Nursery grounds of the orange roughy around New Zealand

M. R. Dunn, G. J. Rickard, P. J. H. Sutton, and I. J. Doonan

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The orange roughy (*Hoplostethus atlanticus*) is a deep-sea species with a centenarian lifespan, a life-history feature that may enable the stocks to withstand prolonged periods of recruitment failure. Most stocks have been substantially depleted, however, so estimating recruitment has become a priority in setting catch quotas to ensure future sustainability of the fisheries. A description of the nursery grounds of the species off New Zealand is provided, using extensive research-survey data from 12 541 bottom trawls and 713 midwater trawls. The juveniles were initially caught on the seabed, near known spawning grounds, and towards the shallower end of the species' distribution, and not in midwater or the shallower or deeper bottom tows. Densities were greatest at 850-900 m. As juveniles grew, their spatial and depth distribution expanded, both shallower and deeper, with a skew towards deeper water, such that by the onset of maturation, densities were relatively high in 850–1300 m of water. The early nursery grounds were in relatively warm water, but on the south Chatham Rise, appeared to be bounded by the presence of a cold-water front.

Keywords: deep-sea, distribution, fisheries, juveniles, orange roughy, recruitment, sustainability.

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Introduction

Concerns have been raised about the vulnerability of deep-sea fish to exploitation (Devine *et al*., 2006, 2007; Morato *et al*., 2006; Sissenwine and Mace, 2007), although much of the detail of life history, including sometimes basic information such as distribution, is poorly known. The concerns are raised because (i) some species form large, predictable aggregations, making them vulnerable to the industrial-scale fishing prevalent in deep-sea fisheries, (ii) catch rates in commercial fisheries and the biomass estimates from research surveys have often declined rapidly following exploitation, and (iii) many species appear to be long-lived, probably associated with low productivity and low resilience to overfishing.

A particular advantage of longevity is a greater ability to withstand prolonged periods of recruitment failure, suggesting that this phenomenon might be natural for long-lived, deep-sea fish (Longhurst, 2002). The gaps between good recruitment episodes could last for many years, even decades. Commercial fishing increases the mortality rate and decreases longevity, reducing this natural resilience, as well, generally, as decreasing the stock size and increasing the importance of recent recruits to the fishery yield. Understanding recruitment is hence of particular importance to ensuring sustainable fishing of long-lived, deep-sea fish.

One of the most valuable of the deep-sea fisheries has been for orange roughy, *Hoplostethus atlanticus* (Branch, 2001; Sissenwine and Mace, 2007), which occur mainly at depths of 700–1500 m and are fished by bottom trawls. The New Zealand fishery for orange roughy was the first to develop in 1979 and was the only substantial one for several years. Others developed off Australia in the late 1980s, in the North Atlantic in 1989, off Namibia in 1995, off Chile in 1998, and in the Indian Ocean in 1999 (Francis and Clark, 2005, and references therein). The species is found worldwide, with the most recent new reports in the southwest Atlantic (Laptikhovsky, 2006; Wöhler and Scarlato, 2006).

The New Zealand fisheries started on the east Chatham Rise, off the east coast of the country's South Island (Figure 1). Soon after, other fisheries started on the Mid-East Coast, Challenger Plateau, and other areas of the Chatham Rise. Fisheries then developed all around New Zealand, although following a rapid decline in abundance, the Challenger Plateau fishery was effectively closed with the introduction of a catch limit of 1 t in October 2000, and the Cook Canyon fishery similarly closed in October 2007 (Anderson and Dunn, 2008). The various fisheries to the east of New Zealand remain open.

There are two main reasons for the lack of detailed knowledge of recruitment variability of the species. First, age determination with sufficient precision to determine year-class strength has proved to be extremely difficult (Andrews *et al*., 2009). Alternative approaches, such as the analysis of length modes, are not viable for orange roughy because after the first few years of life, the length distributions of adjacent cohorts largely overlap so cannot be separated (Bull *et al*., 2001). Second, the nursery grounds for orange roughy have not been identified, so a time-series of prerecruit surveys has never taken place. In fact, knowledge of nursery grounds seems to be poor for most deep-water fish.

It has been suggested that a scarcity of small juvenile orange roughy, those in their first few years of life (roughly <10 cm standard length, SL), is a "worldwide characteristic of orange-roughy fisheries" (Payá *et al*., 2006). The catchability of small juveniles is unknown, but they may escape readily through commercial trawlnets, which usually have meshes of around 100 mm. Small

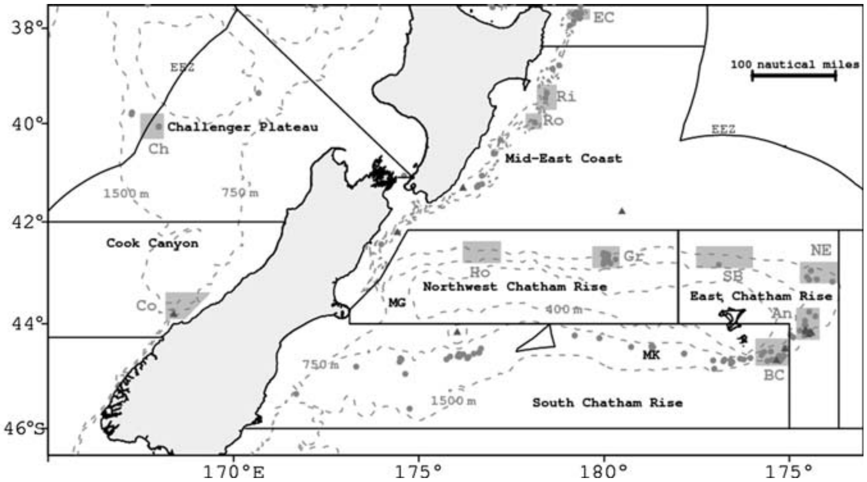

Figure 1. The study area, with the stock boundaries shown as solid lines. The locations of known spawning areas are shown shaded, and are labelled: Ri, Ritchie Bank; Ro, Rockgarden; Ho, the Hole; Gr, Graveyard complex; SB, Spawning Box; NE, Northeast Hills; An, Andes complex and neighbours; BC, Big Chief and neighbours; Ch, Challenger Plateau; Co, Cook Canyon; EC, East Cape hills. Other labels are: MG, Mernoo Gap; MK, Mt. Kiso; triangles, knolls and seamounts (>500 m elevation); dots, hills (<500 m elevation); EEZ, Exclusive Economic Zone boundary. Only the seamounts, hills, and knolls with a summit depth of <1500 m are shown.

juveniles were targeted and caught in fine-mesh, bottom-trawl surveys in New Zealand in the late 1980s, but the densities found were lower than expected from the abundance of the adults (Mace *et al*., 1990; Zeldis *et al*., 1994). As a result, the surveys were abandoned as a prerecruit series in the early 1990s. Larger juveniles (>10 cm SL) have been caught regularly; ~80% of deep-water, research-trawl tows off New Zealand that caught orange roughy produced immature fish (O'Driscoll *et al*., 2003). Although large juveniles can be relatively common in research trawls, their distribution has never been studied in detail, except to note that their overall distribution was similar to that of the adults (O'Driscoll *et al*., 2003).

Some studies have inferred the nursery grounds of orange roughy indirectly using otolith chemistry. Thresher and Proctor (2007) found a peak in strontium (Sr) in otoliths that would have occurred during the first year of life (age 0+). Campana (1999) hypothesized that Sr/calcium ratios would vary with metabolic rate, temperature, and somatic growth rate, such that an increase in Sr would correspond to a low metabolic rate. Thresher and Proctor (2007) therefore hypothesized that the peak in Sr might indicate that early juvenile (age 0+) orange roughy were in a relatively low temperature or unproductive environment, such as deeper water, before migrating into shallower nursery areas. Shephard *et al*. (2007) measured otolith stable isotope ($\delta^{18}O$ and $\delta^{13}C$) composition and reached an alternative hypothesis: that post-larval and early juvenile orange roughy were living in relatively warm water and had a relatively high metabolic rate. The youngest ages sampled were an average of the first 1–2 or 1–3 years of life (ages 0+ to 2+), except for a single case where the sample was of just the first otolith zone (age 0+). In almost all cases, including the single sample from age 0+, the results indicated that the fish had spent their early years in a relatively warm environment. From water-temperature profiles at the sampling sites, Shephard *et al*. (2007) concluded that the depth inhabited by early juveniles was 700–800 m, so hypothesized that orange roughy occupied a mesopelagic niche for up to their first five years. Their analyses indicated that subsequently, between the ages of 5 and 14 years, the fish lived on the seabed in relatively cold water, at an inferred depth of 1200–1400 m.

