Taihoro Nukurangi

# Spatial variability of orange roughy and associated species around the Northwest Hills on the Chatham Rise, New Zealand

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# Final Research Report

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## 7. Executive Summary:

We used research trawl survey data to describe the small-scale distribution and spatial continuity of orange roughy catch rates around the Northwest Hills complex of seamount features on the Chatham Rise to the east of New Zealand. Analyses revealed three distinct spatial patterns. The larger scale spatial structure in the catch rates was defined by the contours running east-west along the Chatham Rise. Orange roughy were caught in a depth band between $850 - 1200$, a depth distribution that is well known. Superimposed on this larger scale structure was a north-south trend in the highest catch rates at $180^o$ longitude. This was created by higher catch rates on the seamounts. There were large differences in catch rates at small separation distances due to the seamount effect. However, not all the high catches were associated with seamounts, some being taken on the 'flat' areas around the hills. At distances away from the seamounts greater than the decorrelation length scale the spatial distributions of orange roughy catch rates were not random, and did not conform to a Poisson process. Data visualisation of the spatial distributions of orange roughy and groups of bycatch revealed strong patchiness and spatial separation by depth of swimbladder fish, elasmobranchs and squid, and oreos. This has important implications for acoustic surveys. Orange roughy overlapped most closely with swimbladder fish distributions, suggesting they may be obscured by species with higher acoustic target strengths. Depth-dependent distributions simplify separation of fish groups when partitioning acoustic backscatter, but patchiness complicates defining where the groups are species occur. We conclude that extensive trawling provides a necessary complement to acoustic survey in order to estimate the biomass of orange roughy.

## 8. Objectives:

Investigate the spatial distribution of orange roughy from existing trawl and acoustic data to evaluate its effects on biomass estimates made using these approaches.

# Spatial variability of orange roughy and associated species around the Northwest Hills on the Chatham Rise, New Zealand

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**Abstract**

We used research trawl survey data to describe the small-scale distribution and spatial continuity of orange roughy catch rates around the Northwest Hills complex of seamount features on the Chatham Rise to the east of New Zealand. Analyses revealed three distinct spatial patterns. The larger scale spatial structure in the catch rates was defined by the contours running east-west along the Chatham Rise. Orange roughy were caught in a depth band between 850 – 1200, a depth distribution that is well known. Superimposed on this larger scale structure was a north-south trend in the highest catch rates at 180° longitude. This was created by higher catch rates on the seamounts. There were large differences in catch rates at small separation distances due to the seamount effect. However, not all the high catches were associated with seamounts, some being taken on the 'flat' areas around the hills. At distances away from the seamounts greater than the decorrelation length scale the spatial distributions of orange roughy catch rates were not random, and did not conform to a Poisson process. Data visualisation of the spatial distributions of orange roughy and groups of bycatch revealed strong patchiness and spatial separation by depth of swimbladder fish, elasmobranchs and squid, and oreos. This has important implications for acoustic surveys. Orange roughy overlapped most closely with swimbladder fish distributions, suggesting they may be obscured by species with higher acoustic target strengths. Depth-dependent distributions simplify separation of fish groups when partitioning acoustic backscatter, but patchiness complicates defining where the groups are species occur. We conclude that extensive trawling provides a necessary complement to acoustic survey in order to estimate the biomass of orange roughy.

*Key words:* acoustic, spatial, orange roughy, fish, New Zealand

# 1 Introduction

Spawning aggregations of orange roughy, *Hoplostethus atlanticus*, are associated with seamounts in both New Zealand and Australian waters [Clark, 1996, Kloser et al., 1996]. In New Zealand, formerly more extensive spatial distributions of orange roughy have regressed to be more tightly associated with seamounts [Clark and Tracey, 1993]. The Northwest Hills (NW Hills) on the northern margin of the Chatham Rise to the east of New Zealand is an area where orange roughy aggregate to spawn in winter. The complex of hills, located between $179^o\ 54'\ E - 179^o\ 42'\ W$ and $42^o\ 37' - 42^o\ 50'\ S$, includes 28 seamount features shoaling to between $750 - 1263\ m$ depths [Bull et al., 2000]. The features are not very dramatic, because their elevations are relatively small (range $66 - 405\ m$). Three of the hills on the Northwest Chatham Rise named Dead Ringer, Morgue and the Graveyard have elevations of 330, 310 and 352 $m$ above their surroundings [Clark et al., 2001]. Although it is well known that orange roughy spawning plumes are generally located over the hills [Clark et al., 2001], there is very little information about the small scale spatial distribution of fish on and around these features.

Previous work [Francis and Bull, 2000] showed a decline in the relative abundance of orange roughy with distance from the NW Hills. Commercial catches have also been shown to be higher near seamounts in the New Zealand region [Clark and O'Driscoll, submitted]. An analysis of acoustic echograms of orange roughy spawning plumes on the Ritchie Bank off New Zealand determined that the plumes were dynamic, but did not detect any obvious diel patterns in spatial distributions [Pankhurst et al., 1987]. This may have been because the scales were very small, spanning only 52 $h$ and $\approx\ 3\ km$ [Pankhurst, 1988]. Spawning plumes of orange roughy did not move off the NW Hills over periods of several days [Bull et al., 2001]. We are not aware of any other work that has examined the small-scale spatial distribution of orange roughy on the NW Hills or on the 'flat' areas surrounding the hills. Virtually all of the previous studies of orange roughy biomass on the NW Hills have been analysed at much larger scales for stock assessment purposes [Anderson and Fenaughty, 1996, Tracey and Fenaughty, 1997]. In fact there appear to be almost no published studies using fishery-independent data to quantify the small-scale distribution of orange roughy either around seamounts or in other regions where they occur.

Acoustic survey is currently the preferred method for assessing the biomass of orange roughy. The spatial distribution of by-catch species around the NW Hills has important implications for biomass assessment of orange roughy using acoustic surveys. Away from the spawning plumes, that are almost 100% orange roughy, the mixture of species presents a challenge to the correct interpretation of acoustic backscatter [McClatchie et al., 2000]. Over the 'flat' areas away from the hills, the acoustic echo integration data is partitioned by species groups when calculating biomass estimates from echo integrals, using the group-specific relation between target strength and fish sizes [Bull, 2000]. Orange roughy are not abundant away from the hills, but because the area is large, the total biomass on the 'flat' areas is large relative to the total biomass [Bull, 2000]. The current limitations of acoustic target identification means that the ratio of by-catch species over the 'flat' areas is best determined by trawling. If the spatial distribution of by-catch species varies non-randomly, e.g. if it is very patchy, then it is necessary to do a lot of trawling to obtain a spatially explicit matrix of ratios for the important species groups in order to accurately partition the biomass. In this paper we determine how patchy by-catch fish distributions were over the 'flat' areas. The answer has important implications for survey design.

## 2 Methods

In this report, we use all the currently available trawl survey data (15 surveys and 394 trawls, Table 1) to quantify the fine-scale spatial distribution of orange roughy on the NW hills. Orange roughy are known to move on and off the hills as the spawning season progresses, and so, ideally, it would be best to temporally stratify the analyses. However, if this were done we would have insufficient spatial coverage to quantify the broader spatial patterns. Consequently we present a temporally aggregated analysis, ignoring seasonal and annual effects, as a first approach. Nevertheless, the bulk of the trawls were in the spawning season (Table 1), which should lessen the seasonal effects.

