Environmental Effects on Recruitment to Canadian Atlantic Fish Stocks

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ENVIRONMENTAL EFFECTS ON RECRUITMENT TO CANADIAN ATLANTIC FISH STOCKS

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ABSTRACT

Perry, R. I., and K. T. Frank [ed.] 1987. Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556: iv + 65 p.

This report presents the contributed papers and proceedings of a symposium held at the Bedford Institute of Oceanography, 7 and 8 November 1985. The objectives were to examine potential influences of the environment on recruitment to Canadian Atlantic fish stocks, and to recommend indices of environment-recruitment relationships which may be appropriate for use in setting management advice. A principal focus of the symposium was the relationships between freshwater runoff and landings established by Sutcliffe and coworkers in the 1970's, and their applicability to more recent data. Other presentations included the use of environmental indices in stock assessments, oceanographic processes and larval retention, and environmental effects on spawning times. The symposium concluded that the Sutcliffe correlations in particular show promise as recruitment indices for certain stocks, although they should be retested using more rigorous statistical techniques and more appropriate data, e.g. as derived from virtual population analyses rather than landings.

RÉSUMÉ

Perry, R. I., and K. T. Frank [ed.] 1987. Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556: iv + 65 p.

Le présent rapport contient les documents et les actes d'un symposium qui a eu lieu à l'Institut océanographique de Bedford, les 7 et 8 novembre 1985. Les objectifs de ce symposium étaient d'examiner l'influence possible de l'environnement sur le recrutement des stocks de poisson dans l'Atlantique canadien et de recommander l'établissement de certains indices des rapports entre l'environnement et le recrutement, lesquels pourraient être utiles dans l'élaboration de conseils sur la gestion des stocks. Les participants au symposium se sont surtout intéressés à l'étude des relations entre le ruissellement d'eau douce et les débarquements de poissons, relations qui avaient été établies par Sutcliffe et ses collègues au cours des années 1970 et à la possibilité de les appliquer aux données plus récentes. D'autres présentations portaient sur l'utilisation d'indices écologiques dans l'évaluation de stocks, les processus océanographiques et la rétention des larves au fond de l'eau ainsi que sur les effets de l'environnement sur les saisons du frai. À la fin du symposium, il a été conclu que les corrélations de Sutcliffe en particulier certains stocks, mais qu'il faudra effectuer d'autres tests en utilisant des techniques statistiques plus rigoureuses et des données plus pertinentes, p. ex. des données tirées d'analyses des populations virtuelles plutôt que des données sur les débarquements.

Introduction

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Perry, R. I. 1987. Introduction, p. 1-4. In R. I. Perry and K. T. Frank [ed.] Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556.

Throughout the history of fisheries management in Atlantic Canada (Fig. 1), there have been numerous attempts to incorporate environmental influences into the process for setting management advice, with varying degrees of success. Brodie and Baird (1986), Shepherd et al. (1984) and Carscadden and Hodder (1985) provide summaries of some relevant examples. However, none of these relationships are used routinely in assessments at present, for reasons ranging from inability to perform on data not available when the analysis was made, to the often large amounts of data required.

One class of environment-recruitment relationships for the Canadian Atlantic coast continually reappears in the literature, however. These are the correlations established by Bill Sutcliffe and coworkers (Sutcliffe 1973; Sutcliffe et al. 1976, 1977, 1983) relating freshwater runoff to landings and, by virtue of appropriate time lags, recruitment of several fish stocks from the Labrador Shelf, Newfoundland, Gulf of St. Lawrence, Scotian Shelf and Gulf of Maine regions. Interest in these correlations remains high (Sheldon et al. 1982; Sinclair et al. 1986), although as yet no formal experimental program has attempted to determine the processes underlying such relations.

Accordingly, the Marine Environment and Ecosystem Subcommittee (MEES) of the Canadian Atlantic Fisheries Scientific Advisory Council (CAFSAC) decided to sponsor a symposium to examine these Sutcliffe correlations in detail, and to consider their use as tools in the process of setting management advice. Sutcliffe's analyses were predominately exploratory in nature, often using less than adequate data, e.g. landings. Therefore, the symposium was asked to consider several questions concerning these relationships. How well do these correlations perform on recent data, collected since publication of the relationships? Do better data, such as derived from virtual population analyses (VPA) rather than landings, improve the correlations? Are the relationships sufficiently well grounded to be of use in management advice, and how would they be incorporated? Finally, are there other environment- recruitment relationships for Canadian Atlantic fish stocks which may be equally as promising for consideration as standard management tools? This is the report of that symposium.

The meeting was held on 7 and 8 November 1985 at the Bedford Institute of Oceanography, Dartmouth, N.S.; participants are identified in Table 1. Two formal objectives were established: i) to examine potential influences of the environment on recruitment in the Canadian Atlantic region, and ii) to recommend indices of environment-recruitment relationships which may be appropriate for use in setting management advice. Eleven papers were presented, eight of which are included in this report. The abstract of a ninth paper, which was stimulated by questions and discussion during the symposium, is also included. Four of the presentations are complete reports, while the remainder are extended abstracts of material which has been or will be published elsewhere. Following each paper is a brief synopsis of the questions and discussion of the presentation as recorded by the editors of this report.

The symposium was organized so that more general aspects of environment-recruitment relationships were discussed during the morning, with the afternoon devoted to specific consideration of the Sutcliffe correlations. Considerable time was allotted for discussion of the ideas and their applicability to management requirements. The first presentation, by Mahon, set the scene as to how data on such relationships can be applied to the setting of management advice within the Canadian Atlantic context. He discussed the importance and the difficulties of good estimates of early age fish for subsequent determination of adult year-class strength and the setting of total catch quotas. His presentation suggested a means by which environmental data could be incorporated immediately into the stock assessment process, at least for certain stocks. The next two papers dealt with the physical oceanographic aspects of recruitment. Loucks and coworkers examined fluctuations and persistence of the sea surface temperature (SST) field along the Atlantic coast over large spatial and temporal scales, in particular its association with surface winds. They concluded that SST anomalies are predictable, extensive in space and persistent in time, and may therefore extend over the early life history of several species of fish, thus influencing recruitment. Akenhead examined and modelled a common assumption in recruitment studies, that ichthyoplankton may be retained and recruitment enhanced by gyral circulations about offshore banks. He found that, for the Flemish Cap, larval spatial pattern which is apparently related to convergence on top of the bank may instead be due to on-off bank diffusive losses of larvae and resulting differential mortality.

The paper by Messieh considered a different aspect of the environment-recruitment relationship, that of environmental influences on adult maturation rates and inducement to form spawning aggregations. He provided a model to predict arrival times of herring on spawning grounds in the Gulf of St. Lawrence, with implications for the release of eggs and their subsequent survival. The paper by McGlade also examined larval transport-retention concepts, in particular the persistence of pollock larvae in shelf areas normally considered dispersive. She suggested the interaction of larval behavioral characteristics with large- and small-scale oceanograhpic processes played an important functional role, and as with the presentation by

Akenhead, demonstrated the need to critically evaluate assumptions of environment- recruitment relationships.

The next two papers focussed specifically on the Sutcliffe correlations. Drinkwater provided an excellent background review of the development of Sutcliffe's hypotheses relating river runoff to recruitment on the Canadian Atlantic coast. He discussed the performance of these correlations when applied to data collected since publication, and produced revised regression equations for the relationship between Labrador cod and Hudson Bay outflow (originally published in Sutcliffe et al. 1983), using updated VPA estimates. He then examined new correlations using VPA estimates of recruitment rather than landings for cod and haddock stocks off Newfoundland, in the Gulf of St. Lawrence and on the Scotian Shelf. For certain stocks, trends based on the regression equations correlated well with observed recruitment.

The abstract by Drinkwater and Myers was not presented at the symposium, but was stimulated by the discussion following Drinkwater's presentation. It further examined the question of whether there was an overall effect of environment on landings, rather than on the basis of individual stocks. The finding of no significant overall effect does not destroy the utility of the relationship for specific stocks, but it does advise caution in the general enthusiasm for these types of correlations. Tony Koslow's presentation also urged caution, considering the multivariate nature of environmental factors and the difficulties in relating a single or a few factors with a single or a few stocks. In the final presentation, Rice and Evans discussed the value and pitfalls of developing relationships of recruitment with any factor, e.g. parent stock or environmental variable, without necessarily assuming an underlying functional form.

Participants at the symposium were encouraged by the studies investigating environment-recruitment relationships within the Canadian Atlantic zone and, in particular, by the ability of the "Sutcliffe correlations" to model observed trends, at least for certain stocks. It was agreed better data on recruitment are now available, e.g. recruitment indices from virtual population analyses rather than landings, although they represent a shorter time series. It was also agreed that better and perhaps more appropriate statistical techniques are available to analyze these relationships than the correlation analyses originally performed by Sutcliffe and coworkers. This led to questions of whether Sutcliffe's conclusions follow statistically from the data; it should be noted Drinkwater's presentation for this symposium used the original correlations published by Sutcliffe, but with more recent data. The symposium therefore concluded the Sutcliffe relationships between environment and recruitment are worthwhile to investigate further, and that such investigations should include more appropriate statistical analysis procedures, use of more appropriate environmental and fishery data and the incorporation of resulting relations into stock assessment methods for appropriate stocks. As suggested by Mahon's presentation, such relationships could initially be included as another tool to estimate recruitment before fish become available to survey gear. This would be most important for the faster growing, early recruiting species. It was further recognized that an urgent need exists for process studies to investigate the mechanisms underlying these relationships, particularly with those stocks for which the correlations are strongest.

ACKNOWLEDGMENTS

I wish to thank Robin Mahon for initiating this symposium and for his help with its organization, and Darlene Warren for editing this report. Brenda Fawkes kindly retyped the manuscripts.

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Table 1

Symposium Participants

Participants	Affiliation*	Participants	Affiliation*
S. Akenhead	FRB, Newfoundland	K. Mann	MEL, BIO
D. Bowen	MFD, Scotia-Fundy	J. McGlade	MFD, Scotia-Fundy
P. Boudreau	MEL, BIO	W.D. McKone	RRB, Ottawa
W.R. Bowering	FRB, Newfoundland	I. McQuinn	FRB, Quebec
S. Campana	MFD, Scotia-Fundy	S. Messieh	FRB, Gulf
A. Campbell	FRB, Scotia-Fundy	R. Miller	IMPD, Scotia-Fundy
G. Chouinard	FRB, Gulf	R.K. Misra	FRB, Scotia-Fundy
M. Dadswell	FRB, Scotia-Fundy	R.A. Myers	FRB, Newfoundland
E. Dalley	FRB, Newfoundland	B. Nakashima	FRB, Newfoundland
L. Dickie	MEL, BIO	R. O'Boyle	MFD, Scotia-Fundy
W.G. Doubleday	RRB, Ottawa	F. Page	Oceanography, Dal. Univ.
K. Drinkwater	MEL, BIO	P. Pepin	Oceanography, Dal. Univ.
G. Evans	FRB, Newfoundland	I. Perry	MFD, Scotia-Fundy
K. Frank	MEL, BIO	D. Pezzack	FRB, Scotia-Fundy
J. Gagné	FRB, Quebec	J. Rice	FRB, Newfoundland
J. Horne	Biology, Dal. Univ.	T. Rowell	FRB, Scotia-Fundy
P. Hurley	MFD, Scotia-Fundy	E.J. Sandeman	FRB, Newfoundland
S. Kerr	MEL, BIO	B. Silvert	MEL, BIO
P. Koeller	MFD, Scotia-Fundy	A. Sinclair	MFD, Scotia-Fundy
T. Koslow	Oceanography, Dal. Univ.	P.C. Smith	AOL, BIO
T. Lambert	MEL, BIO	J. Tremblay	IMPD, Scotia-Fundy
G. Lilly	FRB, Newfoundland	R. Trites	MEL, BIO
R. Loucks	Loucks Oceanology	D. Wallace	MFD, Scotia-Fundy
P. Mace	MFD, Scotia-Fundy	G. White	MFD, Scotia-Fundy
R. Mahon	MFD, Scotia-Fundy	K. Zwanenburg	MFD, Scotia-Fundy

*AOL - Atlantic Oceanographic Laboratory
IMPD - Invertebrates and Marine Plants Division
FRB - Fisheries Research Branch
MEL - Marine Ecology Laboratory
MFD - Marine Fish Division
RRB - Research and Resources Branch

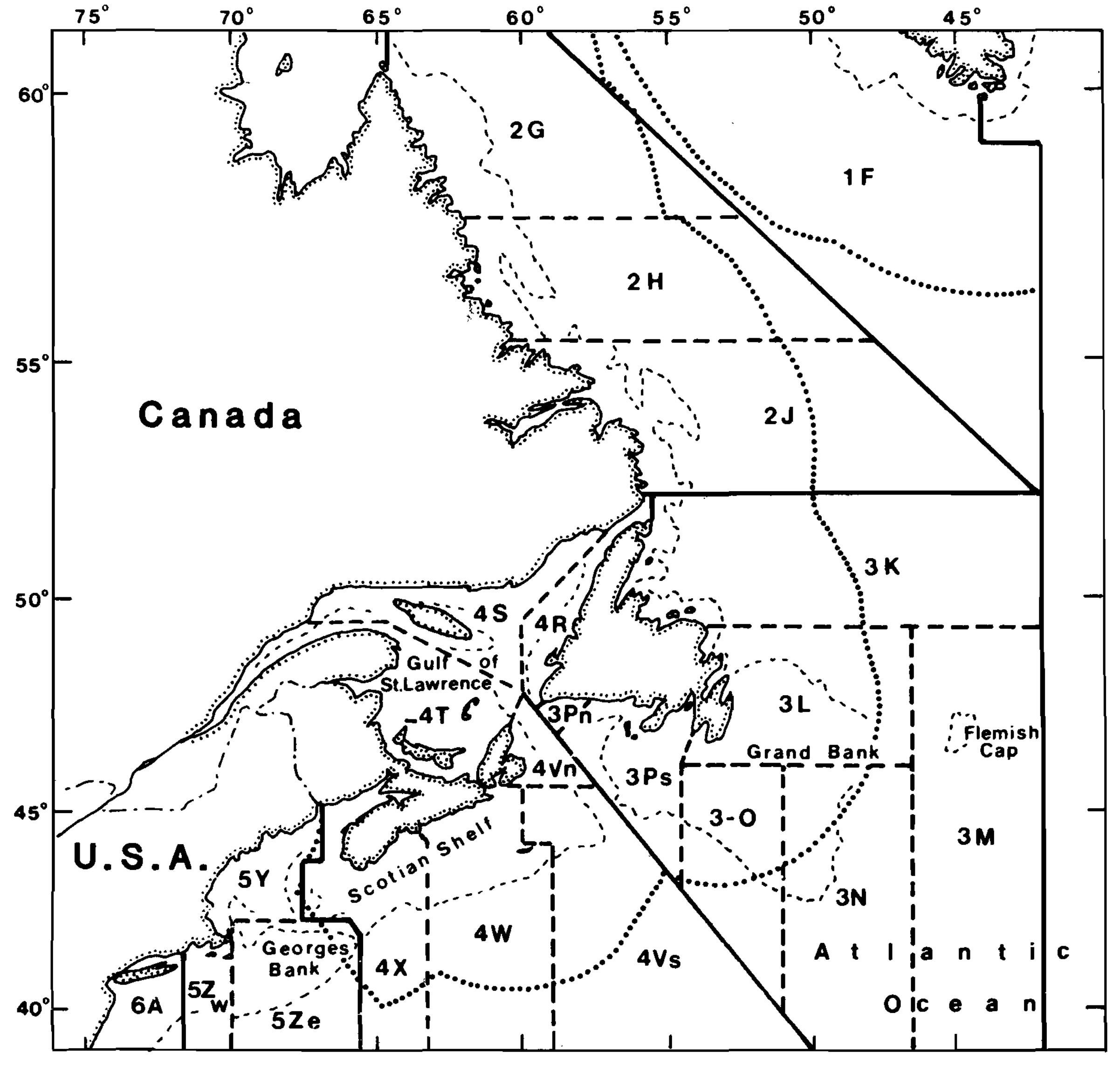

Fig. 1. Northwest Atlantic Fisheries Organization (NAFO) management divisions in Atlantic Canadian waters, and place names referred to in this technical report. Short dashed line indicates the 200-m isobath, while the dotted line indicates the 200-mi exclusive Canadian economic zone.

The Problem of Estimating the Current Size of Year-Classes Recruiting to Commercial Fisheries

Robin Mahon

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Mahon, R. 1987. The problem of estimating the current size of year-classes recruiting to commercial fisheries, p. 5-13. In R. I. Perry and K. T. Frank [ed.] Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556.

Under the current system of groundfish quota management in Atlantic Canada, advice is based on 2-yr catch projections. A review of recent CAFSAC and NAFO projections to 1986 indicates that a substantial amount of advised catch is based on projections from partially recruited ages in the initial year and, in a few cases, even on the geometric mean recruitment. The estimates of abundance for these recruiting age-classes are very dependent on the partial recruitment (PR) coefficients input into SPA, or on survey recruitment indices. PR coefficients are very variable. Consequently, the common practice of using the historical average in estimating cohort abundance and in projecting is prone to substantial error. Other approaches to estimating PR coefficients have not been very successful. Direct estimation of cohort abundance from survey recruitment indices depends on good relationships of these indices with converged SPA output. More often than not, these relationships are poor, or the recent years are outside the observed range of the data. Work is required in three areas: (1) analysis of the causes of variability in PR coefficients, (2) establishment of good recruitment surveys, and (3) understanding and prediction of recruitment from stock/recruitment and environment/recruitment relationships. Since past performance suggests that none of these methods is likely to be consistently reliable, it would seem most appropriate to explore and, where possible, use the full array of potential tools.

INTRODUCTION

Major finfish stocks on the Atlantic coast of Canada are managed on the basis of Total Allowable Catches (TACs). The recommended TACs are based on population projections over a 2-yr period (details in Rivard 1983). In other words, TACs in year t are based on estimates of population-at-age in year t-2. These estimates are subjected to natural and fishing mortality over the years t-1 and t to provide estimates of the expected catch under a particular harvesting strategy. In the case of the Canadian Atlantic, the strategy is the $F_{0.1}$ level of fishing mortality (Gulland and Boerema 1973). A schematic diagram of a catch projection is shown in Fig. 1.

The estimates of abundance-at-age in year t-2 are obtained by Sequential Population Analysis (SPA). For each age three input parameters determine these estimates: natural mortality, fishing mortality and number of fish caught in that year. A knowledge of SPA is assumed in this paper, but details are available in Rivard (1982, p. 13).

Generally, the accuracy of initial estimates of abundance (year t-2) increases with age, as there is more information on the year-class. Depending on the age composition of the projected catch, there is the potential for advice to be based on projections from initial estimates about which we are not at all certain. For the youngest age in years t-1 and t, it is customary to input the geometric mean (GM) of past recruitment (Fig. 1). In the initial year (t-2), the estimated abundance of the recruiting (partially recruited) cohorts depends largely on estimates of how fully recruited they are (i.e. of partial recruitment coefficients), or on the accuracy of predictions from relationships of survey indices for recruitment with sequential population analysis (SPA).

The objectives of this paper are to examine the importance of pre- and partially recruited age-classes in projected catches, to review the commonly used methods of estimating the abundance of these age-classes and to suggest appropriate future lines of research for improving these estimates.

THE AMOUNT OF PROJECTED CATCH FROM PRE- AND PARTIALLY RECRUITED COHORTS

The percentage of 1986 catch projected from the GM and from partially recruited ages is shown for the major stocks (Table 1). For groundfish, the amount of catch projected from the GM is generally small but, for herring, it is substantial. In all cases a large proportion of the catch is currently projected from partially recruited ages.

The contribution of partially recruited ages to the catch is even more extreme in the case of some species for which analytical assessments are not possible. For silver hake, full recruitment is around age 3-4, and ages 1-4 usually contribute about 80% of the catch. The catch composition from 1970-84 shows that, if projections were possible, anywhere from 10-80% (mean = 53%) of the catch would be projected from the geometric mean recruitment.

Clearly, as fishing mortality increases and the age composition of the stock shifts toward younger ages, the proportion of catch contributed by young fish will increase. In recent years, fishing mortality on many major stocks has been closer to F_{max} than to the target level of $F_{0.1}$. Therefore, if the management objectives of $F_{0.1}$ are achieved, the proportion of catch projected from partially recruited ages will decrease. However, equilibrium estimates of catch at $F_{0.1}$ and F_{max} for four stocks suggest that the proportion projected from partially recruited ages will still be considerable (Table 1).

ESTIMATING THE SIZE OF PARTIALLY RECRUITED YEAR-CLASSES

In the Canadian Atlantic, most emphasis has been on determining the terminal fishing mortality on fully recruited ages. This is done primarily by calibrating the results of sequential population analysis for these ages against abundance indices from surveys or commercial catch rates. However, as Table 1 illustrates, the fishing mortality on the partially recruited ages is probably more important than that on fully recruited ages in estimating fishable stocks 2 yr into the future.

Following is a brief review of the ways in which the abundance of pre- and partially recruiting age-classes have been estimated. In practice, the estimates are decided upon after looking at results from all or most of the approaches. Sometimes the estimates from different methods at various ages are combined on the basis of what appears reasonable.

Partial recruitment (PR) coefficients are estimates of the proportion of fully recruited fishing mortality which applies at each of the partially recruited ages (i.e. the age-specific F for input to SPA). The same PR coefficients are also used in the catch projections (see Rivard 1982, p. 57). The first three methods described attempt to estimate the PR coefficients first. These are then used as input to SPA and catch projections. These methods are explained in full detail by O'Boyle (1981). The fourth method provides direct estimates of year-class size from which the PR coefficients are calculated for use in catch projections.

i) The historical average (Cod, 23JKL, 3NO, 3Ps, 4RS3Pn, 4T; Haddock, 5Z)

Sequential population analysis provides age-specific estimates of fishing mortality in the past. The usual approach is to (1) assign an age of full recruitment, (2) calculate, for each year, an average fishing mortality on fully recruited ages, weighted by population numbers, (3) divide this fully recruited F into the SPA estimates of F for the partially recruited ages to estimate the PR coefficient at each age in each year, and (4) take the average PR at each age over some span of years considered to be typical, or at least consistent with the present. In this approach, anomalous years or periods are frequently omitted (Cod 3NO, 4RS-3Pn).

Partial recruitment coefficients can vary for several reasons: changes in growth, avoidance of small fish, targeting of a large year-class, shifts in seasonality of the fishery, changes in gear (mesh size), changes in proportion of catch by various fleet components. If recruitment patterns are highly variable, there is considerable potential for error when using an historical average for estimating current cohort size and/or for projections. The considerable variability in PR coefficients observed for some major groundfish stocks (selected on the basis of the availability of a table of coefficients in the CAFSAC or NAFO Research Document) suggests this may be a significant problem (Fig. 2). This figure may overstate the problem in some cases by using years in which there were small mesh fisheries, now under strict regulation.

ii) Comparison of age composition in the catch with that estimated for the population (Plaice 3LNO; White Hake 4T; Herring 4R, east coast Newfoundland)

A fishery independent (survey) estimate of the relative abundance of age-classes in the population is required. For herring, surveys or discarded purse seine catches have been used (4R, east coast Newfoundland). For groundfish, trawl surveys are commonly used with the assumption that the age-classes appearing in the catch are fully recruited to the survey gear. The ratio of the proportions at age in the catch to the proportions at age in the survey are used as estimates of the PR coefficients. This approach is generally considered to be unreliable (Roff 1981), but has been used when there have been obvious shifts from the historical pattern (Plaice 3LNO).

iii) Gear selectivity patterns (Cod 4VsW; Herring 4T)

When the size selectivity ogives/curves are known for the predominant gear in the fishery, these can be applied to a fishery independent estimate of the size composition in the population to calculate an expected size composition in the catch. Age-length keys are then used to convert the size distributions to age distributions. As above, the ratio of expected proportions at age in the catch (after application of selectivity ogives) to those in the surveys are used as estimates of PR coefficients. This method has not been used often. In the case of 4VsW cod, this method gave results which were inconsistent with observed increases in mesh size in otter trawls. Consequently, more reasonable historical averages were used for some ages.

iv) Indirect estimation by first predicting cohort sizes from survey recruitment indices (Haddock 4VW; Cod 1; 2J3KL, 5Z)

The size of an age-class may be predicted directly from age-specific relationships between SPA output and survey abundance indices. The fishing mortality required to take the observed catch from the cohort is then calculated iteratively from the Baranov catch equation. The ratio of this fishing mortality to that on fully recruited ages is the PR coefficient which may then be used in the projection.