Possible hypotheses for why early juvenile orange roughy are rarely taken in bottom trawls might therefore include that (i) they live primarily in deeper water, and (ii) they are primarily mesopelagic. Another hypothesis could be that (iii) good recruitment is intermittent, so no surveys have yet encountered a large year class as juveniles. Here, we investigate these hypotheses using the substantial, research-trawl dataset available for New Zealand waters to describe, with direct observations, the spatial occurrence, and density of immature orange roughy, including large-scale, ontogenetic shifts in distribution. We focus on the stocks found in central New Zealand waters, which have supported the largest and most persistent fisheries for the species anywhere in the world.

Material and methods

Unless cited otherwise, in this section, the Ministry of Fisheries Science Group (2008) was the source of the fishery information, and Heath (1985) that of the physical oceanography.

Study area

The South Pacific subtropical convergence, where warmer, more-saline subtropical water from the north meets Subantarctic water from the south, dips south around New Zealand from ~45°S on the west coast of the South Island (Figure 1), up the east coast, then eastwards along the Chatham Rise. There is an area of enhanced mixing at the western end of the Chatham Rise, where the Subantarctic water extends, to a variable extent, into Mernoo Gap. The bottom temperatures recorded during trawl surveys at the depths where orange roughy are found are typically around 4–7°C, with a seasonal variability of <1°C (Sutton and Roemmich, 2001). Pacific Deep Water is found at depths of 2000–4000 m and typically has a temperature of 1–2°C, with no seasonal variation. Because of the subtropical convergence and the bathymetry, the Chatham Rise is relatively productive, with

Table 1. Summary of the bottom-trawl dataset used here, showing for each year the minimum and maximum depth fished, and the number of tows by mean bottom depth and by month.

Year	Mean depth (m) Min	Max	Number of tows by mean depth (m) 200–400	400–700	700–1 200	>1 200	Number of tows by month January–March	April–June	July–September	October–December	Total number of tows
1978	233	378	13	0	0	0	0	0	3	10	13
1979	169	1 075	119	177	59	0	62	48	158	87	355
1980	165	910	64	7	1	0	27	19	17	9	72
1981	167	1 220	31	32	74	0	41	21	49	26	137
1982	163	1 160	22	17	149	0	23	19	128	18	188
1983	187	1 230	6	4	136	2	15	1	51	81	148
1984	192	1 230	47	7	251	6	32	62	151	66	311
1985	194	1 418	32	31	293	5	15	50	221	75	361
1986	235	1 285	20	93	490	6	35	126	257	191	609
1987	586	1 270	0	18	736	15	8	218	332	211	769
1988	320	1 335	1	17	515	5	22	29	442	45	538
1989	210	1 538	33	108	763	48	52	49	521	330	952
1990	201	1 535	42	50	812	114	26	139	468	385	1 018
1991	202	1 477	13	80	168	13	32	33	0	209	274
1992	152	2 002	79	148	616	120	396	184	206	177	963
1993	192	1 517	133	152	395	51	381	150	10	190	731
1994	170	1 527	147	131	509	70	373	317	167	0	857
1995	195	1 465	114	141	543	17	219	108	266	222	815
1996	110	1 280	86	55	97	6	97	74	63	10	244
1997	199	1 250	64	79	87	1	121	35	8	67	231
1998	202	1 278	46	84	194	1	119	0	113	93	325
1999	208	1 430	74	105	97	5	135	68	44	34	281
2000	194	1 283	106	219	113	0	147	20	200	71	438
2001	106	1 300	44	82	194	3	122	28	33	140	323
2002	210	1 451	50	93	221	11	123	35	190	27	375
2003	202	1 257	66	76	34	1	113	44	0	20	177
2004	207	1 299	41	69	121	7	100	0	120	18	238
2005	201	1 364	51	76	259	11	105	115	64	113	397
2006	216	1 365	30	70	103	1	85	53	23	43	204
2007	206	1 610	51	52	84	10	94	19	84	0	197
Total			1 625	2 273	8 114	529	3 120	2 064	4 389	2 968	12 541

greater species diversity and richness than the Subantarctic, species richness being greatest between 500 and 1000 m, and higher on the warmer northern flank than on the south (McClatchie *et al.*, 1997).

The division of the fisheries for orange roughy off New Zealand into management stocks has been largely based on the locations of spawning grounds, patterns in the fisheries, and genetic studies. The largest fisheries are on the northern and eastern flanks of the Chatham Rise, the largest spawning aggregations in the so-called Spawning Box, and the next largest in the Graveyard Complex. Genetic differences indicate that the orange roughy on the Chatham Rise are distinct from those on the Mid-East Coast (Smith and Benson, 1997). The East Cape stock is found just to the north of the Mid-East Coast and is treated as a separate stock because there is simultaneous spawning in both areas. There are several differences between the orange roughy on the east and west coasts of New Zealand (Horn *et al.*, 1998; Thresher and Proctor, 2007). Like the Mid-East Coast and East Cape stocks, the stocks on the west coast are north of the subtropical convergence and bathed in relatively warm subtropical water.

Trawl-survey dataset

Research-trawl data were selected from the New Zealand Ministry of Fisheries trawl database, where the average bottom depth at the location was >200 m, the gear used was any form of bottom or midwater trawl, gear performance was rated as at least satisfactory, the latitude was between 37 and 49°S, and the longitude between 165°E and 173°W. The resulting dataset consisted of 294 voyages, with 12 541 bottom trawls (Table 1) and 713 midwater trawls (Table 2), made by 31 vessels. Of these, 101 surveys were directed at orange roughy and 21 at oreos (Oreosomatidae) using bottom trawling, so were predominantly at depths of 700–1300 m. For each tow, the details of the fishing method, location, timing, duration, and environmental conditions were recorded. During each survey, the catches per tow were sorted by species, and up to 40 orange roughy sampled randomly for SL, weight, sex, and gonad stage, then either the whole catch or 200 more orange roughy randomly sampled for sex and SL.

Four selections from the dataset were used for analysis. The first included only midwater research trawls. Between 1979 and 2007, 60 surveys were made by 12 vessels (Table 2). Tows from commercial vessels that used midwater trawls to target hoki (*Macruronus novaezelandiae*) near the seabed were excluded. Most of the research tows were made using midwater trawls fitted with a codend of 40–100-mm mesh during hoki (479 tows) or orange roughy (90 tows) surveys (O'Driscoll, 2002). A fine-mesh midwater trawl, with a headline of ~18 m, door spread of ~75 m, and a codend mesh of 10–12 mm, was deployed in 140 tows to sample mesopelagic layers. In all, 210 tows were made over the

Table 2. Summary of the midwater-trawl dataset, showing for each year the minimum and maximum mean depth the gear was fished, the number of tows by the depth the gear was fished, and the number of tows by the bottom depth where the gear was fished and by month.

	Mean tow depth (m)		Number of tows by mean tow depth (m)			Number of tows by mean bottom depth (m)				Number of tows by month				
Year	Min	Max	<400	400–700	700–1 200	200–400	400–700	700–1 200	>1 200	January–March	April–June	July–September	October–December	Total number of tows
1979	277	734	2	8	1	2	8	1	0	3	0	8	0	11
1981	448	448	0	1	0	0	1	0	0	1	0	0	0	1
1983	25	556.5	32	9	0	8	33	0	0	0	0	41	0	41
1985	350	842.5	2	2	6	2	1	7	0	0	0	6	4	10
1986	12.5	1 146	30	1	5	8	9	17	2	0	0	36	0	36
1987	190	822.5	24	5	7	17	11	8	0	0	0	33	3	36
1988	200	808	22	24	4	9	33	8	0	0	6	44	0	50
1989	200	500	28	16	0	13	30	1	0	0	0	44	0	44
1990	35	675	23	14	0	6	17	14	0	0	0	37	0	37
1992	31.5	651.5	41	6	0	0	19	18	10	47	0	0	0	47
1993	233.5	233.5	1	0	0	1	0	0	0	0	0	1	0	1
1995	137.5	924	6	0	27	4	2	27	0	0	6	27	0	33
1996	96	1 000.5	29	18	8	18	24	13	0	42	0	13	0	55
1997	203.5	1 124	33	12	5	15	24	11	0	0	4	45	1	50
1998	182.5	804	14	1	2	11	4	2	0	0	0	17	0	17
1999	171.5	591	18	9	0	8	19	0	0	10	0	17	0	27
2000	252.5	761.5	7	12	2	6	13	2	0	0	0	20	1	21
2001	82.5	540	39	9	0	23	19	6	0	12	0	36	0	48
2002	150.5	513	15	3	0	9	5	4	0	0	0	18	0	18
2003	196.5	625	23	5	0	15	9	4	0	1	0	27	0	28
2004	76	827.5	1	0	1	1	0	1	0	0	0	1	1	2
2005	10	1 071.5	26	7	16	12	17	20	0	11	14	21	3	49
2006	38.5	851.5	11	7	2	3	11	6	0	5	1	13	1	20
2007	131	855.5	12	15	4	0	3	28	0	19	0	12	0	31
Total	–	–	439	184	90	191	312	198	12	151	31	517	14	713

depths known to be frequented by orange roughy demersally, but all midwater tows were included in the analysis to allow all possible midwater locations for juveniles to be investigated (Table 3).

