



NIWA

Taihoru Nukurangi

**Stock relationships of orange roughy in New
Zealand waters**

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**Final Research Report for
Ministry of Fisheries Research Project DEE1999/01
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Final Research Report

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7. Executive Summary

Four techniques were evaluated to determine stock relationships of four orange roughy fisheries in the Tasman Sea: the Lord Howe Rise (HOWE), Northwest Challenger (NWCH), Southwest Challenger (SWCH), and Westpac Bank (WPAC). The techniques have been applied to stock discrimination of orange roughy in other areas. Two techniques based on a phenotypic approach (otolith shape) and life history traits (age and size at maturity) were applied using existing otolith collections. Length frequencies, derived from observer data, were compared between areas. Biological data on spawning times in each area were reviewed, along with oceanographic data for this region of the Tasman Sea.

A comparison of estimated age (A_{mat}) and length (L_{mat}) at onset of maturity derived from otolith samples from the four areas did not identify any clear stock differences. Data from the early period in the fishery (1988–1993) indicated a significant difference in A_{mat} between fish from HOWE and WPAC and SWCH. There were no significant differences among areas for L_{mat} . Comparison with published data from the Challenger Plateau showed significant differences among samples taken on the Challenger Plateau for both A_{mat} and L_{mat} . It appears that factors related to the fishery, and to sampling practices, produce significant variation in these life history traits.

Results of harmonic randomisation tests on otolith shape revealed two groups:

HOWE/NWCH and SWCH/WPAC. There were significant size differences between HOWE and NWCH (and between HOWE-SWCH and HOWE-WPAC) with larger fish on HOWE. There were smaller (<1 cm), but significant differences between SWCH and WPAC. There was considerable between-year variation in the time of the onset of spawning at SWCH (three weeks) and WPAC (four weeks). In both areas the time of spawning was later in the early 1990s than in the late 1990s. Time of onset of spawning was consistent at HOWE (about mid-July in each year) and SWCH (second week of July) during 1989-93. No major oceanographic features that might isolate stocks were identified in this region of the Tasman Sea, although data are sparse.

Other studies on Challenger-HOWE roughy have shown significant genetic differences between HOWE and NWCH/SWCH with mtDNA haplotypes. Microchemistry of the otolith found significantly higher levels of lead in HOWE than NWCH and SWCH, and significantly higher levels of copper in HOWE than SWCH.

The biological differences among orange roughy taken from HOWE, NWCH, and SWCH indicate that these fisheries could be managed as independent stocks. There were no biological differences between SWCH and WPAC and these fisheries probably exploit one straddling stock

8. Objectives

OVERALL OBJECTIVE:

1. To determine stock relationships for orange roughy (*Hoplostethus atlanticus*) within and adjacent to the New Zealand EEZ.

SPECIFIC OBJECTIVE:

1. To determine stock relationships for orange roughy from four areas within and adjacent to the New Zealand EEZ – Lord Howe Rise (outside the EEZ), Northwest Challenger (outside the EEZ), Westpac Bank (outside the EEZ), and Southwest Challenger (inside the EEZ).

9. Methods

9.1 Analysis of length frequencies

Length data were obtained from the New Zealand Ministry of Fisheries Scientific Observer Programme (SOP) based on catches from commercial vessels. The few catches from research surveys were excluded a.) because length data from research surveys and from the SOP on the Chatham Rise, to the east of New Zealand, have shown a difference in mean length (Francis & Tracey 2000), and b.) the research data only covered the SWCH and WPAC between 1986-1990.

Orange roughy length frequency samples were available from the winter of 1988 to the winter of 1999 for the four areas:

Lord Howe Rise (HOWE)	164° 30' E to 167° 00' E
	35° 12' S to 36° 30' S

Northwest Challenger (NWCH)	166° 30' E to 169° 00' E 36° 54' S to 38° 00' S
Southwest Challenger (SWCH)	167° 30' E to 169° 18' E 39° 30' S to 41° 36' S
Westpac Bank (WPAC)	167° 00' E to 167° 24' E 39° 36' S to 40° 00' S

Only samples from catches greater than 1 t and from the months of June or July, the spawning period, were selected, to maximise comparability between areas and years. Variability in the size of catch associated with each sample was accounted for by scaling each length frequency by catch weight/sample weight. Where sample weight was not recorded it was estimated from the length distribution and a length-weight relationship. Scaled length frequencies were combined over each area and year and over each observed trip.

For each combination of scaled length frequencies the mean length by sex was calculated, then a simple average taken of male and female mean lengths after Francis *et al.* (1992). Length frequency distributions by sex, area, and year were produced, and the variation in mean length over areas, trips, and years tested with ANOVA.

9.2. Assessment of age and length at first maturity

The mean age and length at maturity was estimated for four population samples HOWE, NWCH, SWCH, and WPAC. The method followed that used by Horn *et al.* (1998) to describe between area differences in age and length at maturity in orange roughy from several fishing grounds in the New Zealand EEZ and Atlantic Ocean.

Estimates of age at maturity (A_{mat}) and length at maturity (L_{mat}) are based on the assumption that the transition zone in the otolith marks the onset of sexual maturity in orange roughy. The transition zone appears in the otoliths of adult orange roughy and is an area in which annulus width decreases rapidly and the otolith composition changes from predominantly opaque to more translucent material (Francis & Horn 1997). For L_{mat} it is assumed that the otolith radius is directly proportional to fish length throughout the life of the fish, so that:

$$L_{mat} = L(r_{tz}/r_{tot}),$$

where L = fish length, r_{tz} = radius from nucleus to transition zone, and r_{tot} = radius from nucleus to otolith margin. Francis & Horn (1997) demonstrated that the relationship between fish length and otolith radius is not linear for large fish, but the likely bias to L_{mat} owing to an assumption of linearity is small (Horn *et al.* 1998).

Forty otoliths from female fish with standard lengths ranging from 35 to 40 cm were selected from each area (Table 1). All otoliths had been collected by Ministry of Fisheries scientific observers from commercial catches taken between May and July, over several years. Only otoliths from females were used to avoid potential sex differences. The otoliths were prepared using the method described by Tracey & Horn

(1999). Otoliths were embedded individually in epoxy resin, sectioned along a line between the primordium and the postrostrum, and the sections were mounted in quick curing epoxy resin on glass slides. The sections were ground down to give a preparation about 350–400 μm thick. Counts of annuli from the primordium to the transition zone were made with a compound microscope ($\times 30$) illuminated by transmitted light. Straight line measurements from the otolith nucleus to the transition zone, and from the nucleus to the otolith margin, were made on the sections with a micrometer eyepiece ($\times 10$) in the binocular microscope. Data for an otolith were rejected if the number of zones inside the transition zone, or the position of the transition zone, were considered uncertain, (but a minimum of 36 records were obtained for each area). Radial measurements (i.e., r_{tz} and r_{tot}) could sometimes still be obtained even when a zone count could not be determined.

Pairs of sample means were compared with Student's t -test, with significance levels modified with a Bonferroni correction for multiple tests (Zar 1996).

Table 1: Year of collection (with number of otoliths in parentheses) for the four otolith sample collections used to estimate age and length at maturity. All otoliths were collected in the months May to July.

Area	Year (and sample size)
HOWE	1989 (7), 1990 (7), 1992 (23), 1993 (3)
NWCH	1992 (2), 1993(35), 1998 (3)
SWCH	1988 (6), 1989 (2), 1990 (13), 1996 (9), 1998 (10)
WPAC	1988 (19), 1989 (16), 1996 (1), 1998 (4)

9.3. Assessment of otolith shape

9.3.1 Samples

Oolith samples for morphometric and shape analyses were supplied to the Central Ageing Facility (CAF). Samples were selected to provide comparable otoliths from each of the four areas: 150 males and 150 females randomly selected from NWCH, SWCH, and WPAC, between the 30 and 40 cm length class, and all of the available samples from HOWE between the 30 and 40 cm length class. The number of samples and batch details supplied are given in Table 2.

Table 2: Orange roughy otolith samples registered by the Central Ageing Facility (CAF).

Batch	Area	N
101	HOWE	249
102	NWCH	304
103	SWCH	302
104	WPAC	302
Total		1157

A greyscale image of each pair of otoliths was collected using the customised image analysis system developed in the CAF (Morison et al. 1998), and saved in Joint Photographic Effect Group file format (JPEG) for subsequent analysis. Images were collected at a magnification of 2.54x (0.63x primary objective, 6.4x magnification and 0.63x secondary objective). An example of the resultant image is shown in Figure 1.

Otoliths were weighed to the nearest milligram. Biological data, otolith weight and image details, including name and path were combined in a Microsoft (MS) Excel spreadsheets. Otoliths were returned to NIWA after images had been collected.

9.3.2 Otolith shape data collection

Shape and meristic analyses of the orange roughy otoliths were undertaken using the programs developed by Robertson et al. (2001). Each image was opened in Optimas™ and three automated pixel gradient tracings of the left otolith were performed. The first, second and third trace collected perimeter data, area data and x-y coordinate data for the Fourier series respectively. The circularity was calculated by the program using perimeter and area measurements. The data used to compute the Fast Fourier Transform (FFT) were collected as 128 equidistant points around the outline of the otolith. The FFT was calculated as a Cartesian FFT using the x-y coordinates as a complex number ($a+bi$). Each of the automated tracings were started at an arbitrary landmark point on the otolith, which was the dorsal lobe adjacent to the sulcus (Fig. 1). All tracings were counter-clockwise in direction around the silhouette of the otolith.

Some otoliths were broken and could not be used for Fourier analysis. The number and percentage of otoliths analysed from each batch are shown in Table 3. As a sub-sample of the supplied otoliths were analyzed, Komologorov-Smirnov (K-S) (Zar 1996) tests were used to compare the distributions of fish lengths in the original sample supplied to the CAF and in the sub-sample that was analysed.

Table 3. Number and percentage of orange roughy samples used in analysis of otolith shape by Fourier analysis and morphometrics.

Batch	N	Fourier series, area and perimeter	% Analysed
707101	249	178	71.5
707102	304	187	61.5
707103	302	234	77.5
707104	302	227	75.1

9.3.3 Analysis of shape using Fourier analysis

The FFT was calculated in Optimas and the resultant array of 128 complex numbers (Fourier descriptors) saved for later analysis. The 0th descriptor was used to normalize for differences in otolith position in the image and the 1st descriptor to normalize for size and rotation of the image. The remaining Fourier descriptors represented the otolith shape independent of its position, size and rotation.

Determination of the appropriate number of Fourier descriptors

As the number of Fourier descriptors increases, the resultant reconstructed shape converges to the original shape. To determine the number of Fourier descriptors used for later analysis a range finding procedure was performed. An otolith was randomly selected and the Fourier series calculated. The descriptors were normalized for position by setting the zeroth descriptor to $0+0i$. The shape was then reconstructed using the first (and last) descriptor. The number of descriptors was then increased by one and the shape reconstructed. This was repeated until 30 descriptors from each end of the complex FFT were used. The maximum error of 100 percent was defined as the difference between the inverse FFT reconstruction of the otolith outline using the full array of Fourier descriptors and the reconstruction using only the 2nd and last elements of the original Fourier series (Figure 2). These distances were squared and summed, and expressed as a percentage (percent reconstruction error). This test determined the relationship between the number of descriptors and the accuracy of the reconstruction.

Based on the results of the range finding test, nine samples from each area were randomly selected and the inverse FFT calculated from the 12th to (and including) the 22nd Fourier descriptor and the percentage error calculated. The nine randomly selected samples from each area (giving a total of 36 samples) were used to calculate the 11 mean harmonics suggested by the range finder to find the number of harmonics needed to get the mean reconstruction to be within 5% of the original shape.

The relationship between number of Fourier descriptors and percent reconstruction error showed that the complex shape of the orange roughly otolith required twenty two Fourier descriptors to reduce the mean reconstruction error to below five percent (Figure 2). Because the Cartesian Fourier Transform is asymmetric around the middle frequency, both the 2nd to the 22nd descriptors and the 106th to the 127th descriptors from the original Fourier series were used for subsequent analyses.

Test of differences between areas

The reduced set of twenty two Fourier descriptors from each end of the series was used to compare the shape of otoliths from each area. The absolute value (harmonic) of each of the Fourier descriptors in the shape vector was calculated as :

$$\text{Harmonic} = (a+b_j)^{0.5}$$

Where :

a = real component of complex number

b_j = imaginary component of complex number

The mean harmonic distance between each of the areas was then calculated. The estimator used in this study to test differences between areas was the square root of the sum of the squared differences in the mean harmonics. This was calculated as:

$$DH_{jk} = \sqrt{\sum_{i=2}^{44} (\bar{H}_{ij} - \bar{H}_{ik})^2}$$

Where :

DH_{jk} = Observed harmonic distance between area j and area k

\overline{H}_{ij} = i^{th} mean harmonic from area j

\overline{H}_{ik} = i^{th} mean harmonic from area k

The matrix of Fourier descriptors for samples from the two areas being compared was thus reduced to one harmonic distance value. The observed harmonic distance was calculated for each of the area comparisons. This was repeated for each of the area comparisons.

A randomization test was then applied to estimate the probability that the observed harmonic distance would occur by chance alone. Samples were randomly allocated to groups and a new harmonic distance calculated. This process was repeated 5,000 times and a distribution of values for randomized harmonic distance was obtained. The probability of obtaining the observed harmonic distance by chance was estimated as the proportion of randomisations for which the harmonic distance was greater than or equal to the observed harmonic distance.

Each area was pair-wise tested against each of the areas giving a total of six tests for the four areas. All programs for conducting randomisation tests were written in Visual Basic for Applications (VBA) in MS Excel.

Morphometric Analysis

Circularity, otolith area and otolith perimeter data was tested for heterogeneity using Hartley's F_{\max} test before further testing. Morphometric analysis of the orange roughy data consisted of analysis of variance (ANOVA) of the circularity, area and perimeter data. Where significant differences were demonstrated using analysis of variance, Student Newman-Kuels multiple range tests (SNK) were used to determine area groupings (Zar 1996). Ratio measurements taken from landmark locations around the perimeter of the otoliths were not used in this study.

9.4. Assessment of biological and oceanographic information

9.4.1 Analysis of gonad stage data

The reproductive status of female fish was used to determine the timing of spawning activity in each area and year, using data from all available observer samples (i.e. regardless of catch size). Observers only recorded gonad condition in females due to difficulties in the interpretation of the macroscopic stages of male orange roughy gonads. Females had been assigned to one of the following five macroscopic categories: F1 immature to early maturation; F2 maturing; F3 ripe; F4 running ripe; and F5 spent.

