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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.

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
1976	
1977	Jun '77
	Jul '77
1978	Gulf Stream Analysis
1979	
1980	Apr '80
	May '80
1981	
1982	Oceanographic Analysis
1983	
1984	
1985	

Jan' 75

Ocean Frontal
Field Sheets

May '78

Gulf Stream
Analysis

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
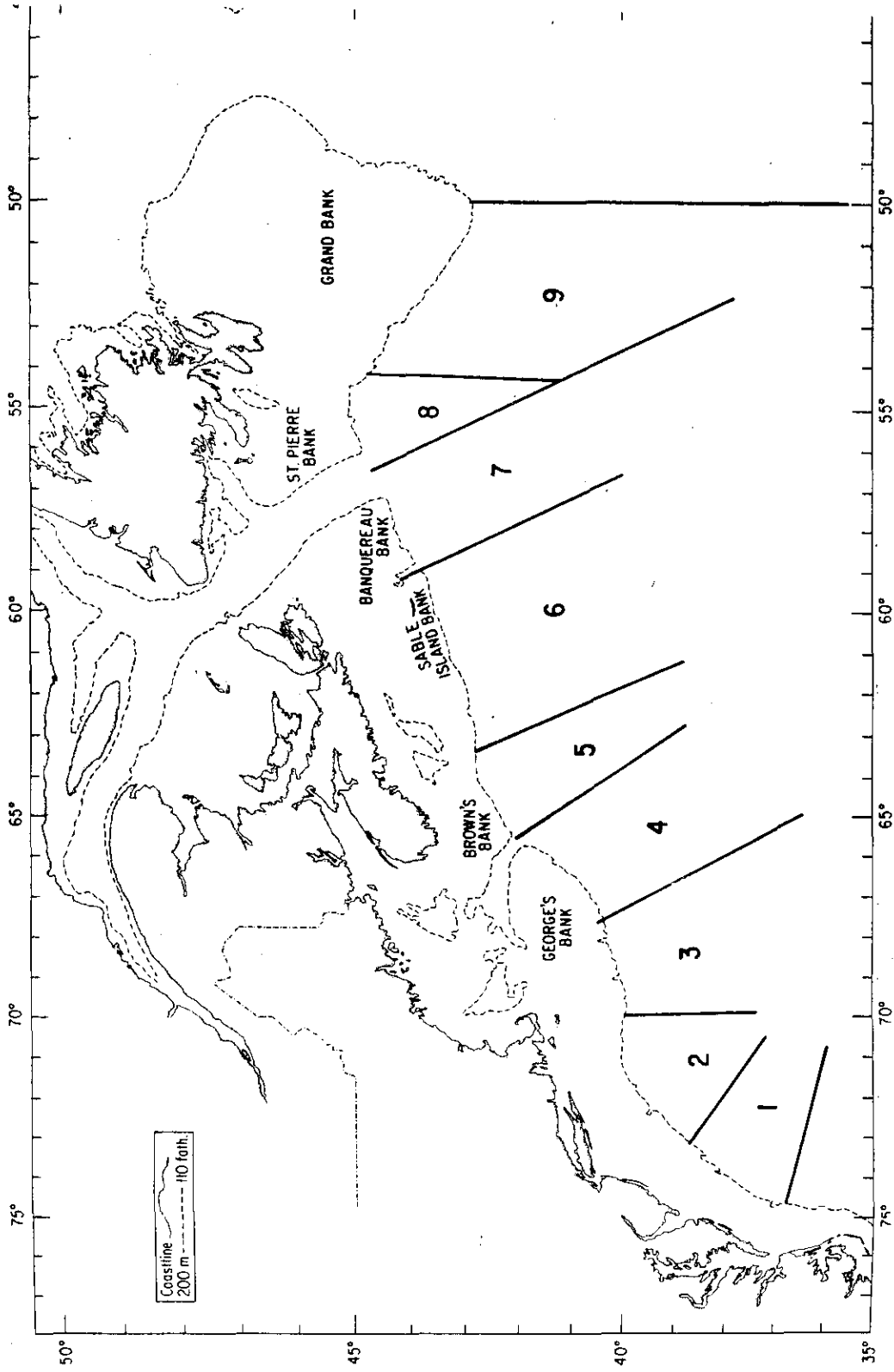
Fig. 1. Regions used in the analysis.