In most groundfish stocks there has been a trend of increasing recruitment over the period covered by the surveys. Consequently, the predicted value frequently falls outside the range of observations. In such cases, it has been common practice to set the size of the cohort equal to the largest or smallest observed in the SPA.

For groundfish, the recruitment indices are usually taken from trawl surveys. These surveys were primarily designed to provide abundance indices for adult fish to be used in calibrating SPA. The recruitment indices from the surveys are frequently poor for the youngest age-classes in the SPA, and even when the relationships are significant, the confidence intervals around the estimates are likely to be large.

ESTIMATING THE SIZE OF PRE-RECRUITED YEAR-CLASSES

Highly variable recruitment will increase the chance of the GM being an inappropriate input value. It will probably also result in inter-annual variability of partial recruitment-at-age. Thus, the use of historical partial recruitment will be less appropriate than when recruitment variability is low. Species or stocks vary considerably and consistently in their recruitment variability (Hennemuth et al. 1980).

Frequency histograms of recruitment for groundfish stocks in the Canadian Atlantic are directly comparable with those of Hennemuth et al. (1980) and, in general, support their conclusions (Fig. 3, 4). Haddock recruitment is more variable than that of cod, and shows signs of multimodality. There is quite a range of variability among cod stocks but, even in the least variable, recruitment fluctuates regularly between half and double the mean. Recruitment in the two flatfish stocks is relatively constant. This type of overview can be useful in determining likely problem areas and in allocating research effort.

DISCUSSION

Clearly, the problem of estimating abundance of recruiting age-classes is crucial if we are to continue with quota management. There are three main areas in which research activity should be increased. These are: (1) analysis of factors responsible for variability in partial recruitment coefficients, (2) implementation of surveys specifically for pre- and partially recruited ages, and (3) understanding and prediction of recruitment.

There is already some feeling for the factors which may cause PR coefficients to change (section on historical average), but there has been little analysis focused on this problem. Presumably, this type of analysis could lead to an ability to predict departures from the average condition; for example, when changes are dependent on fish growth.

Specific recruitment surveys should be more effective than generalized adult surveys in estimating year-class size. Cod generally first recruit to the fisheries at about age 3 or 4 (except 5Z). Therefore, surveys aimed at fish of ages 0-3 should allow 3-4 estimates of the size of a year-class before it even begins to recruit. Current adult surveys appear to be least effective at estimating recruitment for cod and pollock, but are reasonably successful for haddock (probably by chance) and for redfish and flatfish by virtue of their relatively slow growth and older age of recruitment.

Understanding and prediction of recruitment falls into two categories: stock-recruitment relationships and environmental effects. The literature on these two topics is vast (see Sissenwine 1934 for a recent review). By and large, stock recruitment relationships for marine fish stocks have not been clearly definable from the available data. In those cases where recruitment failure has been obvious, these relationships may be of some value in establishing minimum levels of spawning biomass. However, on their own, they do not appear to hold a great deal of promise for predicting year-class size.

Environmental influences on recruitment may be the cause of much of the variability about a mean stock recruitment relationship, or the form of the relationship itself may change with environmental conditions (Shepherd et al. 1984; Tang 1985). In either case, quantification of the combined effects of environment and stock on recruitment may be required before any reasonable predictive ability can be achieved.

Shepherd et al. (1984) pointed out that "... since we cannot at present predict the weather more than a few days in advance, we should be unable to predict year-class strength until the weather that affects it has actually happened. This would therefore give us an advantage of at most a year or two on the use of a 0- or 1-group survey, and it is therefore far from clear that the elucidation of the effects of climate or weather would be worthwhile simply to assist in the setting of short-term management objectives (such as TACs)."

This paper has indicated that the ability to determine the size of year-classes already spawned could be extremely valuable in improving the accuracy of advice. Whereas it is true that environmental indices would give very little time advantage over surveys, there will no doubt be substantial variability in survey estimates, and supporting information from environmental correlations could be invaluable. In short, given the usual uncertainty in fishing data, no one method is likely to be sufficient and we should be exploring the full array of potential tools.

ACKNOWLEDGMENTS

I would like to acknowledge the the many authors of CAFSAC and NAFO Research Documents cited here for permission to use their material. Thanks also to Bob O'Boyle for reviewing the MS and providing many useful suggestions.

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DISCUSSION PERIOD

During the discussion, it was pointed out that the problem of partial recruitment is less severe for those species in which older fish make up a large proportion of the population. However, as fishing mortality increases, good estimates of partial recruitment become much more important. Over the past 5 yr, fishing mortality has generally been $>F_{0.1}$, which may be why this problem is being noticed more. It was also noted that good estimates of partial recruitment are more important to shorter-lived pelagic species than longer-lived demersal species.

Table 1. Cumulative percent of total catch by age as projected for 1986. The solid line shows ages projected from the geometric mean, the dashed line shows ages projected from partially recruited age classes.

Stock	Age 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Equilibrium $F_{0.1}$	F_{max}
Cod 2J3KL				3	16	40	58	74	81	85	91	96	99					
3NO			1	10	14	24	35	60	74	88	97	99						
3Ps			0	2	16	43	60	85	91	94	96	99						
3Pn-4RS				1	7	21	43	68	79	87	94	98						
4T			0	1	9	39	56	67	80	85	95	99						
4VsW			2	11	22	44	67	81	91	95	97	99					55	71
5Z	0	17	53	68	78	90	94	97										
Haddock 4VW	0	0	1	18	47	80	91										55	80
4X	0	1	2	17	38	77	88	94	98								65	91
5Z	0	1	55	57	59	66	70	87	99									
Pollock 4VWX-5		0	7	18	28	56	92	96	97	98							74	88
White Hake 4T			1	6	17	46	72	86	94	97	99							
American plaice 3LNO						1	4	12	20	33	48	67	80	89				
Yellowtail 3LNO				0	3	38	56	78	95	99								
Redfish 4RST					0	0	0	4	4	4	5	9	16	28	40	50		
Herring 4R Spring		0	4	14	30	56	68	73	76	76	78	82	84	85				
Fall		0	2	10	17	20	75	84	87	88	89	90	92	93				
4T Spring		0	20	59	75	88	98	99										
Fall		0	1	22	56	82	89	94	98	99								
4VWX	0	7	31	42	59	78	92	94	96	99								
Mackerel 4-6	1	13	16	65	92	95	96	99										

The catch projections were carried out using PROJECT (Rivard 1982) and input data from NAFO (1985) and CAFSAC (1985a-e).

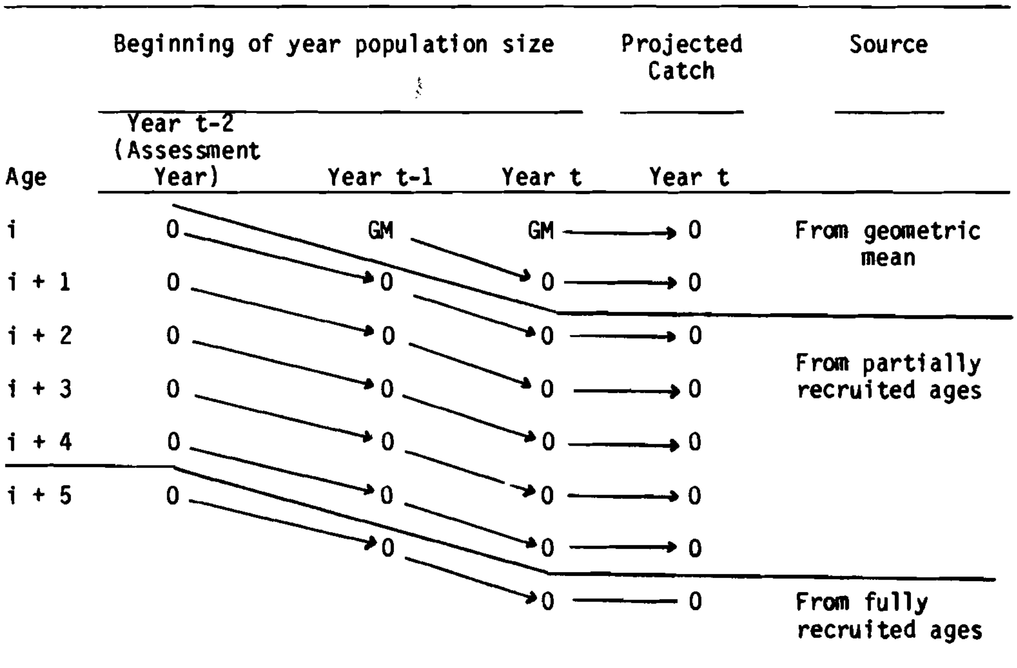

Figure 1. Generalized catch projection showing the source of projected catches.

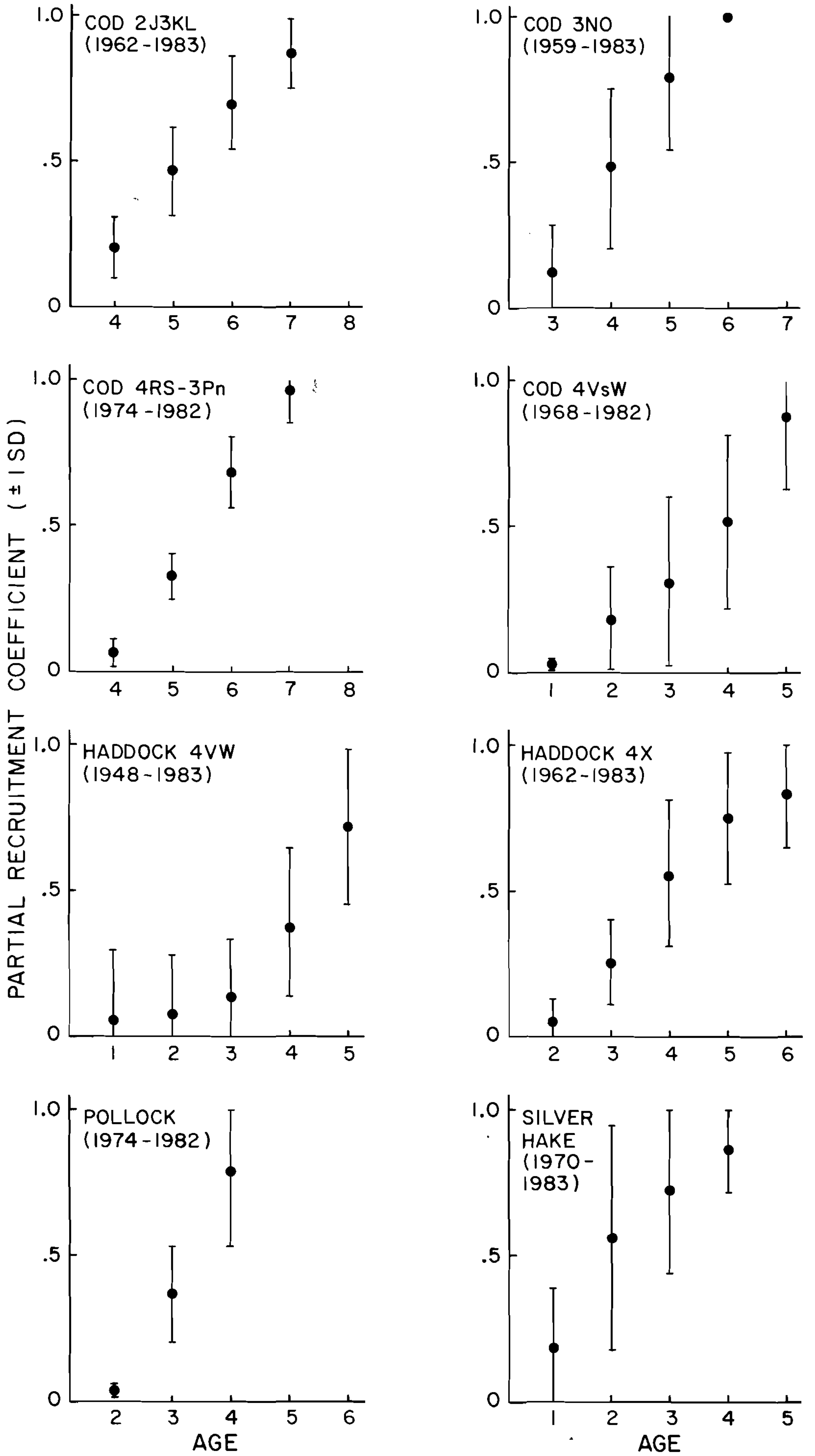

Fig. 2. Variability (mean ± 1 SD) of partial recruitment coefficients for some groundfish stocks. (Data from: Baird and Bishop (1985); Bishop and Baird (1985a); Gascon (1984); Gagne et al. (1984); Mahon et al. (1985); O'Boyle and Gregory (1985); McGlade et al. (1985); and Waldron and Fanning (1985).)

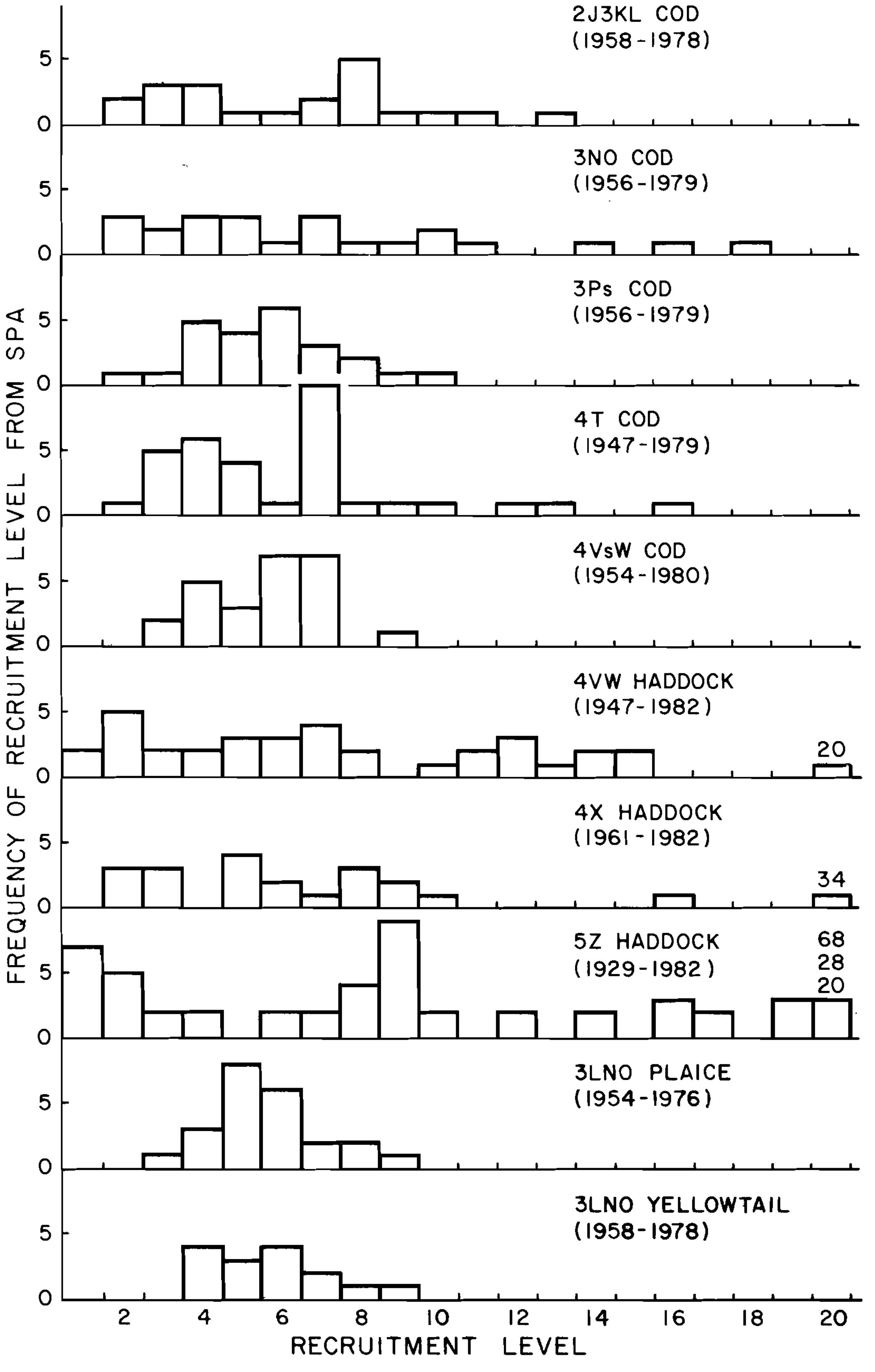

Figure 3. Frequency distributions of relative recruitment (year-classes in parentheses): ratio of recruitment in each year to GM/5. (Data from: Baird and Bishop (1985); Bishop and Baird (1985a, 1985b); Lever and Waite (1984); Lett (1978); Sinclair and Gavaris (1985); Gagné et al. (1984); Mahon et al. (1985); O'Boyle (1985); Waiwood and Neilson (1985); Clarke et al. (1982); and Brodie (1985a, 1985b).)

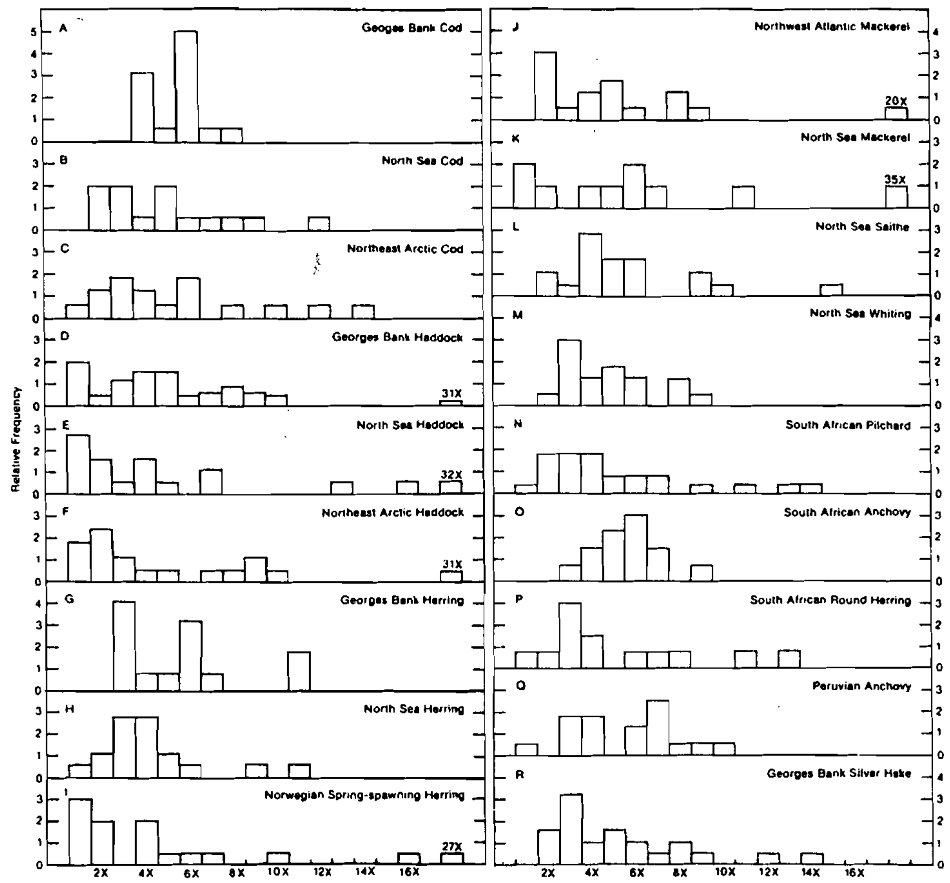

Figure 4. Frequency distributions of relative recruitment for 18 fish stocks: ratio of recruitment in each year to GM/5 (from Hennemuth et al. 1980).

Sea Surface Temperature Patterns in the Northwest Atlantic[1]

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This paper summarizes and extends our previous results. Using the sea-surface temperature (SST) information for the period 1946-80 compiled from ship reports, time series of monthly median SST's have been created for areas of fishing banks and oceanographic features from Cape Hatteras to Greenland in the western North Atlantic. Empirical orthogonal functions (EOF), cross-correlations and power spectra have been computed from these series.

From the EOF analysis, patterns of consistent SST anomalies over large distances along the continental shelves were found. The first two modes alone typically accounted for 44% of the variance in the anomaly field. These patterns persisted from season to season. An error analysis showed that these patterns are distinguishable well above noise.

A cross-correlation analysis between 'same-month' subsets of the time series for a particular area, e.g. west Grand Bank, eastern Scotian Shelf, South Shore, Georges Bank, mid-Atlantic Bight showed that the SST regime is established in winter and persists through spring into summer.

The evidence is that winter anomaly winds extract more or less heat from the water column during this season when the mixed layer is thickest. This widespread thick upper layer of water of altered heat content then responds to subsequent air/sea fluxes quite slowly. The anomaly charts for particular years show the SST patterns correspond well with winter anomaly wind patterns. Onshore winter wind anomalies are associated with positive SST anomalies; offshore winter wind anomalies, with negative SST anomalies. Summer wind anomalies are virtually zero. Summer SST anomalies reflect those of the previous winter.

The EOF time series, representing the temporal variation of, for example, the first mode of the SST anomaly field as a whole, shows long-term variability on the scale of 20 yr. We have examined the smoothed wind record to see if the variation and direction over the long term show the same relationship to SST as described above for particular years.

The implications of this work for fisheries are quite interesting on at least two counts. Firstly, the SST field is predictable to a considerable extent. Secondly, one would speculate that temperature data from the groundfish depths would show the anomaly regime to be established in winter by this same mechanism and to persist even longer than do the SST's.

DISCUSSION PERIOD

Smith: My question concerns the relationship between wind and sea-surface temperature. They act on different time scales, so how does the SST field persist for 20 mo when winds vary on 4-mo (seasonal) scales?

Loucks: Sea-surface temperature anomalies are enhanced at low frequencies by the wind but, once formed, thermal inertia helps to maintain the SST anomaly over several months independent of the wind.

Campana: Could such temperature anomalies occur in "runs," with periods of warm or cold anomalies extending for months or years, for example, over the first year of life of fish populations in certain regions?

Loucks: Yes, it appears this could be the case.

[1]Editor's note: Now published as:

Loucks, R. H., and R. W. Trites. 1985. Analyses of sea surface temperatures in the northwest Atlantic. Can. Tech. Rep. Fish. Aquat. Sci. 1410: 42 p.

Loucks, R. H., K. R. Thompson, and R. W. Trites. 1986. Sea surface temperature in the northwest Atlantic - space and time scales, spectra and spatially smoothed fields. Can. Tech. Rep. Fish. Aquat. Sci. 1430: 80 p.

These references should be used for correct citations.