For areas and years where there was sufficient sampling throughout the spawning period, the progression of spawning was plotted with a "Lowess" curve (Cleveland 1985) fitted to data points representing the proportion of fish in each reproductive stage. From these plots the timing of the onset of spawning was estimated as the point at which 20% of the fish are spent (Pankhurst 1988).

9.4.2 Oceanographic data for the Challenger Plateau and Lord Howe Rise

The limited data on oceanography of the Lord Howe Rise and Tasman Sea were collated and assessed to produce a synopsis of oceanographic conditions in this region, and interpreted in relation to transport of orange roughy larvae and juveniles. The main features of this region were described by Heath (1985). More recent sea surface temperature data, determined from satellite observations, are available (Uddstrom & Oien, 1999), and some limited salinity data are available for surface salinity (Garner 1970; Stanton & Ridgway, 1988).

There have been no direct current measurements using moored current meters in the HOWE, SWCH, NWCH, and WPAC areas. However data are available from satellite-tracked current drogue experiments. For near surface currents these drifters are generally drogued at 15-20 m depth. There are three main sources of information: the CSIRO, the FGGE, and the WOCE data sets. The CSIRO data derive from Australian experiments in the EAC region in 1979/84. The FGGE data come from the First GARP (Global Atmospheric Research Programme) Global Experiment in 1978/79. The WOCE data set (World Ocean Circulation Experiment) comprises global drifter deployments in the 1990/98 period.

9.5. Interpretation of all stock discrimination information on Lord Howe Rise and Challenger Plateau orange roughy

Existing stock structure data on orange roughy from the Lord Howe Rise and Challenger Plateau in the published scientific literature and in unpublished reports and FARDs were reviewed.

10. Results

10.1. Analysis of length frequencies

Length frequency distributions show a generally unimodal shape, typical of orange roughy, in all areas and years (Figures 3-6). There is little evidence for a strong young age-class which might bias the calculation of mean length. There are patterns in the mean lengths over time (Fig 7). In each of the ten years for which data are available for SWCH, the mean length is lower than the mean lengths in other areas in the same year. Similarly, in each of the 5 years for which data are available for HOWE, the mean length is greater than the mean lengths in other areas in the same year.

An ANOVA analysis of tow mean lengths on trip, area, and year indicated that there were statistically significant differences between trips in the same area and year. Accordingly the trip mean length was considered to be the appropriate unit.

Differences between areas were tested using ANOVA on the trip mean lengths. There were 25 trips in HOWE, 17 in NWCH, 38 in SWCH, and 13 in WPAC. A significant area effect ($P < 0.0001$) was indicated by the ANOVA on trip means. The year effect was not significant ($P = 0.32$). Multiple comparisons (using Fisher's LSD method) indicate HOWE is significantly different from the other three sites ($P \ll 0.01$), and that WPAC is just significantly different from SWCH. ($P < 0.01$)

Table 4: Summary of orange roughy distributions of trip mean lengths from four areas.

area	HOWE	NWCH	SWCH	WPAC
min	32.8	31.7	29.7	31.1
LQ	34.6	33.1	31.8	33.4
Median	35.6	33.5	32.7	33.6
UQ	36.4	33.6	33.1	34.2
max	40.2	34.2	34.6	35.9

10.2. Assessment of age and length at first maturity

The number of otoliths and year of collection used for the age and length at maturity estimates are shown in Table 4. Estimates of A_{mat} for each area are given in Table 5. Between-area pair-wise comparisons showed only one significantly different pairing; fish from HOWE had a significantly greater age at maturity than WPAC fish ($P < 0.05$; Table 6).

Estimates of L_{mat} for each sample are presented in Table 7. None of the between-area pair-wise comparisons were significant (Table 6). The four L_{mat} values ranged from 31.0 to 31.6 cm, with HOWE being the highest. Horn *et al.* (1998) used between-area differences in A_{mat} and L_{mat} of orange roughy to infer multiple stocks in New Zealand waters. Based on the comparison of the same parameters for orange roughy from four areas, no clear stock differences are apparent on the Challenger Plateau and Lord Howe Rise. There is an indication that HOWE fish may have higher A_{mat} and L_{mat} values than in the other areas, but only one pair-wise comparison (A_{mat} for HOWE-WPAC) was statistically significant.

An interesting and unexpected result arises from the comparison of a sample of 18 female fish from the Challenger Plateau (Horn *et al.* 1998) with estimates derived in the current study for SWCH and WPAC. The Challenger Plateau sample was taken in July 1990 from the same area as the SWCH sample (collected between 1988-98, *see* Table 1). The estimates of L_{mat} from SWCH and WPAC in this study were significantly larger (Student's *t*-test, $P < 0.01$; Table 6) than the previous estimate for the Challenger Plateau (Tables 6 and 7). The estimates of A_{mat} for both SWCH and WPAC were higher than the previous Challenger Plateau estimate (Table 5), but the differences were not

Table 5: Estimates of mean age at onset of maturity (A_{mat} , years) for female orange roughy, as a function of area. Values derived for the Southwest Challenger sample from two distinct time periods, and from a previously analysed sample of Challenger Plateau (CHAL) females collected in 1990 (from Horn et al. 1998) are listed for comparison. n , sample size (and number of tows); Range, range of age estimates; SD, standard deviation

Area	$n(\text{tows})$	Range	A_{mat}	SD
HOWE	37(23)	20–34	26.00	3.04
NWCH	36(26)	17–33	25.19	3.35
SWCH	36(25)	20–31	24.75	2.61
WPAC	36(27)	18–31	23.78	2.83
SWCH (1988–90)	18(12)	20–28	24.00	2.33
SWCH (1996–98)	18(13)	20–31	25.50	2.73
CHAL (1990)	18(10)	19–28	23.61	2.40

Table 6: Values of t for pair-wise comparisons of A_{mat} and L_{mat} . CHAL refers to a sample of 18 female fish collected on the Challenger Plateau in July 1990 by Horn et al. (1998). Significantly different pair-wise comparisons (following modification with the Bonferroni correction for multiple tests) are denoted by * ($P > 0.05$) and ** ($P > 0.01$).

	A_{mat}			L_{mat}		
	NWCH	SWCH	WPAC	NWCH	SWCH	WPAC
HOWE	1.08	1.89	*3.26	1.24	1.16	0.74
NWCH	–	0.62	1.96	–	0.12	0.53
SWCH	–	–	1.51	–	–	0.42
CHAL	–	1.60	0.23	–	**4.55	**4.91

Table 7: Estimates of mean length at onset of maturity (L_{mat} , cm SL) for female orange roughy, as a function of area. Values derived for the Southwest Challenger sample from two distinct time periods, and from a previously analysed sample of Challenger Plateau (CHAL) females collected in 1990 (from Horn et al. 1998) are listed for comparison. n , sample size (and number of tows); Range, range of length estimates; SD, standard deviation

Area	$n(\text{tows})$	Range	L_{mat}	SD
HOWE	40(23)	27.5–37.8	31.61	2.21
NWCH	37(28)	25.3–34.7	30.99	2.19
SWCH	40(28)	27.0–35.6	31.05	2.11
WPAC	37(27)	26.5–35.6	31.25	2.06
SWCH (1988–90)	21(15)	27.0–35.6	30.76	2.07
SWCH (1996–98)	19(13)	27.6–35.2	31.36	2.16
CHAL (1990)	18(10)	26.3–31.5	28.75	1.61

statistically significant (Student's t -test, $P > 0.05$; Table 6). There are no significant differences between SWCH and WPAC for either parameter in this study (Table 6). The Westpac Bank is a geological feature to the west of the area defined as Southwest Challenger; and significant differences in A_{mat} and L_{mat} between SWCH and WPAC samples would not be expected because these grounds are close together.

Otoliths in the SWCH sample were derived from two distinct periods: the early fishery (1988–1990), and the recent fishery (1996 and 1998). The estimated L_{mat} for the early fishery (30.8 cm) was lower than for the recent fishery (31.4 cm), but the differences are not significant ($t = 0.89$; Table 7). The L_{mat} value for the early fishery was significantly different ($t = 3.41$; $P < 0.01$) to the estimate derived from the 1990 Challenger sample of Horn et al. (1998). For A_{mat} the difference between the early and recent fisheries was marked (Table 5), although there was no statistical significance between these two values ($t = 1.77$; Table 5). However, there was a statistically significant difference ($t = 2.21$; $P < 0.05$) between the A_{mat} value from the recent fishery with that derived from the 1990 Challenger sample of Horn et al. (1998). Otolith samples had been selected from fish taken across many tows (Table 5) to reduce the risk of tow to tow variation in the data.

It was not possible to test for temporal changes in parameters for the three other areas. All the HOWE samples were obtained from the early period of the fishery (i.e., 1989–1993). In the NWCH and WPAC samples, only 3 and 5 otoliths, respectively, were from samples collected later than 1993. However, it is interesting to note that when these 8 otoliths are excluded from the analyses, the A_{mat} and L_{mat} values decrease in both areas, establishing a similar trend to the SWCH data.

The analyses of A_{mat} and L_{mat} parameters estimated from otolith samples have not identified any clear stock differences. If only data from 1993, or earlier are used, then there is a significant difference in A_{mat} between fish from HOWE with those from the WPAC and SWCH. However it appears that factors other than stock characters can cause variations in these parameters. An increase in A_{mat} over time was found on the SWCH. This is unlikely to be a biological response by the fish to the fishery. Orange roughy are very slow growing and most of the fish vulnerable to the trawl would have been mature before the fishery began; any response by immature fish to a reduced abundance of mature individuals is more likely to result in spawning commencing at an earlier, rather than later, age. The results presented here suggest that fish which matured earlier have been relatively more vulnerable to capture. However, the significant difference in L_{mat} values derived from two samples in the same area at approximately the same time (i.e., the 1990 Challenger Plateau samples of Horn et al. (1998), and SWCH 1988–90) indicates that sampling factors can also influence these traits. The asymptotic length of an orange roughy is related to its age (and length) at onset of maturity, and because most of its growth occurs when pre-mature (Horn et al. 1998), an early maturing fish will, on average, be shorter than a later maturing one. Hence, any sampling method which does not provide a representative sample of the entire mature population could lead to a bias in the L_{mat} estimate for the stock.

10.3. Assessment of otolith shape

No significant differences were found between the sample supplied by NIWA and the sub-sample analysed by the CAF using Fourier harmonic analysis and otolith morphology using Komologorov-Smirnov (K-S) tests on length frequency data (Table 8).

Table 8: Komologorov-Smirnov tests of length frequency data from orange roughy otolith supplied by NIWA vs. length frequency of samples analysed by the CAF.

Area	q	q _{0.5}	Significance
HOWE	0.026	2.272	NS
NWCH	0.036	2.272	NS
SWCH	0.017	2.272	NS
WPAC	0.015	2.272	NS

10.3.1 Fourier analysis

The Fourier series did, with increasing asymptotic precision, reconstruct the shape of the otolith (Fig 8a and 8b). The use of the first and last 22 descriptors was used in this study as a shape vector. Previous studies (Castonguay et al. 1991, Campana & Casselman 1993, Friedland & Reddin 1994) used 20 harmonics, but no objective basis for the choice of this number was presented. It was determined empirically that 22 harmonics were needed to represent the complex morphology of the orange roughy otolith, and reduce the error in the shape of reconstructed otoliths to a level of five percent.

The observed harmonic distances from the FFT harmonic analysis between each of the areas are presented in Table 9. The observed harmonic distances represent the harmonic distance between the samples before the randomisation tests. These provide the estimator for the randomisation test to determine the probability that the distance between the mean otolith shape from the sampled areas occurred through chance.

Table 9: Observed harmonic distance between each area for orange roughy otoliths

	NWCH	SWCH	WPAC
HOWE	0.010	0.019	0.023
NWCH	*	0.013	0.019
SWCH		*	0.008

The results obtained using the randomized harmonic difference test suggest two distinct groupings of orange roughy: HOWE/NWCH otoliths being morphologically similar and SWCH/WPAC otoliths being similar (Table 10). The relationship between NWCH and SWCH stocks are harmonically close, but based on a probability of 0.1, the null hypothesis that the otoliths were sampled from the same stock is rejected ($P = 0.09$). The distribution of the randomized distances are shown in Figures 9a and 9b. Pair-wise probabilities that the otoliths were sampled from the same stock are presented in Table 10.

Table 10: Proportion of randomisations for which produced harmonic differences greater than or equal to the observed harmonic distance for each area comparison.

	NWCH	SWCH	WPAC
HOWE	0.474	0.006	0.0002
NWCH	*	0.088	0.005
SWCH		*	0.424

10.3.2 Morphometric analysis

Significant differences were found using the morphometric analysis for each of the ANOVA's; $F_{3,822}=7.4$, $P < 0.001$ for circularity, $F_{3,822}=27.7$, $P < 0.001$ for otolith area and $F_{3,822}=32.7$, $P < 0.001$ for otolith perimeter. The SNK multiple range tests determined for both otolith area and otolith perimeter showed no significant differences between NWCH and WPAC, but all other between area comparisons were significant. The SNK multiple range test on the ANOVA for otolith circularity determined significant differences between SWCH and all other areas, but no significant differences between all other comparisons.

The results from the ANOVA's on otolith area, otolith perimeter and otolith circularity demonstrate differences in otolith meristics between areas, but are less clear than the results from the Fourier randomisation test.

10.4 Assessment of biological and oceanographic information

10.4.1 Time of spawning

Spawning progression plots are shown in Figures 10 to 13. The dates of onset of spawning (20% spent) were estimated from these plots and are summarised in Table 11. There is considerable between-year variation in the time of the onset of spawning in SWCH (three weeks) and in WPAC (four weeks). In both areas the time of spawning was later in the early 1990s than in the late 1990s. Time of onset of spawning was consistent in HOWE (about mid-July in each year) and SWCH (second week of July) during 1989-93. Spawning in NWCH appears to be about three weeks earlier than in HOWE. Although the data in Table 11 overlap for only one year, a few samples collected from NWCH in mid-July 1992, around the onset of spawning in HOWE, consisted almost entirely of spent fish, and a few samples from 1997 and 1998 also suggest a pre-July spawning in NWCH. The range of dates of onset of

spawning in SWCH and WPAC overlap each other and in both areas show that spawning occurs earlier in the late 1990s than in the late 1980s early 1990s.

Table 11: Time of onset of spawning in orange roughy (defined as the date at which 20% of female fish are spent) by area and year in the eastern Tasman Sea. (— = no data; after = no spent fish observed before sampling ceased).