The second set included only tows using a "rough-bottom orange roughy" bottom trawl, towed by RV "Tangaroa". The trawl was a six-panel, rough-bottom trawl with cutaway lower wings, an estimated wing spread of 25 m, a headline height of 5–6 m, a mesh size of 300 mm tapering down to the codend, which was 100-mm mesh, and as groundgear a 600-mm steel and rubber bobbin rig. The net was towed on flat and rough ground, the latter including hills, at ~3 knots, typically for between 30 min and 1 h on the flat and for shorter periods on hills. Between 1991 and 2001, the net was used during 20 surveys, for a total of 2500 tows, including tows in random-stratified, trawl, biomass surveys, and during other research (primarily acoustic studies). The area fished included the west coast of South Island, Chatham Rise (Anderson and Fenaughty, 1996; Tracey and Fenaughty, 1997; Tracey *et al.*, 1997), and the Mid-East Coast (Grimes, 1996).

The third set included only tows using a "prawn" trawl, again towed by RV "Tangaroa". This was a full-wing trawl, with an estimated wing spread of 18 m, a headline height of ~4 m, a mesh size of 80 mm tapering down to the codend, which was 25-mm mesh, and a groundrope fitted with 100-mm rubber disks. The net was towed only on flat ground at ~3 knots, for between 30 min and 1 h. The net was a refinement of that used for early juvenile surveys of orange roughy (Mace *et al.*, 1990). In 1989, the net was used during nine surveys, for a total of 182 tows, to determine the distribution of small, juvenile orange roughy (<10 cm SL): three surveys on Challenger Plateau; two on the Mid-East Coast; and four on the northeast Chatham Rise.

Table 3. The number of midwater tows fished by mean tow depth and mean bottom depth, with the minimum and maximum mean depth the gear was fished.

	Mean tow depth (m)		Number of tows by mean depth (m)			
Bottom depth (m)	Min	Max	<400	400–700	700–950	950–1 200
<400	22	420	191	–	–	–
400–700	10	698	179	133	–	–
700–950	20	924	41	44	69	–
950–1 200	26	1 124	19	6	4	15
>1 200	31	1 146	9	1	–	2

The fourth set of data included all bottom trawls from all surveys (Table 1). This data selection included a variety of bottom trawls fished in several ways. The focus of research surveys for orange roughy and oreos switched from trawl to acoustic methods in the mid-1990s (Clark, 1996), so most of the trawl surveys targeting those species took place before 1995. Trawl surveys included in this dataset, additional to those already described, include five surveys on the north and south Chatham Rise between 2004 and 2007 (346 tows), which were part of combined trawl and acoustic surveys for orange roughy, using a full-wing trawl similar to the "prawn" trawl, with a codend of 40-mm mesh (Doonan *et al.*, 2006); seven trawl surveys on Challenger Plateau between 1984 and 1990 (659 tows), and seven surveys on the Chatham Rise between 1984 and 1990 (1202 tows), all targeting orange roughy using nets similar to the "rough-bottom, orange roughy" trawl, with a codend of 100-mm mesh (Clark and Tracey, 1994; Anderson and Fenaughty, 1996); and 16 trawl surveys for mid-depth (400–700 m) species on the Chatham Rise between 1992 and 2007 (1983 tows), using a full-wing trawl with a codend of 60-mm mesh (Stevens and O'Driscoll, 2007).

Tows were classified as hill tows if the distance between the midpoint of the tow and the position of the summit of the nearest known hill was <1.5 nautical miles. The list of known hills included 840 seamounts, hills, knolls, and pinnacles (M. R. Clark, NIWA, pers. comm.). The depth associated with each tow was the average of the depth at the start and end positions. The density (number km^{-2}) of orange roughy was estimated for the prawn and rough-bottom trawls as the number of fish caught divided by the swept-area, which was calculated as the tow distance multiplied by the wing spread. The wing spread was assumed to be a constant 18 m for the prawn trawl and 25 m for the rough-bottom trawl. Plots of the occurrence of orange roughy in trawl catches were not standardized in any way, because of the wide variety of trawls, vessels, and survey objectives employed. When plotting both occurrence and density, tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 miles longitude by 9 miles latitude.

All length measurements of orange roughy were in SL, rounded to the nearest centimetre below. Catches were examined by length class, grouped into <5, 5–9, 10–15, 16–21, 22–27, and 28+ cm. The <5-cm length class was roughly equivalent to fish in the first year of life (age 0+), and the 5–9-cm length class to the following 3 years (ages 1+ to 3+), with age 4+ fish usually >10 cm (Mace *et al*., 1990). Length classes 10–15, 16–21, and 22–27 cm included immature fish of roughly 4–20 years of age. The final length class included maturing and mature fish. The length at which 5% of the stock was estimated to be mature was roughly 25 cm for Challenger Plateau, 28 cm for the Chatham Rise, and 30 cm for the Mid-East Coast (Ministry of Fisheries Science Group, 2008).

Environmental data

There is little information in the literature on the environment, including water currents and temperatures, encountered at the depths frequented by orange roughy around New Zealand. The environmental analyses were restricted to the Chatham Rise area, because most of the fish samples were obtained there.

Observational temperatures were obtained from the World Ocean Atlas (WOA) climatology (Locarnini *et al*., 2006), analysed onto a series of depths at a horizontal resolution of 1°, and used to plot the horizontal temperature at 1000-m depth. This provides a long-term temperature mean. A vertical section of temperature at 178°30′E was also measured from RV "Tangaroa" in October 2000.

New measurements of the mid-depth ocean off New Zealand have become available since about 2002 from the international Argo programme, which has the aim of deploying 3000 profiling floats in all the world's oceans. These floats typically "park" at depths of ~1000 m, before sinking down to around 2000 m, then profiling to the surface every 10 d (see http://www.argo.ucsd.edu/). The available information includes temperature and salinity profiles between the surface and 2000 m and estimates of the currents at the parking depth from the changing positions of each profile. Temperatures were extracted from the profiles, and new estimates of the velocity at 900 m were made by averaging all the Argo trajectory velocities in 0.5° latitude and longitude bins. This provided an average over the entire span of the Argo programme in New Zealand waters, with the first floats being deployed around 2000, significant coverage achieved in late 2002, and full coverage since 2007. The temperature and current patterns appear to have been stable over this period, so this multiyear average is taken to be representative of the ocean conditions in our area of interest.

To supplement the Argo float data, estimates of the annual mean current-velocity vectors at a depth of 990 m were obtained from a climatological ocean model (Rickard *et al*., 2005). The version analysed here, the "R 25", has a horizontal resolution of 1/12° latitude and longitude and is described by Chiswell and Rickard (2006), is validated against observed surface-drifter data. Relative to the float data, these data provide high spatial resolution and a temporal average, but have not been validated at depth. Therefore, the model output complements the float data, because the latter are used to confirm the general patterns estimated from the model, and the former to provide detailed spatial resolution.

Results

Occurrence in bottom trawls

Orange roughy of all length groups were caught on both hill and flat areas (Table 4). The depth range occupied was narrower on the hill than on flat areas. Orange roughy <10 cm SL were rarely caught with the rough-bottom trawl in any area. Density estimates for the hill and flat areas may not be comparable because the catchability of the net was probably different when being towed down the sides of hills, always from top to bottom, with generally rough ground such as rocky areas, pinnacles, and ledges, compared with being towed on the smooth, soft sediment of the flat regions. Nevertheless, orange roughy of 10–21 cm SL were caught in greater densities in flat tows, and those of 27+ cm in greater densities on the hills. Fish of SL 22–27 cm were taken in similar densities on the hills and the flat.

Orange roughy from the Chatham Rise, Challenger Plateau and Cook Canyon, and Mid-East Coast were more frequently caught as they grew (Table 5). The overall depth range over which they were encountered was greatest for the Chatham Rise (936 m), then the Mid-East Coast (889 m), then Challenger Plateau and Cook Canyon (484 m). For all three areas, however, no orange roughy were caught in tows <560 m or deeper than 1497 m.

Fish in the second length class (5–9 cm SL) were caught over the narrowest depth range (Tables 4 and 5). The limits of the depth range then extended into both shallower and deeper water with increasing length, and the depth limits of their occurrence were widest for fish 22 cm SL and longer. This pattern was consistent across all three areas and was also seen in both hill and flat tows. Orange roughy of <5 cm SL were taken over a relatively wider depth range than those of 5–9 cm SL, but a narrower range than those of 22 cm SL and longer.

