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The Effects of Entrainment of Shelf Water by Warm Core Rings on Northwest Atlantic Fish Recruitment

by

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ABSTRACT

We develop tests for the hypothesis that the entrainment of shelf water by warm core rings decreases recruitment of fish from the Northwest Atlantic from Mid-Atlantic Bight to the Grand Banks. The indices for the extent of entrainment are estimated weekly for the nine principal shelf banks in the Northwest Atlantic using satellite imagery. An entrainment index for each stock is constructed based on independent data for the distribution in space and time for the planktonic stages. Our analysis is exploratory; its purpose is to develop hypotheses that can be rigorously tested using the portion of the data we have not yet analyzed.

RÉSUMÉ

Les auteurs ont testé l'hypothèse voulant que l'entraînement de l'eau des plateaux par des courants circulaires à noyau chand réduise le recrutement des stocks de poisson dans le nord-ouest de l'Atlantique, du La Baie de L'Atlantique Moyer au Grand banc. Les indices d'entraînement sur les neufs principaux bancs du nord-ouest de l'Atlantique a été déterminée par imagerie satellite. Un indice d'entraînement est établi à priori pour chaque stock à partir de données indépendantes sur la distribution spatiale et temporelle des stades planctoniques. L'analyse est explora tif; le but est de développer des hypothèses pour vérification future avec des données exclues de l'analyse.

INTRODUCTION

Large eddies generated by unstable meanders from the Gulf Stream can entrain large volumes of water from the Northwest Atlantic continental shelf (Halliwell and Moores 1979). These eddies are called warm core rings because the central core consists of relatively warm Sargasso sea water. It has been hypothesized that the shelf water entrained by these warm core rings may transport enough fish eggs and larvae to significantly reduce marine fish recruitment (Colton and Anderson 1983; Wroblewski and Cheney 1984; Flierl and Wroblewski 1985; McGlade 1986); however, there is little empirical support for this hypothesis. Interannual variation in marine fish recruitment has also been related to variation in wind-induced Ekman transport (Nelson et al. 1976; Parrish and MacCall 1978; Bailey 1981) and large-scale variations in ocean current systems (Sinclair et al. 1985).

In most such studies relating environmental effects to recruitment confirmatory statistics have been used for analyses that are essentially exploratory (Shepherd et al. 1985). Here, this difficulty of testing significance in an exploratory analysis is overcome by splitting the data into two portions. The first portion is used to choose the hypothesis to be tested and the second portion can be used to evaluate its significance. Cox (1975) analyzed this data-splitting method and found it to be quite efficient.

In this paper we present only the initial exploratory portion of the analysis. We shall restrict our attention to the satellite imagery from July 1980 to December 1984.

Our goal is to develop a few general hypotheses that apply to groups of similar species. These general hypotheses, e.g. that entrainment of shelf water reduces recruitment, will be tested by combining each of the one-sided significance tests for a positive regression slope using Fisher's method for combining probabilities from tests of significance (Fisher 1954, section 21.1) in another paper.

METHODS

Satellite Imagery

Sea-surface temperature (SST) data from Florida to the Scotian Shelf have been collected since the early seventies using advanced very high resolution radiometers (AVHRR) on the NOAA/TIROS series of satellites. Initially these data were interpreted by the U.S. Naval Oceanographic Office who produced weekly experimental ocean frontal analysis (EOFA) charts. Surface temperature fronts (the shelf-slope front, the Gulf Stream fronts, Gulf Stream eddies) were depicted on the EOFA charts based on the satellite-derived thermal imagery for the day closest to the date of issue and augmented by SST data collected from ships of opportunity during the preceding week. A similar product using the same data was published by the U.S. National Oceanic and Atmospheric Administration (NOAA) under the title 'Gulf Stream Analysis'. The NOAA charts showed cloud positions whereas in the EOFA charts if clouds prevented good imagery the frontal positions were estimated based on previous data. Beginning in 1980 these products were replaced by the Oceanographic Analysis charts published by NOAA through the National Weather Service and the National Environmental Satellite Service. At the same time the aerial coverage was expanded to include the Grand Banks and Flemish Cap regions and the frequency of publication increased to three times per week for the area from Cape Hatteras to Newfoundland. The EOFA charts and copies of their field sheets used in the present study were obtained directly from the Naval Oceanographic Office, while the Gulf Stream Analysis charts and the Oceanographic Analysis charts were obtained from NOAA. The charts used for the analysis are identified in Table 1.

Satellite Imagery Analysis

The Northwest Atlantic from the mid-Atlantic Bight to the Grand Banks of Newfoundland were divided into nine regions (Fig. 1). These regions were chosen to correspond to the limits of fish stocks as much as possible. The limits of the regions intersect the divisions used by the Northwest Atlantic Fisheries Organization (NAFO) at the 200 m isobath. The surface area of shelf water beyond the 200 m isobath and the surface area of slope water within the 200 m isobath were recorded for each satellite image for each of the nine regions. The distance of each warm core ring and Gulf Stream meander from the 200 m isobath was also recorded, as was the area between the 200 m isobath and the Gulf Stream.

The analysis of the images was not always unambiguous. The following conventions were used. (1) if cloud cover obscured a region, then linear interpolation between the closest two observations in time was used to estimate the variables. (2) If areas were recorded as mixed shelf and slope water, then only one-half the area was recorded. (3) Occasionally a warm core ring would entrain shelf water from two regions simultaneously. In this case the surface area was divided by the lines in Figure 1. (4) Occasionally the shelf water originating from one region is entrained around a ring and into another region. In this case the surface area was assigned to the region of origin.

Five indices were derived from these data for each region:

A. The number of warm core rings in the region;

B. The surface area of slope water on the shelf (i.e. within the 200 m isobath);

C. The area between the shelf (i.e. 200 m isobath) and the Gulf Stream;

D. The distance from the 200 m isobath to the closest warm core ring (a negative 'distance' was recorded if a ring was within the 200 m isobath);

E. The area of shelf water beyond the 200 m isobath (the surface area of slope water within the 200 m isobath was subtracted from this area);

Examples of these indices are shown in Figure 2.

The indices are intercorrelated. For example, the correlations for region 6 (corresponding to the Scotian Shelf near Sable Island Bank) were:

Index	A	B	C	D	E
A	1	0.21	-0.06	-0.70	-0.34
B	0.21	1	-0.19	-0.23	-0.46
C	-0.06	-0.19	1	0.24	0.38
D	-0.70	-0.23	0.24	1	0.51
E	-0.34	-0.46	0.38	0.51	1

The most surprising correlation between the indices was that the number of warm core rings (index A) was negatively correlated with the area of shelf water beyond the 200 m isobath (index E), in regions 4 to 9. We expected that the surface area of shelf water beyond the 200 m isobath to give a good measure of water entrained off the shelf by warm core rings. The cause of this discrepancy is under investigations.

The area of shelf water beyond the 200 m isobath (E) was positively correlated (median r=0.32) with the area between the 200 m isobath and the Gulf Stream (C) in all 9 regions. This is consistent with the observations of Halliwell and Moores (1979) who found that Gulf Stream meanders induced perturbations in the shelf-slope front.