Year	HOWE	NWCH	SWCH	WPAC
1989	11 July	—	13/14 July	24 July
1990	17 July	—	9 July	—
1991	—	—	—	—
1992	after 15 July	—	12 July	—
1993	13 July	24 June	—	—
1994	—	—	5 July	—
1995	—	—	7 July	—
1996	—	—	—	—
1997	—	—	27 June	2 July
1998	—	—	28 June	24 June
1999	—	20/21 June	25 June	24 June

10.4.2 Oceanographic influences

The four roughy assessment areas (HOWE, SWCH, NWCH, and WPAC) lie between 35°S and 42°S over the Challenger Plateau and its northward continuation as the Lord Howe Rise. In this region of the Tasman Sea oceanographic conditions are considered to be relatively quiescent. This is because the area is well removed from the strong hydrographic and ocean current features found elsewhere in the Tasman Sea. However this region is also a data sparse region for oceanographic measurements so that it is difficult to define some features of the region with any precision.

Hydrologically the upper waters are of subtropical origin, derived from a wind driven subtropical gyre in the South Pacific. The Trade winds drive relatively warm and salty water into the Coral Sea and northern Tasman Sea. Near the Australian coast most of this water turns southwards in an intense boundary current, the East Australian Current (EAC). Around 34°S most of the EAC turns offshore and the main outflow of subtropical water is contained in the Tasman Front, a meandering flow that passes to the north of New Zealand. Where the EAC turns sharply offshore near 34°S it tends to shed a series of mesoscale eddies (typical diameter 250 km) which are found off the Australian shelf between Sydney and Tasmania. These eddies are generally anticyclonic (rotate anticlockwise in the Southern Hemisphere) with cyclonic eddies found only rarely. These eddies carry the subtropical water into the South Tasman Sea and the boundary between this water and the colder, less saline subantarctic water to the south is found at the Subtropical Front. The Subtropical Front is found in a broad zone running from Tasmania and passing around the south of the South Island. The main features of this circulation pattern are shown in Figure 14, which indicates that the orange roughy fisheries are found in the relatively quiescent region between

the stronger Tasman Front and Subtropical Front. In this region the mean sea surface temperature is around 16.5°C and has a seasonal range of +/-2.5°C (Uddstrom & Oien, 1999). Surface salinities are around 35.4 +/-0.1.(Garner 1970; Stanton & Ridgway, 1988). Below the surface mixed layer the temperature decreases with depth being typically around 5°C at 1000 m. Seasonal temperature changes are undetectable below around 200 m (Rahmstorf 1992). Salinity decreases with depth until the salinity minimum of around 34.5 is reached at 900m depth. This minimum is associated with Antarctic Intermediate water (AAIW) carried below the subtropical gyre and therefore entering the Tasman Sea from the North although it is thought that some AAIW water enters the South Tasman Sea from the south.

The EAC spawns about 3 eddies/year and these can be long lived features with coherent eddies having been observed for over 2 years (Bennett 1983), but confined to the west of 160°E. The eddies in the south Tasman Sea eventually dissipate and the circulation on the New Zealand side of the Tasman sea is seen as a relatively slow meandering drift eastwards, sometimes referred to as the Tasman Current. Waters in this flow are constrained to eventually flow around either end of New Zealand. Most of the water passes around the north of New Zealand but some flow does also pass around the south of New Zealand.

Current flows, estimated from satellite-tracked near surface drifters, show slow meandering eastward paths across the Tasman Sea. Such meanders are common in these types of data and are the result of the dominance of eddies in the ocean. The fluctuations span a broad range of time and space scales. They are due to phenomena such as tides, inertial oscillations, wind fluctuations, baroclinic instability and interaction with bottom topographic features. The WOCE buoy tracks in the area are shown in Figure 15. The buoys have a limited life before they stop transmitting to satellite, which accounts for the abrupt termination of some tracks. Looking at individual buoy tracks the fastest flows are seen in the Tasman Front region, with speeds of up to 50 cm s⁻¹. In the south Tasman Sea speeds are much slower, with a maximum around 25 cm s⁻¹. Typical speeds in the WPAC to HOWE area are around 10 cm s⁻¹. The only common feature of the buoy tracks in the south Tasman is a general movement north-eastwards roughly parallel to the coast of the South Island. The relationship of individual tracks to the bathymetry especially the south-west flank of the Challenger Plateau/Lord Howe Rise show some tracks moving northwards along the slope, others moving southwards and yet others passing over the ridge largely unaffected.

Subsurface flows at around 900 m depth have measured using autonomous drifters, over the period 1991/98. These instruments drift at 900 m for 25 days, rise briefly to the surface to report their position via satellite, before sinking to repeat the cycle. The deep drifter tracks in the area of interest are shown in Figure 16. The 25-day buoy displacements are shown along with the four roughy areas and the 500 m, 1000 m, 1500 m and 2000 m bathymetric contours. The maximum speeds in the area are 7 cm s⁻¹, but typical speeds are more like 2 cm s⁻¹. Very few drifters have passed through the roughy areas, but the general meandering nature of the flow at this depth is seen to be similar (but much weaker) than the surface flow.

10.5. Interpretation of stock discrimination information on Lord Howe Rise and Challenger Plateau orange roughy

A range of techniques have been applied to orange roughy stock discrimination in Australia and New Zealand; and many of the independent studies have included samples from either HOWE and/or the Challenger Plateau. Several studies comparing sites within the New Zealand EEZ have shown differences between samples from the Challenger Plateau and other areas; results are summarized in Table 12. The phenotypic character, otolith shape, has been successfully applied to orange roughy stock discrimination in other regions (Smith et al. 1998). Specific comparisons of multiple samples collected within the Challenger/HOWE area have shown:

- significant genetic differences between samples from HOWE and NWCH with an allozyme marker (Smith 1997,1998) and mtDNA haplotypes (Smith 1998), but not two microsatellite DNA markers (Smith 1998);
- significant genetic differences between samples from the NWCH and SWCH with one allozyme marker (Smith 1998);
- significantly higher levels of lead in otolith samples from HOWE than from NWCH and SWCH (Thresher et al. 1999), but no differences between NWCH and SWCH (Thresher et al. 1999); significantly higher levels of copper in otolith samples from HOWE than from SWCH (Thresher et al. 1999);
- larger fish on HOWE than NWCH in the 1980's but not 1990's (Clark & Tilzey 1996, Clark 1998).

Size

Clark & Tilzey (1996) and Clark (1998) provided plots of mean lengths for males and female orange roughy from HOWE and NWCH and showed that HOWE fish were larger than NWCH in the late 1980s and early 1990s, but by 1994-96 there was overlap in mean length; no statistical analyses were undertaken on their data. The present study indicates that the size differences between HOWE and NWCH (and between HOWE-SWCH and HOWE-WPAC) are significant. Consistently larger fish on HOWE (2-3 cm larger than NWCH and SWCH) indicates that there is little short term *exchange* of fish between HOWE and the Challenger sites. An alternative explanation is that the size difference reflects a slow age-related movement with older (and larger) fish moving northwards from SWCH to NWCH to HOWE and then remaining in the area.

The smaller (<1 cm), but significant difference between SWCH and WPAC potentially indicates some biological difference between these two geographically close fisheries. However these small differences might reflect sampling artefacts between fisheries on spawning (pinnacle-based) and non-spawning (flat-based) sub-populations rather than stock differences. In the 1980s the levels of non-spawning fish were higher on WPAC than SWCH (Clark & Tracey 1994). During the 1990s there was a change in fishing patterns. Most fishing was carried out in the June-July spawning period, but on SWCH fishing was focused on long tows (13-14 nm) on the "flat" ground, whereas on WPAC fishing continued to be based on short tows (2 nm) on pinnacles (Clark 1999).

Francis & Tracey (2000) reported that the mean length at WPAC was similar to SWCH in 1988, but different (larger) in 1989. They pointed out that lack of comparability is a major problem with data from commercial catches because of sampling artefacts due to

changes in fleet fishing patterns. We attempted to maximise comparability between areas and years by using only samples from catches greater than 1 t and from the months of June or July, the spawning period. However this could still lead to sampling artefacts if catches were taken from spawning and non-spawning populations, as described above, and larger fish occur in spawning areas.

Length frequencies of orange roughy in the spawning box on the Chatham Rise also vary between years (Clark et al. 2000). Males showed a decrease of >1 cm between 1992-94, which may be due to sampling error, but overall there were no detectable changes in mean length between 1984-1996 (Clark et al. 2000).

Life history

Mean ages and lengths at maturity have been estimated for orange roughy populations in the New Zealand EEZ and in the Atlantic Ocean (Horn et al. 1998). There are significant between-area differences in both traits. In the New Zealand EEZ orange roughy on the Challenger Plateau matured at a smaller age and size than fish from east coast sites (Horn et al. 1998). The present study has revealed significant differences in L_{mat} among samples collected from SWCH. Size at maturity also varied considerably over ten years of sampling on the Chatham Rise (Clark et al. 2000); age at maturity was estimated only for two years over the same period and showed no significant difference (Clark et al. 2000). The observed changes in L_{mat} on the Chatham Rise (Clark et al. 2000), combined with differences found on SWCH, suggest that previous conclusions of discrete stocks of orange roughy based on differences in L_{mat} in small samples may be erroneous. Considering this limitation, then the observed difference in A_{mat} between HOWE and WPAC lend only weak support to a HOWE-Challenger stock division.

Otolith shape

The results from the Fourier harmonic shape analysis indicate significant variation in otolith shape among the area samples. The samples from HOWE-NWCH are grouped and SWCH-WPAC are grouped, with significant differences between these two groups. As otolith shape is a phenotypic character, these differences may reflect underlying genetic differences, environmental differences, or a combination of the two. The mechanisms which drive the differences in otolith morphology between stocks are still poorly understood (Smith et al. 1998), but the following observations point towards a strong environmental component to otolith shape. In other marine teleosts otolith shape has been shown to differ among ages, sexes and year-classes (Bird et al. 1986, Castonguay et al. 1991, Campana & Casselman 1993, Smith 1992). In the Atlantic cod *Gadus morhua* otolith shape changes in response to growth rate, and variation in growth rates may be the most significant cause of variation in otolith shape (Campana & Casselman 1993). Experimental studies with captive fish have shown that otolith morphology varies in response to differences in growth rate (Reznick et al. 1989, Secor & Dean 1989). The age (and hence the growth rate) of orange roughy used in these analyses is unknown, as is the extent to which the observed differences can be attributed to these factors. The Fourier descriptors were standardized for otolith size before analysis, which will at least partially remove any age effect on the differences.

Recently Gauldie & Jones (2000) used a simple measure of otolith shape based on standardised otolith length/otolith width to show differences between orange roughy from the Challenger Plateau and Chatham Rise. They (Gauldie & Jones 2000) also concluded that there were significant differences in growth rates between wide scale

fishery areas, although their growth rate estimates were based on young ages (<20 years) for orange roughy.

Time of spawning

The observed change in time of spawning at SWCH and WPAC is unexpected for orange roughy. Similar changes have not been reported for this species. On the Chatham Rise time of spawning has been consistent over a 12 year period (Clark et al. 2000). Early studies on the Challenger Plateau, based on research surveys of small samples, also found no evidence for a change in spawning time (Clark & Tracey 1994). Pankhurst (1988) suggested that day length was a critical factor in synchronising the reproductive cycle in orange roughy. It has been assumed that temperature shows little annual variation at 800-1000m (Pankhurst 1988), although year to year data are not available for the Challenger Plateau and Lord Howe Rise. In other shallow water species the time of spawning shows plasticity in response to physical variables, such as temperature, and to biotic conditions (Carscadden et al. 1997; Millan 1999). In several shallow water marine species, large fish spawn earlier in the season than smaller cohorts (Dawson 1986, Carscadden et al. 1997; Millan 1999, Slotte et al. 2000).

There are indications that heavy fishing may disrupt schools of orange roughy on the Challenger Plateau (Clark & Tracey 1994). However on the Chatham Rise, to the east of New Zealand, the time of spawning has remained consistent and there have been no detectable changes in mean length over the period 1984-1996 (Clark et al. 2000), in spite of heavy fishing pressure

The marked changes in the time of spawning within areas suggest that it is inappropriate to use spawning time differences as an indicator of stock differences (Clark & Tilzey 1996). The reported differences between HOWE and NWCH (Clark & Tilzey 1996) may be due to temporal rather than spatial differences in spawning times. There is no evidence from this study that spawning on WPAC occurs later than SWCH, as suggested by Clark & Tracey (1994).

Table 12: Summary of stock discrimination studies of orange roughy that include samples from the Lord Howe Rise and/or Challenger Plateau. HOWE = Lord Howe Rise; SWCH = Southwest Challenger Plateau; NWCH = Northwest Challenger Plateau.

Method	Areas	Result	Reference
Genetics			
allozyme, <i>Idh-2*</i>	Tasman Sea	difference HOWE/NWCH, NWCH/SWCH	Smith 1997, 1998
MtDNA haplotypes	NZ EEZ	difference SWCH/Cook Canyon	Smith et al. 1996
Mt DNA	Tasman Sea	no differentiation	Smith 1997
D-loop haplotypes			
mtDNA	HOWE/NWCH/	difference HOWE/NWCH	Smith 1998
<i>Bgl</i> 1 haplotypes	SWCH	no difference NWCH/SWCH	
MtDNA haplotypes	SWC/Australia	difference SWCH and Australia	Smolenski et al. 1993.
microsatellite DNA	HOWE/NWCH/	no differentiation	Smith 1998
	SWCH		
microsatellite DNA	Tasman Sea	no differentiation	Oke, La Trobe, unpub.
Life history			
Age at 1 st maturity	NZ EEZ	Challenger mature at younger than east coast fish	Horn et al. 1998
length at 1 st maturity	NZ EEZ	Challenger mature at smaller than east coast fish	Horn et al. 1998
Phenotypic			
6 morphometric and 2 meristic characters	Puysegur/HOWE	differences in body shape	Haddon & Willis 1995
otolith length/width	SWCH/eastcoast	Differences SWCH/Chatham Rise	Gauldie & Jones 2000
otolith length/height	NWCH/Chatham Rise	No difference	Linowski & Liwoch 1986
Acquired characters			
Parasites	NZ EEZ	differences SWCH/Cook canyon	Lester et al. 1988
	NZ EEZ	Parasite load not related to area	Gauldie & Jones 2000
microchemistry	Australia and NZ	HOWE higher lead than NWCH/SWCH	Thresher & Proctor 1998; Thresher et al. 1999
otoliths			
Biological			
length frequencies	HOWE, NWCH	HOWE bigger fish in 1980s, but not 1990s.	Clark & Tilzey 1996, Clark 1998

Genetics

One allozyme locus has shown significant genetic differentiation among samples collected in the eastern and western Tasman Sea (Smith 1997, 1998a). In the eastern Tasman Sea there are significant differences between NWCH and HOWE and between NWCH and SWCH samples collected in 1996. Allele frequencies provide a powerful test of population differentiation and significant genetic differences among regions have been taken as evidence for discrete stocks. However care is required when interpreting population differences in the Challenger-HOWE data as parallel studies with the *Idh-2** marker to the east of New Zealand have shown both spatial and temporal heterogeneity (Smith & Benson 1997). Replicate tissue collections made in 1997-98 support the initial findings of genetic differences between SWCH and NWCH and between HOWE and NWCH (Smith 1997, 1998a), but the NWCH repeat sample was small (23 fish) due to the low level of fishing effort outside the New Zealand EEZ. Repeat samples would be desirable to test for *Idh-2** temporal heterogeneity.