On the NW Hills the spawning season for orange roughy is between mid-June to mid-July, with mid-spawning occuring in the last week of June [Anderson, 2000]. Work conducted further east on the Chatham Rise and on the Challenger Plateau suggested that the timing of orange roughy spawning is consistent from year to year [Pankhurst, 1988]. Ten fisheries research surveys conducted from three different vessels (*Cordella, Tangaroa* and *Ocean Ranger*) have trawled the NW Hills at more than 7 stations (Table 1). Another seven voyages collected fewer than 7 trawl samples each (Table 1). The timing of these seven surveys was outside of the orange roughy spawning season. Although they were included in the current analyses they were of minor importance, contributing only 22 of the total of 394 trawls, or 5.6% of the trawls analysed (Table 1). Two in-season trawl surveys were run using the *Cordella* or *Ocean Ranger*, which were commercial vessels conducting research under charter. The remaining in-season surveys used the research vessel *Tangaroa*. There are no years in which an in-season and out of season survey was conducted in the same year at the same location using any vessel.

Two acoustic surveys in 1997 (TAN9708) and 1999 (TAN9908), also collected trawl samples. The acoustic surveys were not comparable in terms of either design or data quality. The 1997 acoustic survey was largely exploratory, was based on a grid design, and produced data of dubious quality [Bull et al., 1999]. A second

Table 1
Summary of orange roughy catch sizes (tonnes), total catch of orange roughy for surveys on the Northwest Hills (tonnes), and number of trawls where orange roughy were caught for different research surveys (COR = *Cordella,* TAN= *Tangaroa* and ORA = *Ocean Ranger*). Out of spawning season surveys with few samples in the region are separated from the principal research surveys. '*' denotes out of spawning season surveys. $n$ = number of trawls.

| Voyage | Min | Median | Mean | Max | $\Sigma$ *catch* | $n$ | start date | end date |
|---|---|---|---|---|---|---|---|---|
| COR9002 | 0.001 | 0.124 | 0.187 | 1.590 | 5.996 | 32 | 15 Jun 90 | 5 Aug 90 |
| TAN9206 | 0.003 | 0.151 | 0.198 | 0.746 | 6.141 | 31 | 1 Jun 92 | 27 Jul 92 |
| TAN9406 | 0.002 | 0.306 | 2.526 | 58.420 | 93.459 | 37 | 2 May 94 | 31 Jul 94 |
| TAN9608 | 0.003 | 0.287 | 6.812 | 53.010 | 224.811 | 33 | 10 Jun 96 | 14 Jul 96 |
| TAN9708 | 0.001 | 0.151 | 0.786 | 8.225 | 14.148 | 18 | 14 Jun 97 | 4 Jul 97 |
| TAN9908 | 0.023 | 0.420 | 3.899 | 0.470 | 113.076 | 29 | 12 Jun 99 | 11 Jul 99 |
| TAN0208 | 0.002 | 0.060 | 1.317 | 36.570 | 122.493 | 93 | 20 Jun 02 | 20 Jul 02 |
| ORA0201 | 0.003 | 0.050 | 0.580 | 22.750 | 57.375 | 99 | 10 Jul 02 | 24 Jul 02 |
| *COR8802 | 0.004 | 0.226 | 0.1918 | 0.376 | 1.151 | 6 | 10 Sep 88 | 2 Oct 88 |
| *COR8901 | 0.007 | 0.272 | 0.386 | 1.191 | 2.314 | 6 | 4 Jul 89 | 18 Aug 89 |
| *TAN9401 | 0.003 | 0.0033 | 0.0033 | 0.003 | 0.003 | 1 | 1 Jan 94 | 1 Feb 94 |
| *TAN9501 | 0.001 | 0.0011 | 0.0011 | 0.001 | 0.001 | 1 | 3 Jan 95 | 1 Feb 95 |
| *TAN9509 | 0.100 | 0.200 | 0.488 | 1.165 | 1.465 | 3 | 8 Aug 95 | 14 Aug 95 |
| *TAN0001 | 0.001 | 0.0012 | 0.0012 | 0.001 | 0.001 | 1 | 27 Dec 99 | 22 Jan 00 |
| *TAN0104 | 0.001 | 0.0022 | 0.0027 | 0.005 | 0.012 | 4 | 13 Apr 01 | 22 Apr 01 |

acoustic survey in 1999 [Bull, 2000] covering a more extensive area of the NW Hills, was based on a star transect design centered over hill features [Doonan et al., in press]. The most extensive survey to date was an acoustic survey done in 2002 using both *Tangaroa* (TAN0208) and *Ocean Ranger*(ORA0201) (Table 1).

The gear types, trawl mesh sizes and towing procedures were very similar on *Cordella* and *Tangaroa* surveys [Anderson and Fenaughty, 1996]. A six panel rough bottom trawl with no lower wings was the standard net used. Codend mesh sizes were 100 *mm* on most of the voyages, but were 40 *mm* on COR8901. Length of sweeps and bridles was 50 *m* on most voyages, but were 96 *m* and 48 *m* respectively on COR8901 and were both 45 *m* on ORA0201. Catches were not affected by net windows as these were not used. For the voyages providing most of the trawl stations (Table 1) the differences in gear were minor, and the catch data can be considered to be reasonably comparable.

We proceeded according to the following stages. First we carried out an exploratory data analysis. This involved checking the data for obvious anomalies by generating data summaries, and by plotting variables such as catch and tow distance to check for anomalously high values. We verified that the zonal pattern of relative abundance reported by [Francis and Bull, 2000] could be seen in both the data from voyage TAN9206, and in the combined data set from all surveys. We visually examined catch rate data for obvious trends using spatial plots and tried to explain the observable patterns in relation to the bathymetric contours. We then undertook a more quantitative analysis of orange roughy spatial pattern using omnidirectional and directional variograms to measure the spatial correlation scales. Expanding on the variogram results, we tested whether the catch rates greater than a selected threshold were randomly distributed at scales larger than the decorrelation length scale. The decorrelation scale was defined as the distance over which neighboring data points are correlated at approximately the same level, obtained from the range of variograms. Based on these results we inferred the scales over which bathymetry was the dominant factor structuring orange roughy abundance. All statistical analyses use the R packages [Ihaka and Gentleman, 1996]. Geostatistical analyses were performed with the aid of the GeoR package [Ribeiro and Diggle, 2000], following recommendations in [Isaaks and Srivastava, 1989].

### 2.1 *Data extraction*

Orange roughy catch data from *Tangaroa*, *Ocean Ranger* and *Cordella* voyages covering the Northwest Hills on the Chatham Rise were extracted from a database of trawl survey data. Trawls were only included if the trawl perfomance criteria were either excellent or good (i.e. measured door spread and net headline height were within expected tolerances and, there was no damage to the net on recovery, and the catch was considered to be a representative sample). Distances towed ranged from the shortest possible dip into spawning aggregations to some longer tows on the 'flat' area (maximum tow length = 10.57 km, but the mean and median were 2.85 and 2.78 km respectively). Catches of orange roughy ranged from 0.001 to 58.4 tonnes, but catches were generally small (see section 3.1 and Table 1). Catch rates in $tonnes\ km^{-1}$ were estimated as $(catch/1000)/distance\ towed * 1/0.540)$ where catch was in *kg* and distance towed was in *nautical miles*.