The surface area of slope water on the shelf (B) was positively correlated with the number of warm core rings (A) and negatively correlated with the closeness of the rings to the shelf (D). The surface area of slope water on the shelf may provide the most accurate measure of the effects of warm core rings.

The number of warm core rings (A) was positively correlated with the area between the 200 m isobath and the Gulf Stream (C) in regions 1 to 4. There was no consistent relationship between these two variables in the other areas.

The inter-relationships among the indices are being further investigated by including information on Eckman transport and by the use of time series analysis.

Construction of Stock-Specific Entrainment Indicies

The construction of an entrainment index for each stock will depend upon the biology of the stock and the physics of entrainment. The interpolated value for the number of rings, Fig 2, will be denoted by $S_A(t)$. The stock-specific entrainment index for the effect of the number of rings is calculated by integrating the index weighted by a function $W_a(t)$, which specifies the proportion of eggs or larvae from the stock, a, susceptible to entrainment at time t. That is, the ring number index for stock a, in year i, is

$$\int_{i}^{i+T} W_a(t)\; S_A(t)\; dt,$$

when T is the duration of a year. For each stock two weighting functions were derived from empirical observations: one which described the season in which eggs were susceptible to entrainment, and one which described the season in which eggs or larvae were susceptible to entrainment.

Similar indices were computed for other environmental variables (B-E).

Biological Data

Data on recruitment were obtained from research surveys (Table 2). The seasons in which eggs and larvae are susceptible to entrainment were calculated from the seasonal distribution of spawning, ichthyoplankton surveys, and laboratory studies of egg and larval development. The principal sources are listed in Table 2.

RESULTS AND DISCUSSION OF EXPLORATORY ANALYSIS

George's Bank cod and haddock recruitment were not negatively correlated with the number of rings off George's Bank for the 1981 to 1984 year classes. These stocks in fact showed a slight positive relationship with the ring number index and a negative relationship with the ring distance index (Fig 3 and 4). Similar results were obtained if the indices were weighted by the season in which the eggs were in the water. This is at variance with the results of Flierl and Wroblewski (1985) for the 1975 to 1979 year classes. However, their correlations were based upon a different index: the number of warm core rings "interacting" with George's Bank during the spawning season. It is possible that warm core rings have a positive influence on recruitment for some species; McGlade (1986) found a positive correlation with warm core rings activity and recruitment of pollack.

Recruitment of yellowtail flounder from Southern New England appears to be positive correlated with the area between the shelf and the gulf stream for the 1981 to 1984 year classes (Fig 5). Recruitment was negatively correlated with the amount of slope water on the shelf and the number of rings that could entrain eggs and larvae off the shelf. There was no evidence of any relationship between the Georges Bank yellowtail flounder stock and any of the indices.

Recruitment of redfish from St. Pierre Bank and from the Scotian Shelf appeared to be negatively correlated with the ring number index and positively correlated with the ring distance index. It is reasonable that redfish, which spawns on the edge of the continental shelf (Sherman et al. 1984) should be susceptible to the entrainment of redfish larvae by warm core rings. There was no apparent relationship between recruitment and the amount of shelf water beyond the 200 m isobath.

Recruitment of capelin from the stock that spawns on the Southeast shoal of the Grand Banks appeared to be negatively correlated with the amount of shelf water beyond the 200 m isobath. Capelin recruitment was unrelated to ring activity for the 1980 to 1983 year class (Fig 6). Recruitment of the St. Mary's Bay and Fortune Bay (Newfoundland) herring stock did not appear to be related to any of the indices.

We stress that this analysis is exploratory and has been undertaken to formulate a priori hypotheses that can be rigorously tested.

ACKNOWLEDGMENTS

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Table 1. Sources of satellite data used in the analysis.

	Mid-Atlantic Bight	Southern New England	Western Georges Bank	Eastern Georges Bank	Browns Bank	Sable Island Bank	Banquereau Bank	St. Pierre Bank	Grand Bank
1973	Jan '73								
1974									
1975		Ocean Frontal Analysis				Jan '75			
1976									
1977	Jun '77 Jul '77				Ocean Frontal Field Sheets				
1978					May '78				
1979		Gulf Stream Analysis				Gulf Stream Analysis			
1980	Apr '80 May '80								
1981									
1982				Oceanographic Analysis					
1983									
1984									
1985									

TABLE 2

Sources of Biological Data

Species	Stock	Sources of Eggs and Larval Distribution	Sources of Recruitment Data
Cod	Georges Bank (5Ze)	Sherman et al. 1984	J.J. Hunt, K.G. Waiwood CAFSAC Res. Doc. 85/87
Haddock	Georges Bank (5Ze)	Sherman et al. 1984	K.G. Waiwood, J.D. Nelson CAFSAC Res. Doc. 85/95
Redfish	St. Pierre Bank (4Ps)	Bonnyman 1981	D.B. Atkinson, D. Power NAFO SCR Doc. 86/38
Redfish	Scotian Shelf (4VWX)	O'Boyle et al. 1984	K. Zwancwburg CAFSAC Res. Doc. 85/65
Yellowtail Flounder	Georges Bank (5Ze)	Silverman 1985	NMFS, Woods Hole Lab. Ref. Doc. 86-09
Yellowtail Flounder	Southern New England	Silverman 1985	NMFS, Woods Hole Lab. Ref. Doc. 86-09
Capelin	Southern Grand Bank (3NO)	Bonnyman 1981	D.S. Miller NAFO SCR Doc. 86/79
Herring	St. Mary's Bay Placentia Bay	J.P. Wheeler Pers. Com.	J.P. Wheeler, E.L. Dalley CAFSAC. Res. Doc. 85/94