Black and Dixon (1989) also reported population sub division with the *Idh* heart locus with 4 genetic groups showing spatial and size related differences: Heterozygotes at their *Idh* locus appeared as atypical two- band types (Black & Dixon 1989), whereas *Idh* heterozygotes typically resolved as three bands. It is possible that different electrophoretic conditions used by the two laboratories produced different gel phenotypes.

Studies with mitochondrial (mt) DNA reported genetic sub division between New South Wales and other Australian sites (Table 12) and temporal differences between fish sampled in two consecutive years off South Australia (Smolenski et al 1993). Within the New Zealand EEZ similar studies of the whole mitochondrial genome revealed unique restriction fragments in a sample from SWCH (Smith et al. 1996). Further analyses with this marker found the unique restriction fragment in additional samples from SWCH and NWCH, but not in one sample from HOWE (Smith 1998a). The differences were significant, indicating a genetic difference between HOWE and NWCH/SWCH.

Other mtDNA studies have employed a different molecular tool, haplotypes in the mtDNA control region (Smith 1997, Smith et al. 1996). There is no evidence for genetic subdivision in the Tasman Sea, including samples from HOWE, NWCH, and SWCH (Smith 1997), although the same tool has shown heterogeneity among New Zealand east coast stocks (Smith et al. 1996).

Finding genetic differentiation over the relatively small spatial scale between HOWE and SWCH (HOWE-NWCH: 220 kms; NWCH-SWCH: 300 kms) is surprising given the longevity of orange roughy and the lack of apparent oceanographic barriers to larval and juvenile dispersal. Several marine fishes show little genetic differentiation over ocean wide scales (Waples 1998), including orange roughy (Baker et al. 1995; Elliot & Ward 1992). In contrast interdecadal genetic changes have been reported in Atlantic haddock mtDNA haplotypes (Purcell et al. 1996) and in western rock lobster allozyme frequencies (Thompson et al. 1996). There are also reports of genetic differences among year-classes in marine teleosts (see references in Smith et al. 1990). Some

studies of orange roughy have shown both spatial (Smith et al. 1996) and temporal structure (Smolenski et al. 1993).

There is inconsistency among the Challenger-HOWE genetic data sets. The *Idh-2** allozyme data showed differences between HOWE-NWCH and between NWCH-SWCH (Smith 1997) while the mtDNA *Bgl* 1 haplotype data showed differences among HOWE-NWCH and HOWE-SWCH (Smith 1998a). The differences observed with this latter genetic marker extend and confirm the initial genetic results (Smith et al. 1996) of a unique restriction haplotype that is restricted to the Challenger Plateau. Given the temporal heterogeneity observed with *Idh-2** genetic marker among east coast stocks then the differences among HOWE-NWCH and NWCH-SWCH should be viewed with caution.

Unpublished results applying microsatellite DNA markers to samples from the eastern and western Tasman Sea, including the Challenger Plateau, found no evidence for genetic differentiation (Oke pers com).

Otolith microchemistry

The elemental composition of otoliths has been used as a stock discrimination tool in several marine fishes including orange roughy (Edmonds et al. 1991; Thresher & Proctor 1998; Thresher et al. 1999). A critical review of the technique highlighted several problems in the application of this tool for stock identification (Thresher 1999); in particular sample contamination and lack of replication. A comparison of Australian and New Zealand sites, using only elements that appear to be largely unaffected by handling, found significantly higher levels of lead in a sample from HOWE (35°39'S 165° 11'E) than in all other samples, including NWCH and SWCH (Thresher & Proctor 1998, Thresher et al. 1999). The HOWE sample also had high levels of copper; significantly higher than SWCH, but not NWCH (Thresher & Proctor 1998). There were no significant differences between NWCH and SWCH for five elements (Thresher & Proctor 1998). The differences were based on small sample sizes (around 20 fish per area) and need to be confirmed in larger (50 fish) replicate samples, especially for HOWE with unusually high levels of lead (Thresher & Proctor 1998). Most orange roughy otoliths have shown relatively low levels of lead, at or near the limit of detection (Proctor & Thresher pers comm).

Oceanography

Ocean eddies have been shown to be important in confining larvae and juveniles in some regions (e.g. Chiswell & Booth 1999). Eddies in the ocean are somewhat ubiquitous, occurring over a wide range of spatial and temporal scales. The orange fisheries are in a region of relatively weak but highly variable flows. There is no evidence for the existence of long-lived eddies such as are seen in the EAC extension region west of 160°E, or semi-permanent eddies found off the north-east coast of the North Island. Any eddies in the region would probably be somewhat transitory, and there is no evidence of eddies that are semi-permanently trapped by the bottom topography. However, this is a data sparse region so that direct evidence of topographic trapping may await further investigation.

Plankton studies on the Chatham Rise have shown that the eggs of orange roughy ascend rapidly and remain in the plankton for about 10 days before descending and hatching near the bottom (Zeldis et al. 1994). On the north Chatham Rise the eggs probably drift less than 50 km before hatching (Zeldis et al. 1994). The larvae are thought to be epibenthic (Zeldis pers comm) and the highest concentrations of juveniles are found between 50-175 kms downstream of the main spawning area (Mace et al. 1990).

At present there is no evidence for any major differences in the flow regime between the four orange roughy fisheries. Similarly there are no major differences in the hydrographic conditions in each of the fishery areas, apart from those arising from the different depth regime in each area. The drifter data show that orange roughy eggs will experience stronger flows near the surface than larvae at depth. The relatively low surface flows, coupled with the short planktonic stage (Zeldis et al. 1994), suggest that while there is no isolation between SWCH and WPAC, it is unlikely that there would be exchange of eggs between the SWCH/WPAC and the NWCH spawning sites (Fig 15). Planktonic drift of eggs from HOWE to NWCH would be marginal, based on surface drifter tracks. The genetic differentiation observed between these areas indicates that there is little gene flow between these two areas.

Little is known of the larval and early juvenile phase of orange roughy, but these stages of the life cycle probably occur in midwater or close to the bottom. Late juveniles are caught in bottom trawls on the Chatham Rise. The limited deep drifter tracks for the eastern Tasman Sea suggest weak flows that would limit the passive dispersal of larval and juvenile stages among the geographically isolated fisheries.

Overview

There is no universal method for determining stock relationships in marine fishes, rather management advice is drawn from different sources. Data relevant to determining stock relationships in the Challenger-HOWE area are summarised in Table 13. There are significant differences between samples taken from HOWE and NWCH (distance of 220 kms) with three independent data sets: mtDNA, lead levels in otoliths and mean lengths. The same three tools also showed significant differences among more distant sites HOWE-SWCH. A fourth method, otolith shape, demonstrated two major stock groupings: HOWE-NWCH and SWCH-WPAC.

These independent results suggest that interactions between the three fisheries HOWE, NWCH, and SWCH are restricted and the areas could be managed as separate units. Two fisheries, HOWE and NWCH occur in international waters outside the EEZ.

There are fewer data sets comparing SWCH-WPAC (Table 13), and only one out of 3 methods, length frequencies (Table 13), revealed a difference between SWCH and WPAC. The small difference in mean lengths maybe due to commercial fishing activities harvesting fish from spawning and non-spawning areas. There were no differences between these two areas with otolith shape, but WPAC was different to NWCH and to HOWE for otolith shape. Lack of differences among the WPAC and SWCH fisheries, coupled with their geographical proximity suggest that the two fisheries exploit part of one stock which straddles the New Zealand EEZ.

Table 13: Summary of pair-wise differences among orange roughy samples from the Challenger-Howe area. HOWE = Lord Howe Rise; NWCH = Northwest Challenger Plateau; SWCH = Southwest Challenger Plateau; WPAC = Westpac; NS = not significant.

Areas	Differences (significant unless indicated)	Reference
HOWE-NWCH	Fish length: HOWE larger	This study; Clark & Tilzey 1996; Clark 1998
	Life history: NS	This study
	Otolith shape: NS	This study
	Genetics: mtDNA <i>Bgl</i> 1 haplotypes	Smith 1998a
	Genetics: allozyme, <i>Idh-2</i> *	Smith 1997, 1998a
	Microchemistry: Lead in otoliths	Thresher & Proctor 1998
HOWE-SWCH	Fish length: HOWE larger	This study
	Life-history: NS	This study
	Otolith shape differs	This study
	Genetics: mtDNA <i>Bgl</i> 1 haplotypes	Smith 1998a
	Microchemistry: Copper and lead in otoliths	Thresher & Proctor 1998
HOWE-WPAC	Fish length: HOWE larger	This study
	Life-history: <i>A_{mat}</i> significant	This study
	Otolith shape differs	This study
	Genetics: not tested	-
	Microchemistry: not tested	-
NWCH-SWCH	Fish length: NS	This study
	Life history: NS	This study
	Otolith shape: marginal difference	This study
	Genetics: allozyme, <i>Idh-2</i> *	Smith 1997, 1998a
	Microchemistry: not tested	-
NWCH-WPAC	Fish length: NS	This study
	Life history: NS	This study
	Otolith shape differs	This study
	Genetics: not tested	-
	Microchemistry: not tested	-
SWCH-WPAC	Fish length: SWCH smaller	This study
	Life-history: NS	This study
	Otolith shape: NS	This study
	Genetics: not tested	-
	Microchemistry: not tested	-

11. Conclusions

1. Length frequencies. The mean length of fish from HOWE was significantly greater than fish from NWCH, SWCH and WPAC. There was a small (<1 cm) but significant difference in mean length between fish from SWCH and WPAC, which likely reflects different fishing patterns between these two fisheries.
2. Age and length at maturity. There was a trend of increasing A_{mat} with decreasing latitude with a significant difference between samples from HOWE and WPAC. There were no significant differences among areas for L_{mat} . Comparison with published data from the Challenger Plateau showed significant differences among samples taken on the Challenger Plateau for both A_{mat} and L_{mat} . Previous conclusions of discrete stocks of orange roughy based on differences in A_{mat} and L_{mat} in small samples may be erroneous.
3. Otolith shape. There were two significantly different groups based on phenotypic differences in otolith shape: HOWE/NWCH and SWCH/WPAC.
4. Time of spawning. There was considerable temporal variation in the time of the onset of spawning in SWCH (three weeks) and in WPAC (four weeks). The biological mechanism leading to a shift in spawning time is unclear, but the observed temporal changes invalidate spawning time as an indicator of regional stock differences in the HOWE-Challenger area where there is an incomplete temporal gonad data set.
5. Oceanography. Oceanographic conditions in the HOWE-Challenger area not well defined, but the region is characterised by relatively weak and variable flows. While there are no strongly defined eddies that would confine eggs, larvae and early juveniles, their passive dispersal would be limited by the weak flows.
6. Genetics. Smith reported significant genetic differences between HOWE and NWCH/SWCH with mtDNA haplotypes; and significant genetic differences between HOWE-NWCH and NWCH-SWCH with one allozyme marker, but this marker has shown both spatial and temporal variation Chatham Rise-east coast fisheries.
7. Otolith microchemistry. Thresher and Proctor found significantly higher levels of lead in HOWE than NWCH and SWCH, and significantly higher levels of copper in HOWE than SWCH. There were no significant differences between NWCH and SWCH for five elements.
8. Stock relationships. There were biological differences between orange roughy from HOWE, NWCH, and SWCH. These fisheries could be managed as independent stocks. There were no biological differences between SWCH and WPAC and these fisheries probably exploit one straddling stock.

12. Publications

Progress report to Ministry of Fisheries, August 2000.

13. Data Storage

length frequencies:	data are stored in the <i>obs_lfs</i> data base held at NIWA
life history:	data are stored in EXCEL file on the <i>H:</i> drive at NIWA
otolith shape:	all images and data are recorded on Kodak CD-ROMS
spawning time:	data are stored in the <i>obs_lfs</i> data base held at NIWA
oceanographic conditions:	data are stored on CD, in the data archive held by the physical oceanography group in NIWA.

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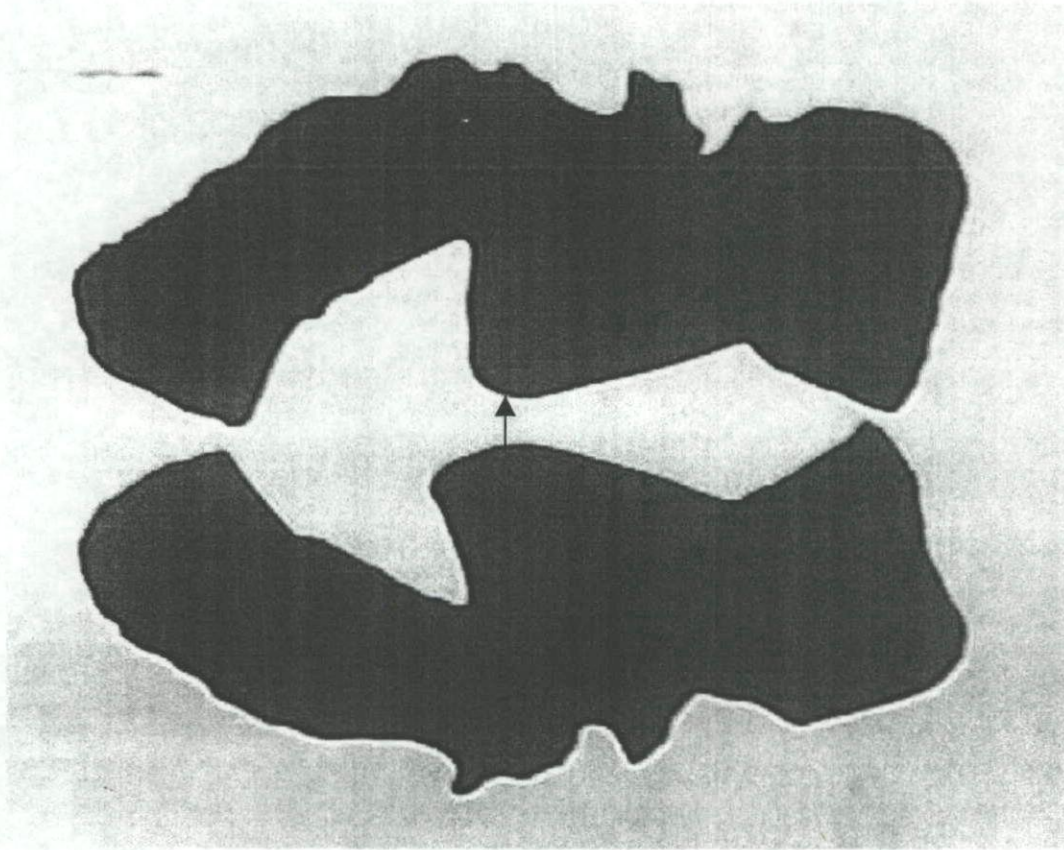


Figure 1: Image of an orange roughy otolith (JPEG format). Automatic tracings started at landmark location marked with an arrow.