Diffusion and Redfish Larvae on Flemish Cap

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Akenhead, S. A. 1987. Diffusion and redfish larvae on Flemish cap, p. 15-16. In R. I. Perry and K. T. Frank [ed.] Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556.

This note is an overture to an analysis of the maps of the abundance of larval beaked redfish on Flemish Cap presented in Anderson (1984). Redfish spawning on the Cap has a normal distribution with standard deviation of 15.6 d and mean of day 114.4 (Penney and Evans 1985). Spawning is located near the 300-m isobath, close to the shelfbreak, centered near 115 km with standard deviation 20 km. One hundred days later, surviving larvae are found near the center of Flemish Cap. Anderson (1984) estimated the larval mortality rate to be 0.047 (±0.0047) $days^{-1}$, and suggested the shift in distribution toward the center might be the result of convergence.

The residual circulation on Flemish Cap follows the bathymetry (Ross 1980, 1981). About 0.025 of the water on Flemish Cap exchanges for Labrador Current water each day (Akenhead 1986). The diffusion on Flemish Cap is not an insignificant effect if about half the larval mortality could be due to diffusion loss from the Cap.

Perhaps the spatial pattern of larval fishes can be explained by radial diffusion, without the need to invoke convergence. Consider that the area beyond the shelfbreak is a sink for larval fishes diffusing off the Cap, i.e. larvae in deep water are lost through advection, larger diffusion or deepsea predators. Then the pattern in space and time, A(r,t), of Flemish Cap is the solution to the equations:

1) $\frac{dA}{dt} = K \frac{d^2A}{dr^2} + \frac{1}{r}\frac{dA}{dr}$; radial diffusion

2) A(R,t) = 0; where R is the outside edge, and

3) A(r,0) = f(r); the initial distribution.

Churchill (1963, p. 192) provides the Bessel function series solution. After a relatively short time, only the first term of the series remains important, i.e. the details of initial distribution diffuse away. The solution is then:

$$A(r,t) = C\ Jo\ (\lambda\ r)\ e^{-\lambda^2 Kt}$$

which has a maximum at the origin and a bell-shaped decline to zero at the perimeter.

Figure 1 shows solutions to this problem for parameters appropriate to Flemish Cap, which include the mean and variance in space and time of spawning, a diffusion rate and the radius of Flemish Cap. The pattern of larval fish due to diffusion is separable from the pattern due to the distribution of spawning effort through time, S(t), assuming each day's eggs diffuse independently of other days. The number of fish of any age, at any time, and at any radius of Flemish Cap is thereby predicted to be:

$$N(r,a,t) = S(t-a) \cdot A(r,a).$$

CONCLUSION

The progressive shift of larval redfish distributions from the edge to the center of Flemish Cap can be ascribed to diffusion without the need to invoke convergence or spatial patterns in mortality.

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DISCUSSION PERIOD

Pepin: Are you implying that the interpretation of larval mortality rates in physically dynamic areas, such as the California current, may be considerably in error?

Akenhead: Yes. There was a paper in the Fisheries Bulletin, 1982, by A. Rosenberg and others who showed that computing the mean age and the residence time of populations from otolith classes compared to analyses done by following length-frequency modes through time gave considerably different results. They found age estimates differed by 2-3 for animals only 10 d old, while average residence times varied from 8 wk using otolith analysis to 18 wk using length-frequency modes.

Koslow: Why do you think they spawn on the edge of the bank?

Akenhead: I don't know for certain. It may be associated with the development and pattern of the spring bloom, which seems to be associated with the shelf break as well. Whether the high chlorophyll reflects high productivity due to mixing processes, or whether it is a lack of grazing by herbivorous zooplankton is uncertain. Later in the summer there seems to be more spawning on the top of the bank, e.g. by cod and Sebastes fasciatus.

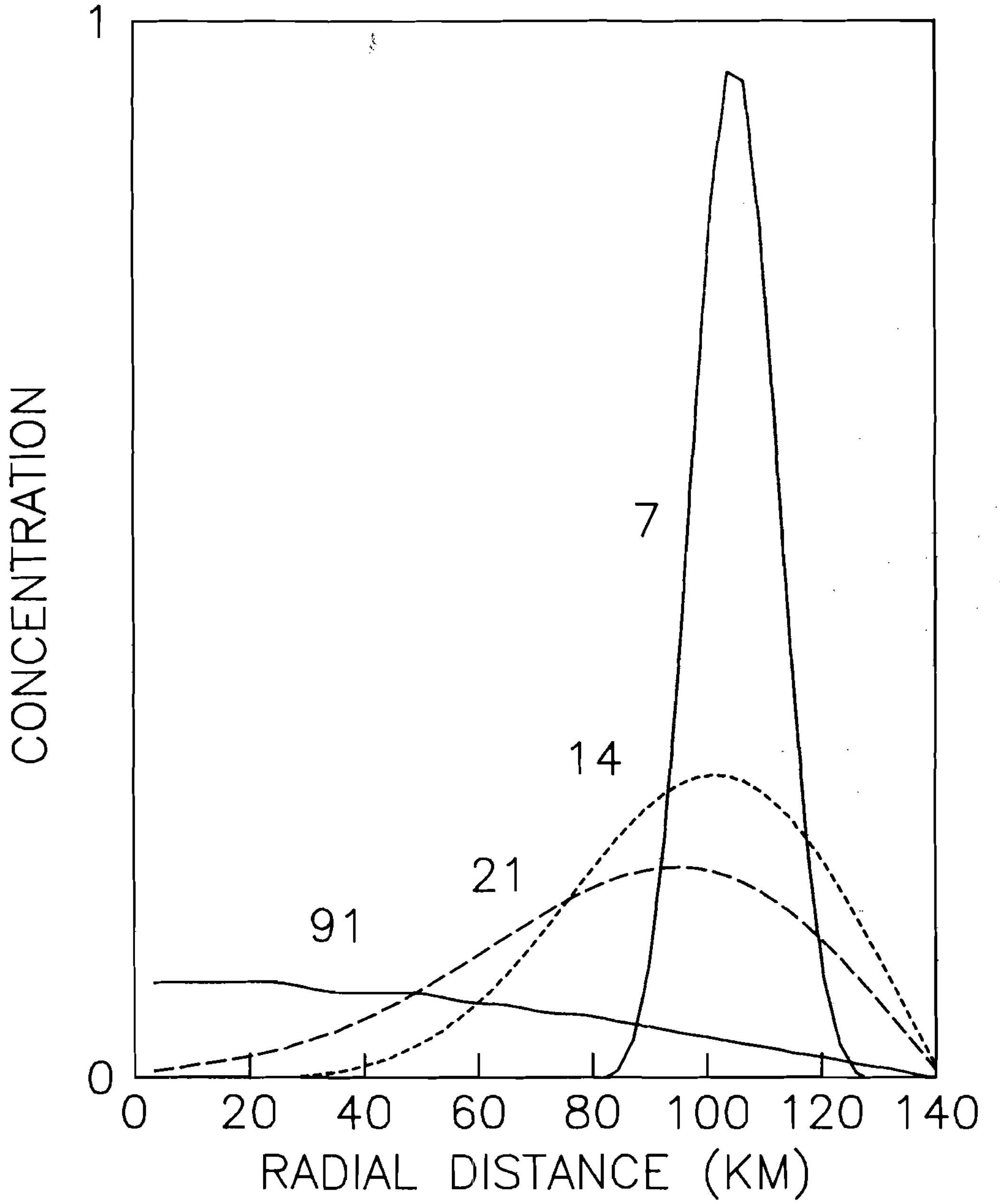

Fig. 1. Time course of larvae dispersing from a patch centered near 100-km radius, after 7, 14, 21 and 91 d. Mortality is 100% at the 140-km radius shelfbreak.

The Effects of Environmental Conditions on the Time of Herring Arrival on the Spawning Grounds in the Gulf of St. Lawrence

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Messieh, S. N. 1987. The effects of environmental conditions on the time of herring arrival on the spawning grounds in the Gulf of St. Lawrence, p. 17-29. In R. I. Perry and K. T. Frank [ed.] Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556.

Timing of arrival of Atlantic herring Clupea harengus on the spawning grounds in the southern Gulf of St. Lawrence is correlated to mean April temperature. Cold years result in delays in herring arrival, whereas warm years result in early arrival. It is maintained that earlier arrival would provide better conditions for spawning success, larval survival and year-class strength.

Vertical distribution of temperature along sections crossing the Laurentian Channel at different locations relevant to herring migration showed the monthly changes in the process of water stratification. The water mass was stratified into three layers: a warm surface layer; a cold intermediate layer (near 0°C); and a warm deep layer (1-5°C). By May, the cold layer had shrunk to a cold core along the Laurentian Channel.

The size and depth of the cold intermediate layer is influenced by meterological conditions during spring. According to Ekman's theory of wind-driven currents, there is a net transport of water to the right of the direction of the wind. Along the slope 'edge' of the Magdalen Shallows, a strong north wind would push down the cold layer along the edge, delaying the spring migration. A strong south wind, on the other hand, would tilt up this layer above the Magdalen Shallows allowing herring to move to the spawning grounds without crossing the cold barrier. It is hypothesized that the variations in the intermediate cold layer during spring provide cues triggering the herring spring migration to the Magdalen Shallows.

INTRODUCTION

There is a large amount of published literature on the effects of environmental factors upon fish populations. For many years fisheries biologists have tried to relate year-class strength to environmental variables such as temperature, salinity and wind (Cushing 1982).

Attention has been given in recent years to the influence of environmental factors for northwest Atlantic fish species on fish distributions (Scott 1982; Perry and Gavaris 1985), catches (Sutcliffe et al. 1977), spawning time (Messieh 1977) and recruitment (Koslow 1984). Environmental effects on larval survival and year-class strength in clupeoids, including Atlantic herring (Clupea harengus), have been reviewed by Blaxter and Hunter (1982).

Stock-recruitment relationships for Atlantic herring are poorly understood (Winters 1976). Anthony and Fogarty (1985) showed that herring recruitment in the Gulf of Maine has varied by a ratio of 20 to 1, and suggested that environmental factors determine year-class survival during the late larval-early juvenile phases. Winters et al. (1985) showed that the recruitment variability of a Newfoundland herring stock was more strongly coupled with favorable temperature conditions than with stock biomass. They supported their conclusion by the pattern of year-class strength in adjacent herring stocks. When one stock shows a large year-class, so do the other stocks, with the same strong year-class over the entire Gulf of St. Lawrence area. Hourston (1980) arrived at the same conclusion for Pacific herring.

Messieh (1977) showed that the timing of arrival of herring on the spawning grounds at Magdalen Islands is negatively correlated with sea temperatures. The biological implication is that warmer temperatures in spring will result in earlier spawning and better conditions for larval feeding and survival. Similar conclusions were made for Georges Bank herring (Berenbeim and Sigaev 1977) and for Pacific herring (Hay 1985). However, no mechanism which might induce temperature changes which would regulate herring migration to the spawning grounds was proposed. The objective of the present study was to elucidate how temperature influences the timing of the herring spring migration from overwintering areas, and its possible effect on year-class success.

DATA SOURCE AND ANALYSES

A considerable amount of sea temperature data has been taken by fisheries research vessels operating in the Gulf of St. Lawrence. Temperature observations from 1965 onward are compiled in a data base by the Marine Environmental Data Service (MEDS). For the purpose of the present study, all available temperatures from surface to bottom, or at deepest available station, were analyzed along eight vertical sections. The sections were taken at different points crossing the Laurentian Channel, Esquiman Channel and St. Lawrence Estuary (Fig. 1). These locations were chosen because of their importance to herring during their migration from overwintering areas to the Magdalen Shallows (Winters and Beckett 1978). The temperature analyses and contour plotting were carried out by a computer program CONMAP available at MEDS. Meteorological data, including monthly mean temperatures, prevailing wind direction and speed recorded at Grindstone Station on one of the Magdalen Islands (Fig. 2) were obtained from the Atmospheric Environment Service.

Linear regressions were used for analyses of the relationships between temperatures and day of herring arrival on the spawning grounds. Day of arrival was determined in Julian days from catch statistics records. Only fixed fishing gear catches were used; mobile gear catches were excluded because of the uncertainty of spawning locations and spawning condition of the fish. Herring catch statistics used were compiled from 1949-68 by Tibbo et al. (1969), and from 1969-75 by McMillan et al. (1984). More recent catch statistics were not included in the analysis because fishing was drastically reduced on the Magdalen Islands after the collapse of its herring stocks in 1975, and also because catch quotas applied to 4T herring resulted in changes in the distribution of fishing effort.

RESULTS

Herring arrival time and temperature

The arrival of Division 4T herring on the spawning and feeding grounds of the Magdalen Shallows (Fig. 2) is a regular annual event. This is demonstrated in the seasonal pattern of herring gillnet landings in the past 35 yr (Fig. 3). The distributions in most of the years are bimodal, one mode in spring and another in fall. The spring fishery extends from April to June. Spawning usually occurs in May, but there is year-to-year variation, with spawning starting earlier in April in some years and extending later into June in other years.

A regression of the mean day of herring arrival on the spawning ground of the Magdalen Islands, vs the mean April air temperature at Grindstone Island for 25 yr since 1949, showed a significant negative correlation ($r = -0.84$). A regression of the mean day of arrival on all spawning grounds in the 4T area combined, vs mean April temperature, showed a similar significant negative correlation ($r = -0.66$). When regressions were repeated using the mean April air temperature at Charlottetown Station instead of Grindstone Station, the correlations in both cases were also significant ($r = -0.82$ and $r = -0.60$, respectively). The parameters of the regression equations are presented in Table 1.

Relationship between air temperatures and sea temperatures

A regression of the mean April air temperatures at Grindstone Island and the mean April air temperature at Charlottetown, P.E.I. (the closest meteorological station to Grindstone Island, situated in the center of 4T area) was positively correlated ($r = 0.92$). The regression of mean April air temperatures at Grindstone Island and mean April sea temperature at Entry Island (one of the Magdalen Islands) also showed a similar positive correlation ($r = 0.88$). The parameters of the regression equations are presented in Table 2.

Seasonal changes in water stratification

Monthly vertical distributions of temperature showed the seasonal changes in the process of stratification. In winter, the water mass was stratified into two layers: a cold layer (0°C or less) reaching a depth of about 100 m and extending throughout the Gulf of St. Lawrence; a deep warm layer (as high as 5.0°C) extending to the bottom.

Figure 4 shows the monthly variations in the water mass from April to November in a representative vertical section (Section O-P) (Fig. 1). This section passes from the North Shore Quebec, southward to Anticosti Island, Gaspé coast, off Chaleur Bay and ends in North Point, P.E.I. In April, the water mass is stratified into two layers: a cold top layer (near 0°C) reaching a depth of about 100 m, and a warm bottom layer (1-5°C). Near the surface, there was an indication of the beginning of water stratification into a warmer surface layer and a cold intermediate layer separated by a weak thermocline.

In May, the intermediate cold layer (0°C) decreased in size, forming a cold core along the Laurentian Channel. Meanwhile, the surface layer became more well defined, with temperatures ranging from 4.0°C at the surface to 1.0°C at about 30 m depth. In June, the cold core shrank and in July became poorly defined. Stratification continued to be strong throughout summer, with temperatures at the surface as high as 16.0°C in August, decreasing to 1.0°C at about 50 m depth. At about 70 m, the temperature gradually increased, reaching about 5°C near the bottom. In October, the thermocline in the surface layer began to decay and, in November, the mixing between the surface and intermediate layers was almost complete.

The cold intermediate layer in spring

Comparison of water stratification during April and May in all eight sections analyzed showed similar general characteristics. Figure 5 shows the vertical temperature distribution in four sections: A-D; G-H; I-J; O-P. The other sections (not shown) are almost the same. During April, the coldwater mass (0°C or less) extended from one side of the Gulf to the other, filling the Laurentian Channel, Esquiman Channel and St. Lawrence Estuary. In all sections, the cold water extended from the surface down to about 100 m deep.

In May, the cold layer had drastically decreased in size and, in most cases, had shrunk to a cold core along the center of the Laurentian Channel (sections A-D; G-H; I-J), the Esquiman Channel (sections O-P). The center of the cold core was at similar depth (about 70 m) in all sections, but its thickness ranged from about 20 m near Magdalen Islands (section G-H) to 60 m near Chaleur Bay (section A-D).

Wind data at Magdalen Islands

Wind data including direction, speed and number of days with gale force during April are recorded for the period 1951-80 (Table 3). Records of wind data were taken by the Grindstone Meteorological Station. The prevailing wind direction during April changed from year to year. Mean wind speed ranged between a minimum of 26.2 km/h in 1979 and a maximum of 38.3 km/h in 1958. Days with gale force (speed ≥62 km/h) ranged from 1 d in 1973 to as high as 13 d in 1958.

DISCUSSION

The influence of temperature on the timing of herring arrival on the spawning grounds shown in the present study is demonstrated by the significant correlation between the mean time of arrival and the mean temperatures for April: the higher the temperature, the earlier the time of spawning. These results agree with earlier studies on herring in the same area (Messieh 1977).

Berenbeim and Sigaev (1977) showed a significant correlation between August sea temperatures and herring spawning time on Georges Bank in the Gulf of Maine. They concluded that the relatively high heat content of the water prior to spawning determines the earlier dates of peak spawning. For Pacific herring, Hay (1985) found a significant correlation between monthly mean temperature for March and the annual mean date of herring spawning in the Strait of Georgia, B.C. However, he found some exceptional cases which illustrate that spawning is not wholly temperature dependent and other factors, e.g. tidal cycles and weather conditions, also operate. He added that spawning might not follow immediately after fish reach physiological maturity, rather spawning must require both physiological readiness and appropriate ecological cues. Such ecological cues were missing in an experimental impoundment where herring were held in a mature state for up to 40 d. However, he did not identify the mechanism involved.

The analysis of vertical water temperature distribution shown in the present study provides further insight on the role of temperature in triggering the herring migration from the overwintering areas to the Magdalen Shallows where spawning and feeding occur. In winter, the water mass is stratified into two layers: a cold top layer (0.0°C or less) reaching a depth of about 100 m and a bottom warm layer (1.0-5.0°C). In spring (April/May), the surface water starts warming up, leaving the cold intermediate layer at depths 70-100 m. The depth of the cold layer coincides with the slope of the Magdalen Shallows, thus creating a thermocline barrier under which the overwintering herring schools stay. It is hypothesized that herring spring migration is triggered by the displacement or disintegration of this cold intermediate layer near the slope (edge) of the Magdalen Shallows.

The disintegration of the thermocline near the edge could be achieved by the shrinkage of the intermediate layer due to spring warmup and/or St. Lawrence River runoff (see May section: (Fig. 5)). It can also be achieved by an upward tilting of the intermediate layer under the influence of a persistent strong south wind (Fig. 6). According to Ekman's theory of wind-driven currents, a net transport of water occurs to the right direction of wind. Therefore, a strong south wind lasting for several days would result in tilting up the cold layer in the Laurentian Channel along the northern edge of the Magdalen Shallows.

The cold intermediate layer hypothesis can explain the year-to-year variations in the time of herring arrival on the Magdalen Shallows. Based on this hypothesis, the overwintering herring stay in the warm bottom layer in the Laurentian Channel until the time when the location of the intermediate layer allows the movement of herring over the edge of the Magdalen Shallows without going through the cold intermediate water layer. The onset of spring and its effect on the intermediate layer is a regular annual event resulting in the usual annual pattern of herring spring migration. Warmer air associated with a south wind would lead to a shrinkage of the intermediate layer allowing the herring to get past the edge to the spawning grounds. Under exceptionally strong or persistent south winds, as that happened in 1958, the displacement of the cold layer leads to herring getting past the edge earlier than usual, contributing to exceptional recruitment. Figure 7 shows a model for the mechanism of herring movement during spring from the overwintering areas to the spawning and feeding grounds in relation to the intermediate cold layer.

There are some previously reported observations which provide evidence in support of this hypothesis. Hachey (1935) found a drastic change in temperature of the water column in a section extending on the Scotian Shelf from Halifax Harbour outwards to a distance of about 56 km. After a storm, he found a warm uniform body of water (14.1-15.7°C) near the coast extending from surface to bottom. In the previous week, the temperature ranged from 4.0°C on the bottom to 20.1°C on the surface. Lauzier (1957) found similar observations in North Rustico and Cheticamp in the southern Gulf of St. Lawrence. In a survey carried out in 1948, he observed that the temperature off North Rustico at 30 m depth increased from 5.0°C to 14.5°C in 1 wk only. Both authors attributed these temperature changes to Ekman transport. Similar observations were encountered during our research surveys (Messieh, unpubl. data; Drinkwater, pers. comm.) where abrupt changes in bottom temperatures occurred over short periods.

Drinkwater kindly provided unpublished data from the thermistor chain and current meters moored in St. Georges Bay in 1979 for over 5 mo. His data showed large events, all wind-related. A northwest wind tends to push surface water into the Bay and forces bottom water out. As the wind relaxes, the bottom water starts to flow back in again. The reverse occurs during a southeast wind. Drinkwater also analyzed temperature data from current meters moored in the Bay in 1975 on an hourly basis, when a tropical storm passed over. Data showed that while no striking change in temperature was observed near the surface, at 30 m changes of over 10°C in a few hours occurred. Such changes lasted only a few hours in one station but up to a day or more at another station.

Evidence of the occurrence of herring concentrations in deep water along the edge is demonstrated by the once lucrative herring fishery, the so-called 'edge fishery' in the mid 1970's. This fishery supported a large purse-seine fleet equipped with sophisticated acoustic gear to locate herring concentrations along the edge. Skippers learned by experience how to take advantage of the wind conditions to monitor the herring movement. After catching the fish in the edge in early April, the skippers followed the moving schools westward where they caught them on the spawning grounds a few days later. Experienced fishermen knew that the timing of herring movement from the edge was critical; a few days difference could be detrimental to a successful catch. As an example, exploratory fishing for herring was carried out in the edge area by five purse seiners on April 25-30, 1981 (Sinclair and Allain 1981). The original plan for departure was April 14, but the trip was postponed due to bad weather. No herring were encountered by any vessel throughout the exploratory period. The skippers were of the opinion that, due to early spring warmup and early departure of ice that year, the herring had already left the edge area by the time the exploratory fishing got underway.

The relationship between the meteorological and oceanographic conditions in the northwest Atlantic have been studied by several investigators. Long-term similarities between air temperatures and sea temperatures in the same geographic area have been reported. Our results showed a significant correlation between sea temperatures at Entry Island and air temperatures at Grindstone Island (r = 0.88). Taylor et al. (1957) found similarities between Boothbay Harbour sea temperatures and Eastport air temperatures. Lauzier (1972) found similarities between St. Andrews sea temperatures on one hand, and Halifax and Sable Island air temperatures on the other hand. These authors concluded that the hydrological and meteorological factors are linked to a large-scale weather system which controls wind patterns, air temperature and precipitation. The biological implications are that large-scale physical processes may be responsible for the observed correlations in recruitment among stocks of the northwest Atlantic fish (Koslow 1984; Sutcliffe et al. 1977).

Anthony and Fogarty (1985) found that recruitments to the Gulf of Maine herring stocks were related to temperature, both directly and inversely. Winters et al. (1985) showed that the recruitment variability exhibited by Fortune Bay herring was more strongly associated with environmental factors than with spawning stock biomass. Garrod and Colebrook (1978) examined several stocks throughout the North Atlantic and showed that differences in recruitment from year to year are affected by differences in wind strength and direction.

The synchrony between hatching and first feeding of fish larvae and the occurrence of favorable food conditions has long been considered an important regulator of larval survival and year-class strength (Frank and Leggett 1982). Dickson et al. (1973) related the recruitment of North Sea cod to temperature. Based on the high correlations between March/April temperature and spawning time, they suggested that the critical events on formation of year-class occur on the spawning ground or near it. It is conceivable that the timing of herring arrival on the spawning ground is important for spawning success, larval survival and subsequently the year-class strength. A warmer spring should result in an earlier spawning, giving larvae more time to grow, thus enhancing first year survival.