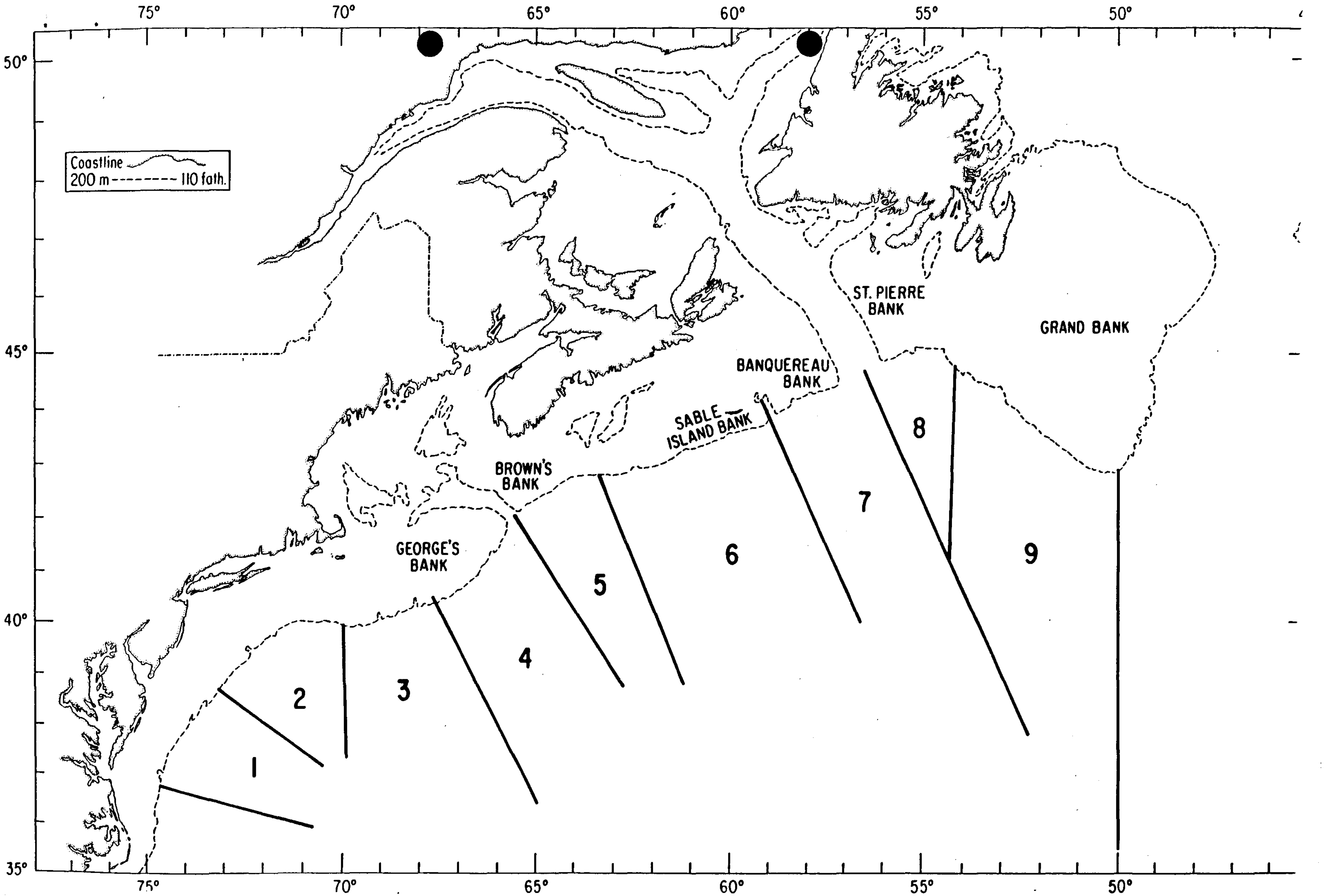
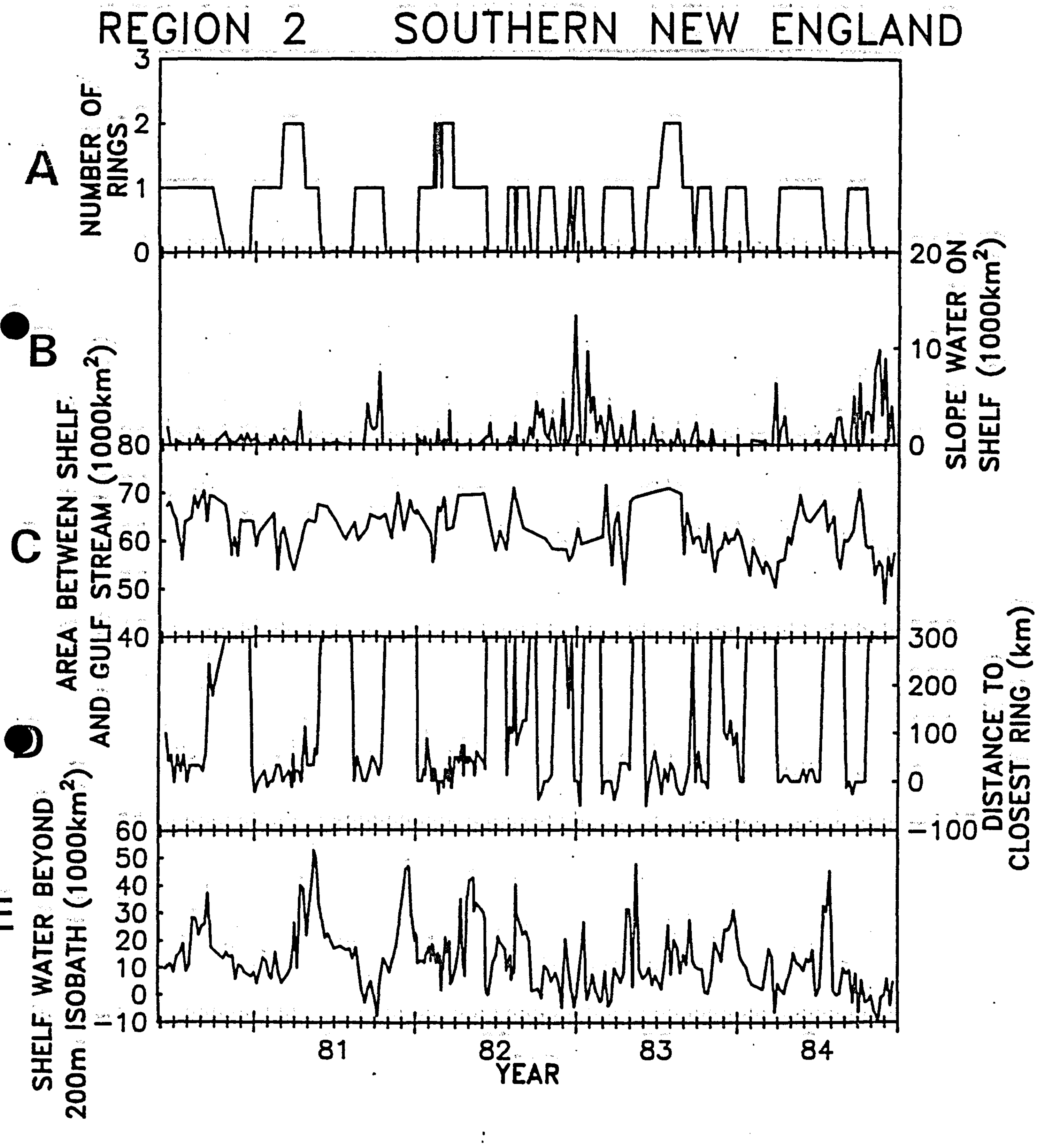


Fig. 1. Regions used in the analysis.



REGION 2 SOUTHERN NEW ENGLAND
A
NUMBER OF RINGS
B
SLOPE WATER ON SHELF (1000km²)
C
AREA BETWEEN SHELF AND GULF STREAM (1000km²)
D
DISTANCE TO CLOSEST RING (km)
E
SHELF WATER BEYOND 200m ISOBATH (1000km²)
81
82
83
84
YEAR

Fig 2(a)