The smallest orange roughy taken (<5 cm SL) were relatively infrequent and were found near the known spawning grounds of Challenger Plateau, Cook Canyon, and east of the Spawning Box, extending to the south of Northeast Hills, with two occurrences at the northern edge of the Andes (Figure 2). Orange roughy of 5–9 cm were more frequent in catches, and their distribution was largely an expansion from the areas occupied by <5 cm SL fish.

Table 4. The limit of depth occurrence of orange roughy in bottom-trawl catches by trawl type, tow type, and fish length class.

			Orange roughy length class (SL, cm)						
Gear	**Terrain**	**Parameter**	**<5**	**5–9**	**10–15**	**16–21**	**22–27**	**>27**	**All tows**
All trawls	Hill	No. tows	3	3	49	194	653	896	1 003
		Min. depth	860	860	754	709	689	689	586
		Max. depth	1 098	1 145	1 266	1 287	1 410	1 410	1 525
	Flat	No. tows	167	279	1 264	3 023	5 111	5 899	11 531
		Min. depth	692	692	639	608	560	560	201
		Max. depth	1 226	1 213	1 407	1 490	1 496	1 497	2 001
Rough- bottom trawl	Hill	No. tows	2	0	10	49	158	248	273
		Min. depth	950	–	853	767	739	739	739
		Max. depth	1 098	–	1 113	1 234	1 299	1 299	1 299
		Density	0.28	0	1.7	28.4	145.6	3 191.7	3 367.6
	Flat	No. tows	6	8	206	822	1 351	1 621	2 105
		Min. depth	820	819	645	608	560	560	560
		Max. depth	1 126	994	1 407	1 481	1 496	1 497	1 518
		Density	0.06	0.05	3.6	56.9	134.5	472.4	667.6

Density is the total number of fish divided by the total swept-area from the rough-bottom trawl outside the spawning season (July). Depths given are the mean depth of the tow. "No. tows" depicts the number of tows out of the total ("All tows") where orange roughy of that size class were caught. "All tows" includes all trawl tows in the dataset, i.e. whether or not orange roughy were caught.

Table 5. The occurrence of orange roughy by area, depth, and fish-length class (SL).

		Orange roughy length class (SL, cm)						
Area	**Parameter**	**<5**	**5–9**	**10–15**	**16–21**	**22–27**	**>27**	**All tows**
Chatham Rise	Min. depth	692	692	656	631	560	560	201
	Max. depth	1 226	1 145	1 407	1 484	1 496	1 484	2 001
	No. tows	150	216	850	1 977	3 609	4 240	8 114
West Coast and Challenger	Min. depth	820	814	813	801	784	722	202
	Max. depth	1 198	1 121	1 121	1 198	1 198	1 206	1 267
	No. tows	15	36	87	275	808	848	1 473
Mid-East Coast	Min. depth	–	703	639	608	608	615	201
	Max. depth	–	1 213	1 351	1 490	1 481	1 497	1 502
	No. tows	0	14	292	806	1 099	1 431	1 889

"All tows" includes all trawl tows in the dataset, i.e. whether or not orange roughy were caught.

The spatial distribution of subsequent length classes generally showed continuing spatial expansion. This was most noticeable for the east and south Chatham Rise, where the limits of occurrence increased first in the south around the end of the Rise, then west along the south Rise, with fish 22–27 and >27 cm SL having a similar and most extensive, spatial distribution. On Challenger Plateau, the distribution increased primarily to the northwest of the spawning grounds. On the east coast of the North Island, there was little change in distribution after 10–15 cm SL, other than a small increase in the overall area covered.

The occurrence of orange roughy of all length classes on the north Challenger Plateau is interesting, because there are no known spawning aggregations or commercial fisheries for the species there. The presence of large and small orange roughy there suggests that the records for juveniles are probably not an artefact caused by misidentification of common roughy (*Paratrachichthys trailli*) or silver roughy (*Hoplostethus mediterraneus*) as orange roughy.

Density on flat areas

There was a general increase in the density of orange roughy with increasing fish length (Figure 3). Orange roughy <5 cm SL were taken at consistently greatest densities at depths of 850–900 m, but with occasional high densities between depths of 800 and 950 m, whereas those of SL 5–9 cm had a similar overall distribution, but with high densities more frequent at depths down to 975 m. The depth range of high densities then continued to increase with increasing fish length, skewing towards the deeper end of the range (>900 m), such that at 22–27 and >27 cm SL, there was a general trend of increasing density with increasing depth, up to the depth limit of the sampling at 1075 m.

Orange roughy <16 cm SL were not caught in high densities by the rough-bottom trawl (Figure 4). The density estimates from those tows confirm a peak in density at ~900 m at a fish length of 16–21 cm SL (Figure 4). At both 22–27 and >27 cm SL, the greatest densities were at 900 m, indicating a continuing spread towards greater depth with increasing length, with the relatively high-density areas extending down to ~1300 and 1450 m, respectively.

Densities of juveniles 16–21 cm SL were higher in patches from the south of the Northeast Hills around the east Chatham Rise onto the south Chatham Rise, to the east of the Graveyard, in the south of the Mid-East Coast area, in the south of the East Cape area, and near Cook Canyon (Figure 5). There were noticeable gaps between these higher density areas between the Graveyard and the Spawning Box, between the area to the west of the Graveyard and the east coast of the South Island, and between the southern parts of the Mid-East Coast and East Cape, i.e. the area around Ritchie Bank. The higher density areas for juveniles of 22–27 cm SL extended into these gaps and were

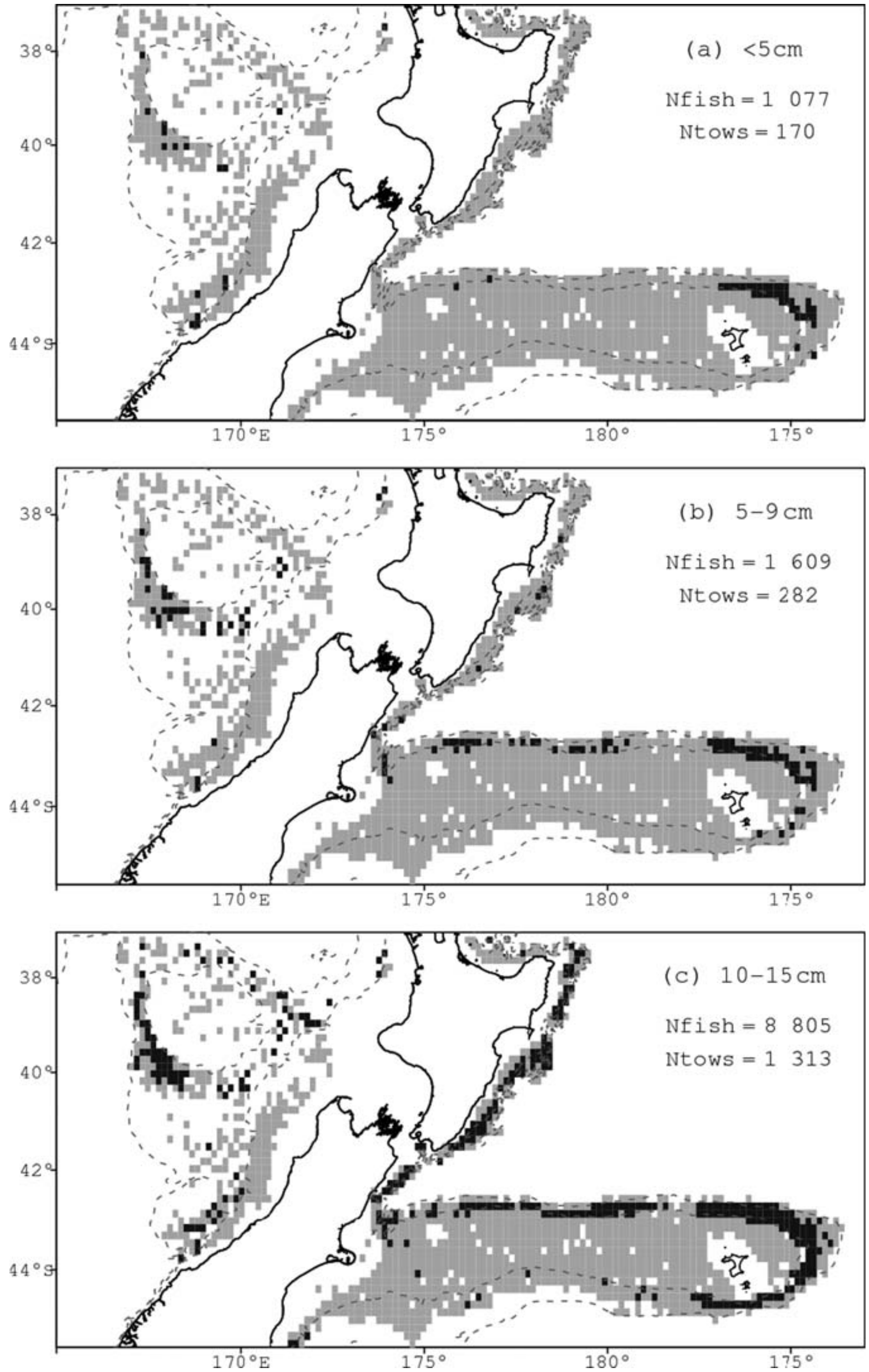

Figure 2. Occurrence of orange roughy in bottom trawls by length class. Grey-shaded areas were sampled, and black-shaded areas show where orange roughy were caught. The broken lines indicate the 750- and 1500-m isobaths. Nfish, number of orange roughy caught; Ntows, number of tows in which orange roughy were caught (out of the total of 12 541 tows) (*Continued*).

more homogenous overall. This was especially noticeable around the eastern part of the Chatham Rise. Although juveniles of 22–27 cm SL were found along much of the south Chatham Rise (Figure 5c), they were at relatively low density west of ~179°W.