REGION 2   SOUTHERN NEW ENGLAND

Fig 2(a)
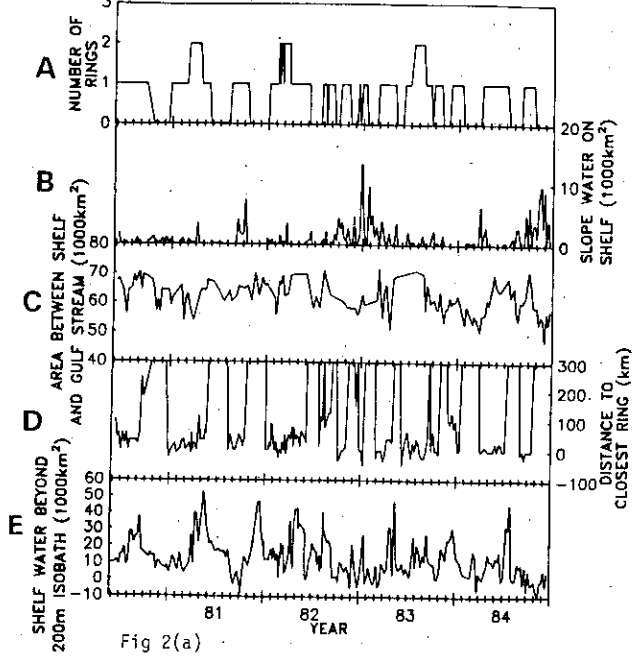
REGION 4   EASTERN GEORGE'S BANK