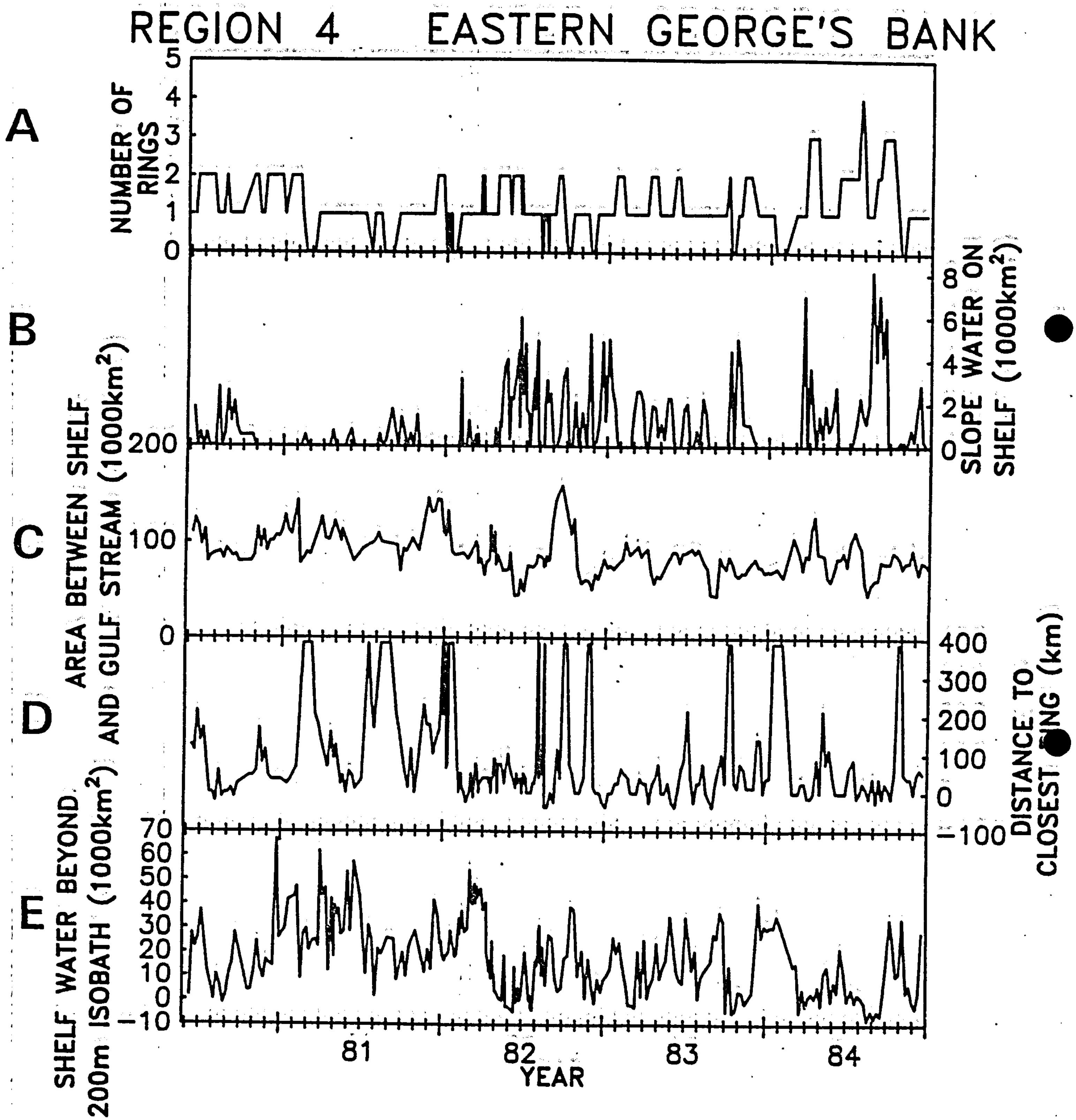

REGION 4 EASTERN GEORGE'S BANK
A
NUMBER OF RINGS
B
SLOPE WATER ON SHELF (1000km²)
C
AREA BETWEEN SHELF AND GULF STREAM (1000km²)
D
DISTANCE TO CLOSEST RING (km)
E
SHELF WATER BEYOND 200m ISOBATH (1000km²)
81
82
83
84
YEAR

Fig 2(b)