### 2.2 *Orange roughy catch rates by latitude and longitude*

Catch rates of orange roughy around the NW Hills were plotted against latitude and then longitude for comparison with *Tangaroa* voyage TAN9406 [Francis and Bull, 2000] to see if elevated catch rates at $180^o$ longitude were also observable in the more extensive dataset. The distribution of sampling effort was shown by plotting the starting location of the trawls. Catch rates were divided into quartiles and plotted in relation to both latitude and longitude. The frequency distribution of catch rates was examined to determine to what degree the data were skewed towards any particular size of catch.

### 2.3 *Spatial continuity of orange roughy*

The first step in investigating spatial continuity was to generate an omnidirectional variogram of the catch rate of orange roughy (*tonnes* $km^{-1}$), where the spatial coordinates were the start positions of trawl tows. Data were left in degrees latitude and longitude for this analysis. Trawls on the hills as well as 'flat' regions were included. Four directional variograms were also calculated, at azimuthal angles of 0, 45, 90 and 135$^o$, using an angular tolerance of 22.5$^o$.

### 2.4 *Point pattern analysis*

Hill trawls were segregated from the rest of the dataset. We used Ripley's $K$ function [Venables and Ripley, 1997] to test whether the location of catch rates greater than a specified threshold away from the hills was random. Selection of a threshold for catch rates was necessary to prevent the test simply being one for randomness of the trawl stations, since some orange roughy were caught at virtually all the stations. The threshold was determined by trial and error with the aid of frequency distributions (Figure 1) to ensure adequate sample size. The median catch rate provided a useful threshold while retaining sufficient samples for a meaningful test of randomness. Removing the hill stations clustered along the 180$^o$ meridian partitioned the data into two blocks. However, the sampling effort was uneven in these regions as shown by a histogram of the number of trawls by longitude (Figure 2). Combining sampling effort with location suggested that stratifying the data into three regions was appropriate. The test variable was station location and for each of the three regions we calculated Ripley's $K$ function expressed as $L(t) = \sqrt{\hat{K}(t)/\pi}$ where $t$ is the distance between points in the pattern. $L(t)$ is linear for a Poisson process [Venables and Ripley, 1997].

### 2.5 *By-catch distribution away from the hills*

The fish species that were caught in association with orange roughy in this region were grouped into 3 categories to examine how the spatial distribution of by-catch species varied away from the hills. The categories were (1) oreos (black oreo and

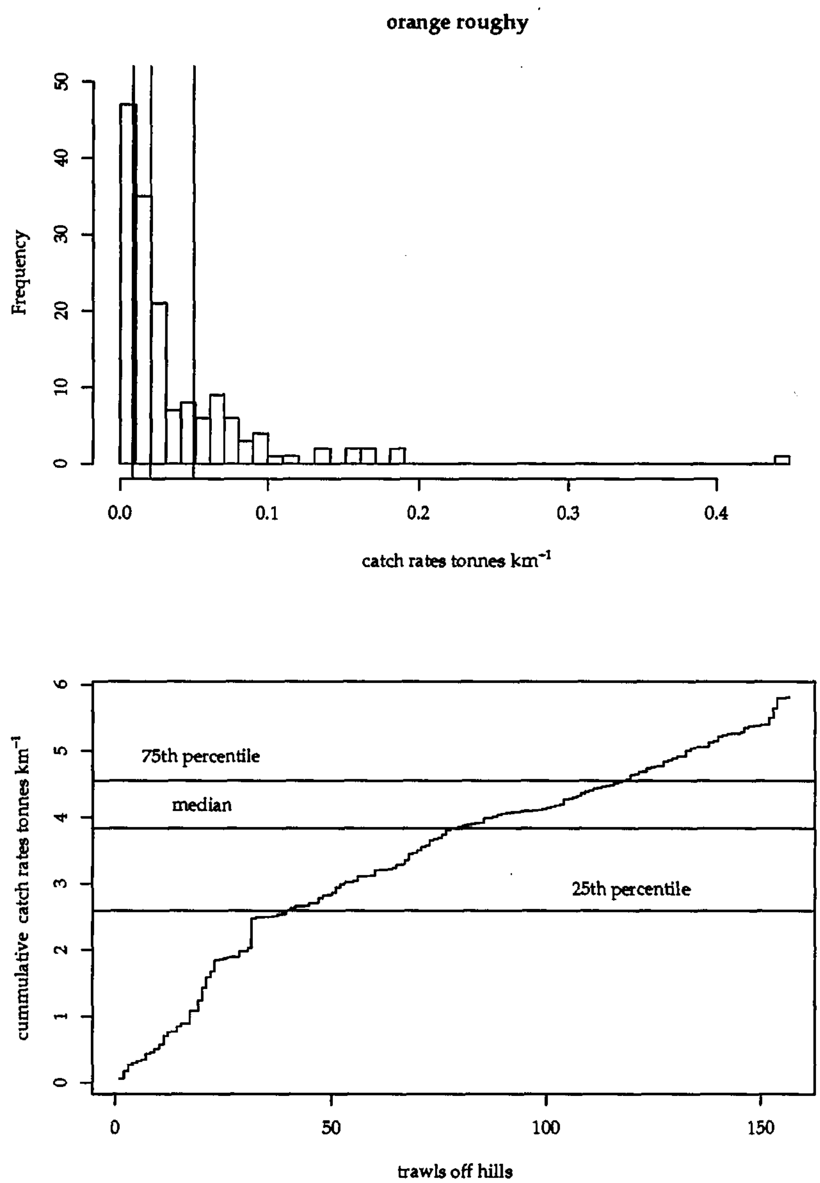


Fig. 1. Distribution of trawl catches away from the hills for all *Cordella*, *Tangaroa* and *Ocean Ranger* voyages. Vertical lines on the histogram mark the $25^{th}$ percentile, median and $75^{th}$ percentile.

smooth oreo) (2) other swimbladder fishes (rattails, slickheads, morid cods, basketwork eels, and hoki) and (3) non-swimbladder fish and squid (warty squid and elasmobranchs, such as deepwater dogfish and chimaerids) [Tracey et al., submitted]. For each trawl the weights of species in each group were summed, converted