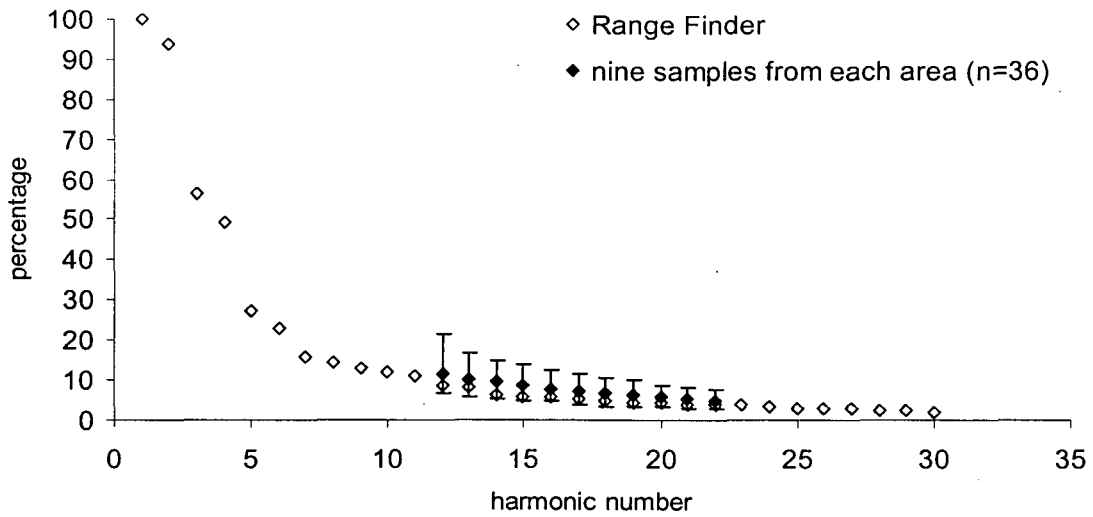


Figure 2: Mean otolith reconstruction error for the range finder otolith randomly selected from all of the samples supplied to the CAF (area : Westpac, length : 32 cm sl., sex : female). The mean reconstruction error from nine randomly selected samples from each area combined. Errors bars are minimum and maximum percentage error reconstruction.

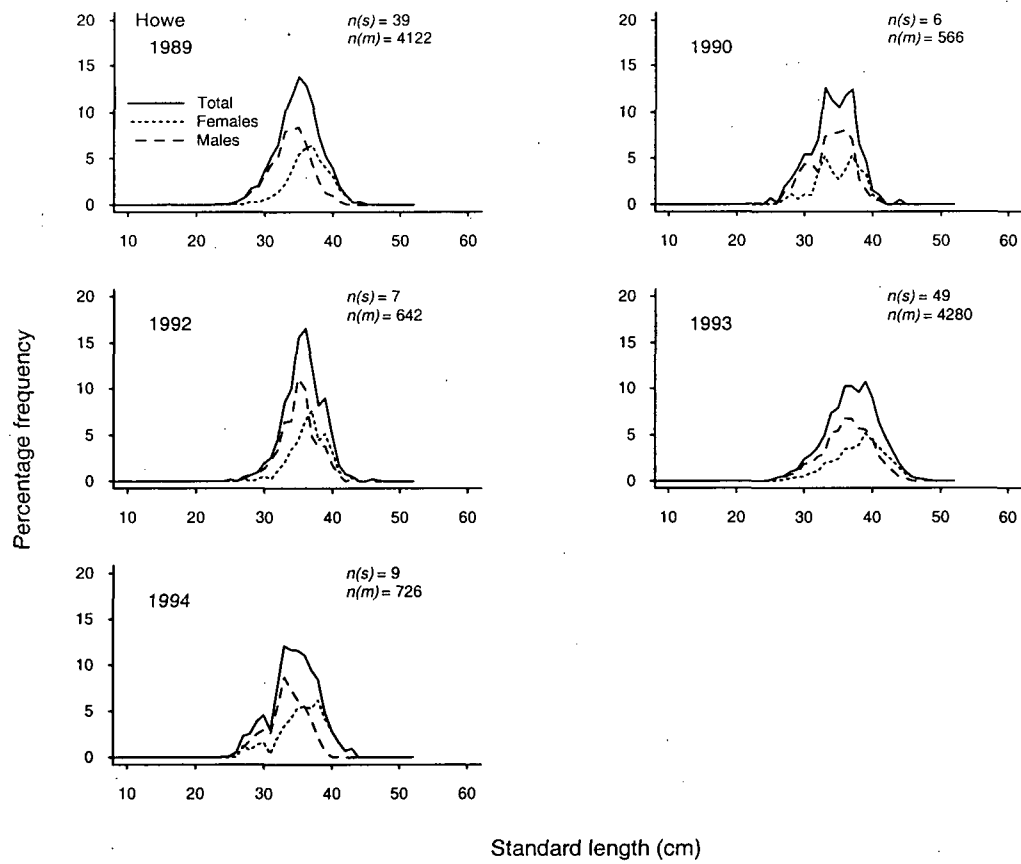


Figure 3: Observer orange roughy length frequency distributions (scaled by catch) from area HOWE, $n(s)$, number of samples; $n(m)$, number of fish measured.

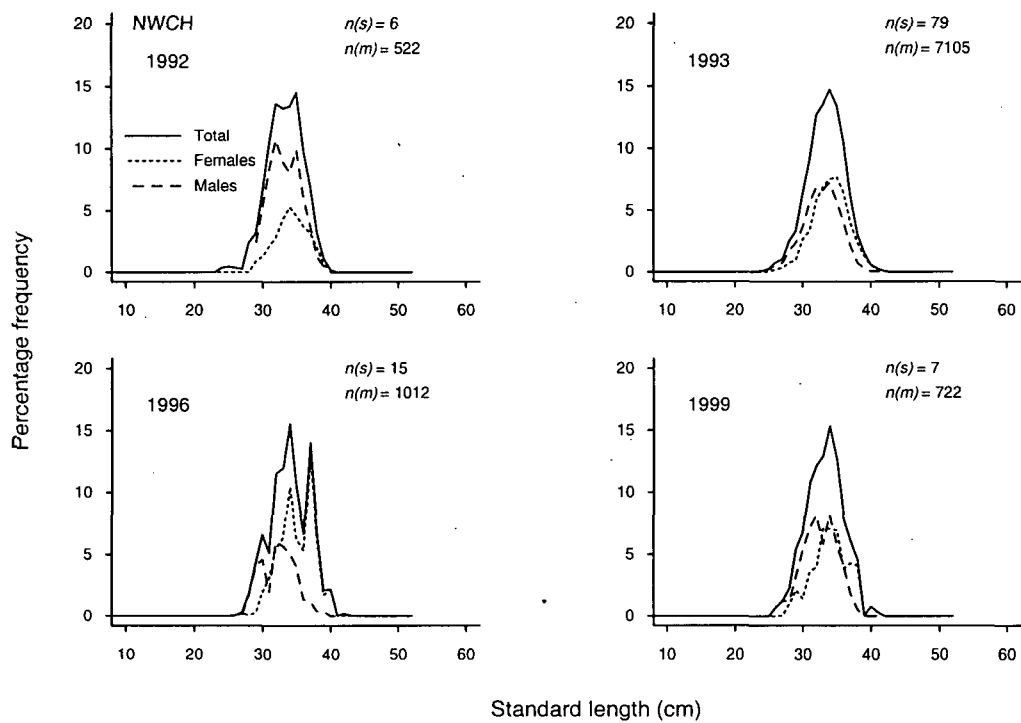


Figure 4: Observer orange roughy length frequency distributions (scaled by catch) from area NWCH, $n(s)$, number of samples; $n(m)$, number of fish measured.

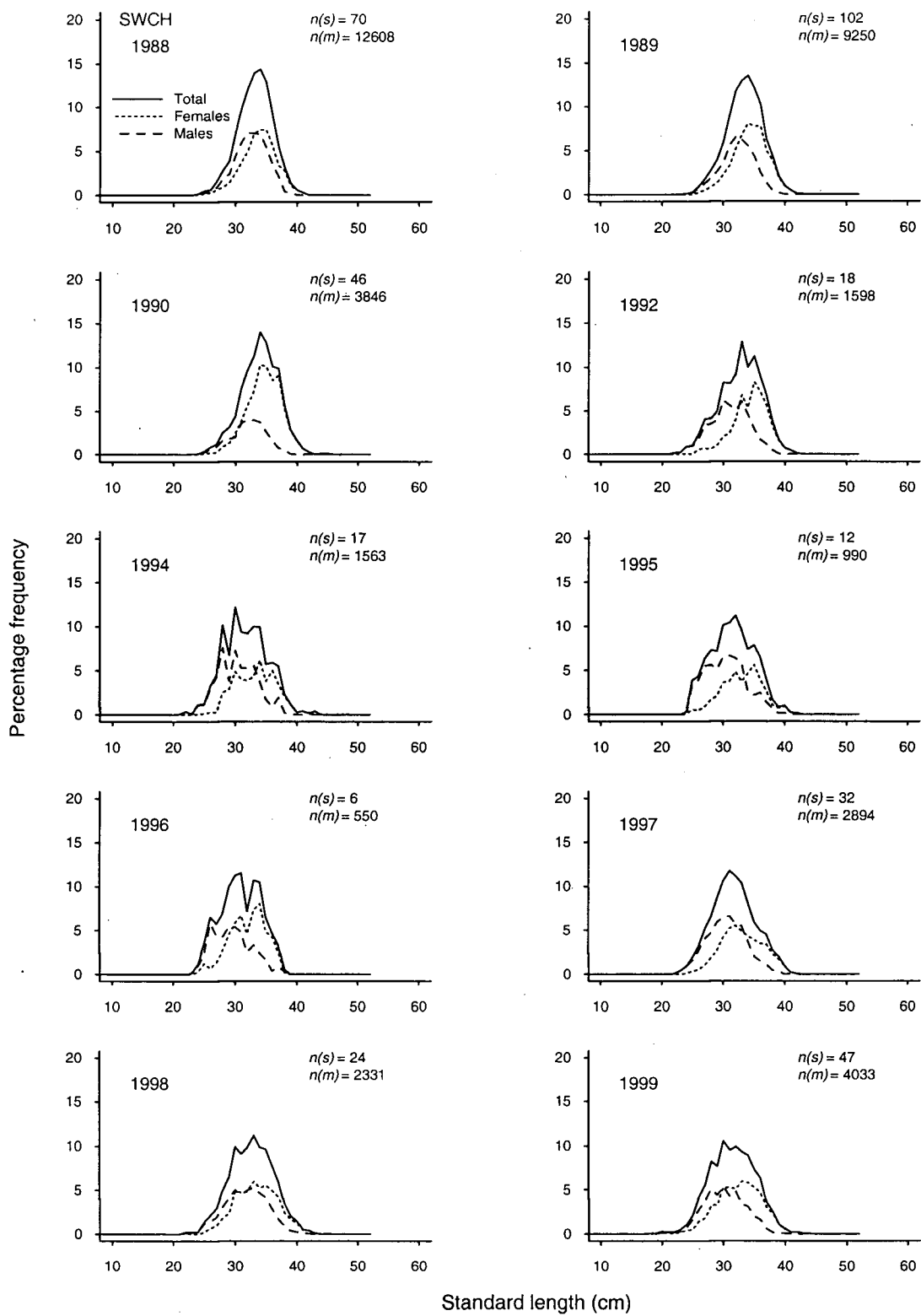


Figure 5: Observer orange roughy length frequency distributions (scaled by catch) from area SWCH, $n(s)$, number of samples; $n(m)$, number of fish measured.

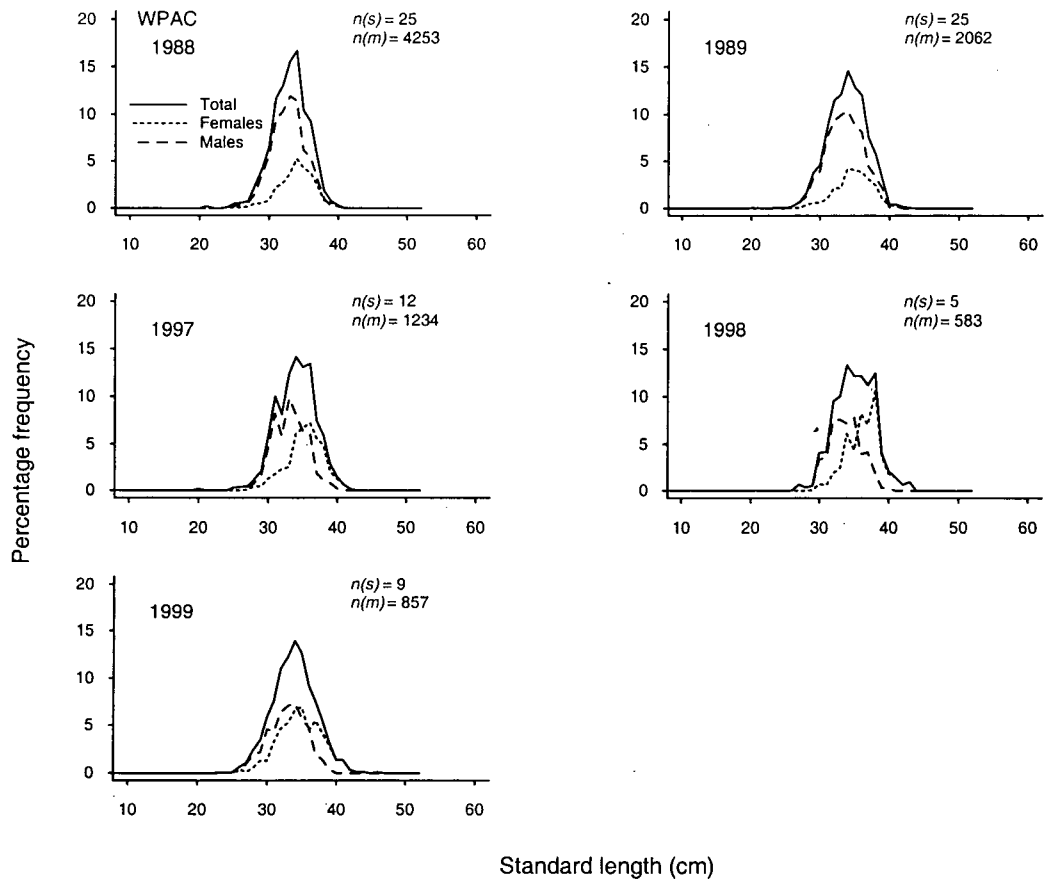


Figure 6: Observer orange roughy length frequency distributions (scaled by catch) from area WPAC, $n(s)$, number of samples; $n(m)$, number of fish measured.