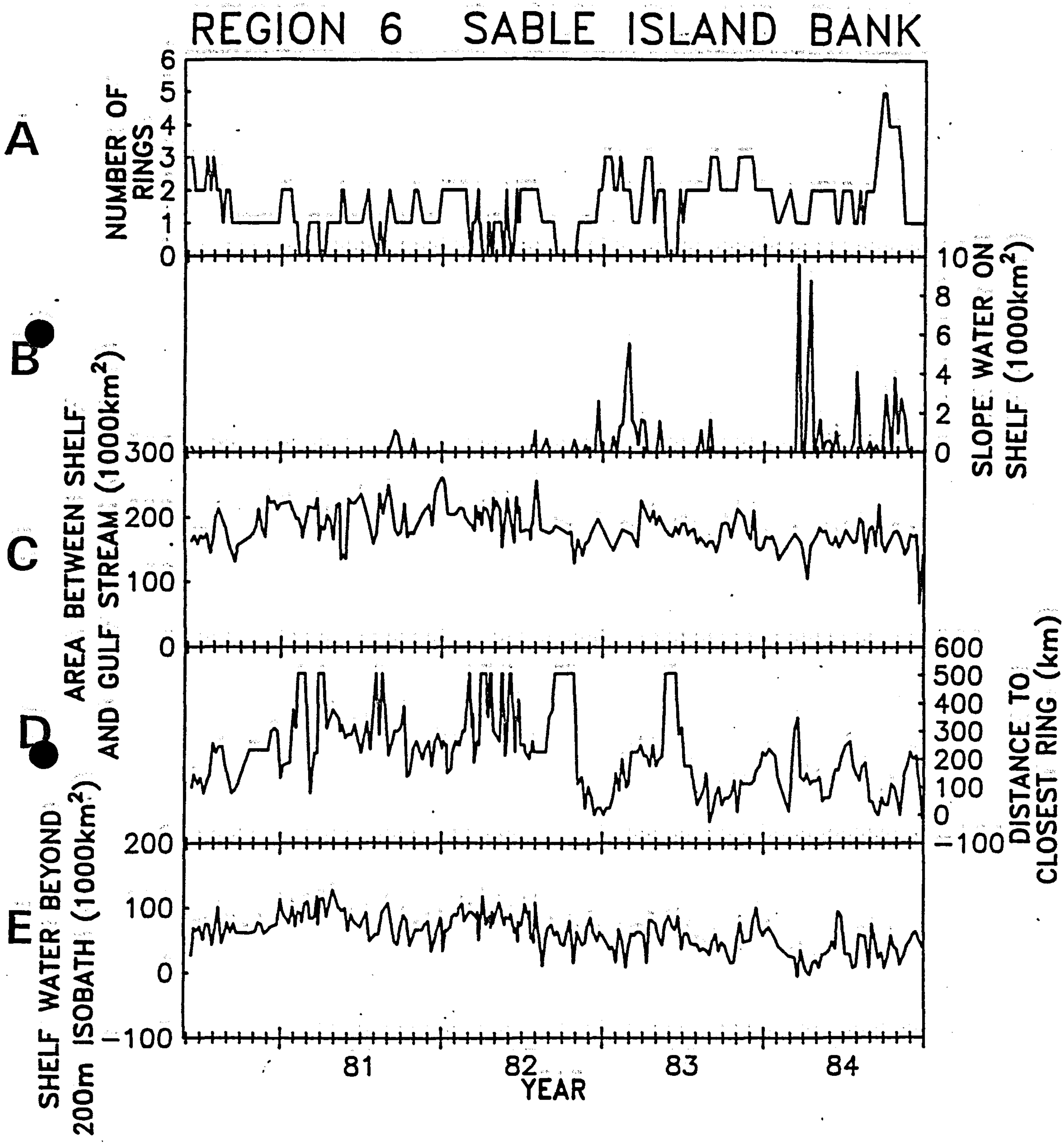
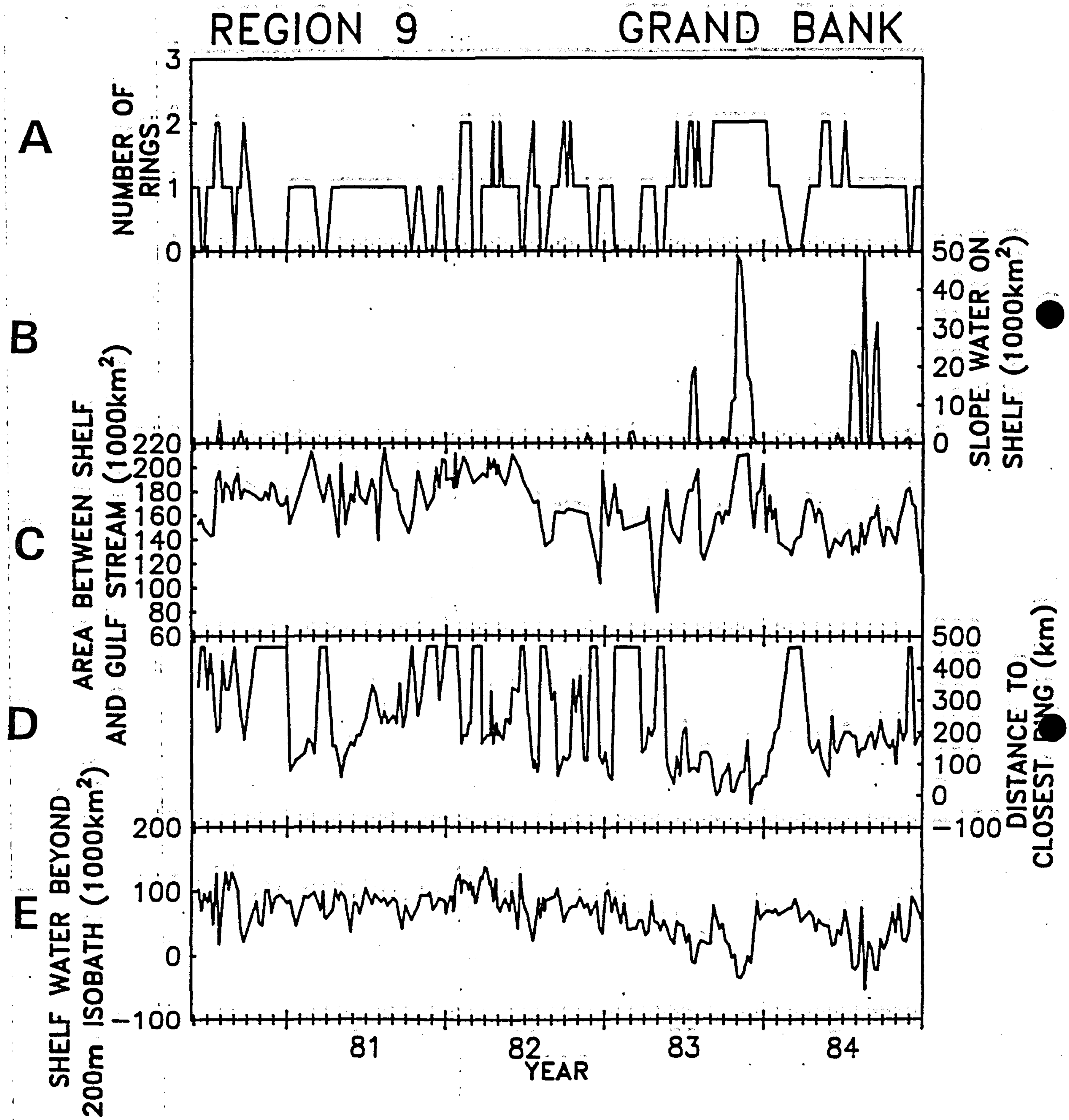

REGION 6 SABLE ISLAND BANK
A
NUMBER OF RINGS
6
5
4
3
2
1
0
B
SLOPE WATER ON SHELF (1000km²)
10
8
6
4
2
0
C
AREA BETWEEN SHELF AND GULF STREAM (1000km²)
300
200
100
0
D
DISTANCE TO CLOSEST RING (km)
600
500
400
300
200
100
0
−100
E
SHELF WATER BEYOND 200m ISOBATH (1000km²)
200
100
0
−100
81
82
83
84
YEAR

Fig 2(c)



REGION 9
GRAND BANK
A
NUMBER OF RINGS
B
SLOPE WATER ON SHELF (1000km²)
C
AREA BETWEEN SHELF AND GULF STREAM (1000km²)
D
DISTANCE TO CLOSEST RING (km)
E
SHELF WATER BEYOND 200m ISOBATH (1000km²)
81
82
83
84
YEAR

Fig 2(d)