Accordingly, it would be expected that the meteorological conditions prevailing during spring are critical in influencing the strength of herring year-class. Warmer temperature and strong southerly wind would accelerate the disintegration of the cold intermediate layer, and result in a successful year-class. Indeed, the exceptionally large 1958 herring year-class which prevailed throughout the Gulf of St. Lawrence and sustained the fishery until the early 1970's supports this hypothesis. In 1958, the mean April sea temperature was one of the highest in 40 years, 3.1°C, compared to a long-term average of 1.1°C. The mean April air temperature was 2.61°C, compared to a long-term average of 0.5°C. Strong persistent south winds prevailed during April 1985, with gale force (≥63 km/h) lasting 13 d, a phenomenon which has not been repeated since then.

The model described in the present report can now provide a general prediction of the time of herring arrival on the spawning grounds. More data are presently being analyzed in an attempt to develop a predictive model for the purpose of use in stock assessments. The hypothesis of the role of the cold intermediate layer on herring migration could have a wider application for other marine species. For example, Lear and Green (1984) observed annual variations in inshore migration of northern Atlantic cod. They reported that the role of offshore and inshore oceanographic structures was as barriers to inshore migration, whether the relative abundance of capelin inshore is important in attracting cod is not understood. The hypothesis presented here can provide a plausible explanation for the cod/capelin interactions, which is worth testing.

ACKNOWLEDGMENTS

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DISCUSSION PERIOD

McQuinn: How cold is the cold layer, and do you feel this is a barrier to herring migration?

Messieh: Temperatures are 0°C and less, and yes, under natural conditions it would be a barrier, although something like mackerel may be able to pass through this thermocline.

Trites: The herring overwinter in the deep water, and then they appear in the top 50 m sometime during spring, so it looks like they must pass through water less than 0°C.

Messieh: The critical temperature is 1°C, and they can avoid 0°C by passing east of Cape Breton Island.

McQuinn: I can see how southerly winds influence the slope of the cold layer and therefore allow faster migration and earlier spawning, but how would this affect recruitment?

Messieh: This is a good point. We have indications that earlier spawning relates to better survival, possibly through faster growth.

Mace: Did you look at the influence of the phase of the moon or tidal cycles on the arrival of herring on the spawning grounds? It looked like your data indicated arrivals changed about 2 weeks between successive years, which is about the difference between the phases of the moon each year. I ask this because, for very limited data, it appears the arrival of herring on the spawning grounds in 4WX may be tied to the amplitude of the tide.

Messieh: I haven't looked at this, but the amount of data here may also be too limited to detect such interannual changes.

McQuinn: There have been suggestions before of a relationship between surface temperatures on the Magdalen Shallows and spawning time. This may be a local relationship which is not very widespread.

Messieh: Yes, it again raises the question of whether surface temperatures are the best data to use. I have suggested vertical profiles are much more useful and pertinent.

Table 1. Correlation between mean day of herring spring arrival on the spawning grounds of the Magdalen Shallows (4T) with mean April air temperatures at the Grindstone and Charlottetown meteorological stations.

Spawning ground	n	a	b	r
Magdalen Island only vs Grindstone Station	25*	132.41	-3.75	-0.84
Magdalen Island only vs Charlottetown Station	25*	137.54	-3.06	-0.82
Magdalen Shallows combined vs Grindstone Station	26	136.58	-2.08	-0.66
Magdalen Shallows combined vs Charlottetown Station	26	139.05	-1.56	-0.60

n = number of years of observations (*one year missing).
a = intercept.
b = slope.
r = correlation coefficient ($p < 0.01$).

Table 2. Correlation between mean air temperature and mean sea temperature on the Magdalen Shallows during April.

Type of observation	n	a	b	r
Air temperature, Grindstone Station vs air temperature, Charlottetown Station	25	1.76	1.12	0.92
Air temperature, Grindstone Station vs sea temperature, Entry Island Station	14*	0.63	0.87	0.88

n = number of years of observation.
a = intercept.
b = slope.
r = correlation coefficient ($p < 0.01$).
*Entry Island Station was not operational in some years.

Table 3. Meteorological data from Grindstone Island (one of the Magdalen Islands) showing prevailing wind direction, speed and number of days with wind speed ≥63 km/h and air temperature during April for the period 1958-80.

Year	Prevailing wind direction	Mean wind speed (km/h)	Days with speed 63 km/h	Mean temperature (°C)
1949	N	30.4	-	0.44
1950	SE	33.3	-	0.44
1951	NE	35.7	-	4.17
1952	M	M	-	1.22
1953	M	M	-	3.22
1954	M	M	-	-0.67
1955	M	M	-	0.39
1956	M	M	-	0.61
1957	M	M	-	-
1958	S	38.3	13	2.61
1959	M	M	M	1.06
1960	M	M	M	0.39
1961	M	M	M	-0.11
1962	NW	31.2	8	1.00
1963	N	35.8	9	-0.67
1964	M	M	M	-0.28
1965	M	M	M	-0.61
1966	M	M	M	0.72
1967	N	28.4	4	-2.06
1968[a]	WNW	32.5	6	1.83
1969	WNW	28.7	3	0.11
1970	N	31.0	7	0.28
1971	S	29.8	7	1.28
1972	NW	26.8	2	-1.83
1973	E	27.0	1	0.00
1974	WNW	28.7	3	0.11
1975	NW	29.2	7	-0.70
1976	SE	27.6	3	0.70
1977	NW	34.0	7	-0.30
1978	NNW	30.9	4	-0.90
1979	S	26.2	2	1.10
1980	E	30.1	9	2.00

M = missing data.
[a]In 1968 onward, wind data observations changed to the 16 point system.
°C converted from °F, hence 2nd decimal.

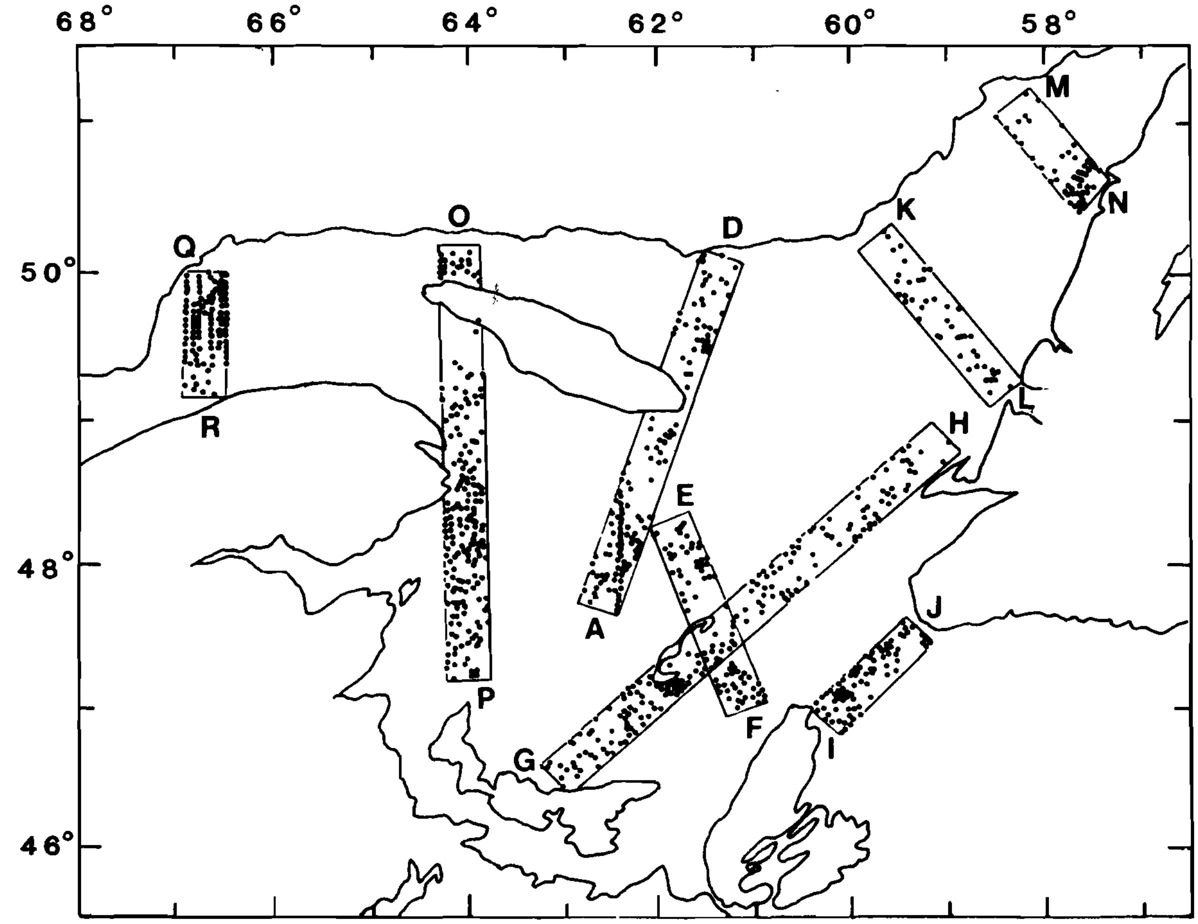

Fig. 1. Map of Gulf of St. Lawrence showing eight sections for vertical temperature distributions used in the analyses.

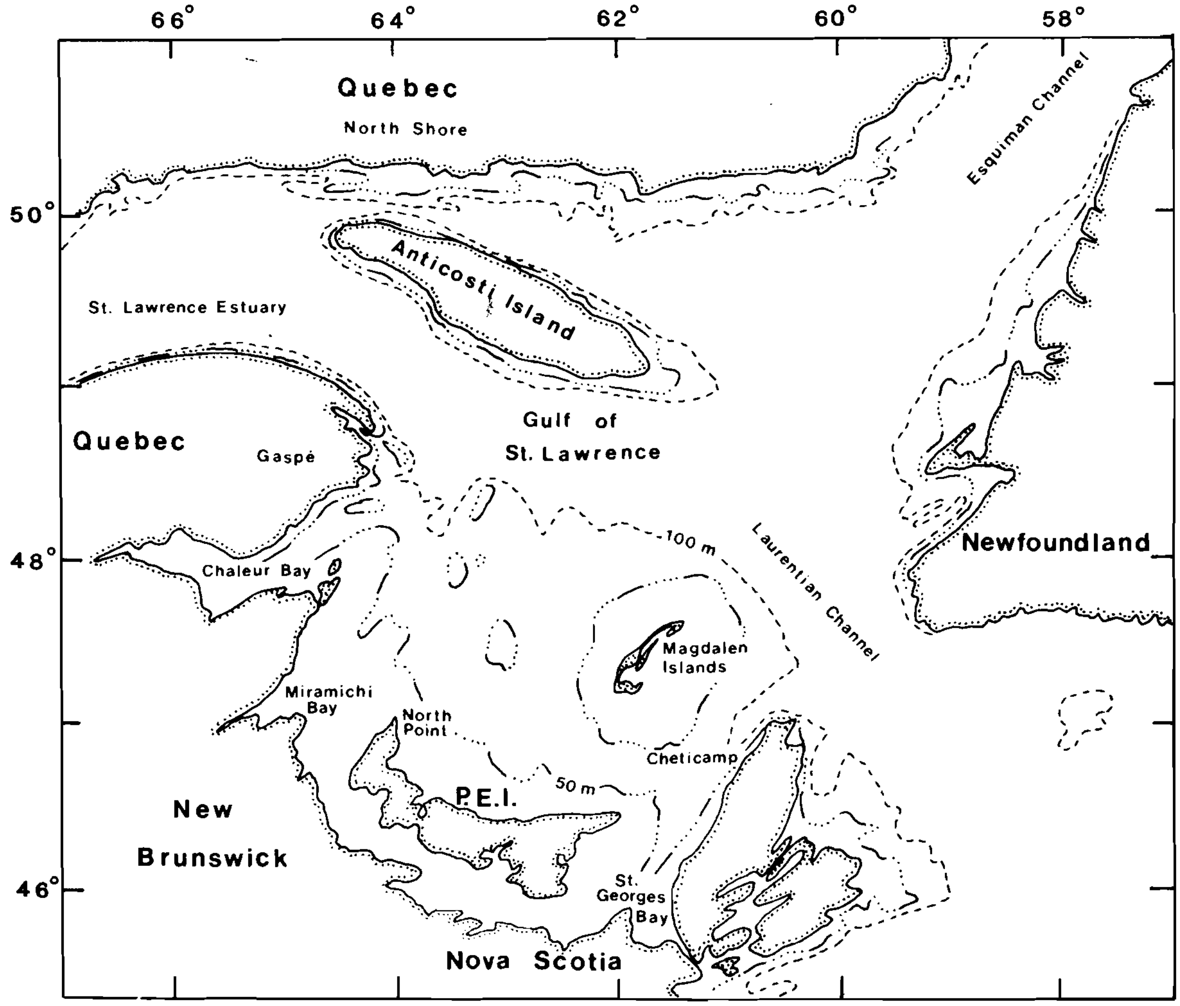

Fig. 2. Map of Gulf of St. Lawrence showing areas mentioned in the text.

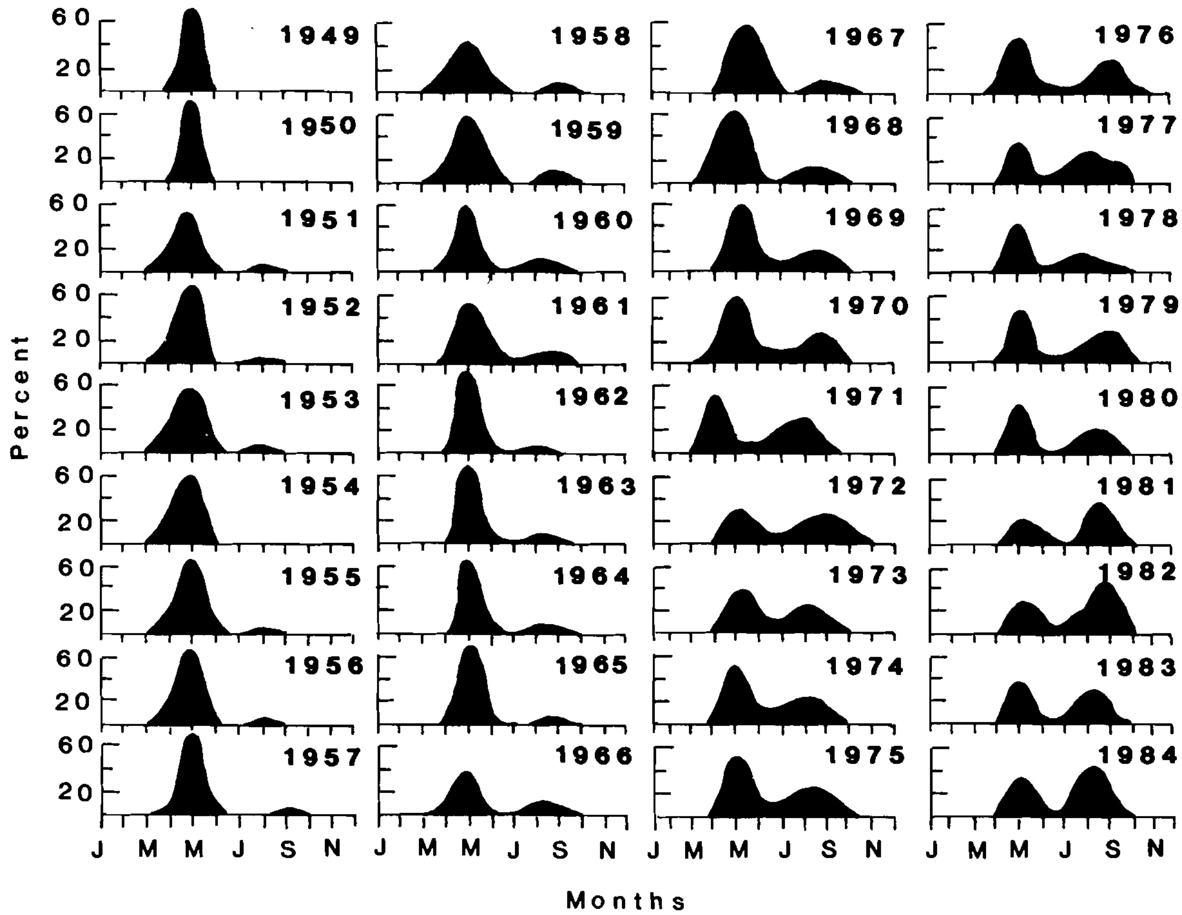

Fig. 3. Seasonal pattern of herring gillnet catches in the Magdalen Shallows (Div. 4T) since 1949.

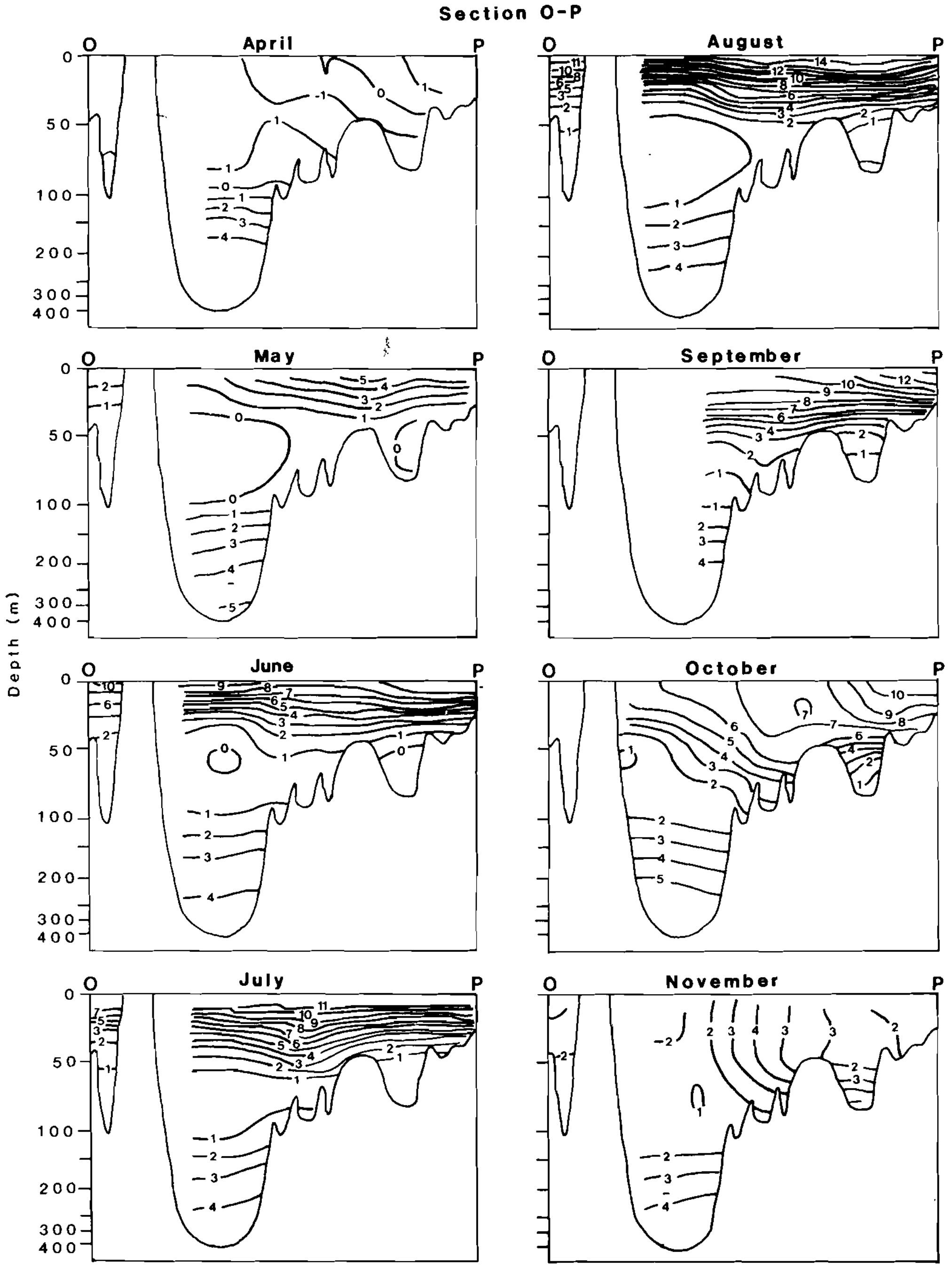

Fig. 4. Monthly variations of water mass vertical temperature distribution along section O-P.

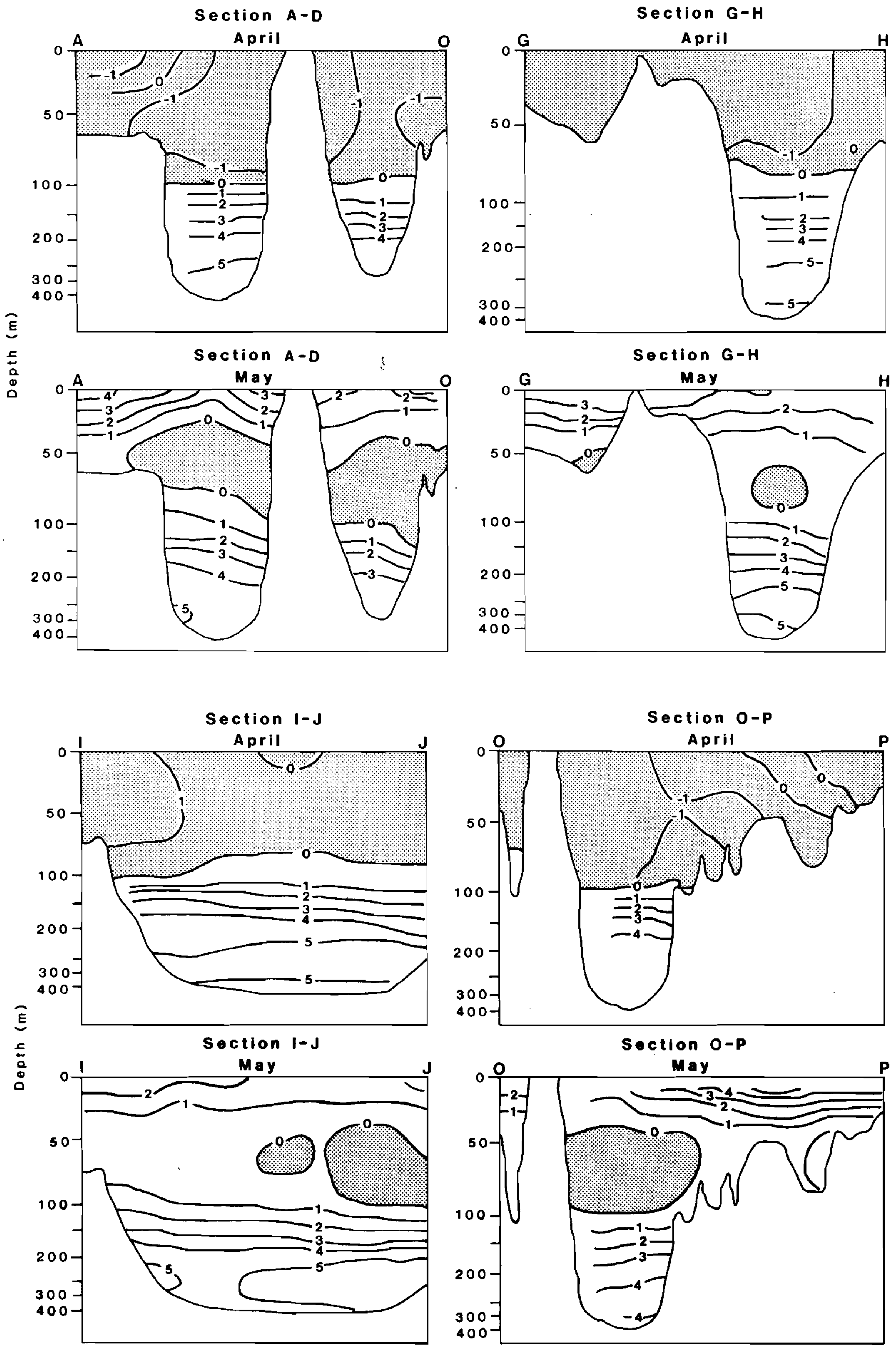

Fig. 5. Vertical temperature distribution along four sections: A-D, G-H, I-J and O-P, showing the cold water layer in April and May.