Fig 2(b)
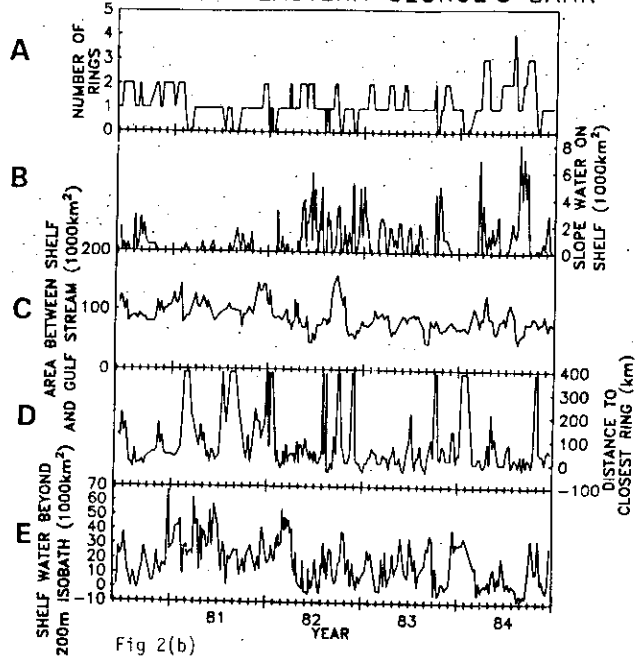
REGION 6   SABLE ISLAND BANK

Fig 2(c)
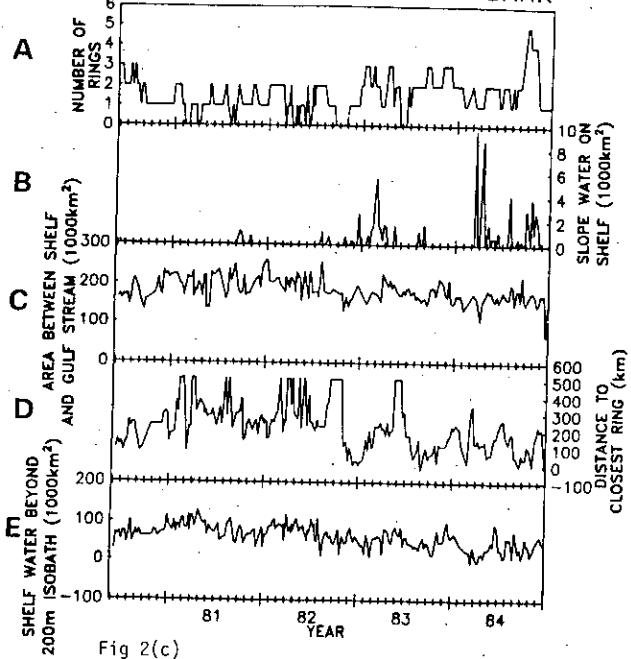
REGION 9   GRAND BANK

Fig 2(d)
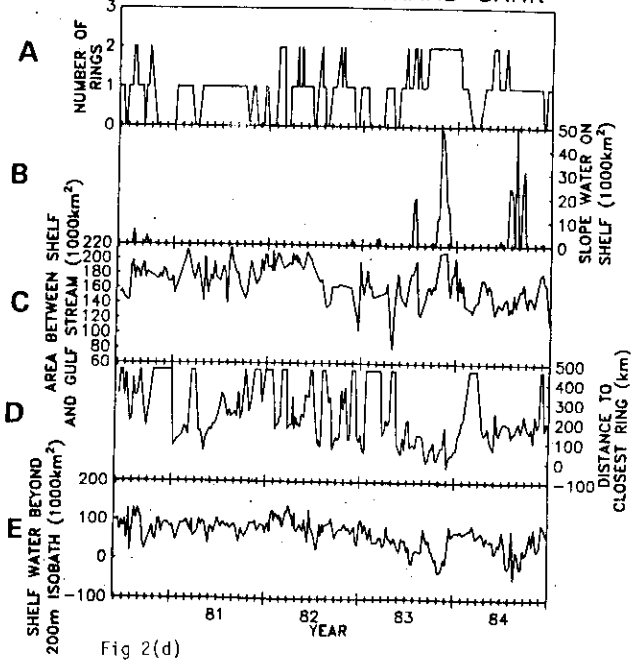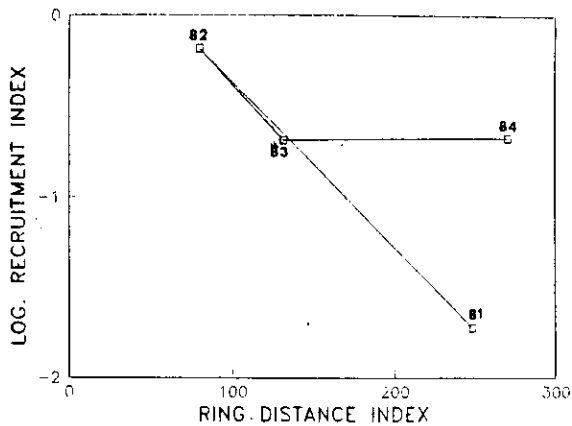
COD. GEORGE'S BANK

HADDOCK, GEORGE'S BANK
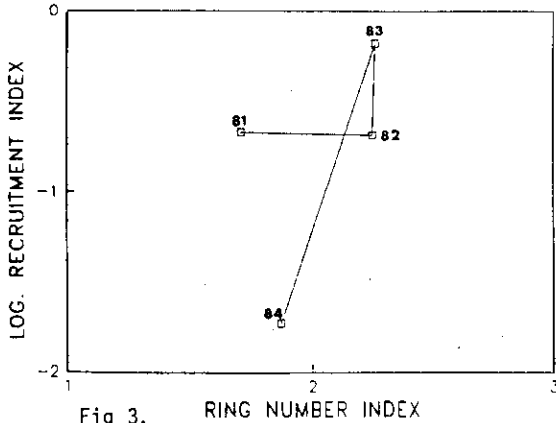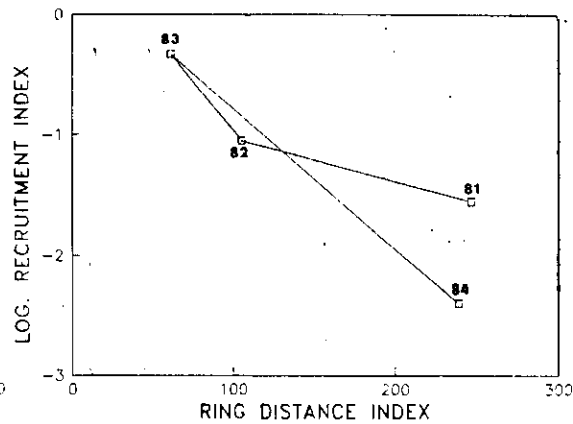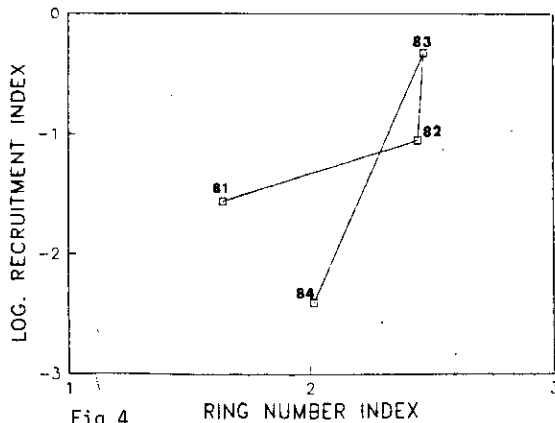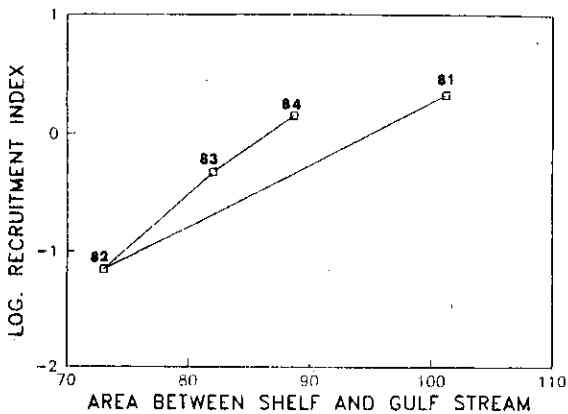
Fig 3.

Fig 4.

YELLOWTAIL FLOUNDER, S. NEW ENGLAND

CAPELIN. SOUTHERN GRAND BANKS

Fig 5.

Fig 6.