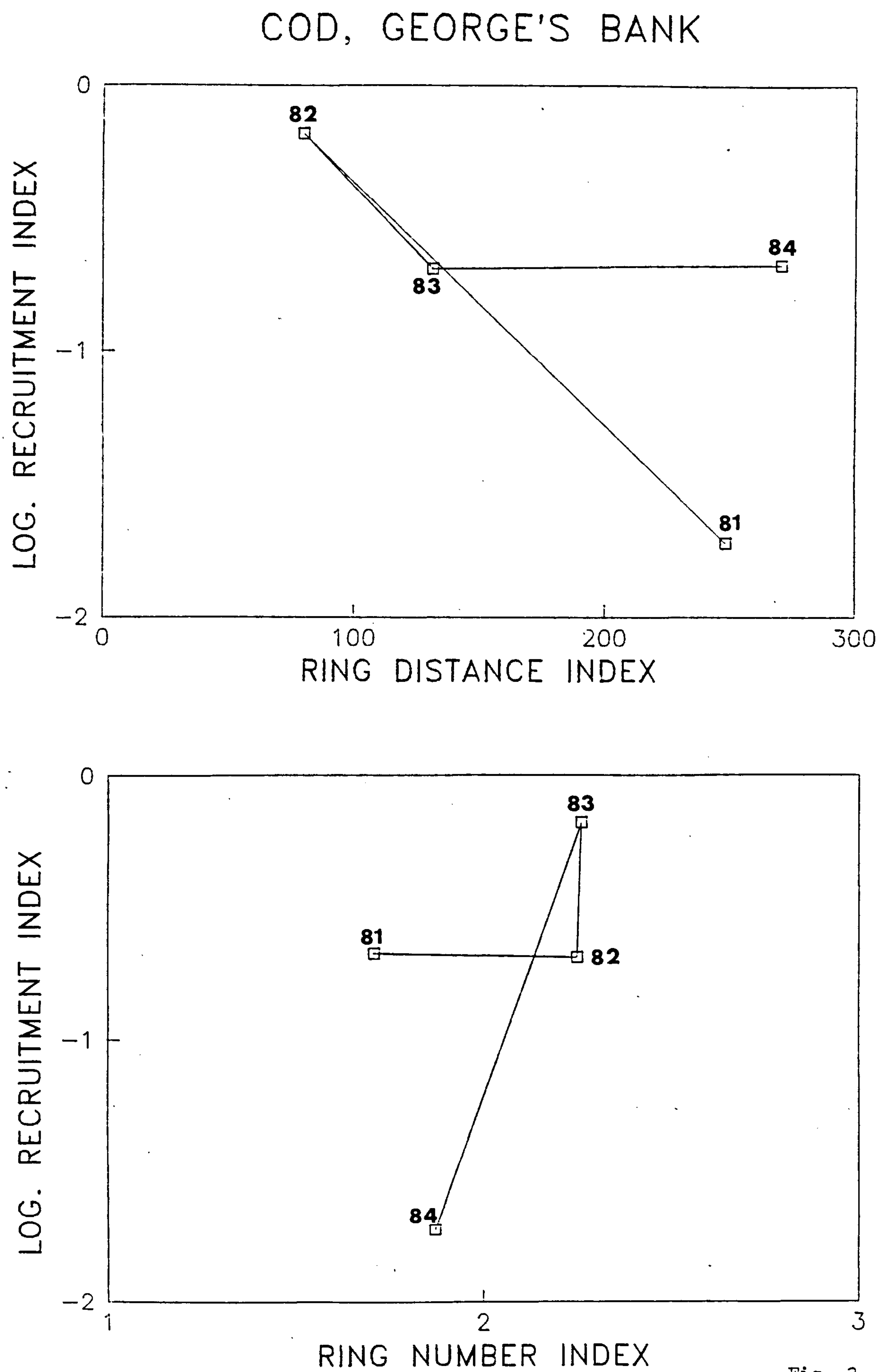
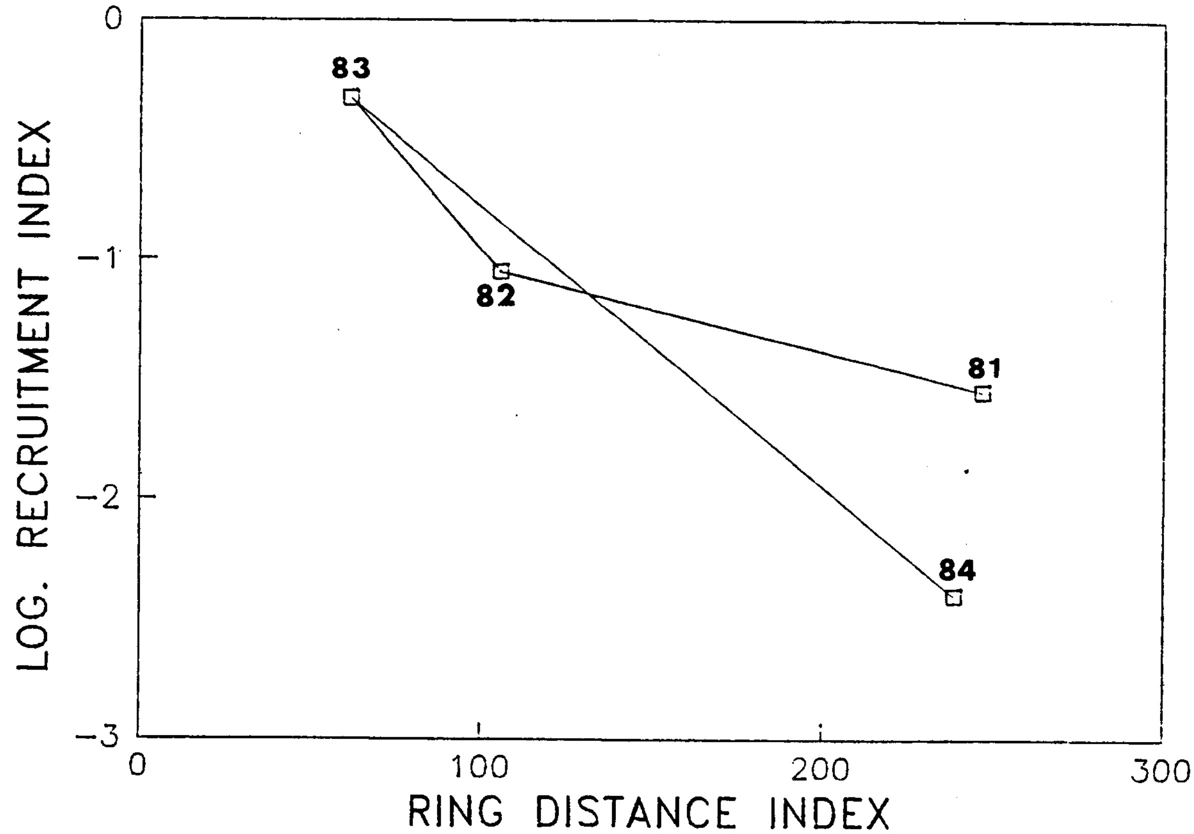

COD, GEORGE'S BANK
LOG. RECRUITMENT INDEX
RING DISTANCE INDEX
0
-1
-2
0
100
200
300
82
83
84
81
LOG. RECRUITMENT INDEX
RING NUMBER INDEX
0
-1
-2
1
2
3
83
81
82
84