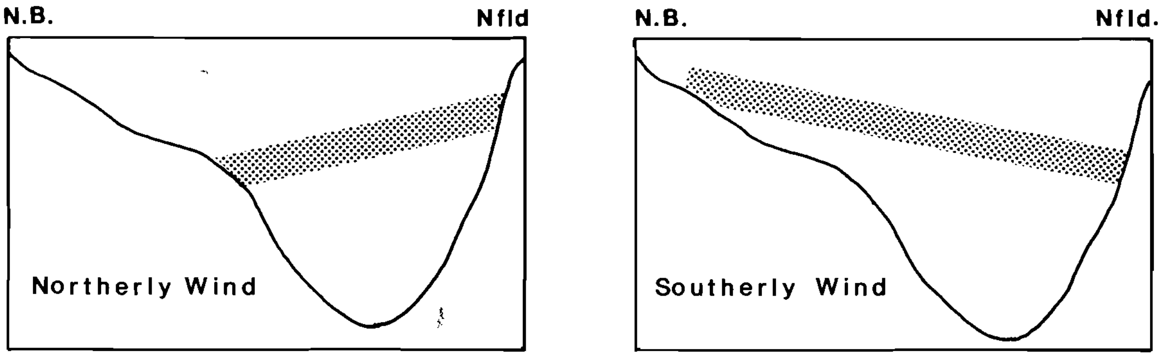

Fig. 6. A section across the Laurentian Channel showing the internal adjustment of the cold intermediate layer under the influence of strong north and south winds, according to Ekman's theory of wind-driven currents.

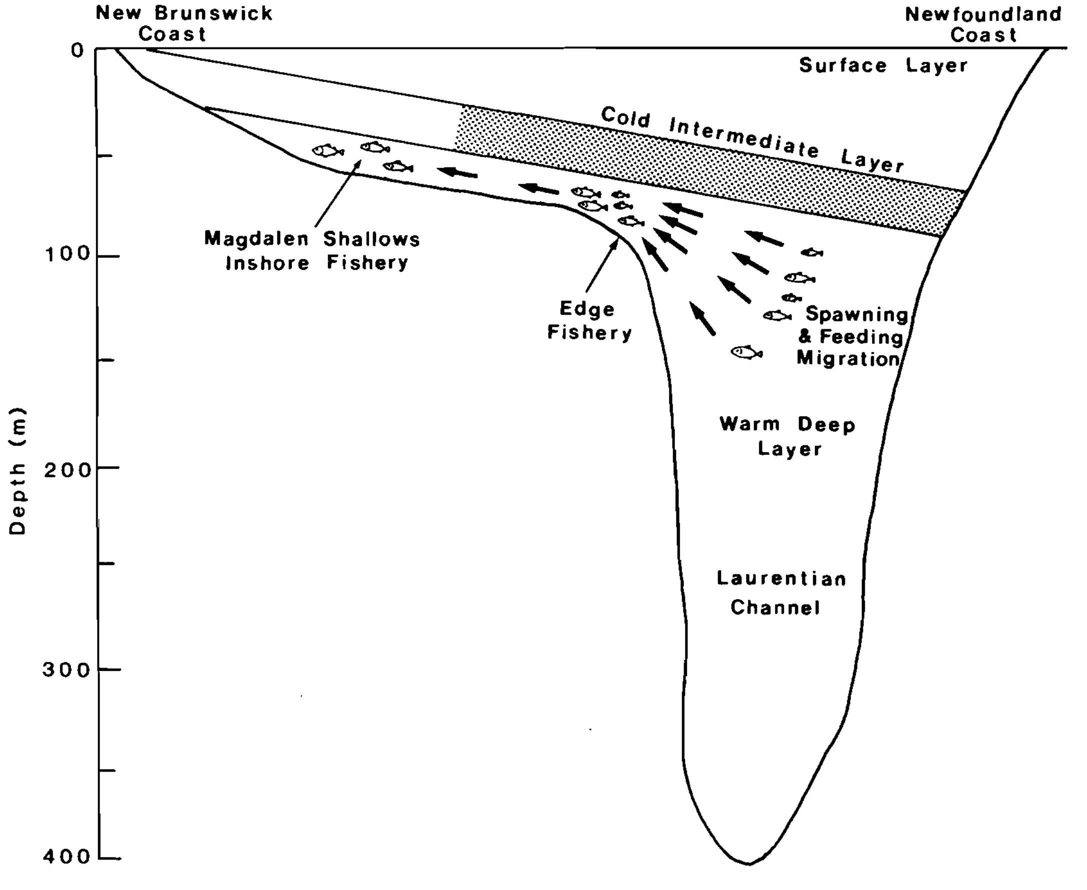

Fig. 7. A theoretical model for the mechanism of herring movement from the overwintering area to the spawning and feeding grounds, in relation to the cold intermediate layer.

The Influence of Gulf Stream Gyre Activity on Recruitment Variability in Pollock (Pollachius virens)

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McGlade, J. 1987. The influence of Gulf Stream gyre activity on recruitment variability in pollock (Pollachius virens), p. 30-40. In R. I. Perry and K. T. Frank [ed.] Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556.

An hypothesis to explain year-class variability in pollock on the Scotian Shelf with respect to Gulf Stream gyre activity is proposed, in which the presence of eddies adjacent to the Shelf break prevents large-scale offshore advection of eggs and larvae, except in areas of jet-stream activity. Empirical evidence from surveys of spawning adults and eggs and larvae, together with year-class strength indices from commercial and research vessels, is used to validate the hypothesis. Preliminary conclusions support the thesis that background production of pollock is determined in areas shoreward of the Nova Scotia Current, and that strong and weak year-classes reflect the temporal and spatial coincidence of spawning activity and the presence of gyres in the outer areas of the Scotian Shelf. Monitoring gyre activity is thus seen as an excellent source of information upon which to predict year-class strength in pollock.

INTRODUCTION

The size of a year-class and its success in being recruited by a fishery is one of the key phenomena in fisheries management. Most organizations concerned with management have thus conducted comprehensive surveys to identify the presence and abundance of eggs, larvae and juvenile fishes in a spatial and temporal context. For example, DFO (Department of Fisheries and Oceans) has run SSIP (Scotian Shelf Ichthyoplankton Program) and various broadscale surveys, NOAA's Northeast Fisheries Center adopted MARMAP (Marine Resources Monitoring, Assessment and Prediction) and the state of Massachusettes has run inshore surveys for juvenile fishes.

The initial success of most of these programs has been tied up with description of the occurrence of resources. However, the theoretical framework in which these data have been analyzed relates strongly to the concepts of passive larval drift (Harden-Jones 1968), density-dependent control of abundance at the adult stage through stock-recruitment relationships (Ricker 1954; Beverton and Holt 1957; Ware 1980) and a formalization of Hjort's "critical period" hypothesis (Hjort 1914) in the match-mismatch theory (Cushing 1975).

The underlying principles of these theories are by now well known to most fisheries biologists, but their implications with respect to the evolutionary consequences for species in both the short term and long term do not appear to have been considered. The case against them becomes clearer as we try to match observation with prediction. For example: (i) there is accumulating evidence that the eggs and larvae of certain marine species such as cod, haddock and pollock are observed over long periods in areas that could generally be described as highly dispersive (McGlade 1983; O'Boyle et al. 1984; Smith and Morse 1985). Under the concept of passive larval drift, fish larvae are, however, depicted as passive elements within the surface-layer circulation, having no control over their distribution and, when taken away from the "normal" distributional area, give rise to inter-annual variability; (ii) "normal" in this sense leads on to the match-mismatch hypothesis which predicates year-class strength on food limitation at the larval stage; these data have been extended by others including Lawrence (1977) and Lasker (1978) and it now appears that the density-dependent, food-limited concept is the principal hypothesis for population control. And yet, we are discovering that many marine species at their egg and larval stages, whilst not spatially coincident with their obvious food sources, are not food limited (Iles and Sinclair 1982; Methot 1983; de la Fontaine et al. 1984; Sinclair and Tremblay 1984), thus undermining the tenability of the hypothesis; (iii) the evidence of a stock-recruitment relationship for most commercial species is not clear in that the theoretical curves used are highly circumspect and often overlook the main components of a relationship, namely the variance associated with the parameters of mature stock abundance and the recruitment generated.

If larvae can maintain themselves in highly dispersive and energetic regimes, as it appears they can, for example, in estuarine conditions (Fortier and Leggett 1982; Henri et al. 1985), and if comparable marine organisms such as zooplankton can also exist in spatially discrete areas through their life cycle (Russell 1927), then surely similar mechanisms such as vertical migration, which we know to occur in marine planktonic organisms (Vinogradov 1968; Longhurst 1980, 1985; Sorokin 1980; Tremblay and Roff 1983) can be postulated for maintenance of position by fish larvae. The fate of eggs is somewhat different and controlled to a certain extent by buoyancy and viscosity within the water column, as the eggs of marine organisms such as the gadoids rise through the water column during the process of hatching; this implies that the stability of the water column in a horizontal sense must be relatively high or at least maintained within a limited radius (less than 20 km) for at least 7 d. Thus, if we are to understand the causes of year-class variability, we must examine both meso- and micro-scale oceanographic events plus behavioral effects to see whether or not it is possible for eggs and larvae to be maintained or lost according to some observed phenomenon. This paper is directed at the evidence pertaining to pollock (Pollachius virens) and oceanographic conditions along the Scotian Shelf.

DISTRIBUTION AND BEHAVIOR DURING THE LIFE HISTORY OF POLLOCK

Behavioral characteristics of the species include a semi-pelagic life history in which diel movements and schooling are apparent. A summary of diel variation in catches of pollock from research surveys (1970-81 A.T. Cameron) shows that the highest abundance of pollock from sets containing more than 250 fish occurred during daylight hours and were fewest during the night (Table 1). There is some variability in this sigmoidal movement from area to area, but the general relationship holds throughout. This vertical movement is observed in all ages of fish caught by the survey gear, viz. ages 1+, from which we may reasonably assume that it exists phenomenologically at earlier stages.

Pollock of ages 1 and 2 yr appear to be concentrated in certain areas across the Scotian Shelf and up towards the Bay of Fundy; it has been postulated that fish spawned in offshore areas move inshore to become what are commonly referred to as "harbour" or juvenile pollock. The extent of this migration is now known, but there is evidence that juvenile pollock exist out on the Scotian Shelf throughout the year (Fig. 1). That there are high concentrations inshore is not in dispute, rather the relationship between the inshore and offshore concentrations. Preliminary returns for pollock tagged as juveniles in coast areas suggests a Shelf-wide dispersal, followed by aggregation in areas considered to be spawning grounds (W. Stobo, pers. comm.; McGlade et al. 1985). The temporal distribution of pollock by strata highlights these areas of concentrations (Fig. 2): corroboration through maturity staging has shown that the Gully (Stratum 52), Western and Emerald Banks (Strata 56, 57, 60, 61, 62), inshore of Sambro Bank (Stratum 70), La Have (Stratum 72), Roseway, Baccaro (Strata 75, 76), Browns Bank (Strata 81, 82) and off southwest Nova Scotia and the north of the Bay of Fundy (Strata 85 and 91) all contain spawning areas.

If we now examine the distribution of eggs and larval pollock on the Scotian Shelf and the Gulf of Maine both from the Scotian Shelf Ichthyoplankton Program (SSIP), the Marine Resources Monitoring Assessment and Prediction (MARMAP) program and historical data (Bigelow 1927; Bigelow and Schroeder 1953; Colton and Temple 1961; Colton et al. 1979; Sherman 1980; McGlade 1983; Sherman et al. 1983; O'Boyle et al. 1984), it is clear that both occur in the same general area over considerable periods of time, despite highly variable patterns of ocean circulation (Fig. 3). The rate of development from spawning to hatching is approximately 7 d (D. Markle, Univ. of Oregon, Corvallis, pers. comm.), thus the distribution of eggs and stage 1 larvae provides not only a good indication of spawning activity, but also suggests that the eggs and larvae are relying upon a mechanism to maintain their spatial contiguity, as they appear to have overcome the dynamics of an along-shelf current system for periods at least as long as 2 wk and potentially up to 3 mo.

Thus, identification of the fate of water masses in the area is critical to our understanding of population control in pollock. The three main sources of water are: (1) runoff from the Gulf of St. Lawrence, (2) the Labrador Current and (3) North Atlantic Water including the Gulf Stream and North Atlantic Central Water. From surface circulation data, we know that the inshore branch of the Labrador Current penetrates into the Gulf of St. Lawrence where it mixes with river water before coming onto the shelf as the Nova Scotian Current. Sutcliffe et al. (1976) have postulated that this 'ocean pathway' affects year-class variability in commercial fisheries. The course of the Nova Scotian Current at Halifax is located 25-75 km offshore but, beyond this, its fate is doubtful as at least part is diverted offshore in a large cyclonic gyre (Smith 1979). Over the outer banks, the current field is variable: at the shelf break offshore flow in the surface layer (20 m) can be 5 cm s^{-1}, at mid-depth (100-150 m) it can be an onshore flow of 2 cm s^{-1} and at bottom a south-westerly flow with an offshore component of 3 cm s^{-1}. However, there is some consensus that the shelf-water/slope-water interface is an effective boundary, given the release of barotropic energy and subsequent hydrodynamic effects of the along-shore movement of slope water. Such vertical structuring in the area of pollock spawning is of course a key element in the hypotheses outlined above, viz. that adults and larvae can maintain themselves over a location by vertical movements within these current fields. Success at maintaining location in this way is one solution to overcoming advection in a passive sense.

If we can assume that the ability to locate and utilize water masses as a result of active movement or even neutral buoyancy at the egg stage is paramount to year-class success, then we must look at not only vertical profiling within a spawning area, but also at the global phenomena that cause changes in the seasonal patterns of water masses. The highly irregular topography of the shelf is characterized by deep basins at mid-shelf (e.g. Emerald Basin - 260 m deep) and shallow outer banks. Several channels through the outer banks (e.g. the Gully) promote cross-shelf exchanges between deep (greater than 100 m) and shelf and slope waters (Houghton et al. 1978), but the series of banks across the shelf near Sable Island limits exchanges of deep shelf water between the eastern and western ends of the shelf (Hachey 1953). The boundary between shelf and slope water is marked by a front which is coincident with the 10°C isotherm in winter and spring in the 34.5‰ isohaline, approximately 120 km off the shelf break. Whilst it is rarely found over the shelf during this time, the impact of the warm slope water (a mixture at the surface of coastal and Gulf Stream water), and the Labrador slope water (a mixture of the offshore branch of the Labrador Current and the North Atlantic Central Water occurring below 200 m) is unknown, but is likely to exist via the energy transmitted by the anticyclonic or Gulf Stream Rings. In the summer time, the distribution of water masses over the Scotian Shelf has been described by Houghton et al. (1978) as being comprised of surface waters from the Gulf of St. Lawrence, surface slope water, intermediate slope water (100-150 m), deep water from the Gulf of St. Lawrence and deep slope water (200-300 m). The eastern end of the Scotian Shelf is dominated by the Gulf of St. Lawrence water, but at Halifax and westwards, there is up to 40% dilution by slope water types. Deep water in Emerald Basin, which has the same characteristics as the offshore.slope water, is the result of intrusions through the Scotian Shelf. Variability in this structure results from the seasonal cycle in meteorological forcing and insolation, deep ocean variability, and wind driving due to storms and tidal forcing; all of these phenomena have different time and space scales over which they decay and dissipate. Generally, however, the higher frequency motions near the shelf break and shelf/slope front promote vertical mixing and transport of slope water nutrients to enrich the euphotic zone, and the lateral movements of the slope water masses near the shelf break are governed by seasonal wind and deep ocean forcing (Smith et al. 1978; Smith 1983). In the presence of oceanographic events, such a large-scale ring activity adjacent to the shelf, there is evidence to support off-shelf transport of water at a depth of 40-100 m through high-speed "jets" (R. Schlitz, N.M.F.S., Woods Hole, pers. comm.). This phenomenon, whilst incidental and somewhat restricted (e.g. less than 15 km across a "jet"), would have an obvious impact on eggs and larvae in the area.

If we look at the temporal variations in density of pollock from the research vessel surveys, we see that the concentrations by strata are very similar, especially in the areas around The Gully, Emerald Bank, Browns Bank and German Bank (Fig. 4, 5); viz. the spatial coherence between years is striking and suggests that the stratification scheme for the RV surveys for pollock could be substantially reduced to encompass areas of high and low abundance across the Shelf. The persistence within areas of high densities of fish also suggests that, whilst fish migrate along the length of the Scotian Shelf, concentrations of pollock are always to be found in the vicinity of the topographical areas given above. In the instance of large year-classes, such as 1979 and 1982, we can see that whilst the actual catch rates of spawning pollock are low, they are concentrated in The Gully and inshore from Emerald to Browns Banks, whereas the poorest year-class observed in the time series (1981) was coincident with some of the highest catches of pollock, but these were concentrated along the outer parts of the Shelf, suggesting that the eggs and larvae, despite vertical retention, were entrained in water masses moving off-shelf, and hence lost to the population. The 1984 year-class may thus be good because the large concentrations of adults were located on the inner part of the Shelf and in The Gully as well as on the outer strata.

The water mass activity on and off the Shelf at this time may also be impacted by the Gulf Stream and the occurrence of eddies which are a prime source of energy input to the Shelf. In 1979, for example, we observed activity in November and December, whilst in years of poor recruitment, no such gyres were in the vicinity of the Shelf during the winter months (Table 2). As gyres move up close to the Shelf, they may in fact be entrained into the Shelf water itself, but more likely their presence helps to retain water on the Shelf close to the Shelf break. The rotational movement will of course mean that at the leading edge, water may be entrained off the Shelf and vice versa at the training edge, but essentially the timing is over a sufficiently long period to enable eggs to hatch and become larvae. After this time, mechanisms of vertical movement may indeed suffice to keep the larvae within the general area as suggested by other authors (Sinclair and Iles 1985; Henri et al. 1985).

To test these data, we can relate the categorization of year-classes through coincidence of gyre activity with more formal estimates as given by occurrence of pre-recruits from Canadian and U.S. (inshore) surveys, and from the commercial catch (Table 3). From this we can see that in each case there is an exceptionally good agreement for all years including both the 1983 and 1984 year-classes, and the obvious correlations would lead us to suggest that the 1985 year-class will also be good. More important, the environmental indicator, albeit for the qualitative description of good or poor year-classes, anticipates the more traditional indices by up to 3 yr. This in itself is a great advantage when estimating future yields based on historical recruitment levels, and may even suggest that, in fact, there is some causal relationship between year-class strength and offshore gyre activity, in coincidence with spawning activity in the outer strata of the Scotian Shelf groundfish survey. It also serves to highlight the importance of the interaction between large-scale and small-scale oceanographic events in the potential outcome of spawning.

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DISCUSSION PERIOD

Koslow: I don't deny there may be a relationship as you say, but isn't it backwards, that gyre activity entrains water off the shelf?

McGlade: I realize this is in competition with the prevailing view, but the larvae are obviously being maintained. You can either put the onus on the individual fish, or on some causal relationship with oceanography.

Smith: Is it true there could be an alternate hypothesis, that it depends on the distribution of spawning such that poor year-classes occur with spawning along the shelf edge? For example, if there was some other environmental factor which forced them offshore, then a bad year could be caused by normal entrainment at the shelf edge.

McGlade: There was some activity inshore as well, comparable to an average year-class; what the contribution of these areas is to the final stock, I don't know.

Frank: I believe pollock have a broad spawning period, about 3 or 4 months. Could the co-occurrence of eggs and larvae be due to this protracted spawning?

McGlade: The range of spawning times for the whole shelf and into the Gulf of Maine is protracted, but it appears that it is quite short for any specific spawning ground, e.g. the Gulley. This co-occurrence of eggs and larvae could not therefore have come from the same spawning and, in fact, the plots of egg distributions and larval distributions represent different times.

Frank: If you relied on a single gear type, there is a problem with capturing fish that may actually be transported from other areas, so that some qualification should be made to the shortcomings of the sampling design.

McGlade: Yes, in fact we are not sure the juveniles, for example, are captured quantitatively. But at least we have a minimum, that the fish of the given size were actually caught in those areas at that time.

O'Boyle: At the center of your hypothesis is the idea that Gulf Stream gyre activity would cause some kind of retention on the shelf. Can eddies off the shelf induce eddies on the shelf?

Smith: It can induce circulation on the shelf. In some examples we have seen cold water drawn all the way across the shelf by an eddy offshore of Cape Sable. As for putting water onto the shelf, the full extent of the eddy cannot move onto the shelf because of the constraints of topography; however, it may induce surface circulations.

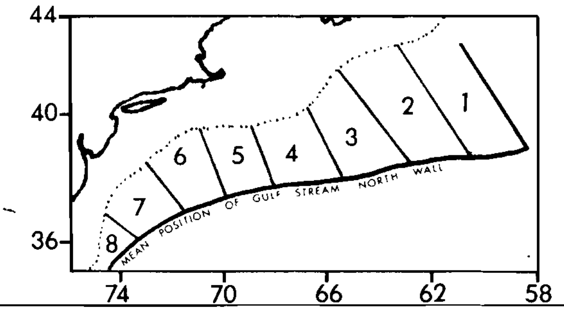
Akenhead: Is there something about slope water intrusions that makes it particularly predator free or food rich, and would increase survival?

McGlade: You have a good point. It may be that such movement of slope water may increase the supply of available nutrients and therefore production.

Table 1. Ranking of abundance in pollock sets from RV surveys (1970-81) by time period.

Time period	Ranking of RV sets with pollock (N 250) 1 = lowest 6 = highest		
0100-0400	1	3	
0401-0800	2	5	(Av. sunrise time occurred within this period)
0801-1200	3	6	
1201-1600	4	4	
1601-2000	5	7	(Av. sunset time occurred within this period)
2001-2400	6	1	

Table 2. Position of Gulf Stream zones and observations of eddies by month for 1977 - 1982.