Occurrence in midwater

Orange roughy were caught in 36 of the 713 midwater trawls. All but one of these catches were associated with spawning plumes during July on flat areas of the Spawning Box and Challenger Plateau (Figure 6). In all 36 midwater tows, no orange roughy were measured that were <22 cm SL, and only 2% of those measured were <28 cm SL.

In all, 73 tows were completed at depths of 700–950 m where the water depth exceeded 700 m, and of these, 11 used codends of very fine mesh. Although no small (<28 cm SL) orange roughy were caught in any of these tows, more than 100

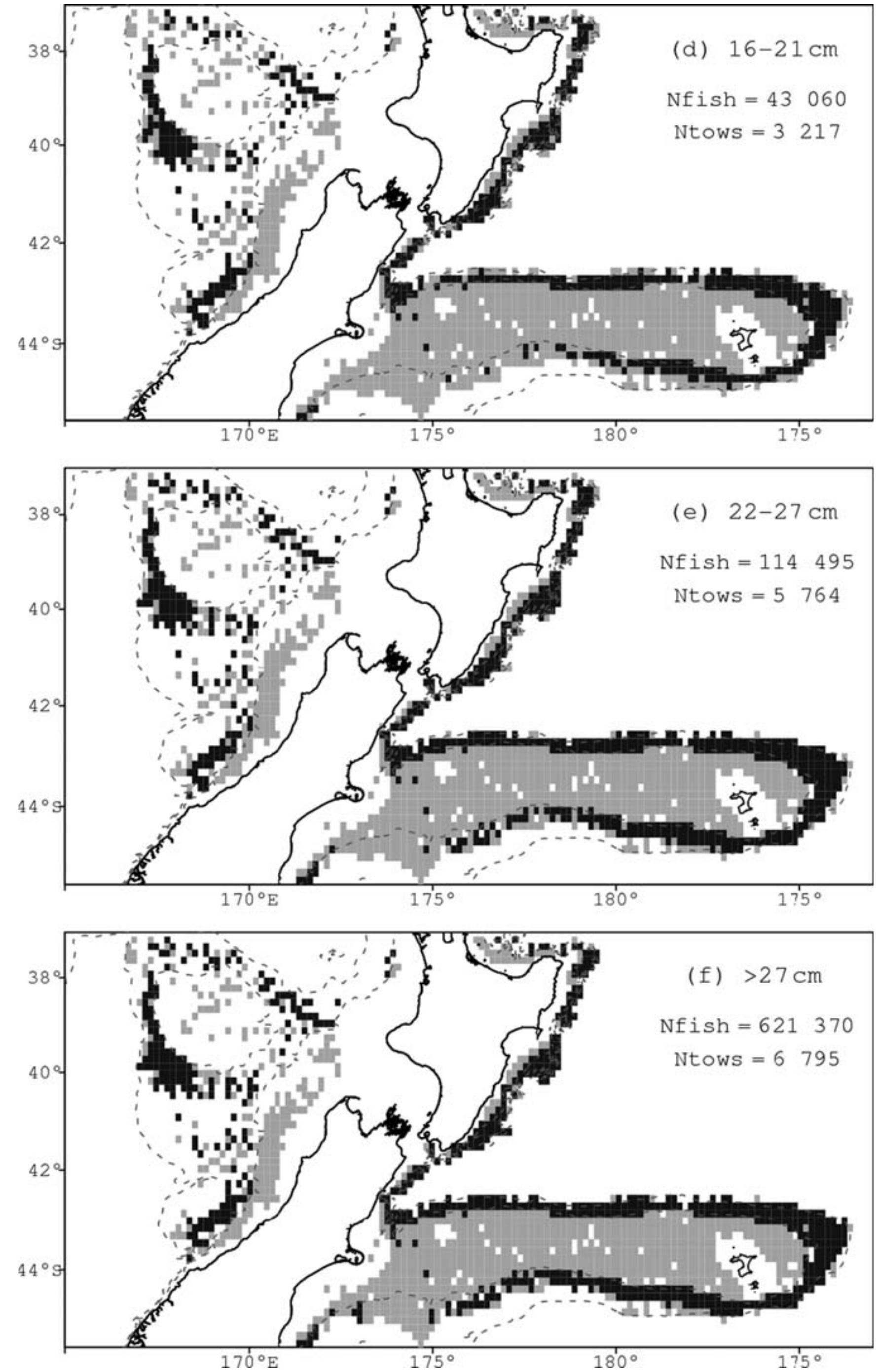

Figure 2. (Continued).

species were caught, including larger orange roughy, many small mesopelagic fish species (e.g. Myctophidae, *Photichthys* spp.), larger, active swimming species such as Ray's bream (*Brama brama*), silver warehou (*Seriolella punctata*), and squid (e.g. *Todarodes* spp., *Histioteuthis* spp.), demersal species such as oreos (*Neocyttus rhomboidalis*), and even midwater-foraging sharks (e.g. *Deania calcea*). Therefore, if juvenile orange roughy had been present in midwater, it is likely that some would have been captured.

Oceanography

The temperature profiles for the Chatham Rise demonstrated that the bottom temperature at the depths at which juvenile orange roughy were centred (850–900 m) was ~6.5°C, warmer than the depths at which large fish were found, the centre of which was at ~1150 m, where the bottom temperature was ~5°C (Figure 7).

A front was apparent on the south Chatham Rise, where colder water from the Subantarctic met the warmer water current from the north, and both were deflected south (Figure 8). This feature