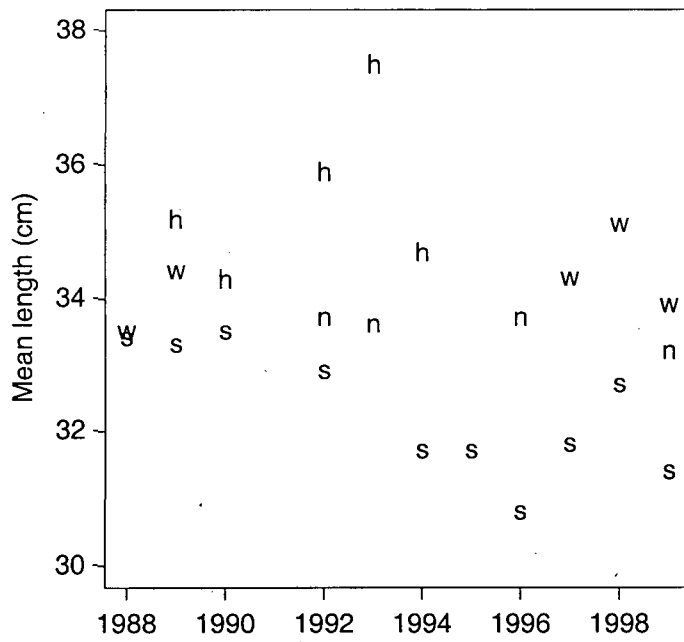


Figure 7: Mean lengths of orange roughy (average of mean male and mean female lengths) by area and year from observer length frequency data scaled by catch. h, HOWE; n, NWCH; s, SWCH; w, WPAC.

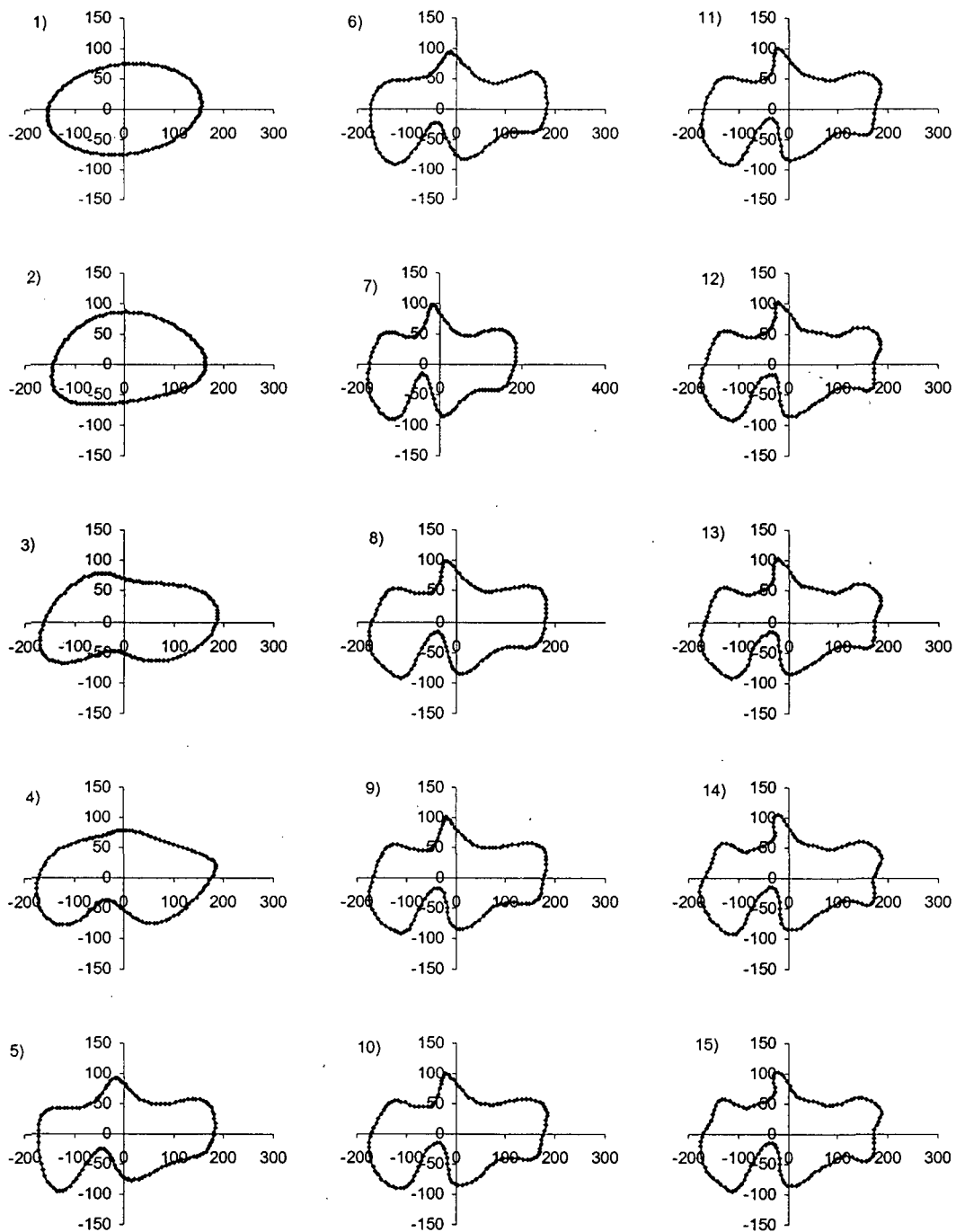


Figure 8a. Otolith reconstruction using the first and last 15 complex numbers sequentially from the inverse of the Fourier transform. The reconstruction is from the range finder otolith randomly selected from all of the samples supplied to the CAF (area : WPAC, length : 32 cm sl., sex : female).

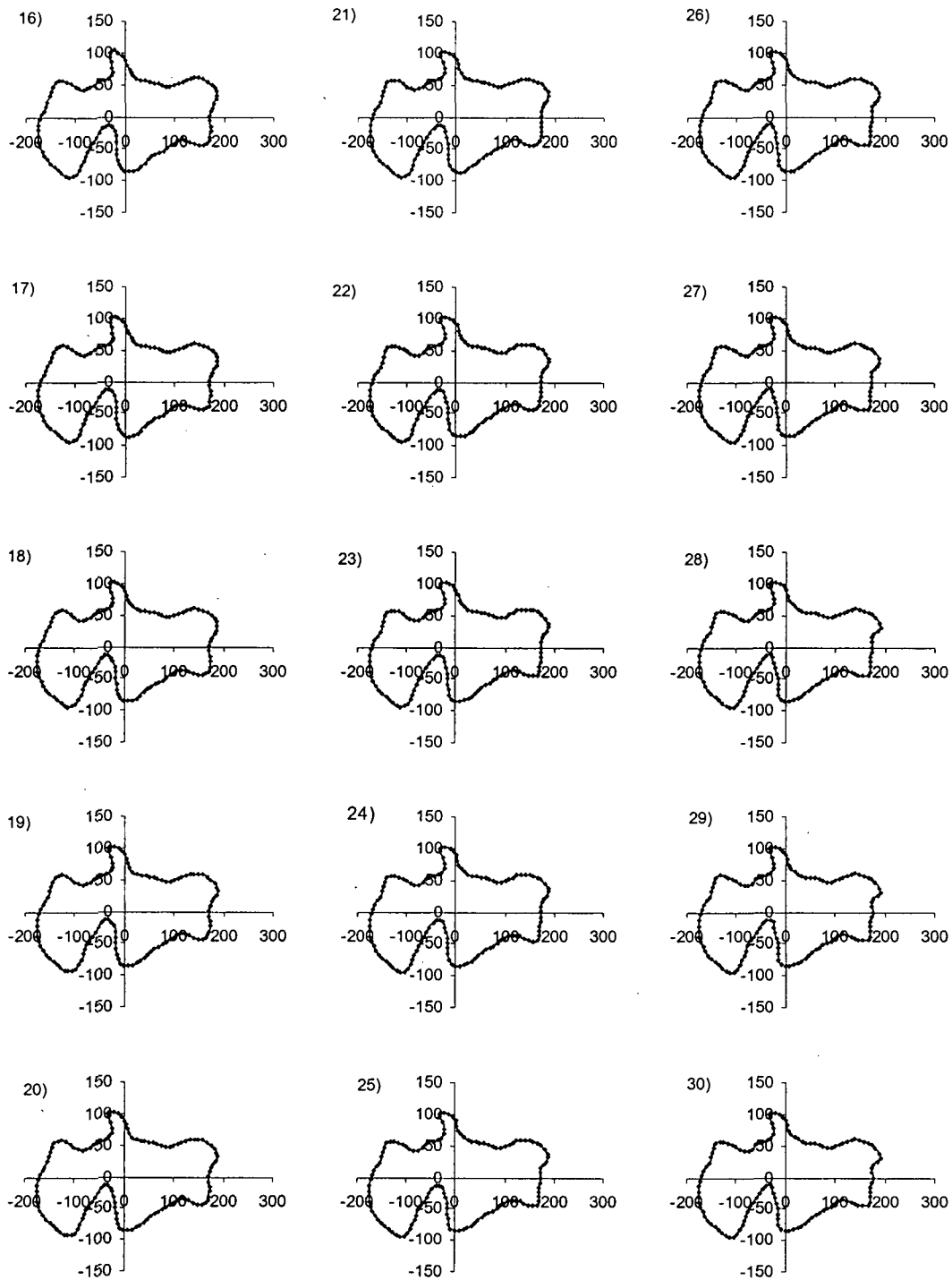
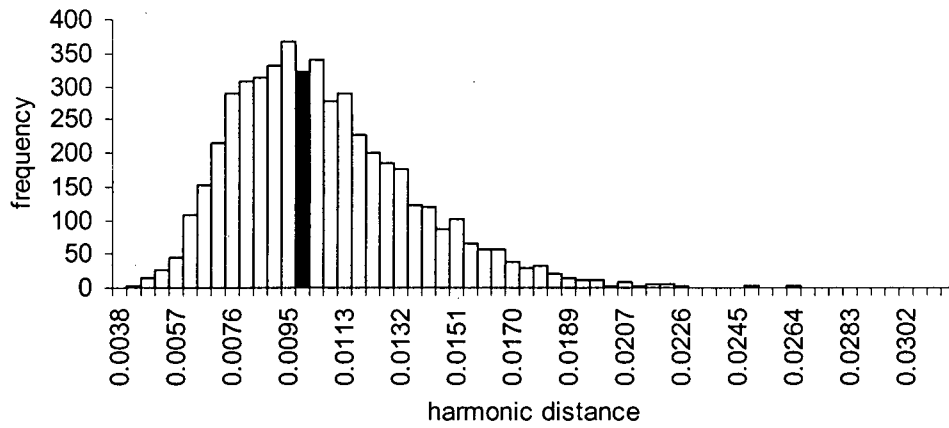
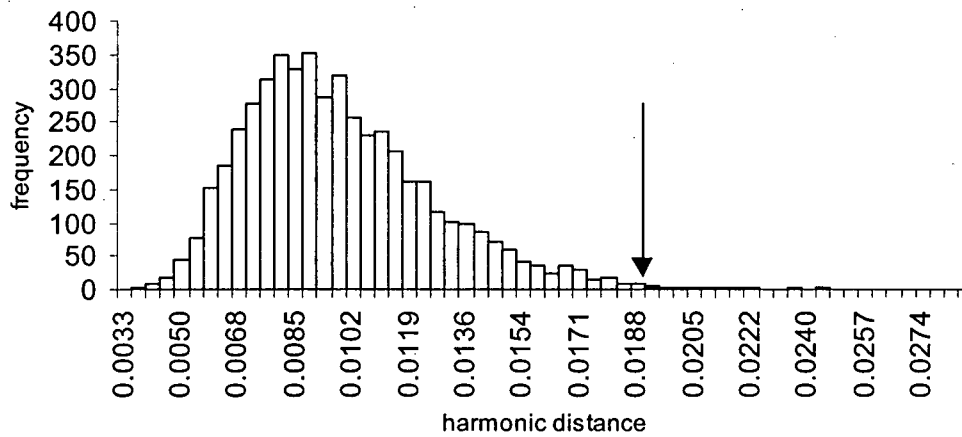


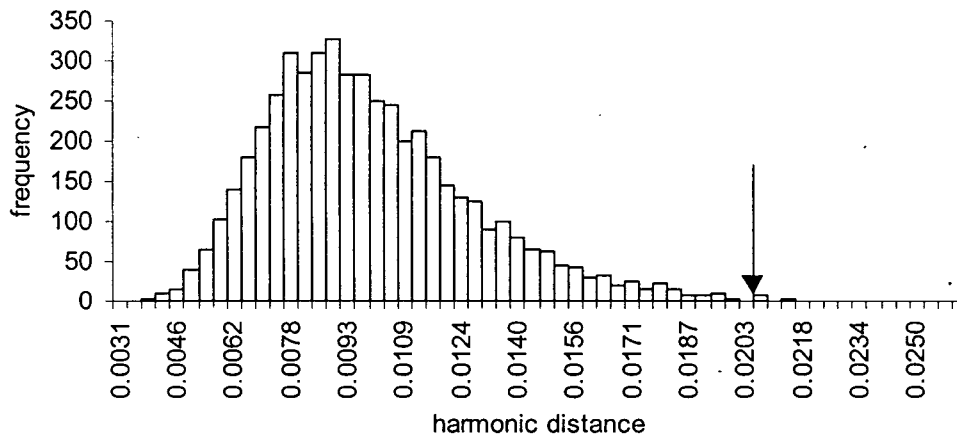
Figure 8b. Otolith reconstruction using the from the 15th to the 30th (and 113th to 106th) complex numbers sequentially from the inverse of the Fourier transform. The reconstruction is form the range finder otolith randomly selected from all of the samples supplied to the CAF (area : WPAC, length : 32 cm sl., sex : female).