Zone	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1		77-B		77-D	77-D 77-F	77-D	77-D					
2	77-A		77-C	77-C	77-C			77-D	77-D			
3	76-F	77-A		77-E	77-G					77-D		
4	76-G		77-A		77-E	77-E		77-I			77-D	
5		76-G		77-A	77-A	77-A	77-E		77-I	77-I		77-D
6	76-D		76-G		77-H		77-A	77-E	77-E		77-I	77-I
7				76-G		77-H	77-H	77-A	77-A			
8					76-G			77-H				
1						78-F		78-G				78-I
2					78-C	78-E	78-F	78-F				
3				78-B	78-B	78-D	78-E	78-E				
4				78-A	78-A		78-D			78-H	78-H	
5						78-A	78-A	78-D	78-D			
6	77-D	77-D						78-A		78-D	78-D	
7	77-I	77-I							78-A			78-D
8										78-A		
1	78-I							79-F		79-H	79-H	79-H
2		78-I				79-D				79-G	79-G	
3			78-I	78-I	78-I		79-E	79-E			79-J	79-G
4				79-B	79-C	78-I	78-I		79-E	79-I	79-I	79-K
5			79-A	79-A	79-B	79-B	79-B	78-I	78-I	79-E		79-I
6					79-A	79-A		79-B		78-I	79-E	79-E
7							79-A		79-B		78-1	
8										79-B		
1						80-C			80-F			
2	79-H			80-B		80-D	80-C	80-F		80-F	80-F	
3	79-G	79-H 79-G	80-A		80-B		80-B	80-E	80-E			80-F
4	79-K			80-A		80-B				80-E	80-H 80-G	80-H
5	79-I	79-K	79-G 79-K	79-G	80-A	80-A		80-B		80-G		80-G
6	79-E	79-I		79-K	79-G 79-K		80-A		80-B			
7		79-E	79-I			79-K	79-K	80-A	80-A	80-B		
8										80-A		
1					81-D		81-D					
2			81-B			81-D	81-E	81-E	81-E			81-G
3	81-A			81-B						81-E		
4	80-F				81-C	81-C						
5	80-G	80-F	80-F				81-C	81-C				81-F
6		80-G	80-G	80-F	80-F				81-C			
7				80-G		80-F				81-C		
8							80-F					
1		81-G	82-C					82-E			82-J	82-J
2	81-G		81-G	81-G						81-I	82-I	
3	82-A	82-A			81-G	81-G	81-G	81-G	81-G 82-F	82-H		82-I
4			82-A	82-A 82-D_1	82-D_1	82-D_1	82-D_2	82-D_2			82-H	
5	82-F	82-B	82-B				82-D_1	82-D_1	82-G			82-H
6		81-F	81-F	82-B	82-B					82-G		
7				81-F		82-B	82-B	82-B	82-D	82-D_1	82-G	
8					81-F				82-B		82-D	82-G

Table 3. Year-class stengths as indicated by surveys, commercial catch and environmental (Gyre) activity.

Year	Canadian RV Survey	Environ-mental	Commercial Catch	USA RV Survey
1979	1	1	1	1
1980	2	1	1	2
1981	3	3	3	3
1982	1	3	3	2
1983	1	1	-	1
1984	-	1	-	1
1985	-	1	-	-

1 = good; 2 = average; 3 = poor

Figure 1. Distribution of age 1 and 2 year-old pollock (spring, summer, and fall).

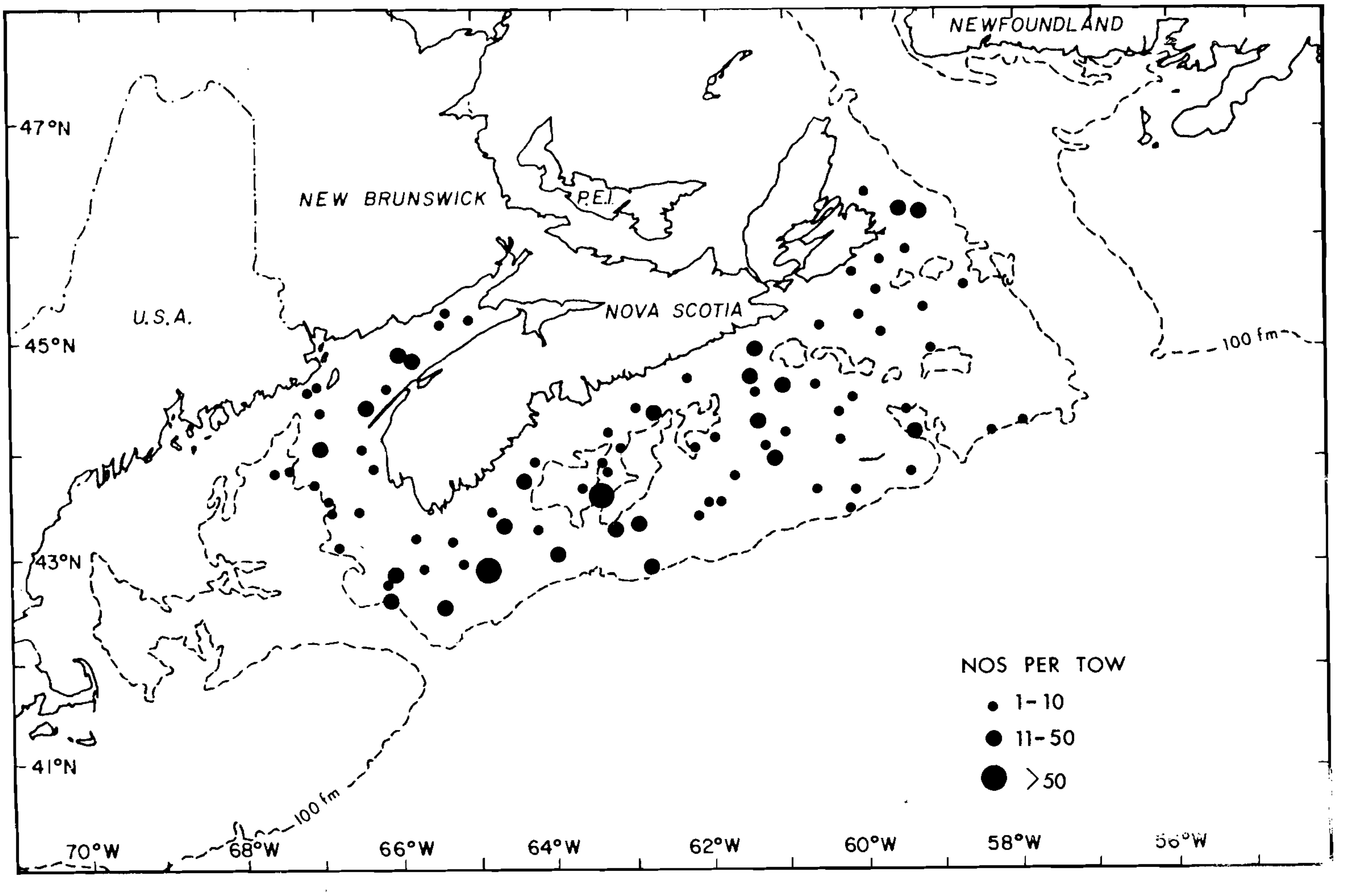
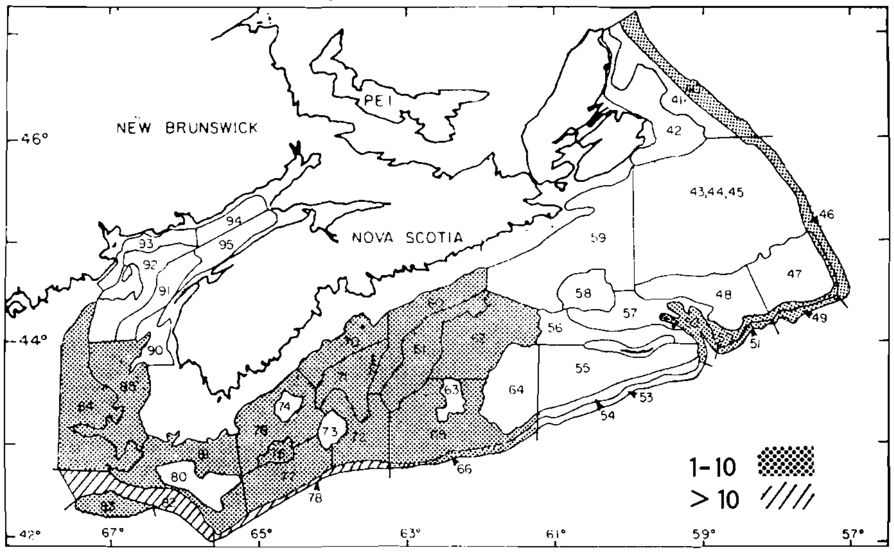
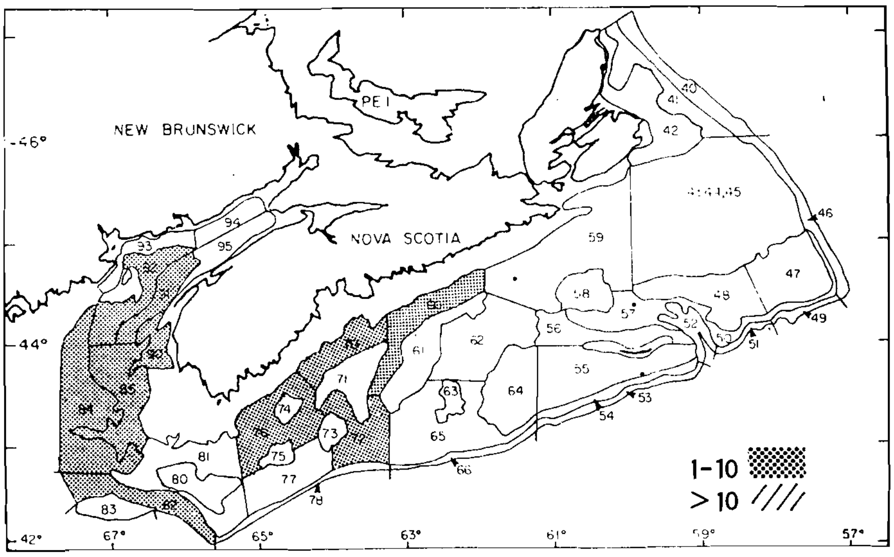


Figure 2 . RV survey catch rates for spring (1978-84), summer (1970-84), and fall (1978-83).

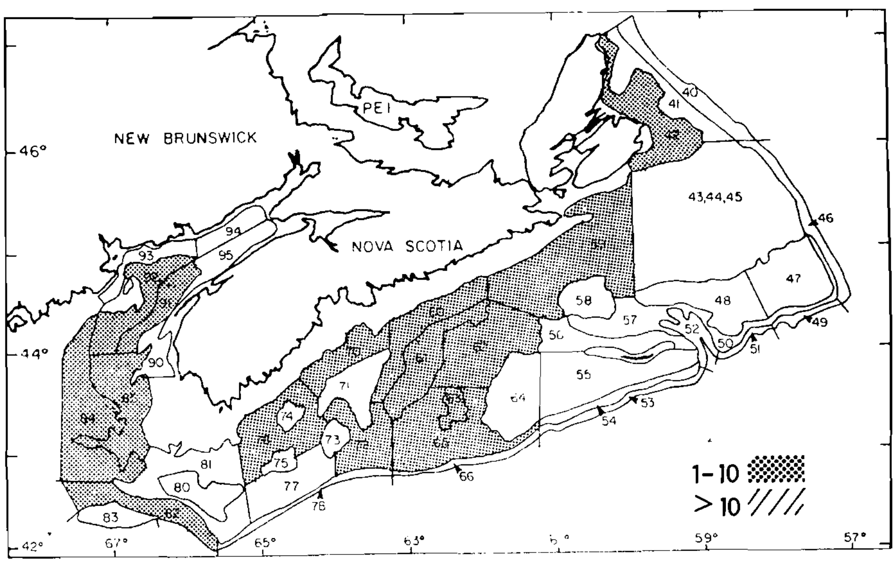
SPRING



SUMMER



FALL



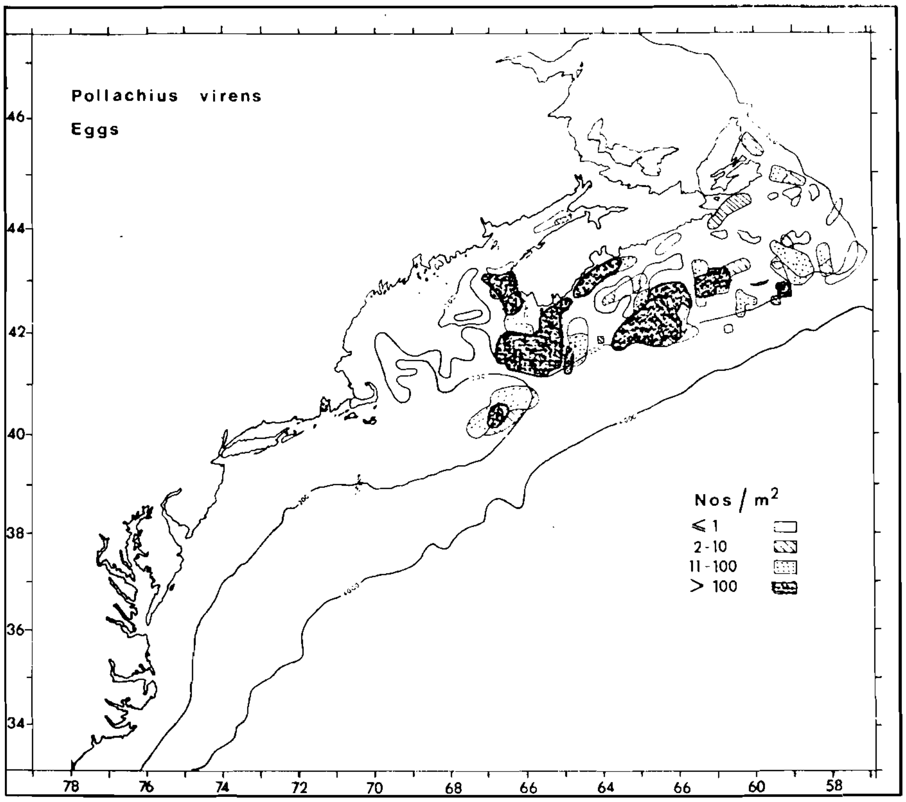


Figure 3a. Distribution of pollock eggs from S.S.I.P., F.E.P., and Bay of Fundy larval herring cruises (see text for details).

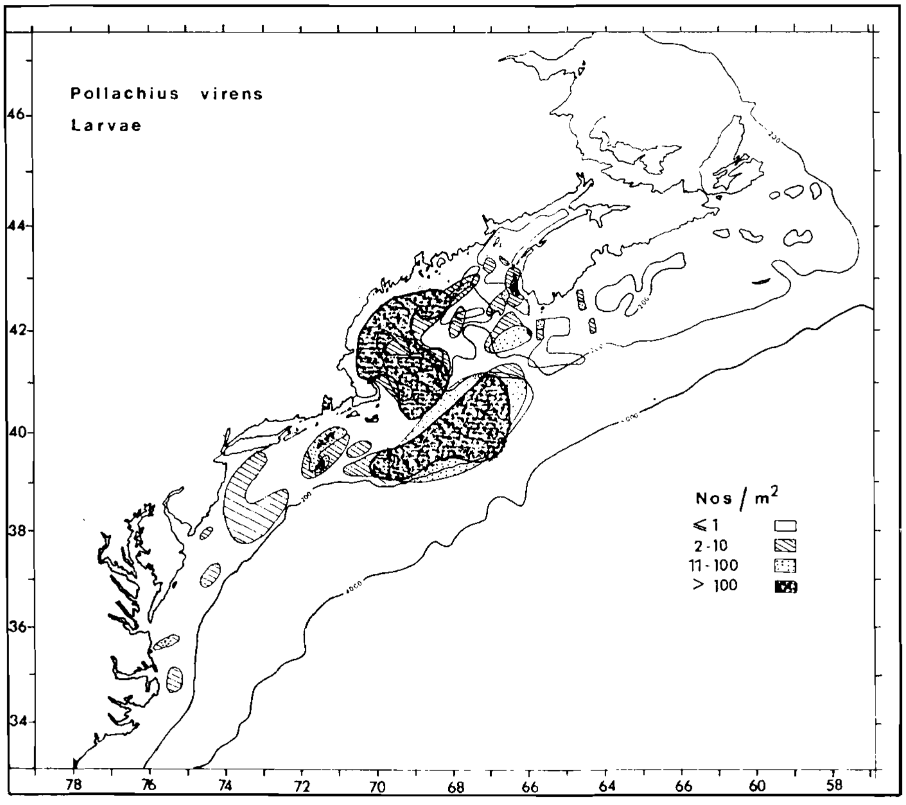


Figure 3b. Distribution of pollock larvae from F.E.P., Bay of Fundy, and MARMAP Research Vessel cruises (see text for details).

Figure 4. Catch rates by strata from Canadian RV surveys.

Fall RV Surveys: 1978 - 1980
Catch Rates (kg)

Spring RV surveys: 1979 - 1981
Catch Rates (kg)

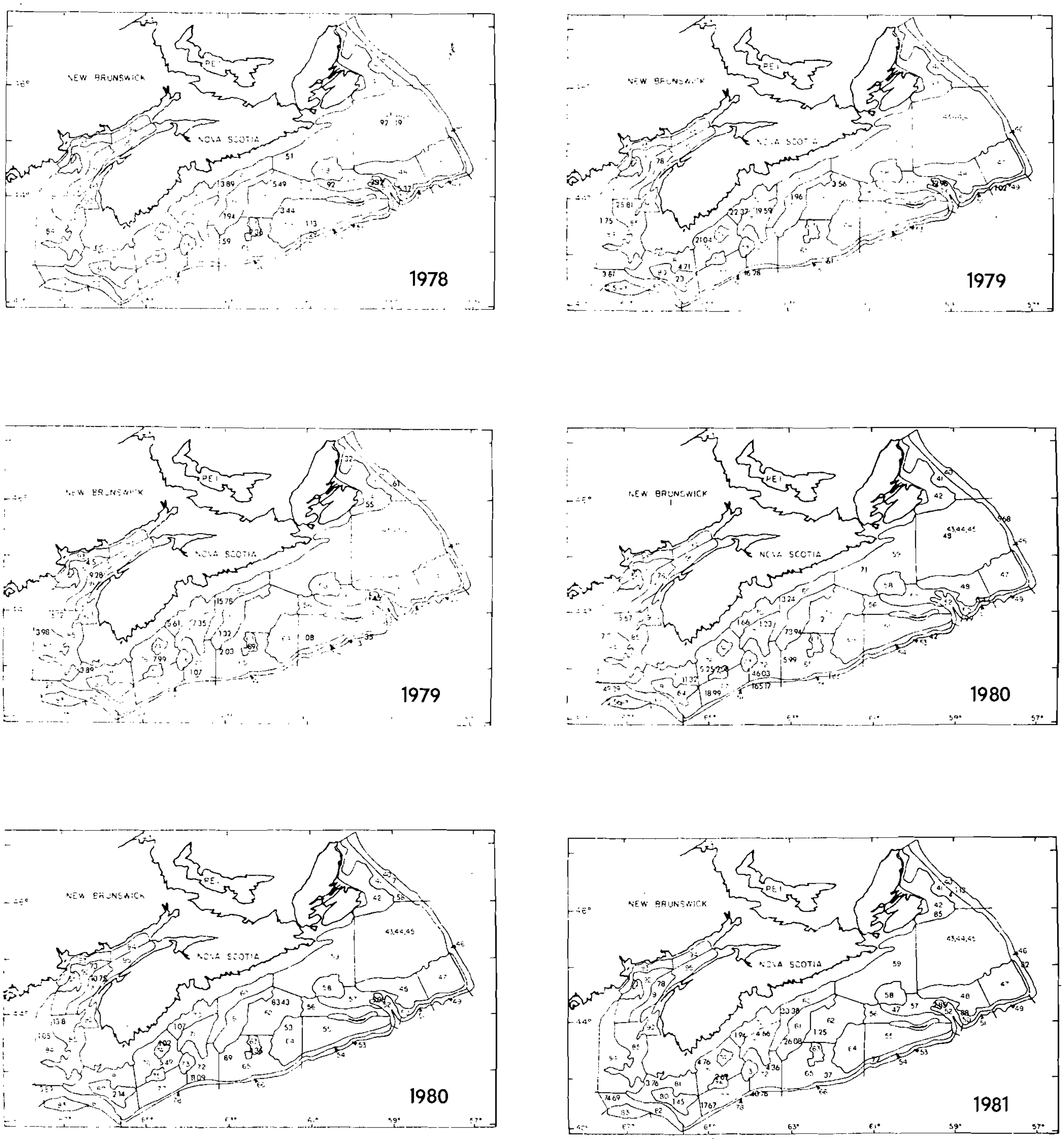
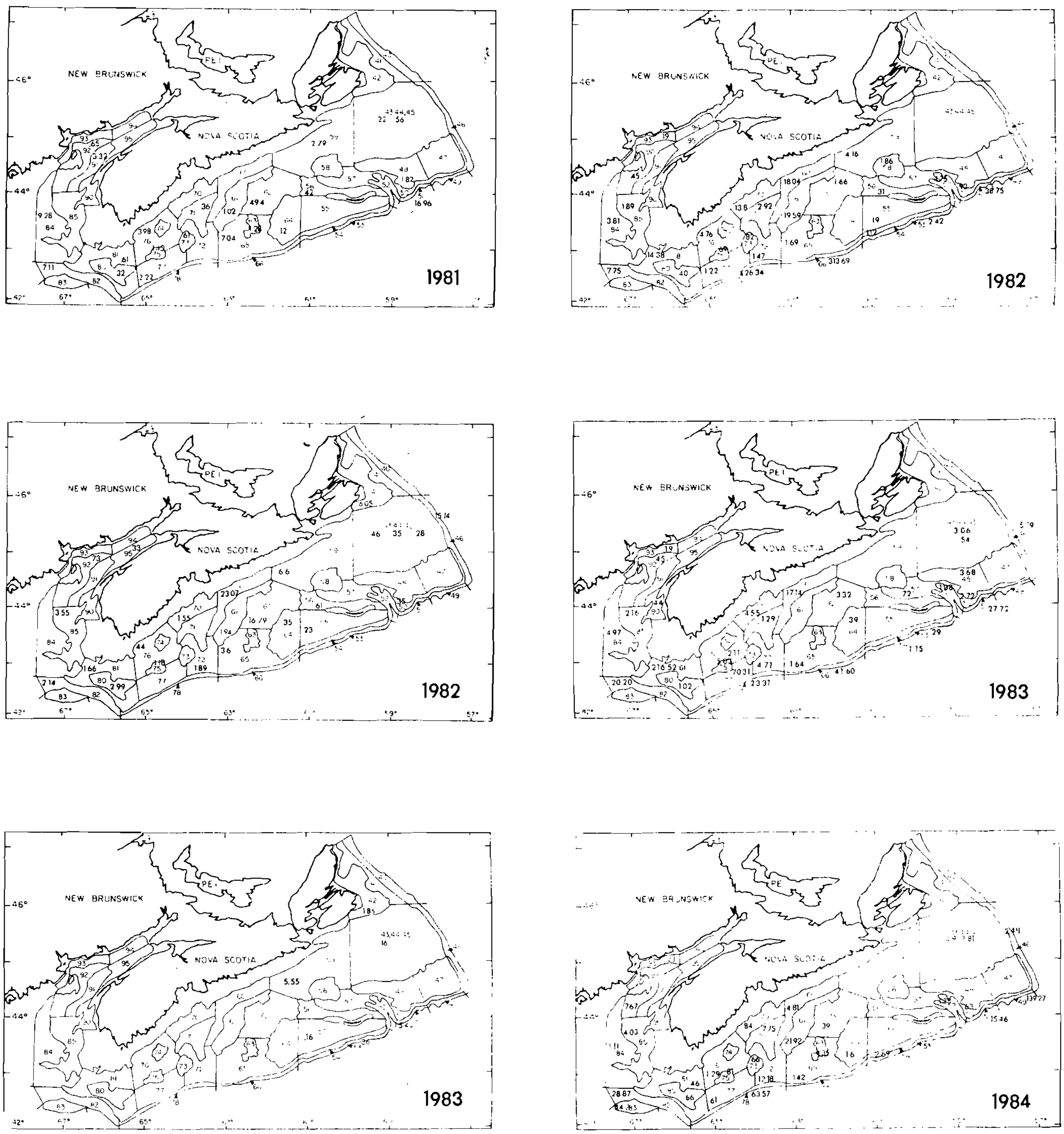


Figure 5. Catch rates by strata from Canadian RV surveys.