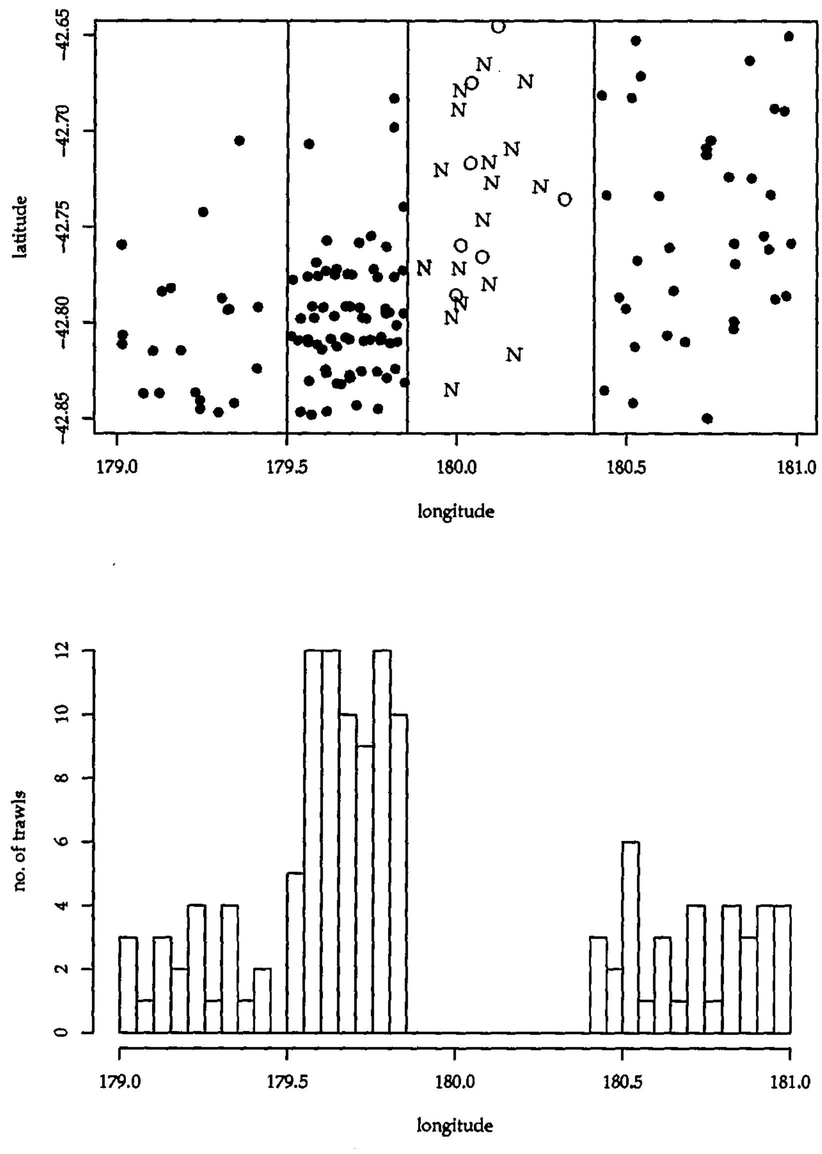


Fig. 2. Locations of all trawl catches away from the hills for all *Cordella, Tangaroa* and *Ocean Ranger* voyages. Hills (O and N) are marked as in Figure 6. Trawls are grouped into 3 regions based on the density of sampling. Strata boundaries were chosen based on reasonably similar numbers of trawls by longitude as shown in the bottom panel.

to catch rates (using the equation presented above), and logit transformed to reduce the influence of extreme values on the spatial distributions [Fox, 2002]. Spatial plots were created using the Generic Mapping Tool package (GMT) [Wessel and Smith, 1988]. Catch rates were averaged into $0.05^o$ squares of latitude and longitude and remapped onto a regular grid. A surface was iteratively fitted to the averaged data and smoothed using tensioned splines [Smith and Wessel, 1990]. The surfaces were overlaid on contour plots of bathymetry to show the distribution of fish biomass around the hills and plotted on a linear scale with exaggeration along the meridians to visualise the surfaces.

## 3 Results

### *3.1 Orange roughy catch rates by latitude and longitude*

Highest catch rates were found between $180^o - 179^o\ 54'\ W$ longitude (Figure 3) as reported previously based on the TAN9406 data [Francis and Bull, 2000, but note the different units]. In addition there was evidence of higher catch rates to the west at $179^o\ 20'\ E$ and $178^o\ 30'\ E$. In terms of latitude, higher catch rates were made between $42^o\ 42' - 42^o\ 54'\ S$ (Figure 3). Sampling intensity was highest between $179^o\ 30'\ E$ and $179^o\ 50'\ W$ (Figure 3).

### *3.2 Small-scale spatial trends*

Three spatial trends were obvious in the catch rates of orange roughy on the NW Hills. First, there was a larger scale general northeast-southwest trend. This trend was aligned to the bathymetric contours, as shown by matching the depth contours with the $0 - 75^{th}$ percentiles of orange roughy catch rates (Figure 4). Catch rates declined as water depths either shoaled to less than $800 - 850\ m$ or deepened beyond $1200\ m$. The $50^{th} - 75^{th}$ percentile of catch rates were generally further south and shallower than the $25^{th} - 50^{th}$ percentile (Figure 4). Second, there was a clear north-south trend centered on $180^o$ in the the upper quartile of catches rates (Figure 5). This was related to the locations of the seamounts, as shown by matching the upper quartile of catch rates to the seamount contours. Note that the trawl positions were the position of the vessel at start of tows, rather than the position of the trawl. Because deep trawls can be up to $1\ km$ behind the vessel, the trawls appear to be on the sides of the hills. We have no way of accurately correcting for this. Higher catches were taken from seven hills along the $\approx 180^o$ axis. Upper quartile catch rates at $179^o\ 42'\ E$ off the main trend axis corresponded to the location of another hill (Dead Ringer)(Figure 5). Last, there were also upper quartile catch rates at scattered locations that did not correspond to the position of the originally known