HOWE vs. NWCH

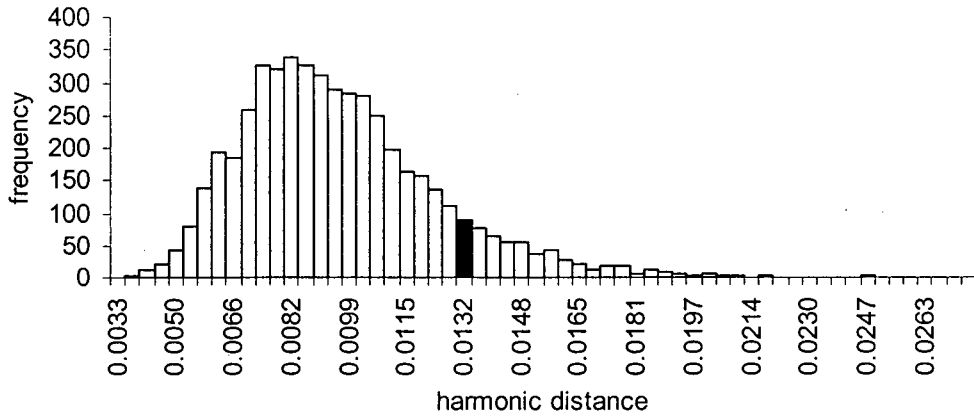


HOWE vs. SWCH

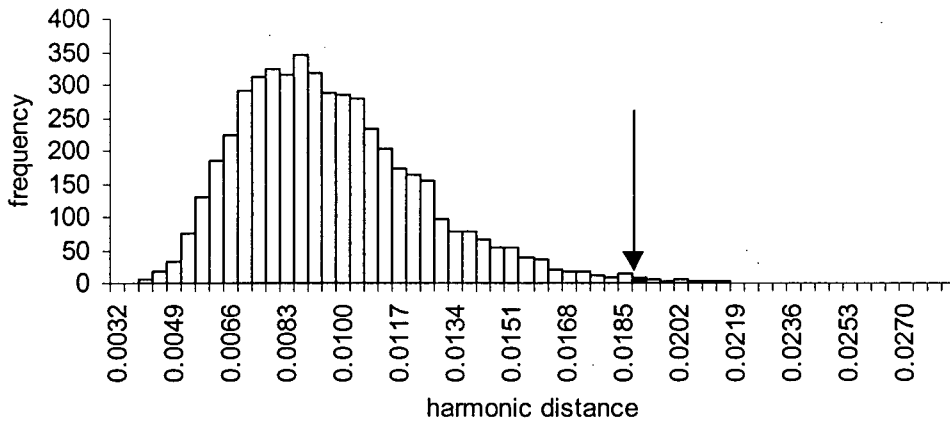


HOWE vs. WPAC

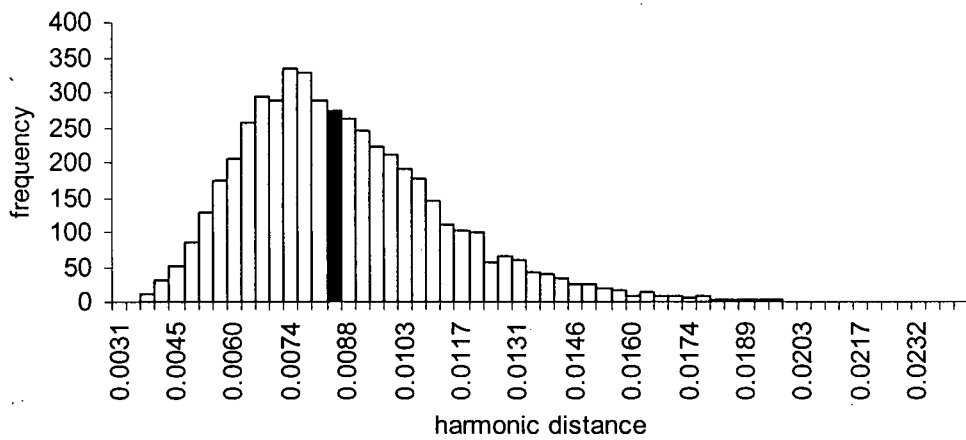
Figure 9a: Distribution of randomized harmonic distances between each of the fishing areas. Shaded bar / arrows represents the location of the observed harmonic distance for the pair-wise comparisons of the fishing areas.



NWCH vs. SWCH



NWCH vs. WPAC



SWCH vs. WPAC

Figure 9b: Distribution of randomized harmonic distances between each of the fishing areas. Shaded bar / arrows represents the location of the observed harmonic distance for the pair-wise comparisons of the fishing areas.

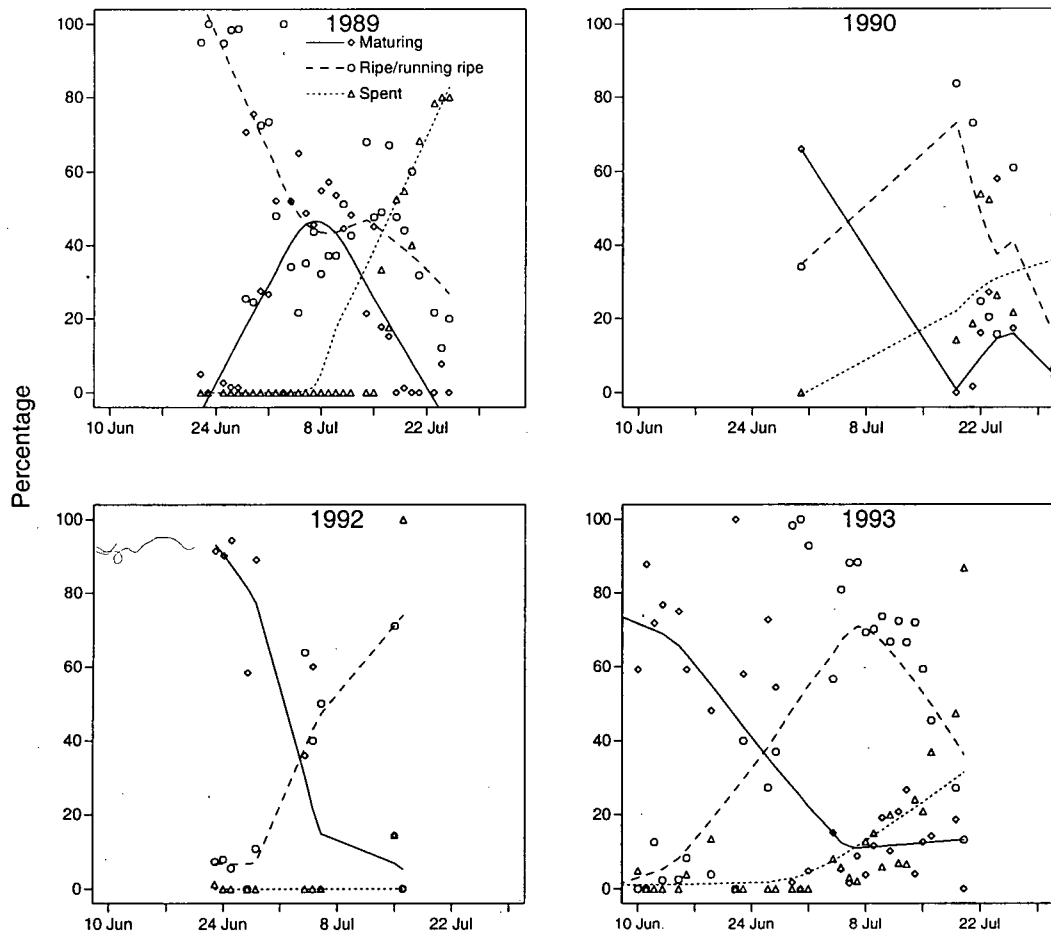


Figure 10: Daily changes in female orange roughy gonad stage proportions during the spawning season in area HOWE, from observer data.

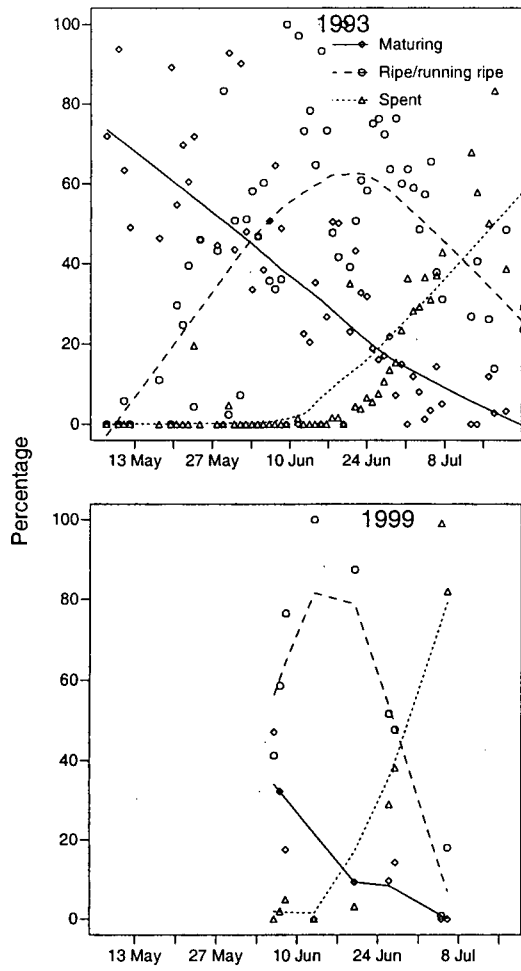


Figure 11: Daily changes in female orange roughy gonad stage proportions during the spawning season in area NWCH, from observer data.

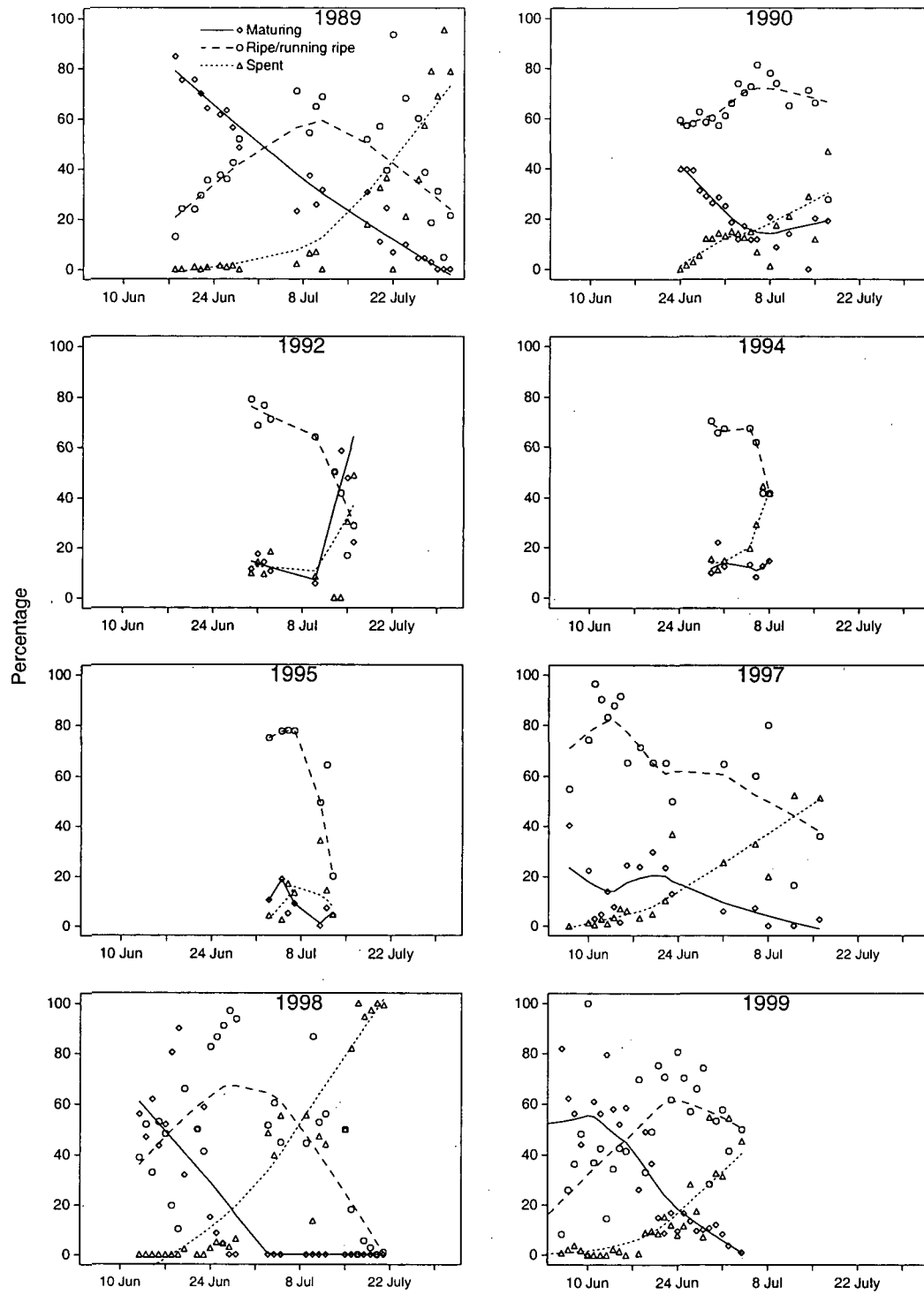


Figure 12: Daily changes in female orange roughy gonad stage proportions during the spawning season in area SWCH, from observer data.