Fig. 3

HADDOCK, GEORGE'S BANK



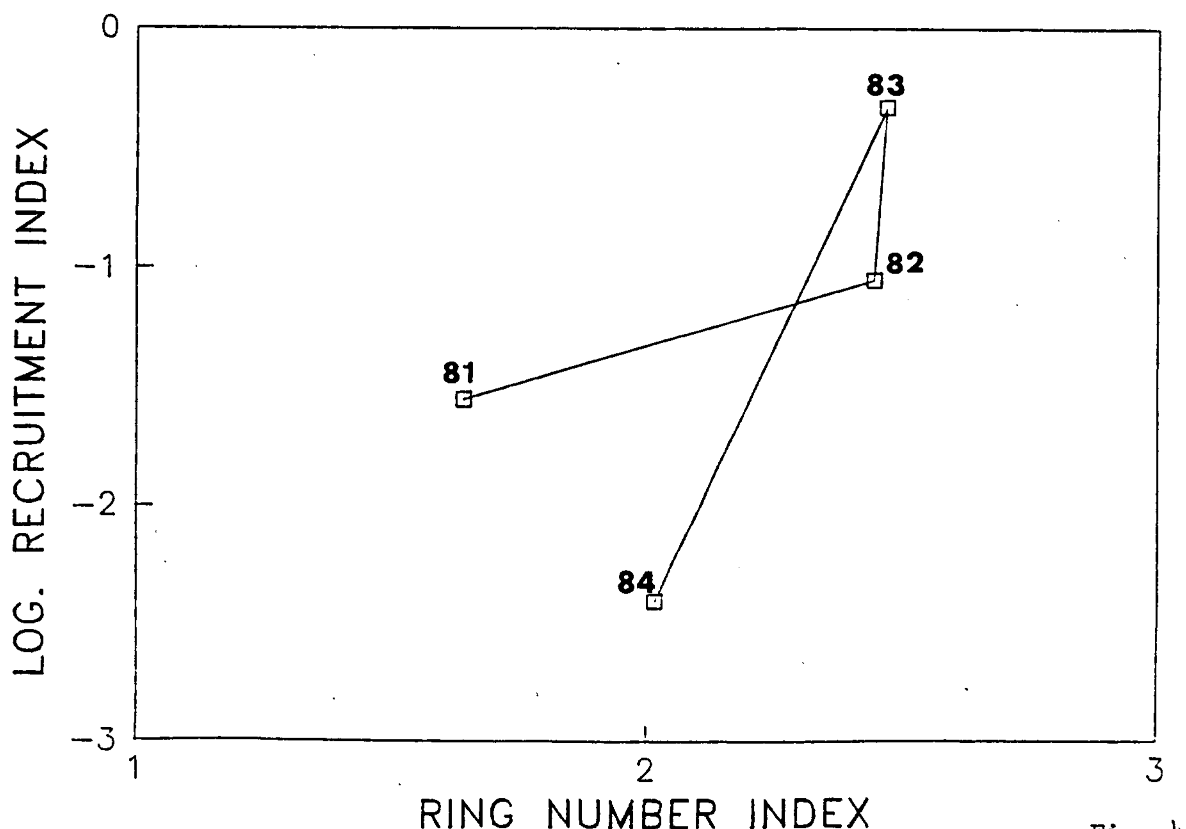
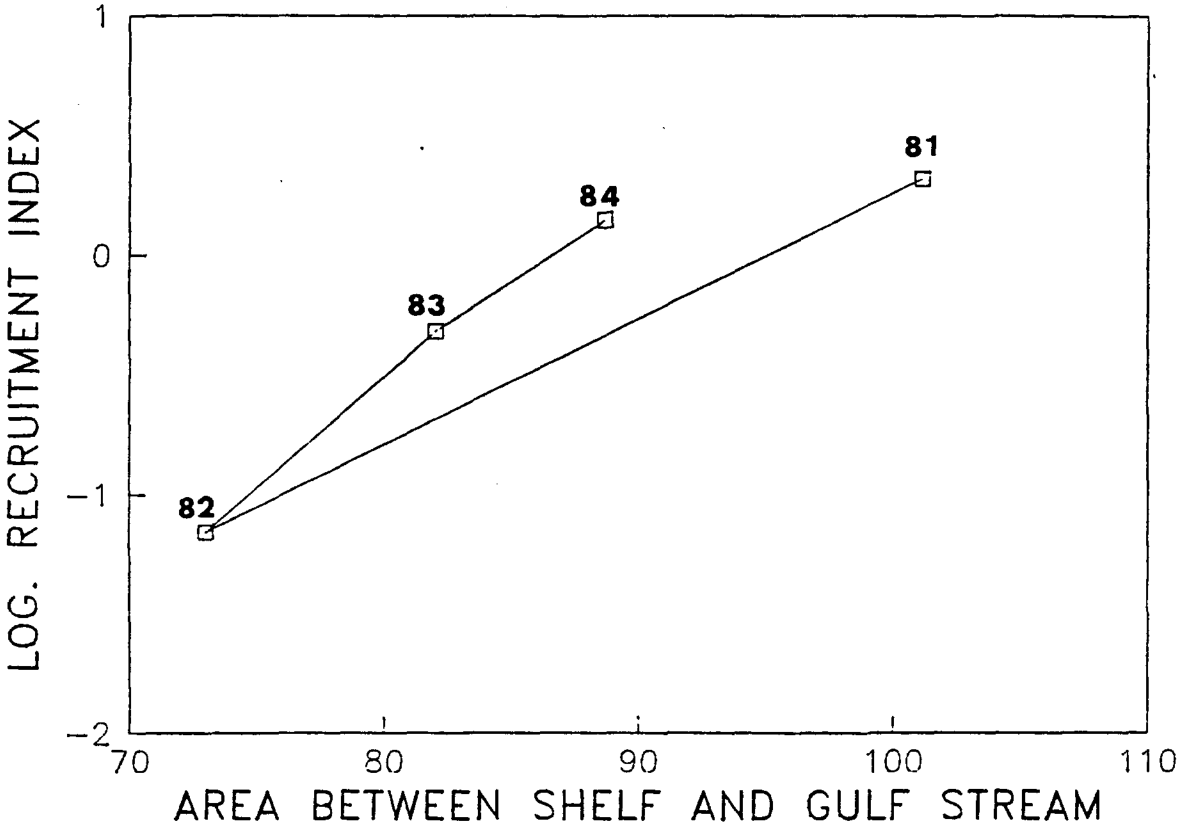