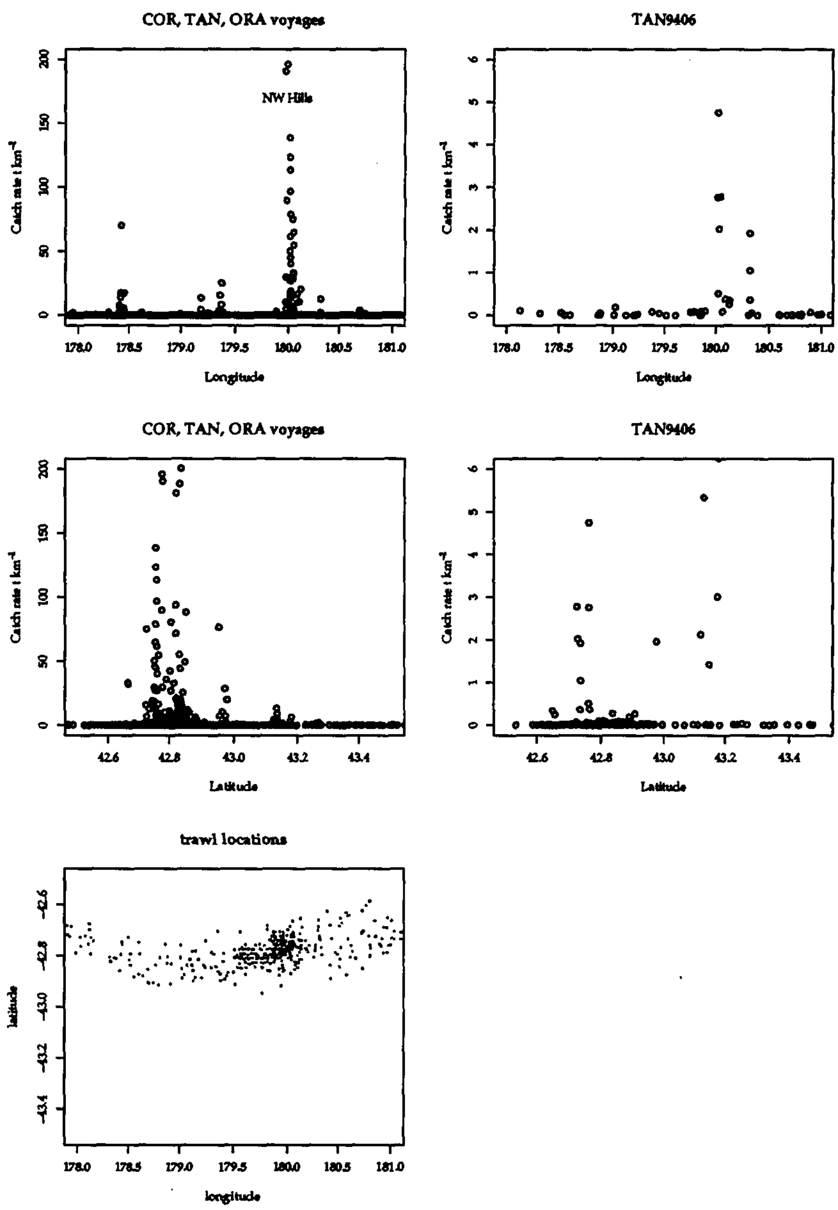


Fig. 3. Catch rates of orange roughy on the Northwest Hills of the Chatham Rise plotted against latitude and longitude. Top left and middle left panels are for all *Cordella, Tangaroa* and *Ocean Ranger* voyages. Top right and middle right panels are for *Tangaroa* voyage TAN9406 for comparison with earlier work [Francis and Bull, 2000]. Note the larger catch rate scale for the more extensive dataset compared to theTAN9406 data.

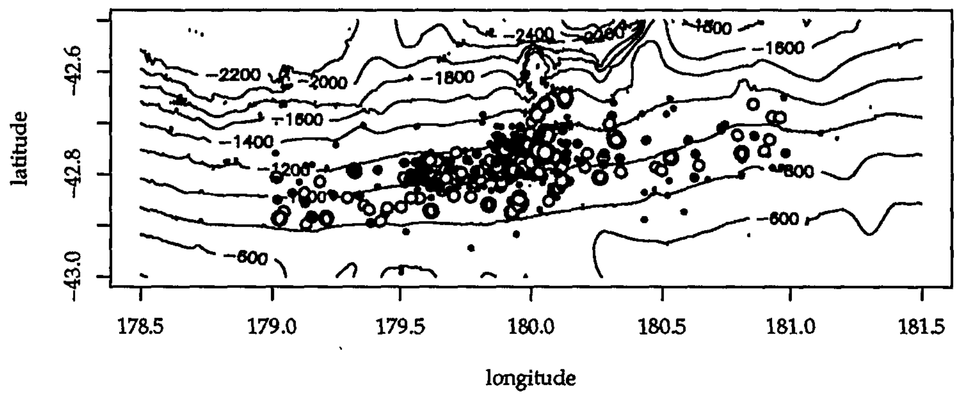


Fig. 4. Spatial distribution of catch rates of orange roughy (*tonnes* $km^{-1}$) on the Northwest Hills divided into quartiles to show the relation of catch rates to bathymetry (large red dots = catches in the upper quartile, small black dots = catches in the lower quartile, and two intermediate sized dots are for $25-50^{th}$ (green dots) and $50-75^{th}$ quartiles (yellow dots)).

NW Hills [Bull, 2000]. To determine whether these catches were taken on recently discovered hills [Bull, 2000] we plotted all the known hill locations and overlaid catch rates $> 75^{th}$ percentile ($> 0.13$ *tonnes* $km^{-1}$)(Figure 6). This showed that not all of the high catches were taken on the hills. There were nine trawls on the 'flat' areas around the hills that yielded these high catch rates.

### *3.3 Spatial continuity of orange roughy*

We used variograms to examine the scale-dependent differences between catch rates on the hills and on the 'flat' areas surrounding the hills. Both the omnidirectional variogram (Figure 7) and the directional variograms (Figure 8) showed rapid decline in semivariance at short lags. This was a result of large differences in catch rates at short separation distances between trawls on the hills and trawls on the surrounding 'flat' areas. This difference produces a rather peculiar looking variogram compared to the more commonly observed power function. As is customary, we interpreted the range as the point at which the semivariance levels off, or at which correlation remains approximately constant (Figure 8), and used this as the decorrelation length scale. Away from the hills, at distances greater than the decorrelation length scale, the differences between catch rates in different trawls was much smaller.

Comparison of the directional variograms showed that the ranges were comparable between the directions, indicating a decorrelation length scale of $\approx 0.2$ *degree units*

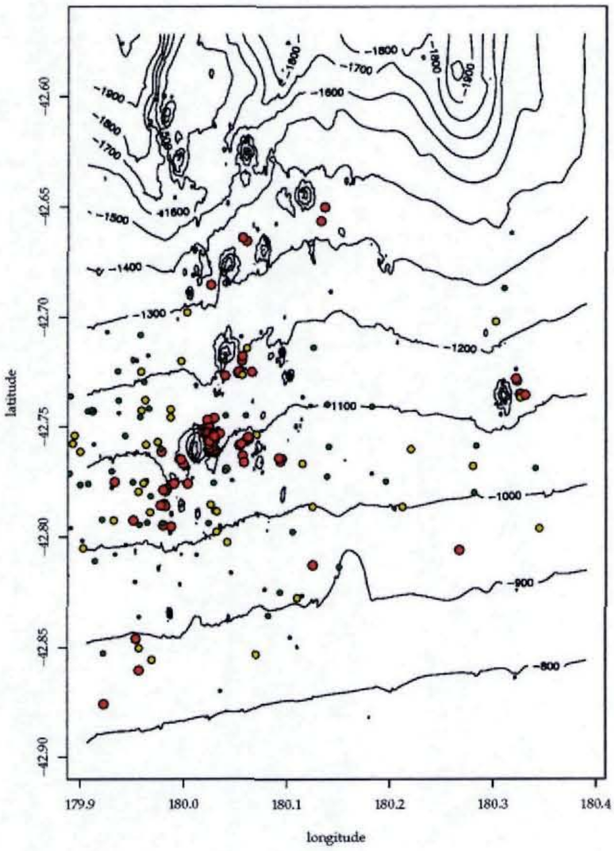


Fig. 5. Spatial distribution of catch rates of orange roughy (*tonnes* $km^{-1}$) on the Northwest Hills divided into quartiles to show that the location of high catch rates are primarily on the hills. Colour coding of dots is the same in Figure 4.

or 16.3 *km* at $180^o$ meridian $42^o$ $42'S$ (Figure 7). Since the semivariance was not standardised, it was noticeable that the sill of the $22.5-67.5^o$ variogram was higher than those for the other three directions. This reflects greater total variance of the catch rates along the contours, which would arise from inclusion of larger catch rates on the hills in this direction (Figure 4). The trends in semivariance suggested that catch rates on the 'flat' were isotropic in the other three directions (Figure 8).