Fall RV surveys: 1981 - 1983
Catch Rates (kg)

Spring RV surveys: 1982 - 1984
Catch Rates (kg)



"Sutcliffe Revisited": Previously Published Correlations between Fish Stocks and Environmental Indices and their Recent Performance

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During the seventies and early eighties, W. H. Sutcliffe and coworkers examined the relationships between fish and their environment over a large area of the northwest Atlantic using correlation analysis. They showed that in the Gulf of St. Lawrence the Quebec landings of four species were significantly correlated with runoff from the Gulf of St. Lawrence. In the Gulf of Maine, 10 out of 17 commercial species were significantly correlated with coastal sea surface temperatures and the St. Lawrence River runoff. In each case, there was a lag between environment and fish which was equal to the approximate age the particular species was recruited into the fishery. This suggests an environment effect in the early life stages. On the Labrador Shelf, a significant positive correlation was found between cod in NAFO subareas 2J3KL and surface layer salinities at Station 27, off St. John's, Newfoundland. In this paper I have extended the time series used in earlier correlation studies and re-examined the relationships. Using linear regressions based on data in the original correlations, predictions of fish catch or abundance were calculated for more recent years. In certain species the fish catches were well predicted, in others trends were predicted but amplitudes were incorrect, and in others trends were poorly predicted.

INTRODUCTION

Dr. W. H. Sutcliffe of the Marine Ecology Laboratory conducted investigations into environmental effects on fisheries in the northwest Atlantic during the seventies and early eighties (Sutcliffe 1972, 1973; Sutcliffe et al. 1977; Loucks and Sutcliffe 1978; Sheldon et al. 1982; Sutcliffe et al. 1983). Through correlation analysis, he explored relationships between river discharge, coastal sea-surface temperature and salinity and various commercial fish and shellfish species in the Gulf of St. Lawrence, Gulf of Maine and Labrador Shelf. For several species, significant correlations were observed. As part of the MEES Workshop on Environmental Effects on Recruitment of Canadian Atlantic Fish Stocks, I agreed to re-examine those correlations in light of recent data. The results are given following a brief summary of the Sutcliffe work. Further correlation analyses are provided that involve environmental indices and VPA (virtual population analysis) estimates of cod and haddock stocks from the Scotian Shelf and the Grand Banks.

REVIEW

Sutcliffe (1972) observed a direct correspondence between fluctuations in the amount of local freshwater runoff and the rate of primary production in a Nova Scotia coastal inlet. He reasoned that the correlations arose through nutrient enhancement of the near-surface waters and, because nutrient concentrations within the freshwater rivers were too low to account for observed primary production levels, the nutrient effect probably occurred through the circulation patterns and mixing induced by the freshwater inflow.

Lacking adequate data from the inlet for testing long-term relationships between freshwater runoff and biological production, he turned his attention to the Gulf of St. Lawrence, a system dominated by freshwater discharge and where long time series of both runoff and fish landings were available. Significant positive relationships were found between Quebec landings of halibut, haddock, lobster and soft-shell clams and St. Lawrence River discharge (Sutcliffe 1972). Maximum correlation coefficients occurred when the species landings lagged the river discharge by an amount approximately equal to the age at maturity (i.e. the age at recruitment). This suggested that runoff was correlated with survival during the species' first year of life and is consistent with the concept that reproductive success is established during early life stages. Even higher correlation coefficients resulted from the analysis of monthly St. Lawrence River discharge and landings of the various species with the spring discharge correlating most closely with the lagged fish abundance (Sutcliffe 1973).

Sutcliffe extended his work correlating fish landings from the Gulf of Maine with river discharge from the St. Lawrence River. Using long-term records of cod catches from Georges Bank, significant correlations were obtained with river discharge, a result as striking as the one found by Martin and Kohler (1965) for the same species with SST (sea surface temperature) measured at St. Andrews, New Brunswick. This led to the question, is the St. Lawrence River discharge somehow causally related to SSTs? The mean circulation (averaged over months and years) is known to flow counterclockwise around the Gulf of St. Lawrence, seaward on the southern side of Cabot Strait and generally southwestward off Nova Scotia and the eastern United States with excursions into the Bay of Fundy and clockwise around Georges Bank. Therefore, this circulation pattern carries the water from the St. Lawrence River system, albeit modified by mixing with seawater, down to and past the New England States. However, the question remained, how important was its influence? Sutcliffe et al. (1976) pointed out that the discharge into the Gulf of St. Lawrence (424 km^2/yr) was a quantity greater than the sum of the entire freshwater discharge along the eastern United States from the Canadian border to southern Florida (353 km^3/yr). The large runoff into the Gulf of St. Lawrence was known to determine the mean and seasonal salinities and the stratification of the waters in the Gulf itself (Lauzier 1957; Lauzier et al. 1957). Also, the waters over the Scotian Shelf off Nova Scotia are largely composed of waters originating from the Gulf of St. Lawrence (McLellan 1954).

Sutcliffe et al. (1976) found significant correlations between the lagged discharge of the St. Lawrence, Ottawa and Saguenay Rivers (termed RIVSUM) and coastal SSTs. The lags increased with distance from the rivers and were consistent with known ocean drift speeds. They also found that the annual changes in the SSTs in the Gulf of Maine more closely resembled variations in RIVSUM than variations in the discharge of local rivers. The correlations were all positive; therefore, "warm" years corresponded to "high" discharge years.

The mechanism underlying the St. Lawrence runoff with the coastal SSTs was believed to be through its effect on stratification. Freshwater runoff is equally as important as solar heating in determining the stratification in the Gulf of St. Lawrence (Bugden et al. 1982). Increased stratification during high discharge years reduces mixing allowing a higher percentage of the available solar heating to be trapped near the surface. This heat was considered to be advected southward by the mean circulation and combined with local heating to produce the observed temperatures over the Scotian Shelf and Gulf of Maine.

The relationship of fish catches in the Gulf of Maine to both local SSTs and RIVSUM were explored by Sutcliffe et al. (1977). Examining 17 commercial marine species of fish and shellfish, they found the catches of 10 of the species were significantly correlated ($p < 0.05$) with SSTs at St. Andrews, New Brunswick, or Boothbay Harbour, Maine. Of these, 6 were also correlated with RIVSUM, as were two other species. On average, the environmental indices explained about 65% of the variability in the fish records. Like the Gulf of St. Lawrence, maximum correlations occurred if the fish were lagged by a time equivalent to their age at commercial size. Greater than half of the significant correlations were positive and only four were negative. The species exhibiting negative correlations (cod, redfish, yellowtail flounder and soft-shell clams) are considered to be "cold" water species and near the southern limit of their geographical distribution. Thus, in high discharge ("warm") years the "cool-water" species do poorly. In contrast, many of the positively correlated species are generally near the northern limits of their range (e.g. butterfish, menhaden) and do well during "warm" years.

Inclusion of fishing effort improved the correlations for those species (cod, haddock, yellowtail flounder and menhaden) where effort data were available (Sutcliffe et al. 1977). This led to the development of a fish-production model for cod and yellowtail flounder based on SSTs and fishing effort (Loucks and Sutcliffe 1978).

Sutcliffe and coworkers next examined the Hudson Bay region. The total freshwater discharge into Hudson and James Bay is 523 km^3/yr (Prinsenberg 1980), an amount larger than the runoff into the Gulf of St. Lawrence. The seasonal cycle is more pronounced with a peak monthly discharge rate in June of nearly $6 \times 10^4\ m^3s^{-1}$, almost 5 times larger than that of the St. Lawrence River system. The peak discharge can be traced as a saliniy minimum occurring during July-August in Hudson Bay (Prinsenberg 1983), during July-September along the Labrador coast (Lazier 1982), and during October off St. John's, Newfoundland (Sutcliffe et al. 1983). The route and travel times of the salinity minimum are consistent with the known mean circulation.

Sutcliffe et al. (1983) investigated the effects of the Hudson Bay runoff on the southern Labrador Shelf, northern Newfoundland and the northern Grand Bank cod stocks. Having insufficient discharge data from the Hudson Bay rivers but knowing its effect on the salinity of the waters off Labrador and Newfoundland, cod abundance was correlated with available long-term salinity records. Correlations between VPA estimates of abundance of age 4 cod and corresponding summer salinities for each of the first 3 yr of the life of the cod were high and accounted for 80% of the variation in the cod. The correlation was positive, indicating high cod abundance with high salinity water (i.e. during years of low runoff). The following hypothesis was suggested. Temperature and salinity characteristics of the waters on the Labrador Shelf and off Newfoundland are formed near the eastern entrance of Hudson Strait through intense vertical mixing. This mixing brings nutrient-rich (high salinity) deep water into the surface layer which subsequently is carried by the mean circulation onto the northern Labrador Shelf. Once on the shelf, the nutrients promote primary production. The Labrador Current carries the water, together with the phytoplankton, southward along the Labrador Shelf. Zooplankton feed upon the phytoplankton, small fish feed upon the zooplankton and eventually the large fish (e.g. cod) feed upon the small fish. The time required for this food chain to develop, together with the southward advection by the Labrador Current, can explain the low fish concentrations on the northern Labrador Shelf and high concentrations on the southern shelf. In years when the Labrador Shelf salinity is high, there are more nutrients available in the surface layers and biological production, including cod, increases. During times of high river discharge into Hudson Bay, stratification increases, thereby suppressing the vertical mixing in the Hudson Strait region. This leads to fewer nutrients, as well as lower salinity, in the near-surface waters and a subsequent decrease in the cod production along the Labrador Shelf.

There exists certain problems with correlation analysis of the type performed by Sutcliffe and his coworkers. One problem is the determination of the true statistical significance of correlations. The common method is based on the assumption that each observation is independent, a criterion not satisfied by either the environmental or fish data. This problem was overcome as a more conservative and rigorous test for significance was derived which took into account the marked persistence in the data (Sutcliffe et al. 1976). Another problem of correlation analysis is that it can produce spurious correlations. Two important pieces of evidence suggest, however, that the correlations of Sutcliffe were not spurious. First, the highest correlations occurred for a lag time between the runoff and fish catch which generally equals the mean age at commercial size - a finding in agreement with the general belief that survival is most strongly influenced by events in the first year of life of the fish. Secondly, in the Gulf of Maine, negative correlations were found for northern-oriented fish species and positive correlations for southern-oriented species.

Recent studies have questioned the importance of freshwater runoff implied in the early Sutcliffe papers (Koslow 1984; Koslow et al. 1986; Sinclair et al. 1986). It was suggested that climatic events in the ocean forced by large-scale atmospheric circulation may be the primary mechanism regulating recruitment and that the role of freshwater runoff may be small. While the scientific debate over both the significance of Sutcliffe correlations and the possible factors relating environment and fish will no doubt continue, the purpose of the present paper is to investigate the longevity of the correlations.

RECENT DATA

Methods

To determine how the relationships found by Sutcliffe and his coworkers between environment and fish have fared during recent years, a linear regression analysis of fish landings and environmental indices was performed. Only data contained in the original analyses were used. The regressions were then used to predict fish landings during the intervening years. In keeping with the original analyses the annual fish and environmental time series were filtered using 3-yr, equally weighted running means except where noted. The filter reduces the variance at annual time scales and increases the persistence (i.e. autocorrelation). This persistence means a reduction in the information content of the data sets. When applying statistical significance tests, the effective number of independent points (n*) in the time series are required. For a time series of n points, n* is given by:

$$\frac{1}{n^*} = \frac{1}{n} + \frac{2}{n^2} \sum_{j=1}^{n-1} (n-j)(r(jt)) \qquad (1)$$

where r(jt) is the autocorrelation of the j^{th} lag of period t (Garrett and Toulany 1981). The autocorrelation of the product of the two variables was determined and used in (1). As j increases, the error in r can become large due to the decreased number of points. Therefore, to avoid such errors the summation in (1) was taken up to j=5. Note that a negative correlation decreases n*. For those few time series in which n* becomes large (>n) or negative within the summation j=5 due to negative correlations, the summation in (1) was reduced until n* became small and positive. This procedure for determining n* is modified slightly from that used in Sutcliffe et al. (1976).

Gulf of St. Lawrence

As stated previously, in investigations of the Gulf of St. Lawrence, Sutcliffe correlated the annual Quebec landings of four species - haddock, halibut, lobster and soft-shell clams with the discharge from the St. Lawrence River. Initially, annual means of runoff were used (Sutcliffe 1972) but later halibut and lobster were correlated with monthly means. In the present study I have, for reasons of consistency with later papers, recalculated the correlations for the same years but using monthly means of RIVSUM. The results are presented in Table 1. Haddock in the Gulf of St. Lawrence declined to near zero levels shortly after Sutcliffe published his papers. The stock is believed to have migrated each year during summer from off the Scotian Shelf into the Gulf. The decline in the Gulf catches in the seventies is felt to be due to reductions in the Scotian Shelf stock (R. Mahon, BIO, pers. comm.). Haddock have not returned to the Gulf and I have not included them in the present study for this reason.

For the remaining three species, linear regressions of catch on river discharge were calculated (Table 2) and then used to predict recent catches. The results are shown in Fig. 1. The trend and amplitudes of both lobster and soft-shell clams are relatively well predicted while halibut has been poorly predicted from the linear regressions. Lobster and halibut include all available catch data up to 1984 inclusive. The clam catches include years up to 1981. In 1982 and 1983, catches are listed at or near zero but in 1984, it was over 600 mt. The cause of the sudden decline is unknown and I have not included those years.

Predictions of Quebec lobster landings from RIVSUM have been published previously by Sheldon et al. (1982). They used the annual landings for the years from 1950 to 1979 to generate the regression:

$$C = 0.17\ R_1 + 0.16\ R_2 - 1.79 \qquad (2)$$

where C is the catch (10^3 t), R_1 is the average February and March RIVSUM and R_2 is the average July-October RIVSUM for 9 and 10 yr previously, with RIVSUM in $10^3\ m^3s^{-1}$. Figure 2 shows the high similarity between the predictions from (2) and the actual landings for the last 5 yr.

Gulf of Maine

Seventeen commercial fish species within the Gulf of Maine were previously examined for relationships with SSTs and RIVSUM (Sutcliffe et al. 1977). The U.S. landings from the New England States were used for 12 of the species including alewife, butterfish, hard-shell clams, soft-shell clams, cusk, silver hake, red hake, herring, menhaden, pollock, scallops and striped bass. Cod, haddock, halibut and redfish data were U.S. landings within NAFO Subarea 5. Yellowtail flounder landings were for southern New England (NAFO Subarea 5Zw and the western section of 5Ze). Sutcliffe et al. (1977) found the statistical significances of the correlations with environmental parameters for cusk, haddock, silver and red hake, pollock and striped bass to be generally low ($p > .1$) and hence these species have not been considered in the following analysis. Also, yellowtail flounder was not used as recent data for the southern New England stock were unavailable. New England landings for the years subsequent to those used in Sutcliffe et al. (1977) were obtained from the U.S. Fisheries Statistics published by the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration but these data only extend the series up to 1977, an additional 6 yr. For alewife and butterfish, the New England catch is derived almost exclusively from NAFO Subarea 5 and I have used the U.S. catch from Subarea 5 for the period 1978-82 inclusive. Cod and redfish landing data are available up to and including 1982.

Correlation coefficients between the fish landings and the SST at St. Andrews, New Brunswick and Boothbay Harbour, Maine, are presented in Table 3. They are based on data for those years available to Sutcliffe et al. (1977). Correlations with RIVSUM have not been included because river discharge is highly correlated with the SSTs and it is a geographically distant signal. The results in Table 4 are similar to those given in Sutcliffe et al. (1977) except for the statistical significances which have been calculated using a slightly different method (see Methods Section). A 3-yr running mean was used for all species in contrast to the 2-yr running mean for herring used by Sutcliffe et al. (1977). Linear regressions were calculated and then used to predict fish landings in later years. Some of the results are plotted in Fig. 3 and their regression coefficients are listed in Table 4. The performance of the predictions are summarized by species:

Alewife - Predicted landings were higher and exhibited larger variability than those actually observed. Both series indicated peak catches in the mid-seventies.

Butterfish - The predicted landings roughly corresponded to actual landings during the first half of the seventies; the 6-fold increase over the last half of the decade was not predicted.

Soft-shell Clams - The predicted trend of decreasing landings over the early seventies was not observed as actual landings increased slightly.

Hard-shell Clams - Both the amplitude and trend of the fish landings were poorly predicted.

Cod - Cod landings rose dramatically over the last half of the seventies. This was not predicted as the regression indicated an initial decline in the early seventies and then a relatively steady catch.

Herring - The amplitude and trend were poorly predicted. Actual landings were steady during the early seventies and then rose slightly during the middle years of the decade. In contrast, the predicted landings suggested a peak catch in the early years and a decline in the middle years.

Menhaden - The increasing catches over the early seventies were predicted; however, the amplitude was underestimated by a factor of 3.

Redfish - The regression overestimated the landings although the amplitude and frequency of the fluctuations during the seventies were well predicted.

Scallops - The amplitude and trend in landings were closely predicted by the regression, although the absolute values were above actual landings.

Labrador Shelf/Grand Banks

In the review section it was noted that as part of the study of the Labrador Shelf a linear regression was published relating age 4 cod abundance in NAFO Subareas 2J3KL and the summertime surface salinities at Station 27 off St. John's, Newfoundland, depth averaged to 50 m (Sutcliffe et al. 1983). Cod abundances were VPA estimates published in Wells and Bishop (1980) and updated one year (1980) through personal communication with Wells. At the MEES workshop it was pointed out that the VPA estimates after 1976 given by Wells and Bishop (1980) have been revised. The new estimates, together with more recent data, were kindly provided by R. Mahon (BIO, pers. comm.) and are listed in the Appendix.

In view of the revised VPA estimates, the linear regression coefficients were recalculated with the new data but still included only those years used by Sutcliffe et al. (1983). The new regression is:

$$\text{numbers } (\times 10^5) \text{ of age 4 cod} = -29100 + 284(x_1) + 251(x_2) + 396(x_3)$$

where x_i (i = 1,2,3) is the mean depth-averaged salinity for the months July through September in the i^{th} year of the cod's life. The regression is based on the years 1962-80. For age 4 cod in 1962, the salinity years for the regression are 1958, 1959 and 1960. In Sutcliffe et al. (1983) they refer to the regression period 1958-76 which are the birth years of the 4-yr-old cod. The new regression accounts for 80% of the cod variation (r = 0.87) similar to the explained variance of the regression given by Sutcliffe et al. (1983). The new regression was then used to predict cod abundances since 1980, the results of which are given in Fig. 4, together with the recent VPA estimates. The observed rapid increase in cod abundance in the early eighties was predicted. A slight decline in cod is predicted during the mid-eighties. The most recent VPA estimates (1983 and 1984) indicate an earlier decline, but these latest estimates have not converged and so their certainty is questionable. Further data are required to clarify whether or not such a trend is real.

NEW CORRELATIONS

In the earlier work by Sutcliffe fish landings were used as proxy variables for fish abundance or recruitment because they were the only long time series available. In more recent years VPA estimates have become more readily available. For the purposes of the workshop, I obtained VPA records for cod (age 3 abundance for NAFO Subareas 3NO, 3Ps, 4T, 4VW) and haddock (age 1 abundance for 4VsW, 4X) from R. Mahon (BIO, pers. comm.) and correlated them with environmental data in a manner similar to Sutcliffe et al. (1977).

The most recent estimates using VPA methods have not converged. Therefore, abundance estimates for 1983 and 1984 were not used in the correlations. Cod stocks from around Newfoundland (3NO, 3Ps) were correlated with monthly means of Station 27 salinities depth-averaged over the top 50 m. For those months when no salinity data were available, linear interpolation between adjacent months was used. The Gulf of St. Lawrence stocks (cod 4T) and Scotian Shelf stocks (cod 4VsW; haddock 4VsW, 4X) were correlated with RIVSUM. This is consistent with the expected areal extent of the influence of the St. Lawrence River discharge.

The abundance of four of the six stocks were correlated with their environmental variable at significance levels $p < 0.1$ (Table 5). Linear regressions were determined for these stocks (Table

6) and the results plotted together with the actual VPA estimates (Fig. 6). Predictions of fish abundance for recent years have also been plotted based on the regressions and the latest environmental data. The most recent VPA estimates are given but as stated above such estimates are provisional.

The 3Ps and 4VsW cod are well modelled by the regressions. Although the data are uncertain, the 1983 and 1984 VPA estimates suggest the trends in these two stocks have been correctly predicted. While the rapid decline in 4X haddock during the early sixties and the large peak in 3NO cod in the mid-sixties were reproduced from the linear regressions, the models for these two stocks do not perform as well during the seventies. The regressions suggested larger variability in the stocks than was observed.

CONCLUDING REMARKS

The primary purpose of the exploratory correlation analysis used by Sutcliffe and coworkers was to point out the possibilities of environmental influences in fish stock recruitment. In this paper, at the request of the organizers of the MEES workshop, I used the relationships between fish and environment found by Sutcliffe, to predict more recent trends in the fisheries and then compared them with the observations. Perhaps not surprisingly, the predicted landings for several fish stocks were poor, e.g. halibut in the Gulf of St. Lawrence, cod and hard-shell clams in the Gulf of Maine, while for many other stocks the predictions were good, e.g. Quebec lobster, scallops and redfish in the Gulf of Maine, cod in southern Labrador and northern Newfoundland.

It should be recognized that the failure of the linear regressions to accurately predict the trends in landings does not necessarily indicate a lack of environmental influence. This may be due to several possible factors. First, the environment is only one among many factors influencing fish production. Thus the linear regressions presented within this paper which ignore fishing effort and biotic effects would only be expected to adequately predict the observed data if these effects remain relatively constant over the time period examined. Constant fishing pressure might be valid in the Quebec lobster fishery, for example, but is unlikely for many of the species within the Gulf of Maine as foreign fleets fished heavily in the region during the sixties and seventies. Prior to this time the New England landings accounted for all or the majority of the catch of most species within the Gulf of Maine. The USSR landings, in particular, rose dramatically and dominated the catch of several species during the same years used to test recent predictions. The change in fishing pressure by the foreign fleets must have had an effect on the U.S. landings and might be the reason for the seemingly poor agreement between environmentally predicted and observed fish landings in several of the Gulf of Maine stocks. Secondly, as Skud (1982) has discussed, certain species alternate as dominant and subordinate species, e.g. mackerel and herring off Canadian waters. He suggested that the dominant species may be environmentally regulated whereas subordinate species are influenced more by competition and predation. Changes in dominance from one species to another could result in failure of the environment-fish correlations when based on individual species. Thirdly, in the case of many of the Gulf of Maine stocks, only six more years of fish data were available for the analysis. Given the high persistence in the data (especially after 3-yr running means were applied), the extra 6 yr generally represents only one new independent data point, making it difficult to test statistically whether the relationship has held up or not.

In spite of the many possible pitfalls, the landings for several stocks were closely predicted by the environmental regressions. These stocks may be those for which fishing effort or other factors influencing recruitment remained relatively constant or ones where environmental influences indeed dominate. Further investigation is required to determine the actual role of the environment on these stocks.

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DISCUSSION PERIOD

Myers: I still can't evaluate whether Sutcliffe's correlations as a whole are valid. The methodology bothers me. I suggest combining all the data and their probability values and seeing if there is an overall relationship. My second methodological point is a suggestion to use a Box-Jenkins transfer function approach rather than arbitrary 3-yr running means.

Drinkwater: Your points are well taken. This is a rare piece of work where those types of analyses can be done, where environmental correlations are established on more than two or three species.