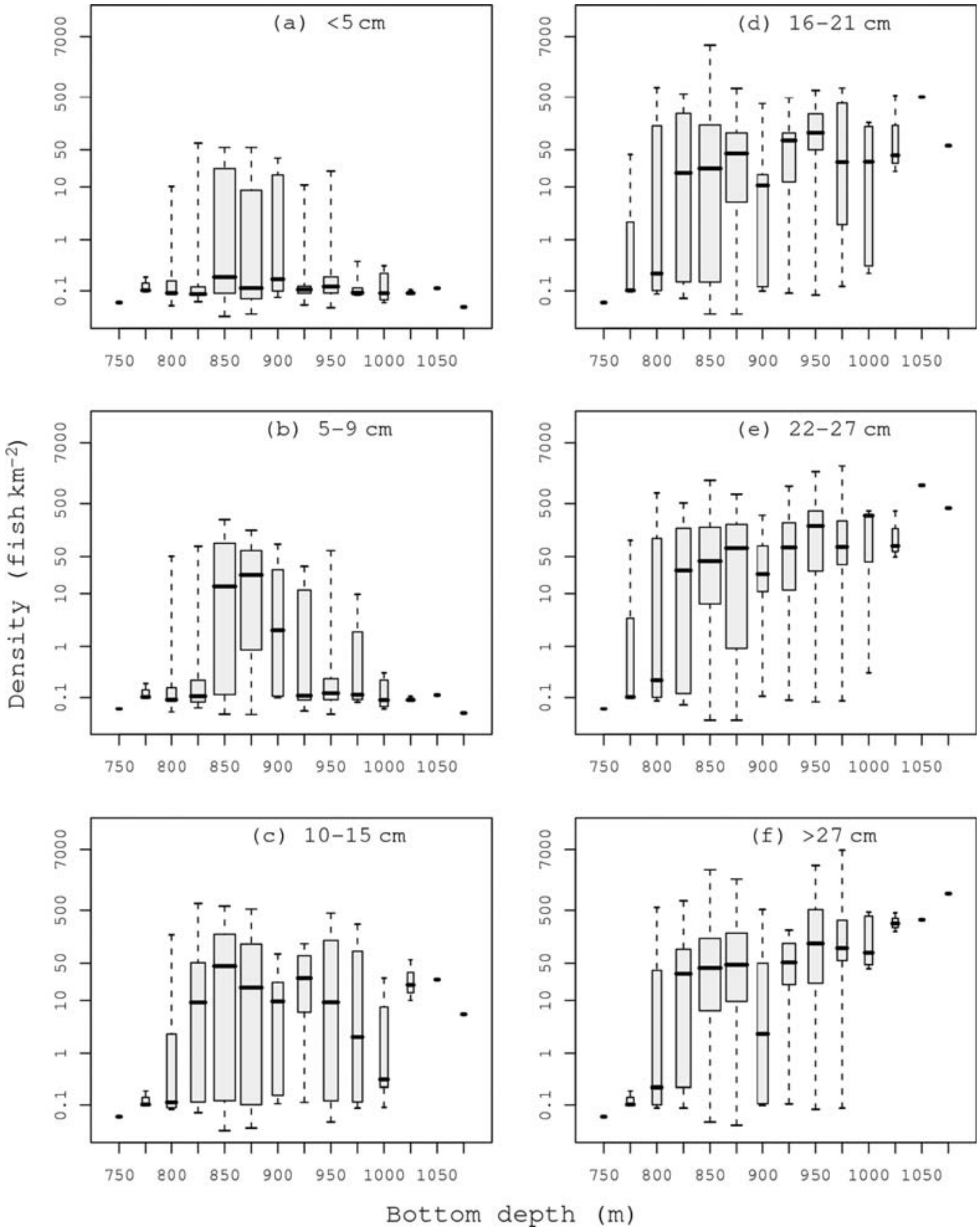

Figure 3. Density of orange roughy (log scale) in prawn-trawl surveys by 25-m depth bin and length class. The box limits extend from the lower to the upper quartile, with the solid line indicating the median, and the whiskers extend to the most extreme values. Bar width is in proportion to the square root of the number of tows ($n = 1-37$).

was more pronounced in the Argo float data (Figure 9). Associated with this front was a drop in temperature from east to west of 1–2°C (Figures 9 and 10). The higher density areas of juvenile orange roughy (<28 cm SL) on the south Chatham Rise were east of ~179°W (Figure 5), which is at the western edge of this frontal region.

The areas where juvenile orange roughy were at relatively high densities on the east Chatham Rise and Mid-East Coast (Figure 5) appear to be located in areas of relatively warm water (Figure 10).

Discussion

Early juvenile orange roughy were in greatest densities over a relatively narrow depth range, which was at the shallower end of the species' overall depth distribution. They were not found at all in midwater tows, but on the seabed in both hill and flat areas. The comparison of density estimates between hill and flat areas may be misleading because catchabilities are probably different for the two habitats. In addition, orange roughy are known to form aggregations around bottom features (Clark, 1999; Lorance *et al.*, 2002), and it could therefore be sheer chance as to whether a tow fishes an aggregation. Such a patchy distribution should result in trawl-survey biomass estimates with a high coefficient of variation (*CV*). For trawl surveys on the flat away from the spawning aggregations, the *CV*s are typically low (10–12%; Doonan *et al.*, 2006; Smith *et al.*, 2008), suggesting no patchy distribution in such areas, at least not at the scale of the tow. Conversely, the *CV*s for

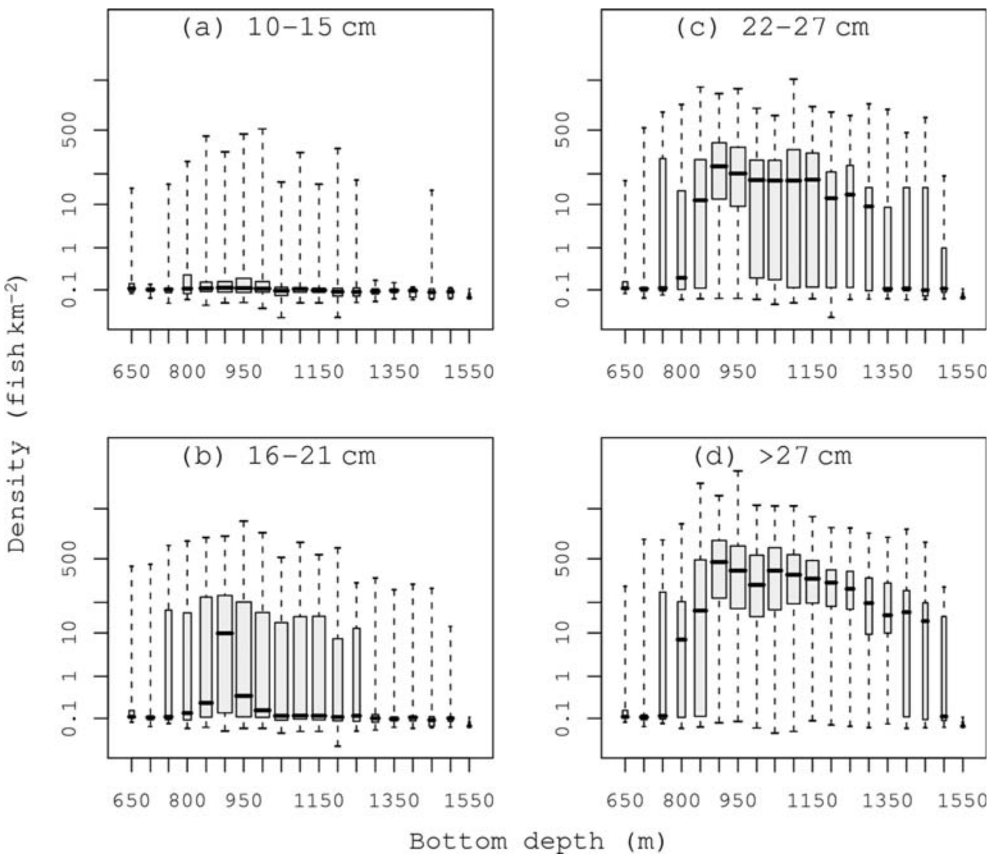

Figure 4. Density of orange roughy (log scale) in rough-bottom net tows by 50-m depth bin and length class. The box limits extend from the lower to the upper quartile, with the solid line indicating the median, and the whiskers extend to the most extreme values. Bar width is proportion to the square root of the number of tows ($n = 3-332$).

tows on specific bottom features are typically high (29–114%; Tracey and Fenaughty, 1997), consistent with aggregations there. The hill habitat is less extensive than the flat habitat. In trawl surveys of the Mid-East Coast, for example, the area of the hill strata was <2% of the area of the flat strata (Grimes, 1996). Therefore, if hill areas are important as nursery grounds, the fish density there would have to be orders of magnitude higher than on the flat. Our results suggest that this not to be the case and, if anything, that absolute densities of juveniles 10–21 cm SL on the flat might be higher than on the hills. Shephard and Rogan (2006) also found relatively few small orange roughy on hills compared with the flat in commercial trawls and suggested a size- or maturity-based movement from the flats to the hills. Adult orange roughy and many other fish species form aggregations in association with hills (Clark and O'Driscoll, 2003), so perhaps small juveniles avoid such areas, and instead inhabit open, soft-bottomed areas, where predation may be less intense (Ross and Quattrini, 2007).

In all but one instance, the areas where the smallest orange roughy were caught were located close to, or in relation to surface currents downstream from, the known spawning grounds (Zeldis *et al.*, 1994), as is common for many fish species (Van der Molen *et al.*, 2007). As juveniles grow, the spatial and depth distribution expands away from the initial areas. Such spatial expansion was most apparent on the south Chatham Rise. The depth distribution was skewed towards deeper water, and at >27 cm SL, the density was clearly greatest on the hills. By 22–27 cm SL, the orange roughy were found over a similar spatial area and depth distribution to maturing and adult fish (O'Driscoll *et al.*, 2003). Such a spread away from relatively discrete initial areas with increasing length suggests connectivity and an ontogenetic shift in distribution that is actually rather conventional, with initial nursery grounds being associated with spawning grounds over a relatively small area, and at a shallower depth than the adults.

The juveniles of <5 cm SL (age 0+) were relatively rare in catches, but had a wider depth distribution than orange roughy of 5–9 cm SL. Perhaps the fish in their first year settle over a relatively wide area, moving into preferred areas shortly thereafter. Alternatively, those outside such preferred areas may suffer greater mortality. We found no evidence to support the hypothesis of Thresher and Proctor (2007) that early juveniles were in especially cold and deep water. It is therefore possible that their peak in Sr could have been associated with the stress of descending into the relatively cold bottom water after the larval mesopelagic phase, or it could indeed just be an obligate physiological feature of early development (Thresher and Proctor, 2007).