### *3.4 Point pattern analysis*

A test for randomness indicated that the point pattern of greater than median catches of orange roughy away from the hills was not random. The plot of $L(t)$ was not straight (Figure 9) as expected for a Poisson process. The significance of the deviation from linearity was tested using 100 simulations of a binomial point process [Venables and Ripley, 1997] where the number of points was equal to the the num-

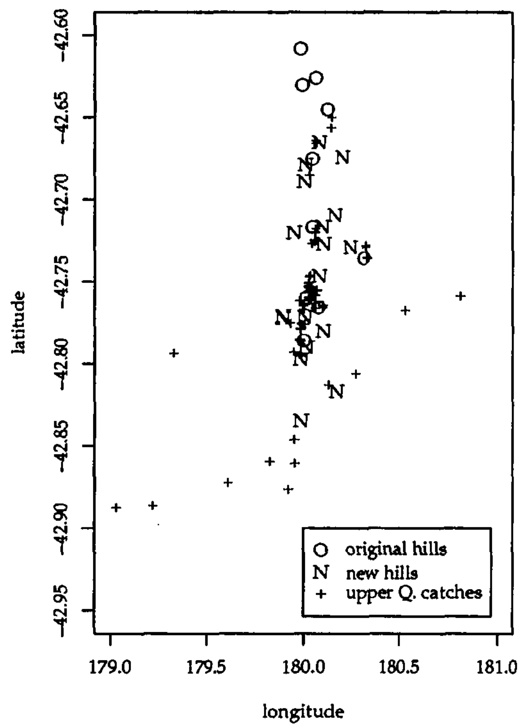


Fig. 6. The upper quartile catch rates are plotted in relation to previous known locations of hills and newly discovered hills to show that not all the high catch rates were obtained on the hills.

ber of trawls in each stratum. For all three strata, $L(t)$ was outside the envelope of the simulations (Figure 9) indicating that the deviation was significant. We inferred from this that the non-random distribution did not conform to a Poisson process.

Directional variograms were calculated for each of the three regions in Figure 9 but the semivariances did not exhibit a clear range, sill or nugget. A model for the underlying spatial process away from the hills remains unclear and may not be obtainable with existing data. A possible limitation is insufficiently fine grain (or resolution) of the trawl sampling, but volume of data is likely to be more important. There is likely to be less problem with the extent (or domain) of the data. Although the depth range for orange roughy in the New Zealand region is $409 - 1586$ $m$ [Anderson et al., 1998] the trawl sampling covered the depth range of the orange roughy around the NW Hills adequately (Figure 4). We did not find a suitable model to describe the non-random spatial process of orange roughy distributions away from the hills. Nevertheless data visualisation provided some useful insights.

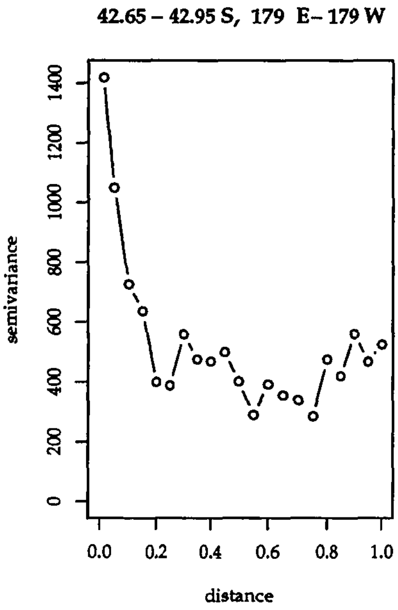


Fig. 7. An omnidirectional variogram based on catch rates on Northwest Hills for all *Cordella, Tangaroa* and *Ocean Ranger* voyages. Distance is in degree units.

## *3.5 Data visualisation of orange roughy and by-catch distributions away from the hills*

The spatial patterns of orange roughy biomass and the three main groups of by-catch species were quite different. The biomass of by-catch species groups, expressed as catch rates, were examined to determine whether there was any distance away from the NW Hills at which their distributions were relatively even, or whether their spatial distributions were patchy. It is evident from inspection of Figures 10-13 that distributions of both orange roughy and the by-catch species groups were patchy at all scales for which we have data. In addition the spatial pattern of each group was different. Orange roughy were clustered approximately symmetrically around the seamounts (Figure 10) in contrast to the other three groups. The distribution of swimbladder fishes overlapped most closely with that of orange roughy (Figure 11), but was more spread along the 900 – 1200 *m* contour interval. Non-swimbladder fish were most abundant shallower than 1000 *m* (Figure 12). Oreos were most abundant around the seamounts and to the north-east in water deeper than 1000 *m* (Figure 13).

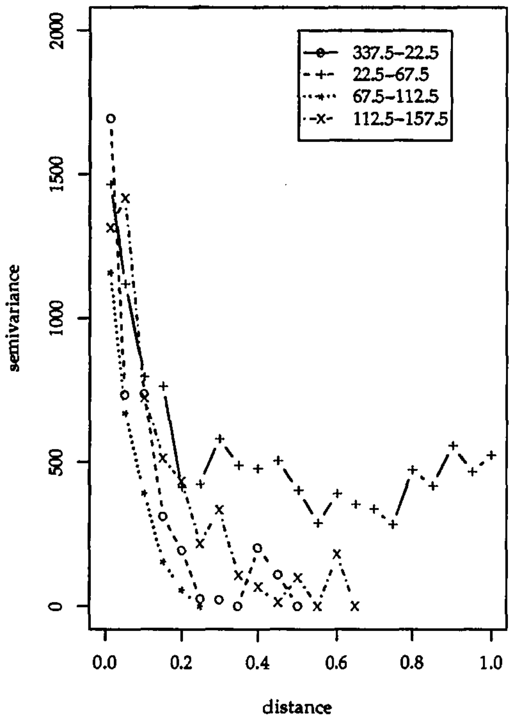


Fig. 8. Directional variograms based on catch rates on Northwest Hills for all *Cordella*, *Tangaroa* and *Ocean Ranger* voyages. Distance is in degree units. Directions are azimuthal angles (i.e. $0^o$ = north-south), and tolerances about the direction are $22.5^o$ for all plots.

## 4 Discussion

The analyses presented here show that densities of orange roughy in the spawning season are strongly associated with the seamount features of the NW Hills. Patches of roughy tend to be approximately symmetrically distributed up to 40 km to either side of the hills near the $180^o$ meridian in depths ranging from $800 - 1200$ *m*. Outside that range, there were few orange roughy. Among the by-catch groups, the oreos were also associated with the seamounts to a large degree, but were generally not abundant in the NW Hills area.

We did not expect the spatial separation of species groups that we found. Spatial separation of the by-catch groups is useful for acoustic target identification. It was fortuitous that the distributions of the most abundant swimbladder fish, the relatively uncommon oreos (which also have swimbladders) and non-swimbladder fish generally occur in separate regions of the survey area. These regions are broadly defined by depth. Swimbladder fish, excluding the oreos generally are more abundant between $900 - 1200$ *m*. Oreos occur close to the seamounts and in waters deeper

