark Ross and FPRV Dorada. Post processing of the bathymetric data was completed by Nathan Cunningham and Adrian Hine.