The hypothesis of Shephard *et al.* (2007) that juvenile orange roughy live in warmer, shallower water was supported by our observations. Shephard *et al.* (2007) also hypothesized that orange roughy in their first 5 years of life were mesopelagic. We found no records of orange roughy of <22 cm SL in midwater trawls, and Thresher and Proctor (2007) also reported no small

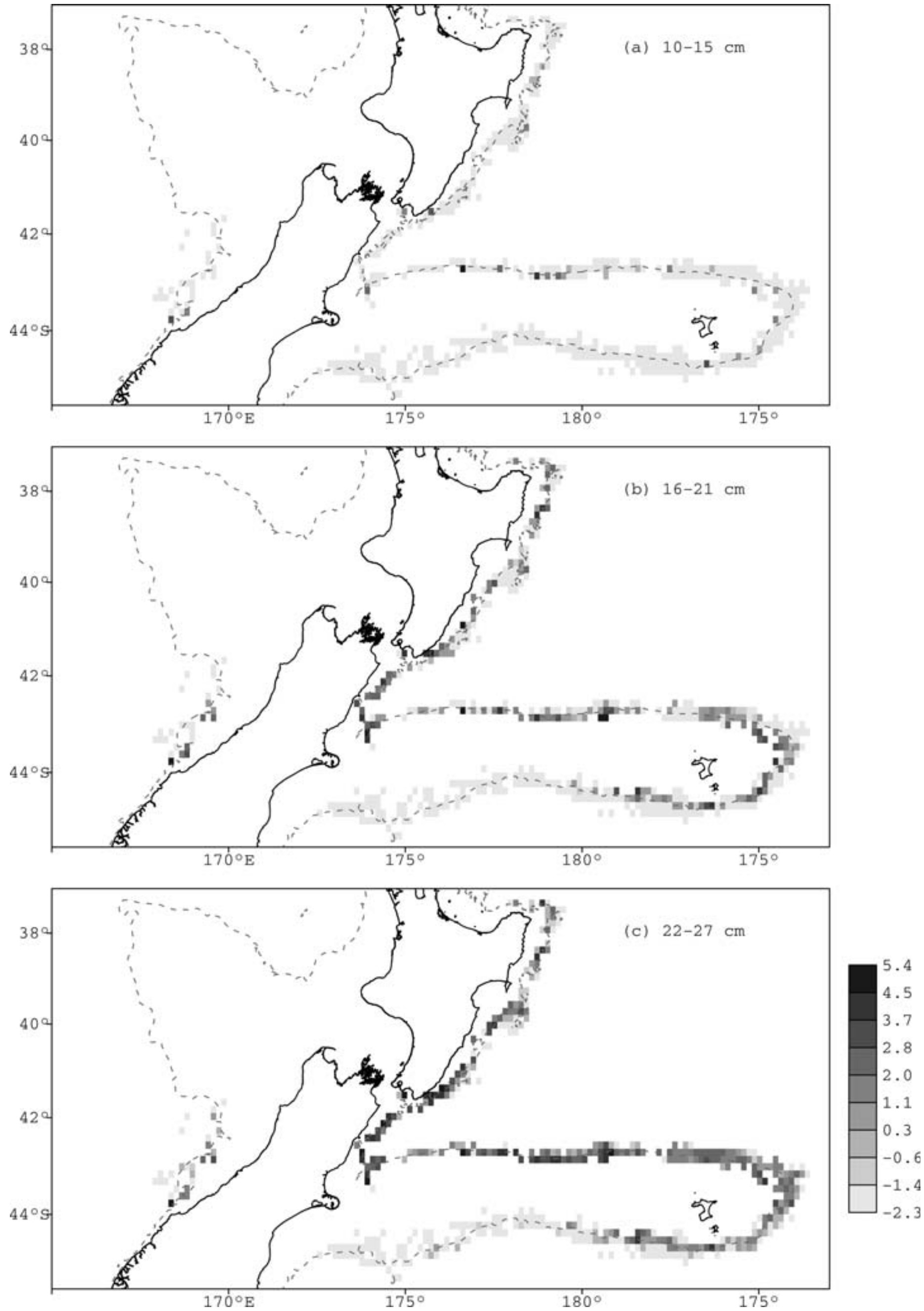

Figure 5. Density of orange roughy by length class from catches in the rough-bottom trawl. The broken line indicates the 1000-m isobath.

juveniles in midwater, despite extensive sampling. These observations do not, therefore, support a mesopelagic early-life hypothesis. Although dietary studies show that juvenile orange roughy feed on bentho- or mesopelagic prey, they conclude that they probably do not undertake diel vertical migrations themselves, although many of their prey do (Rosecchi *et al*., 1988; Bulman and Koslow, 1992). This again supports the hypothesis that orange roughy tend to have an affinity with the seabed.

More specifically, Shephard *et al*. (2007) concluded that early juveniles were mesopelagic, because in the area they sampled, relatively warmer water was found several hundred metres off the bottom, at a depth of 700–800 m. An alternative hypothesis from the Shephard *et al*. (2007) data would be that the early juveniles were indeed at 700–800 m, but that the fish were on the seabed and inshore of the adult distribution: judging from their Figure 1, such bottom depths would be <50 km away from the areas frequented by the adults. Those authors also concluded that a second juvenile phase was associated with a move to relatively cold, deep water (1200–1400 m). Our observations indicated that the depth range occupied by juveniles extended to include deeper water as the fish grew, with a shift at about the same size (age 5+, equivalent to 10–15 cm SL in New Zealand), but we did not find a distinct shift in distribution from the shallow nursery ground to a second, alternative, deep-water nursery ground.

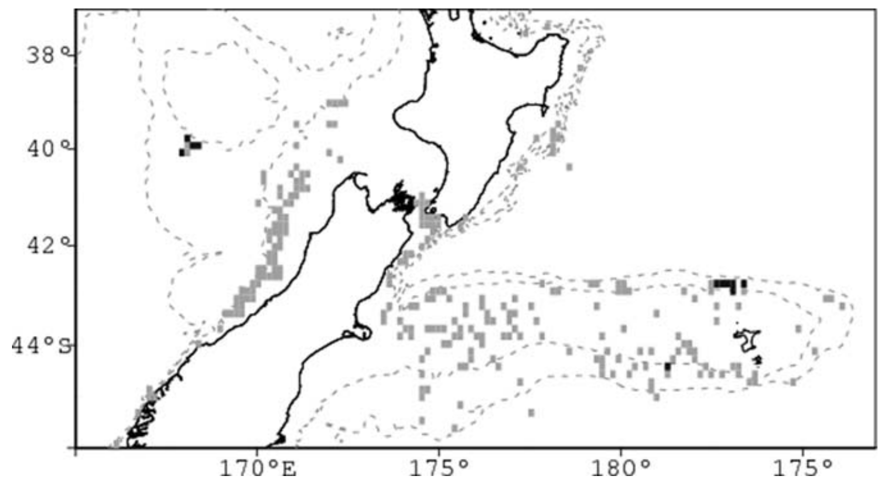

Figure 6. Occurrence of orange roughy in midwater trawls in the 22–27 and 28+ cm SL classes. Only orange roughy of 28 cm SL and over were caught on Mt Kiso (south Chatham Rise). Grey-shaded areas were sampled, and black-shaded areas show where orange roughy were caught. The broken lines indicate the 750- and 1500-m isobaths.

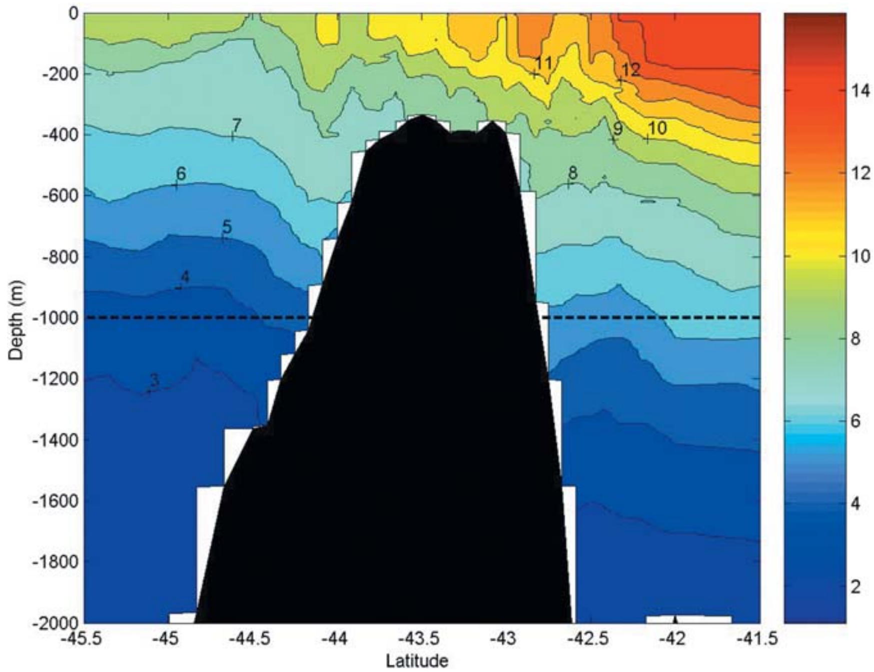

Figure 7. Temperature (°C) across Chatham Rise at 178°30E as measured in October 2000. The horizontal dashed line locates the 1000-m depth for reference.