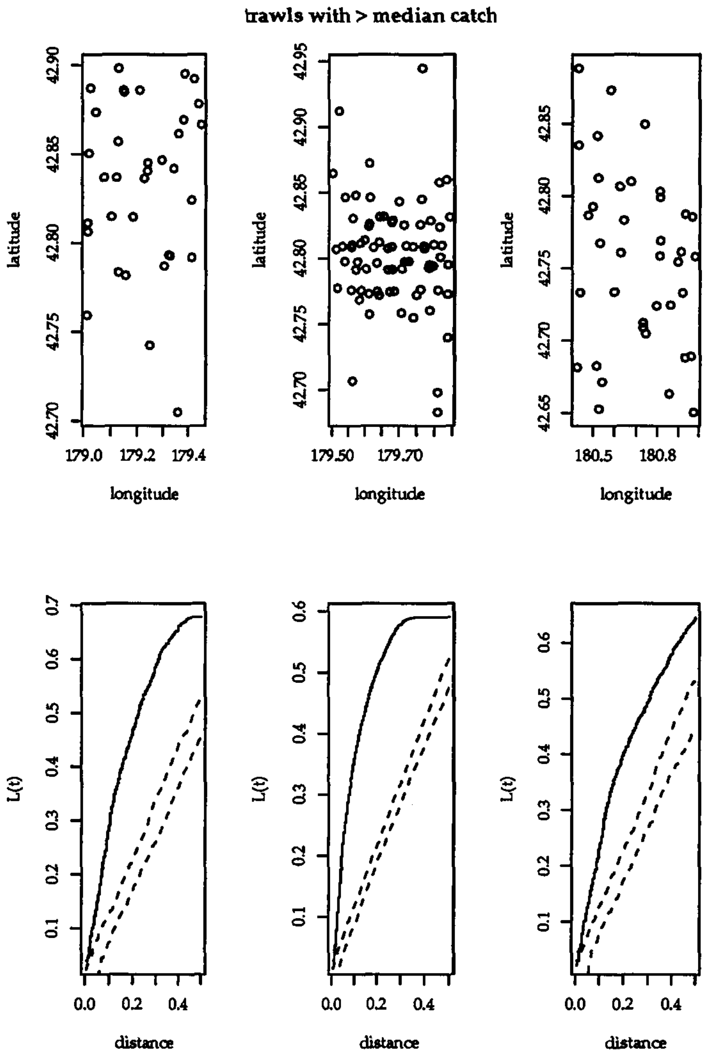


Fig. 9. Upper panel: Locations of trawl catch rates greater than the median catch rate in Figure 1 for the three strata defined in Figure 2. Lower panel: Solid lines show Ripley's $K$ (expressed as $L(t)$, see text) for each strata based on the the locations where > *median* catch rates were taken. Dotted lines show upper and lower bounds for a simulated Poisson point process.

than 1000 $m$ but were spatially segregated to the north-east. Elasmobranchs and squid are commonest in water shallower than 1000 $m$. This means that it should be easier to partition the acoustic backscatter with respect to by-catch. When this spatial separation is combined with new target identification techniques that can distinguish between orange roughy, swimbladder and non-swimbladder fishes based on their echo characteristics [Barr et al., 2000, Barr, 2001], it seems likely that it

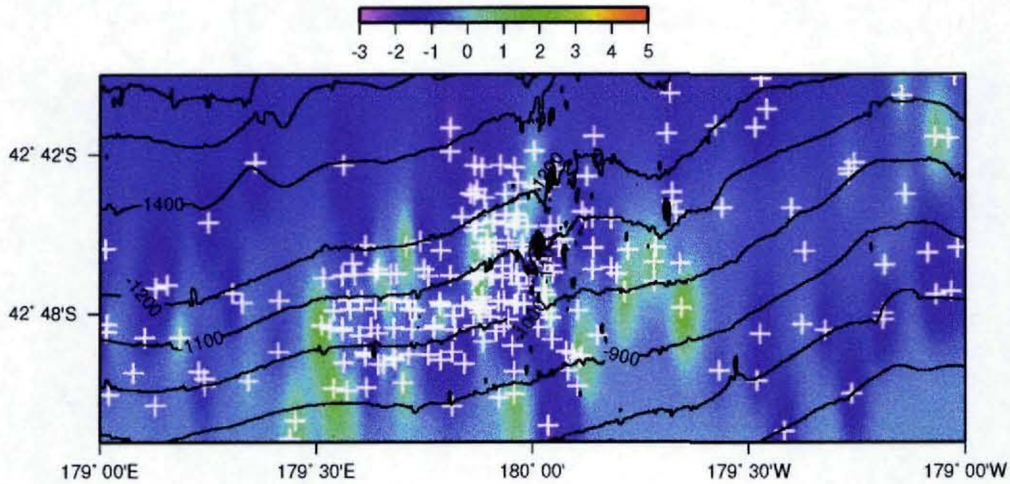


Fig. 10. A fitted surface of the spatial distribution after logit transformation of orange roughy catch rates around the NW Hills overlaid on the depth contours. The location of trawls providing the catch rate data are indicated by crosses.

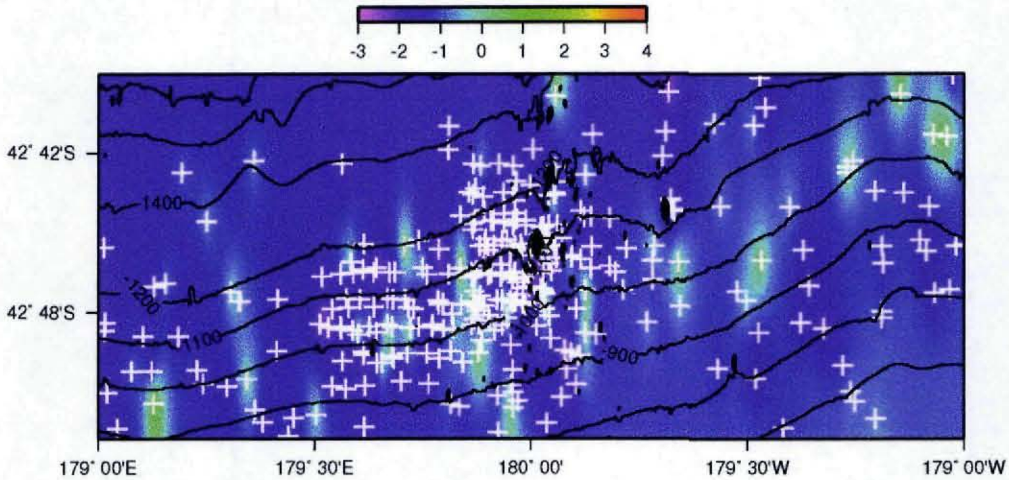


Fig. 11. A fitted surface of the spatial distribution after logit transformation of non-swimbladder fish catch rates around the NW Hills overlaid on the depth contours. Catch rates were summed for four-rayed rattails (*Coryphaenoides subserrulatus*), basketwork eels (*Diastobranchus capensis*), hoki (*Macruronus novaezelandiae*), big-scaled brown slickhead (*Alepocephalus* sp.), white rattail (*Trachyrhinchus longirostris*), Javelin fish (*Lepidorhynchus denticulatus*) and Johnson's cod (*Halargyreus johnsonii*). The location of trawls providing the catch rate data are indicated by crosses.