Fig. 4

YELLOWTAIL FLOUNDER, S. NEW ENGLAND



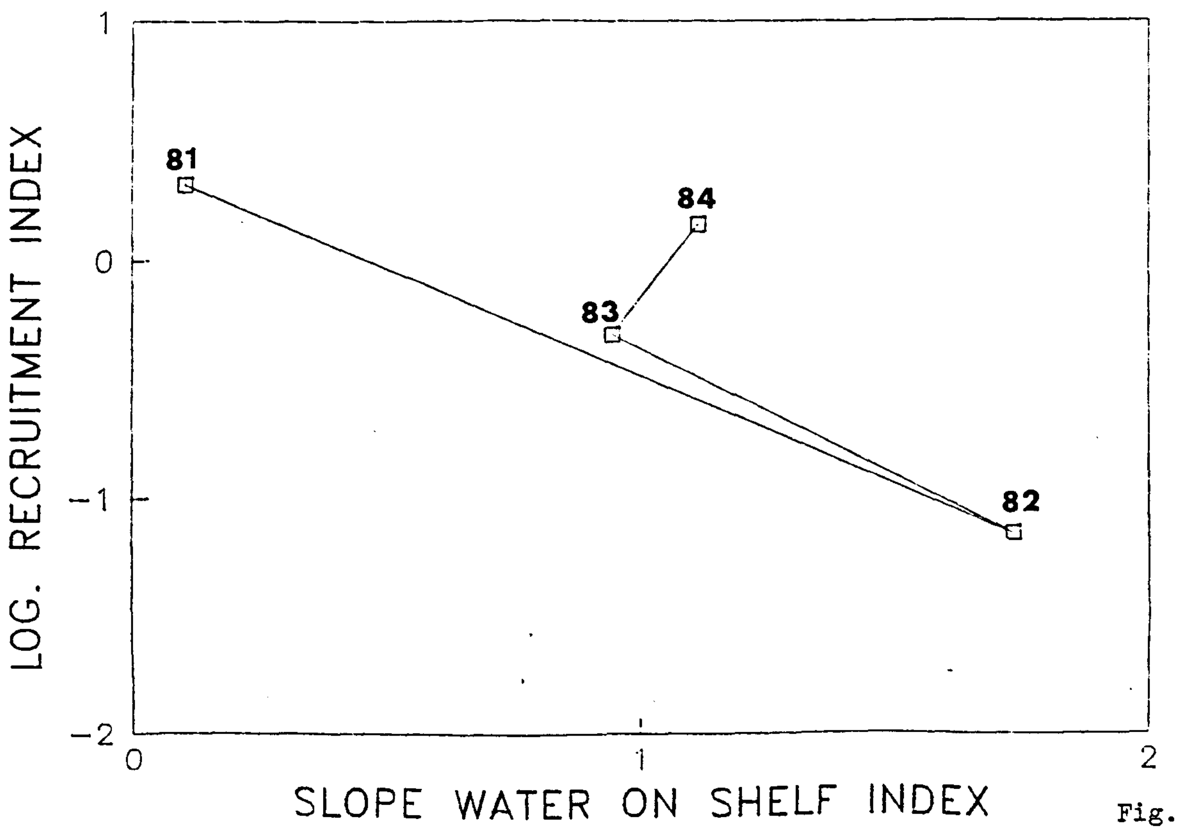
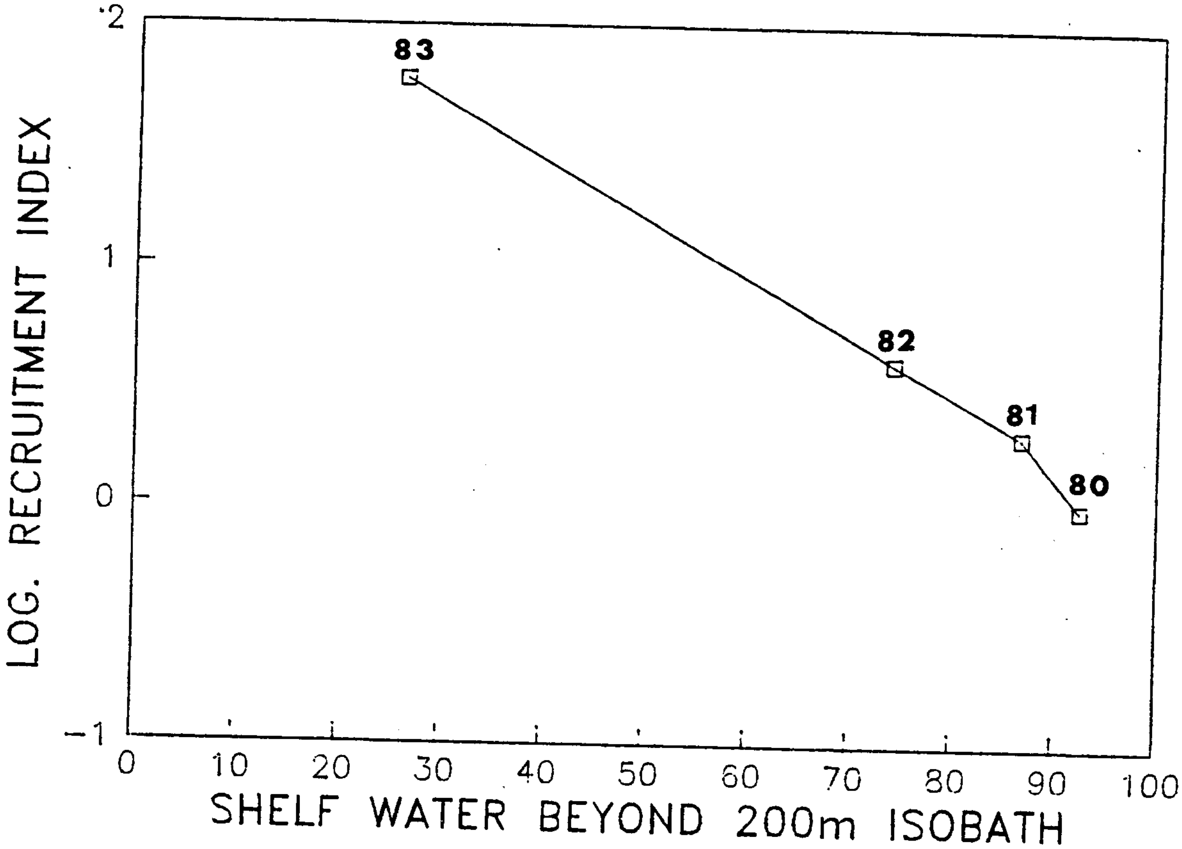


Fig. 5

CAPELIN, SOUTHERN GRAND BANKS



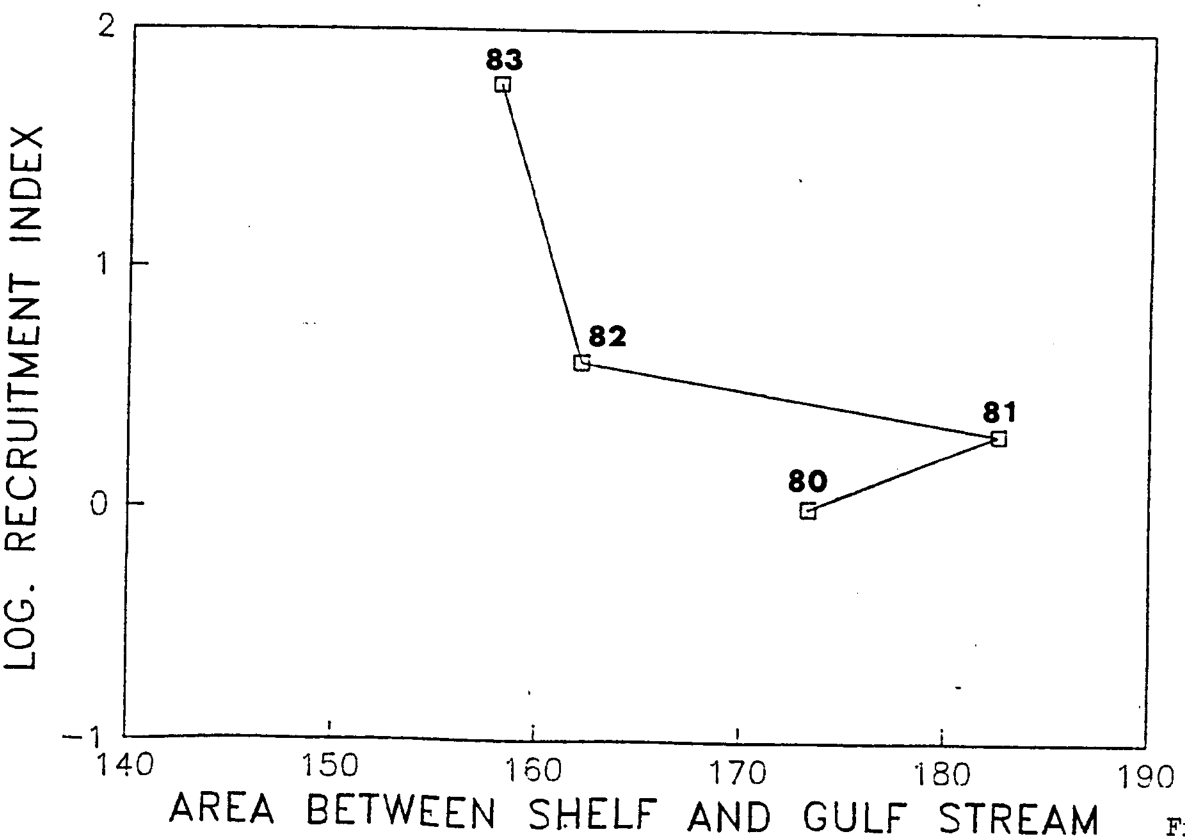


Fig. 6