Although the overriding evidence from direct sampling is that early juvenile orange roughy are not mesopelagic, this as yet does not prove conclusively that they do not occupy midwater. We have been informed of a single occasion when one fish (<10 cm SL) was retained using a multiple-closing codend system attached to a small pelagic trawl around a seamount feature (R. Kloser, CSIRO, pers. comm.). In addition, a midwater trawl survey was completed in 1992 on the south Chatham Rise and areas of the Subantarctic to search for mesopelagic juveniles of black and smooth oreo (*Allocyttus niger* and *Pseudocyttus maculatus*). Both species are suspected to have a mesopelagic juvenile phase (Ministry of Fisheries Science Group, 2008), but the survey failed to catch a single specimen in 64 tows and to date the only juveniles in New Zealand have come from bottom trawls. However, juvenile oreos are rare in bottom trawls until ~20 cm TL, which is not the case for orange roughy, juveniles of such size and smaller having been encountered on the seabed often.

Shephard *et al*. (2007) reported a difference in temperature between early and later juvenile habitat, with an inferred temperature for post-larval and early juvenile (ages 0+ to about 5+) habitat of ~8.8°C and for older juvenile (ages about 5+ to 14+) habitat of ~6.2°C. These inferred temperatures are higher than found at similar depths on the Chatham Rise, and the

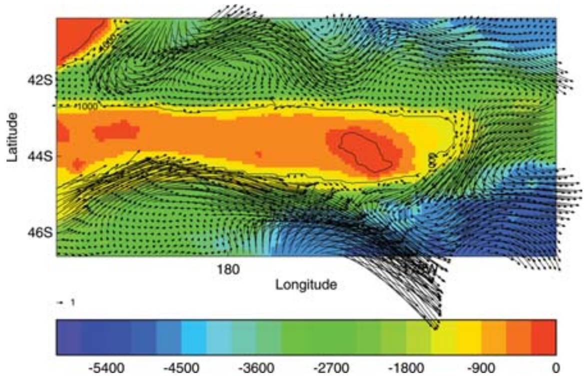

Figure 8. Horizontal velocity vectors at 990 m from the climatological ocean model plotted on top of the model bathymetry from 0 to 6000 m, with the 1000-m isobath labelled. The reference vector indicates a flow speed of 1 cm s^{-1}. Model solution has a horizontal resolution of 1/12° of latitude and longitude, and every second horizontal point is plotted for clarity.

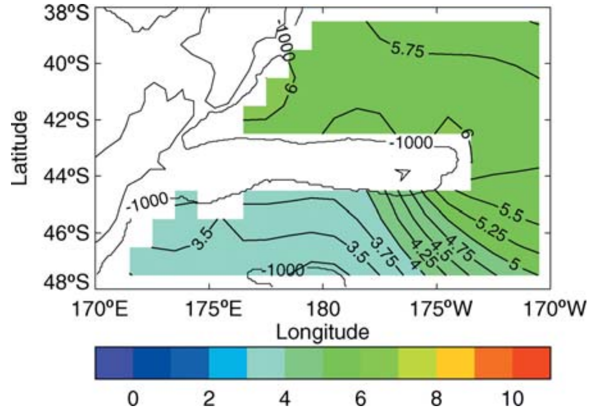

Figure 10. WOA 2005 temperature (°C) at 1000 m for the area east of New Zealand. Temperature contours are plotted every 0.25°C, with the 1000-m isobath labelled.

magnitude of inferred temperature difference between early and later juvenile habitats was greater, 2.6°C compared with our 1.5°C.

Perhaps the front area on the south Chatham Rise acts as a boundary to the distribution of juvenile orange roughy, which prefer warmer temperatures. Boundaries to distribution caused by temperature sensitivity might contribute to stock separation. As the adult distribution extends into cooler water, these fish may be less constrained by the drop in temperature across fronts, but on the south Chatham Rise the scarcity of orange roughy to the south-west would suggest that this colder area is less preferred by adults (Tracey and Fenaughty, 1997). The deep-water trawl fisheries primarily target oreos to the west of the front and orange roughy to the east (Ministry of Fisheries Science Group, 2008). This is consistent with oreos and orange roughy preferring relatively "cold" and "warm" water, respectively. In addition, some fishers have suspected temperature sensitivity to play a role in the distribution of recruited (largely adult) orange roughy and have used net sensors to find small changes in temperature, then concentrated their fishing on the warmer side of these boundaries where they believe the orange roughy would be more abundant.

It is also possible that deep-sea currents or eddies might contribute to stock separation. For example, the two large current oscillations on the north Chatham Rise (Figure 8) are situated just north or northeast of the two main spawning grounds, and they could help to entrain and separate the eggs and larvae originating from each. Further work with particle-diffusion models might help establish whether such large-scale features are related to distribution patterns, and if indeed this is a reasonable hypothesis.

The identification of nursery grounds is a first step towards estimating the relative or absolute abundance of prerecruiting orange roughy. The areas we have identified could perhaps be surveyed for prerecruit abundance, but it would be prudent to design such

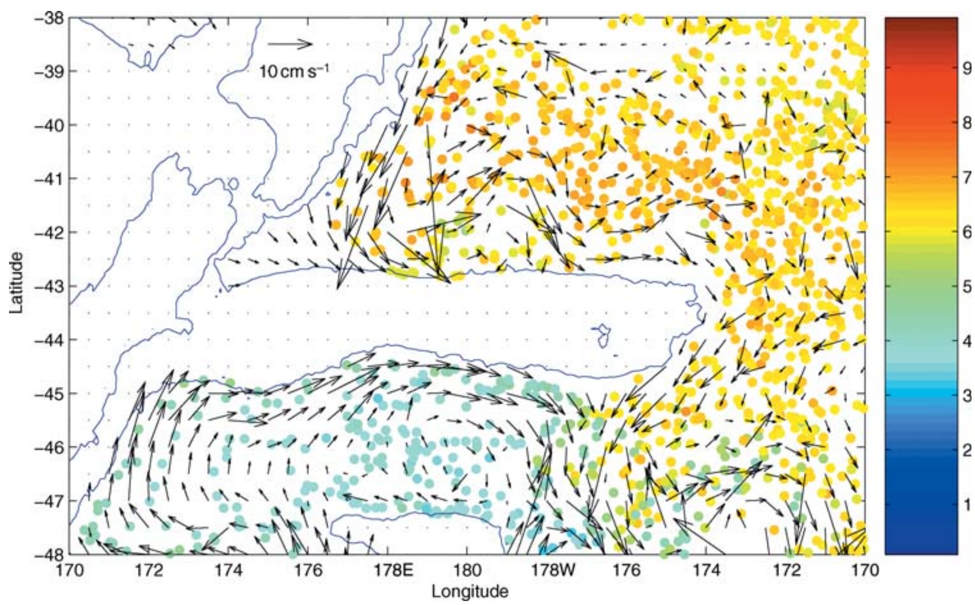

Figure 9. Temperature measured at 900 m from Argo float profiles, with estimates of the velocity at 900 m overlaid. The velocity vectors have been averaged in 0.5° latitude and longitude bins.

surveys to confirm the hypothesized nursery ground boundaries, because these could, for example, be density-dependent. The observation that early juvenile abundance in trawl catches from nursery grounds on the northeast Chatham Rise was much lower than expected given the abundance of adults (Mace *et al*., 1990) would suggest either low catchability or that abundance was relatively low. This observation remains true for all the stocks examined, because the number of juveniles caught in any of the nursery grounds seemed to be much lower than might have been expected. The biomass of the northeast Chatham Rise stock has apparently failed to rebuild despite catches being reduced in the early 1990s to levels thought to be sustainable (Sissenwine and Mace, 2007; Ministry of Fisheries Science Group, 2008). This sustainable catch was estimated using population models assuming constant (virgin) recruitment levels. Current research therefore focuses on using existing trawl-survey data from the nursery grounds to attempt to validate, or disprove, this recruitment assumption. At present, however, a preliminary explanation for a lack of rebuilding would appear to be reduced productivity in the form of poor recruitment.

Acknowledgements

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