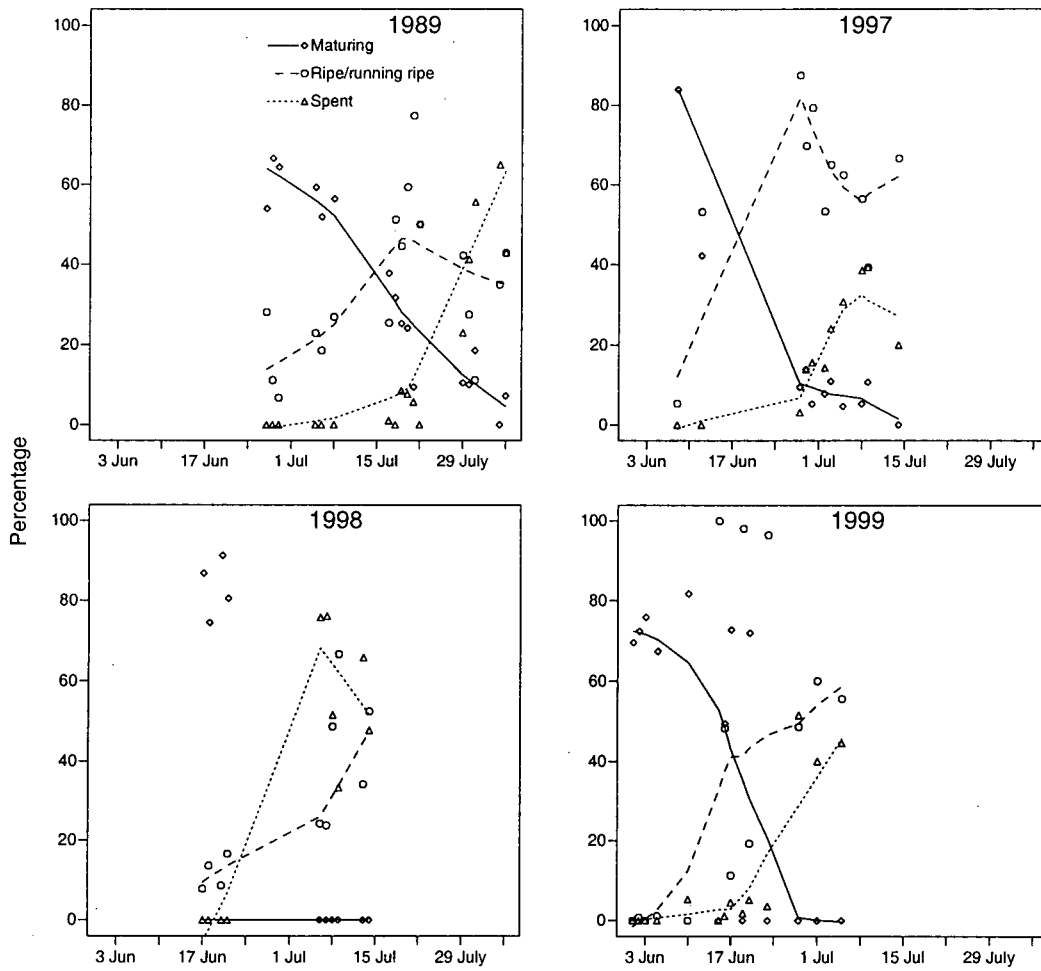


Figure 13: Daily changes in female orange roughy gonad stage proportions during the spawning season in area WPAC, from observer data.

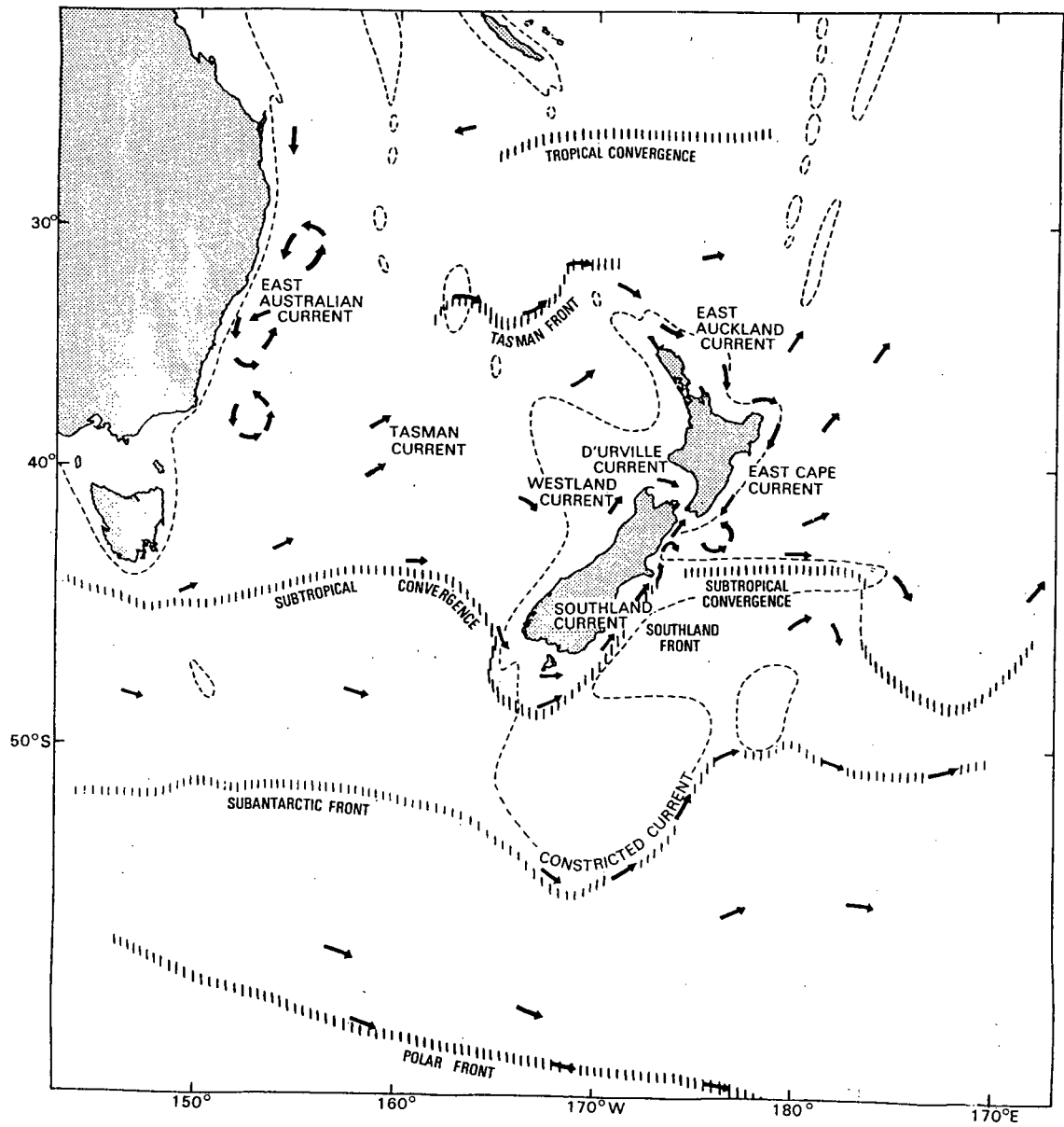


Figure 14: General circulation and position of oceanic fronts in the New Zealand region, from Heath (1985).

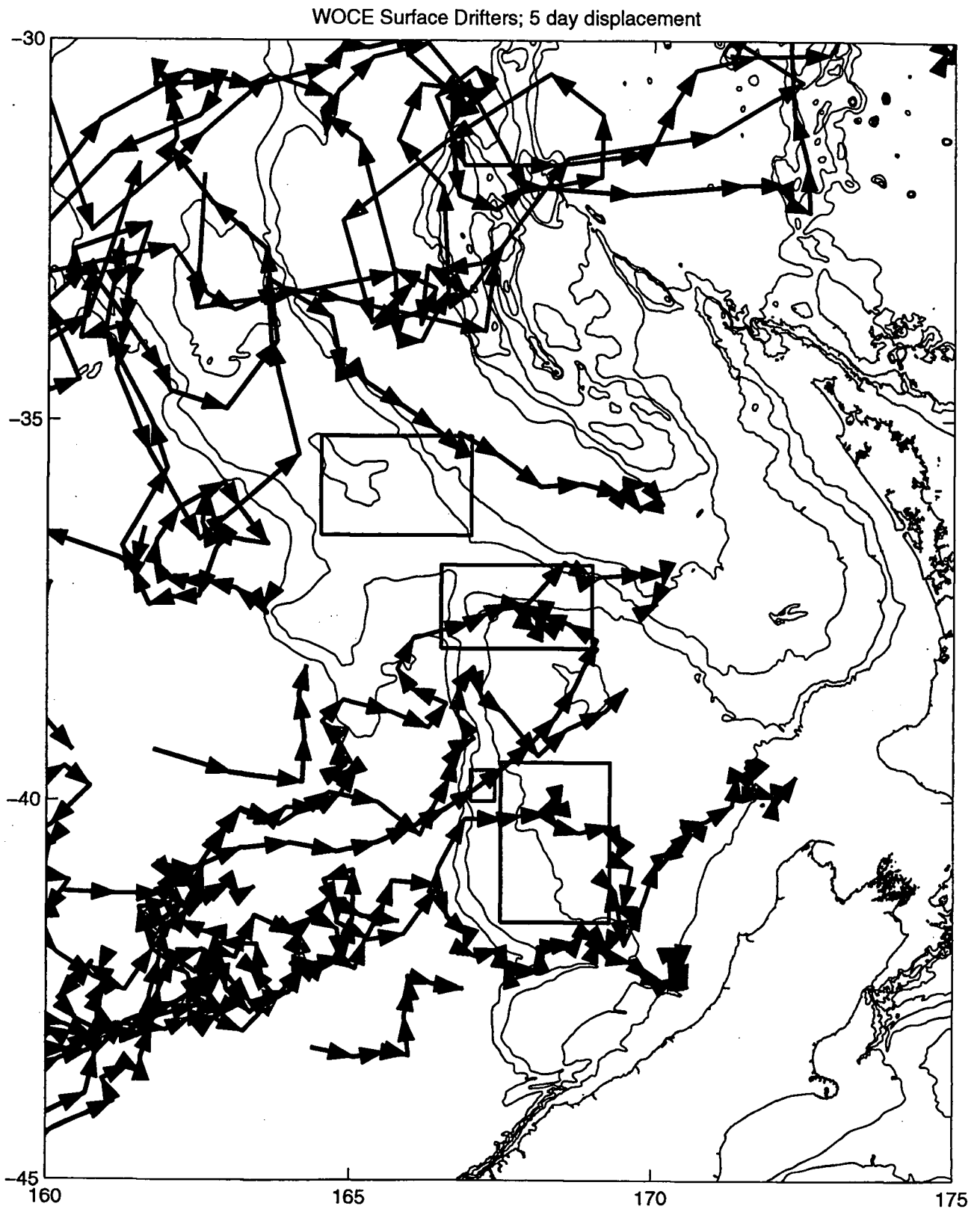


Figure 15: WOCE Surface drifter tracks, 5 day displacement vectors along with the roughy areas and the 500m, 1000m, 1500m and 2000m contours.

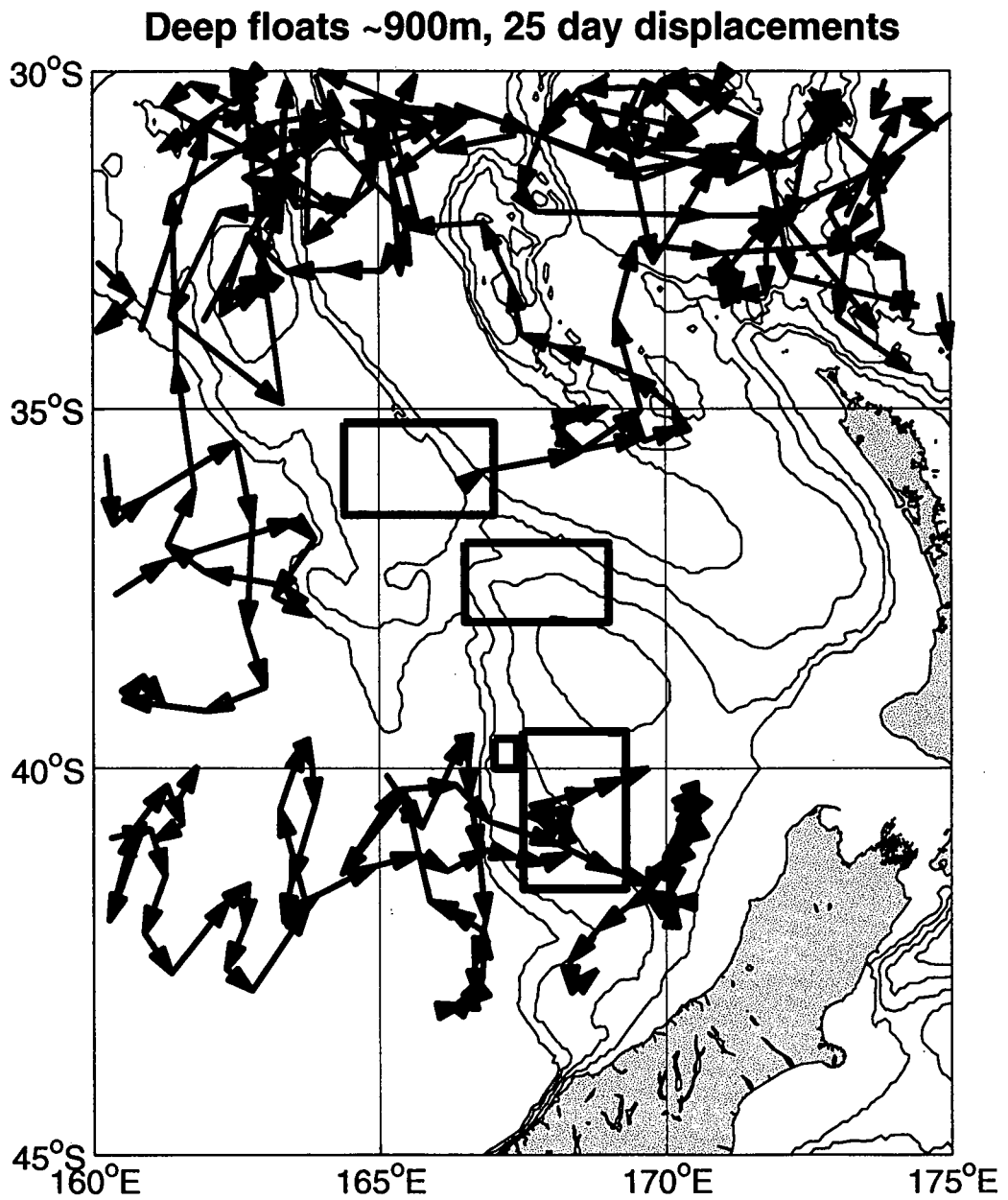


Figure 16: WOCE Deep drifter tracks, 25 day displacement vectors along with the roughy areas and the 500m, 1000m, 1500m and 2000m contours.