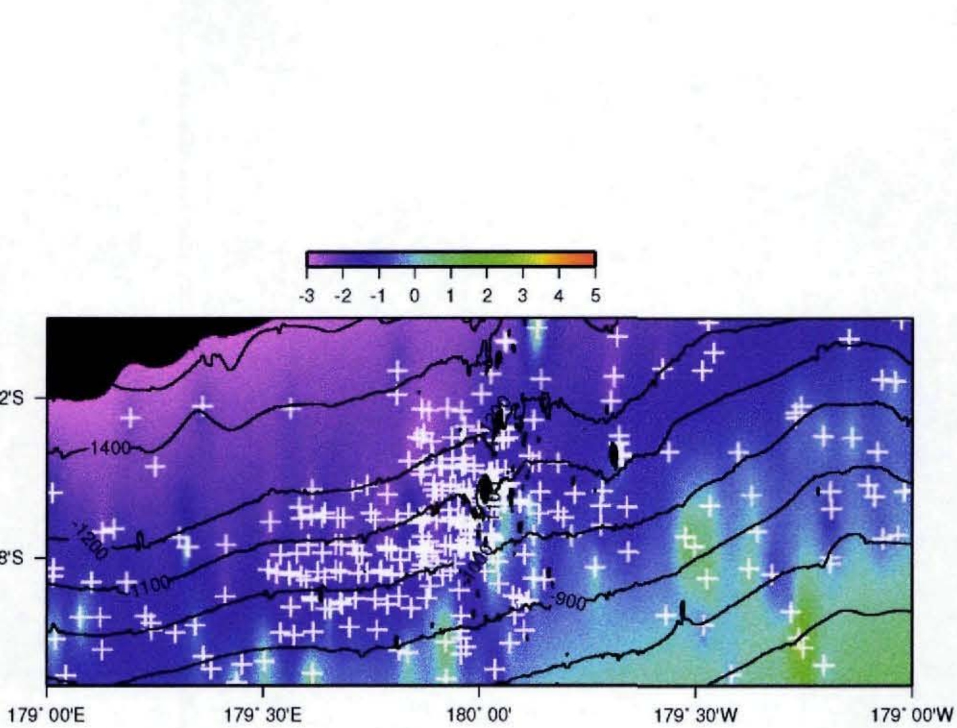


Fig. 12. A fitted surface of the spatial distribution after logit transformation of non-swimbladder fish catch rates around the NW Hills overlaid on the depth contours. Catch rates were summed for warty squid (*Moroteuthis* spp.), shovelnosed spiny dogfish (*Deania calcea*), Baxter's lantern dogfish (*Etmopterus baxteri*), smooth skin dogfish (*Centroscymnus owstoni*), *Centroscymnus crepidater* and widenosed chimaera (*Rhinochimaera pacifica*). The location of trawls providing the catch rate data are indicated by crosses.

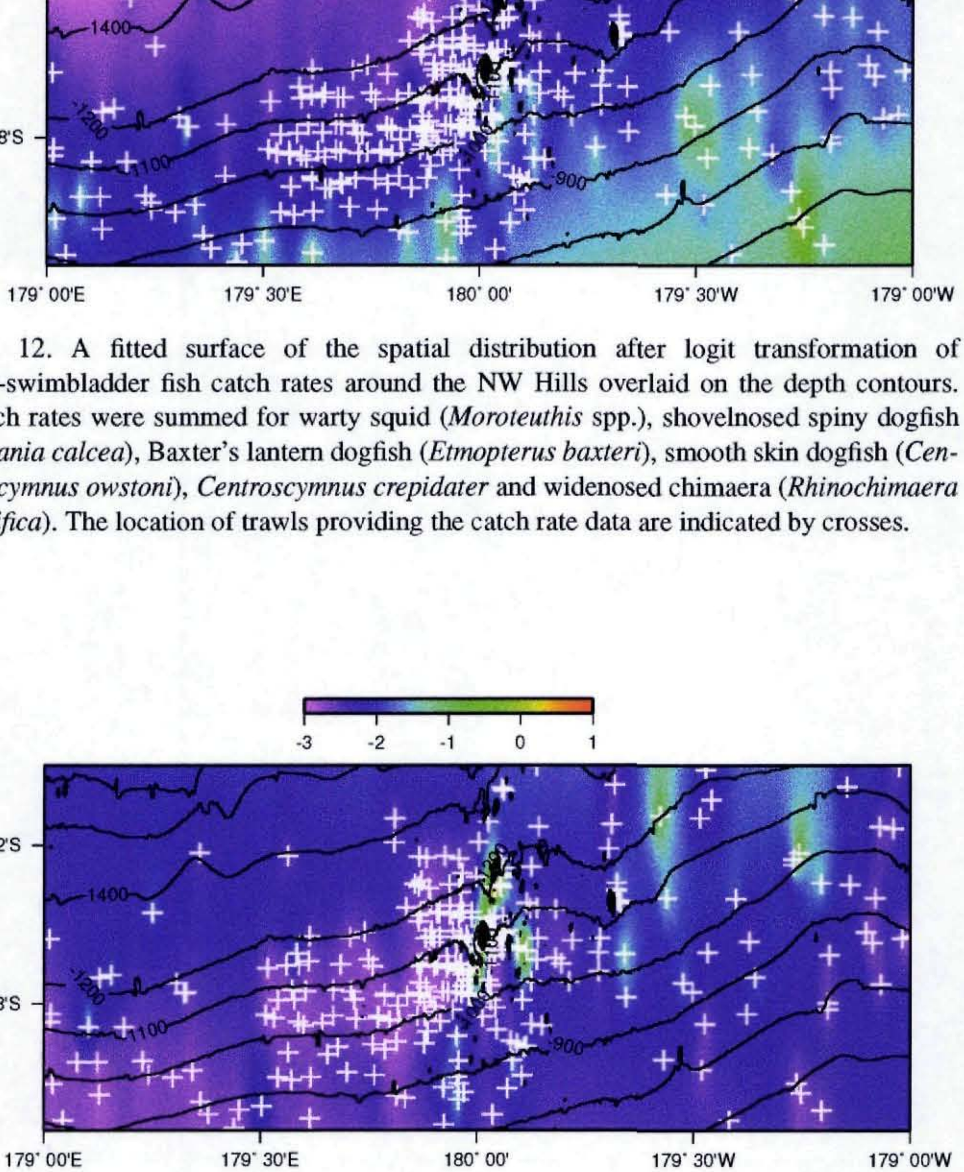


Fig. 13. A fitted surface of the spatial distribution after logit transformation of oreo catch rates around the NW Hills overlaid on the depth contours. Catch rates were summed for black oreos (*Allocyttus niger*) and smooth oreos (*Pseudocyttus maculatus*). The location of trawls providing the catch rate data are indicated by crosses.

will be possible to separate orange roughy from the species mix in the 'flat' areas away from the hills.

However, the analysis also shows that the spatial distribution of orange roughy on the 'flat' areas overlaps with the distribution of swimbladder fish by-catch. This is unfortunate from the acoustic survey perspective because the target strength of orange roughy is very much lower than that of swimbladder fish. Consequently, the acoustic backscatter from one swimbladder fish is equivalent to that from many orange roughy, and backscatter from orange roughy may be masked by backscatter from swimbladder fish [Kloser et al., 2000].

Both the distribution of orange roughy and those of the by-catch groups are non-random and highly patchy. When this is considered with the depth-dependent distributions of the by-catch groups, we conclude that it is necessary to continue to occupy many trawl stations during acoustic surveys in order to determine the appropriate by-catch ratios for partitioning the acoustic backscatter. While the depth-dependent distributions tend to simplify the problem of partitioning the backscatter by functional group (swimbladder, non-swimbladder, etc.), the patchiness effect works in the opposite sense. High patchiness means that a spatially explicit matrix of ratios for the functional groups will be necessary to accurately quantify the biomass of orange roughy over the 'flat' areas away from the hills.

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