Frank: If the structure of the real or hypothetical food web within an area were known, it would be interesting to look at predator-prey relationships. Dow looked at how one species might respond positively to temperature, but as a subordinate to some other species it might respond differently. Skud had shown the same with mackerel and herring. Therefore, knowledge of the food web structure might be a different way to approach analyses of environment-recruitment data.

Drinkwater: That certainly could be some of the reasons why some corrrelations break down after a few years.

Zwanenburg: What is needed is to examine and define the parameters of the fishery and the environment that we feel comfortable comparing and for which we are able to interpret when correlations exist.

Pepin: Do you want to predict trends or absolute recruitment values? Is the objective of using an environmental variable to get a idea of recruitment, e.g. a high or low year-class? This seems a more reasonable goal than predicting precise recruitment values.

Perry: And Mahon's presentation indicates a method to apply these estimates in routine stock assessments.

TABLE 1

Correlation coefficients (r) of Quebec landings with lagged monthly means of RIVSUM. n* is the effective number of independent points and P is the significance level. Data were smoothed using a 3-yr running mean.

Species	Years	Month	Lag(yr)	r	n*	P
Halibut	1932-70	1	10	0.86	5	0.06
Lobster	1939-70	3	9	0.91	4	0.09
Soft-Shell Clams	1951-68	1	6	0.64	6	>0.1

TABLE 2

Linear regression coefficients between Quebec landings in mt. (Y) and the lagged monthly mean RIVSUM in m^3s^{-1}(X) where Y = AX + B and the data have been smoothed using a 3-yr running mean.

Species	Month	Lag(yr)	A	B
Halibut	1	10	4.2	-254.2
Lobster	3	9	22.9	-855.8
Soft-Shell Clams	1	6	14.1	-847.1

TABLE 3

Correlation coefficients (r) of New England and NAFO subarea 5 (S5) landings with lagged monthly means of coastal SST (sea surface temperature). BH = Boothbay Harbour, Maine. St. A. = St. Andrews, New Brunswick. n* is the effective number of independent points and P is the significance level. Data were smoothed using a 3-yr running mean.

Species	Years	Temp.	Month	Lag (yr)	r	n*	P
Alewife	1928-71	St.A.	4	6	0.85	6	0.03
		B.H.	2	5	0.84	7	0.02
			12	7	0.87	6	0.02
Butterfish	1928-71	St.A.	4	4	0.72	6	0.10
			11	5	0.75	6	0.09
		B.H.	4	5	0.79	6	0.06
Clams (Soft-Shell)	1928-71	St.A.	12	7	-0.79	5	0.10
		B.H.	12	7	-0.90	7	<0.01
Clams (Hard-Shell)	1928-71	St.A.	8	2	0.80	5	0.10
		B.H.	10	3	0.74	5	>0.10
Cod (S5)	1925-73	St.A.	8	4	-0.83	6	0.04
	1914-73	B.H.	11	4	-0.73	9	0.03
Herring	1928-71	St.A.	11	2	0.72	6	0.10
		B.H.	10	2	0.74	6	0.10
Menhaden	1928-71	St.A.	4	3	0.87	6	0.02
		B.H.	2	2	0.88	7	0.01
			12	3	0.87	6	0.02
Redfish (S5)	1936-73	St.A.	3	8	-0.73	21	<0.001
		B.H.	12	8	-0.72	7	0.04
Scallops	1928-71	St.A.	11	6	0.80	5	0.10
		B.H.	11	5	0.83	5	0.08

TABLE 4

Linear regression coefficients between Gulf of Maine landings in m.t. (Y) and lagged monthly means of SST in °C (X) where Y = AX + B. The data were smoothed using a 3-yr running mean.

Species	SST Station	Month	Lag (yr)	$A(10^3)$	$B(10^3)$
Alewife	St.A.	4	6	3.59	-9.45
Butterfish	B.H.	4	5	0.48	-1.07
Clams (Soft)	B.H.	12	7	-0.93	7.52
Clams (Hard)	St.A.	8	2	0.64	-6.42
Cod	St.A.	8	4	-12.91	199.42
Herring	B.H.	10	2	12.07	-86.96
Menhaden	B.H.	2	2	6.07	-3.32
Redfish	B.H.	12	8	-5.87	-51.14
Scallops	B.H.	11	5	1.70	-8.28

TABLE 5

Correlation coefficients (r) between VPA abundance estimates of cod and haddock from NAFO Subareas and lagged environmental variables. n* is the effective number of independent points and P is the significance level. Data were smoothed using a 3-yr running mean.

Species	Years	Enviro. Var.	Month	Lag (yr)	r	n*	P
Cod 3NO	1959-82	Stn. 27 Sal.	9	2	0.87	4	0.10
Cod $3P_s$	1959-82	Stn. 27 Sal.	9	1	0.84	8	0.01
Cod 4T	1950-81	RIVSUM	-	-	<0.40	-	>0.10
Cod $4V_sW$	1958-82	RIVSUM	7	3	-0.87	5	0.05
Haddock 4VW	1948-81	RIVSUM	11	1	-0.65	5	>0.10
Haddock 4X	1962-81	RIVSUM	12	1	-0.78	7	0.04

TABLE 6

Linear regression coefficients between fish abundance (Y) and lagged monthly means of Station 27 salinities or RIVSUM in $m^3 s^{-1}$ (X) where Y = AX + B. The data were smoothed using 3-yr running means.

Species	Enviro. Var.	Month	Lag (yr)	A(10^3)	B(10^3)
Cod 3NO	Stn. 27 Sal.	9	2	173.67	-53.64
Cod $3P_s$	Stn. 27 Sal.	9	1	50.04	- 1.51
Cod $4V_sW$	RIVSUM	7	3	-1.44	2.09
Haddock	RIVSUM	12	1	-2.61	2.99

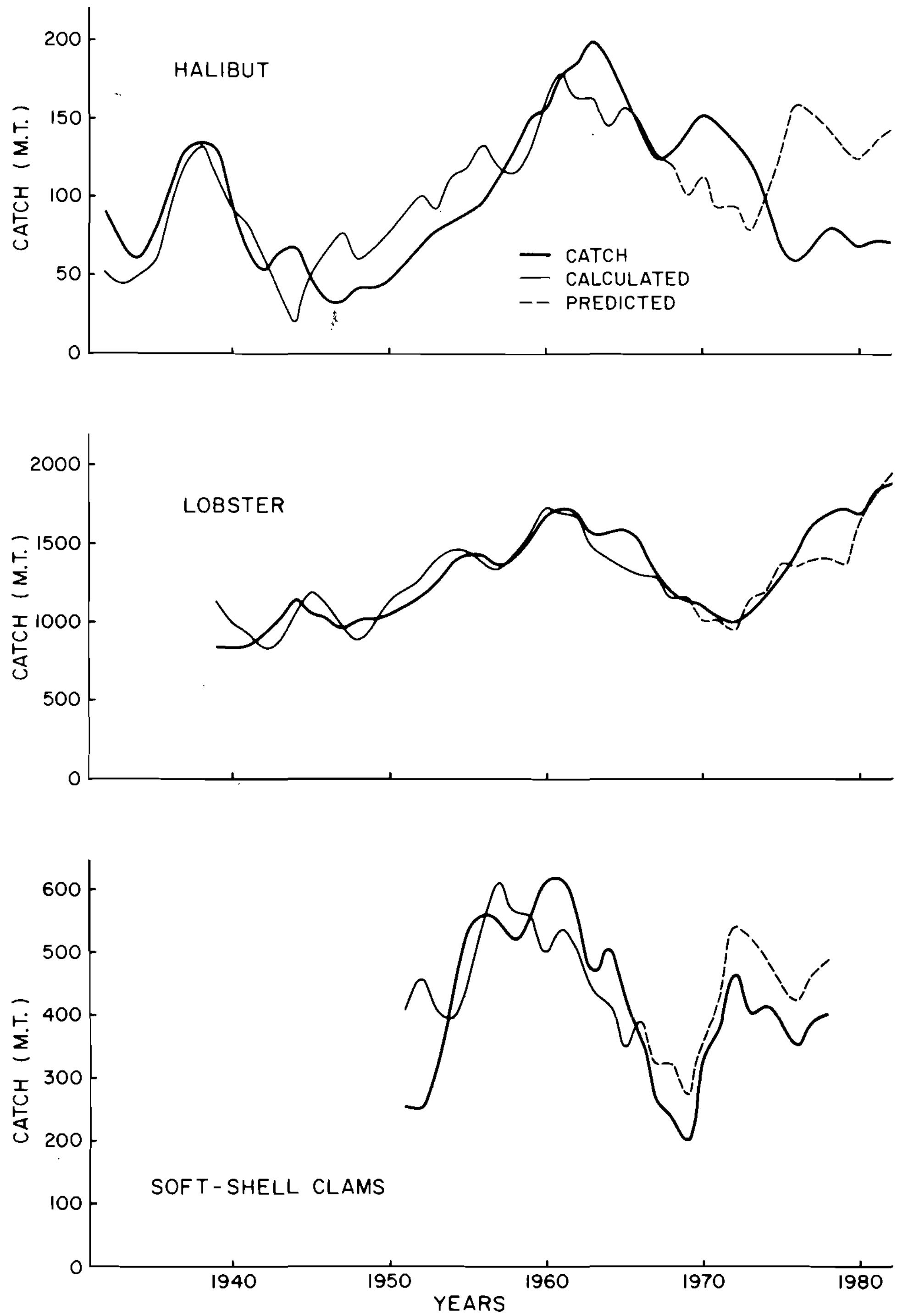

Fig. 1. The observed, calculated and predicted catches of halibut, lobster and soft-shell clams from Quebec. Calculated catch was determined from linear regressions with RIVSUM using data prior to the late 1960's (Table 2). The catch predictions were also based on the regressions. The data were smoothed using a three year equally-weighted running mean.

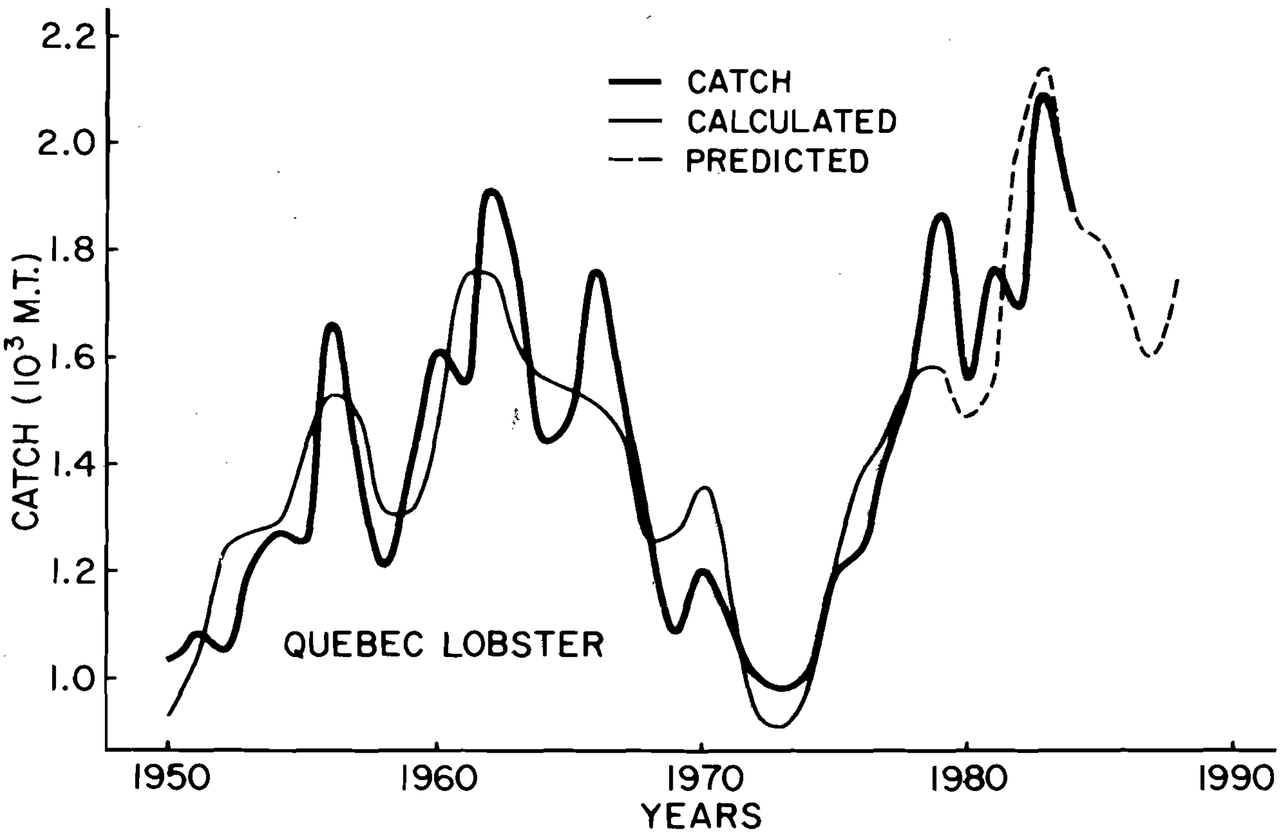

Fig. 2. The observed, calculated and predicted annual catches of lobster from Quebec. The calculated catch was determined from a linear regression with RIVSUM (see text). The catch predictions were also based on the regression.

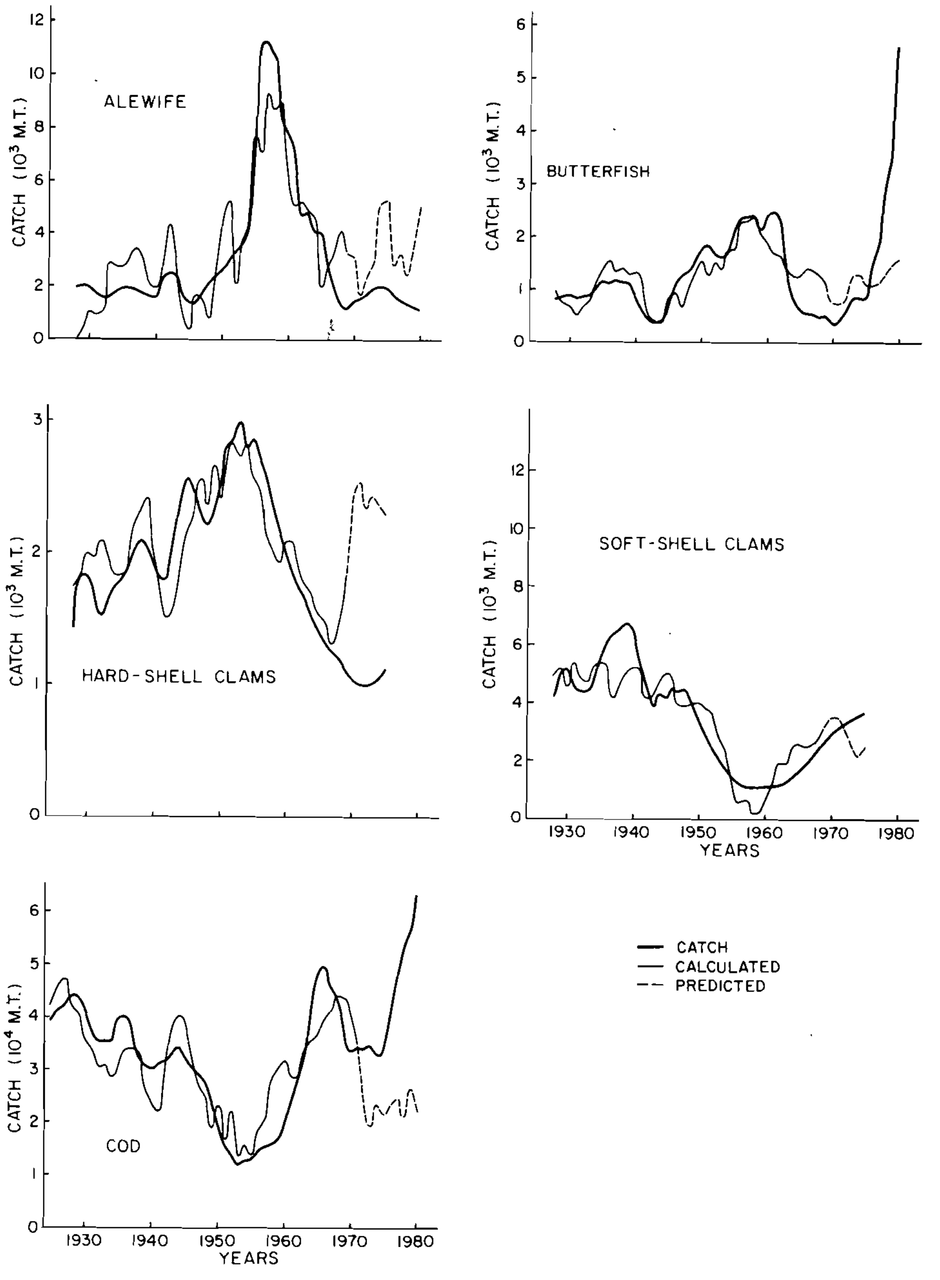

Fig. 3. The observed, calculated and predicted catches of several stocks from the Gulf of Maine. Calculated catch was determined from linear regressions with coastal sea-surface temperatures (Table 4). Predicted landings were also based on the regressions. The data were smoothed using a three year equally-weighted running mean.

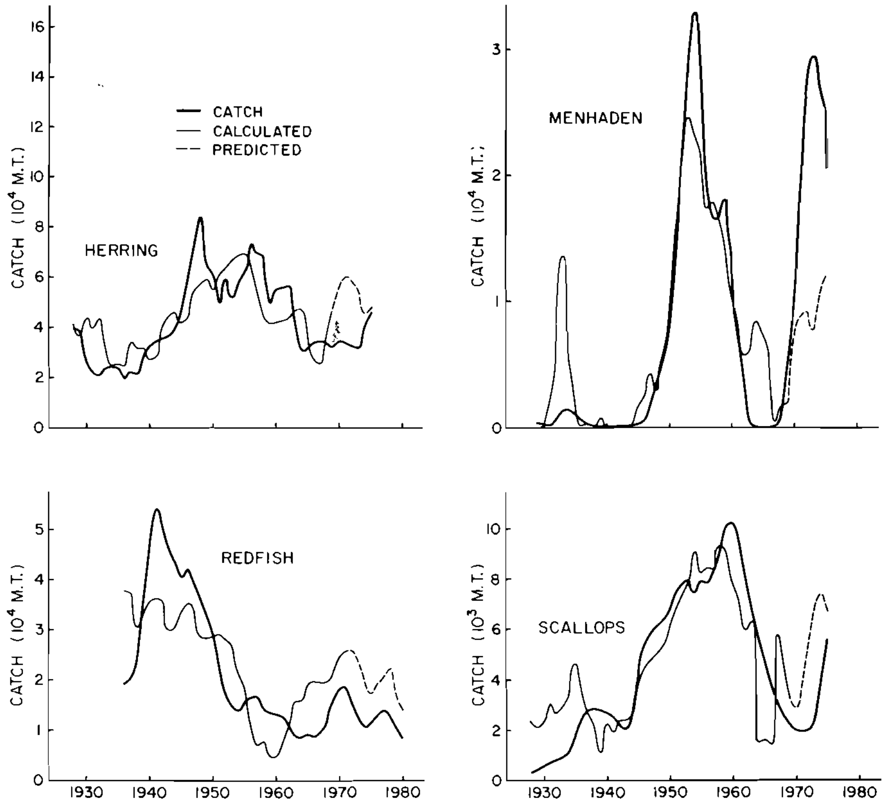
CATCH
CALCULATED
PREDICTED
HERRING
MENHADEN
REDFISH
SCALLOPS
CATCH (10⁴ M.T.)
CATCH (10³ M.T.)
1930 1940 1950 1960 1970 1980

Fig. 3. Cont'd.

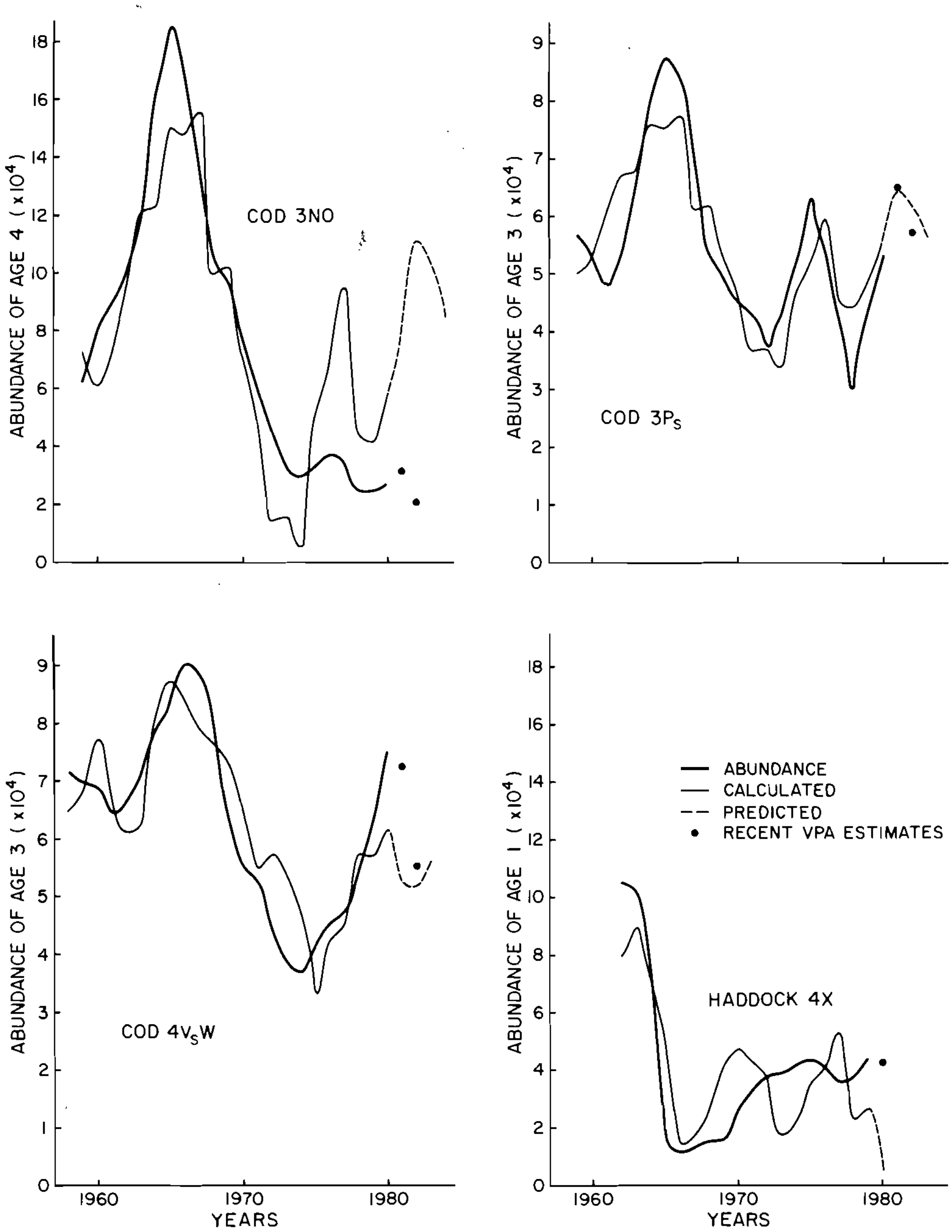

Fig. 4. Calculated and VPA estimates of annual abundance of age 4 Atlantic cod in NAFO Subareas 2J3KL. Calculated abundance was determined from a linear regression with summer salinity at Station 27 (see text). Predicted values were obtained from the same regression.

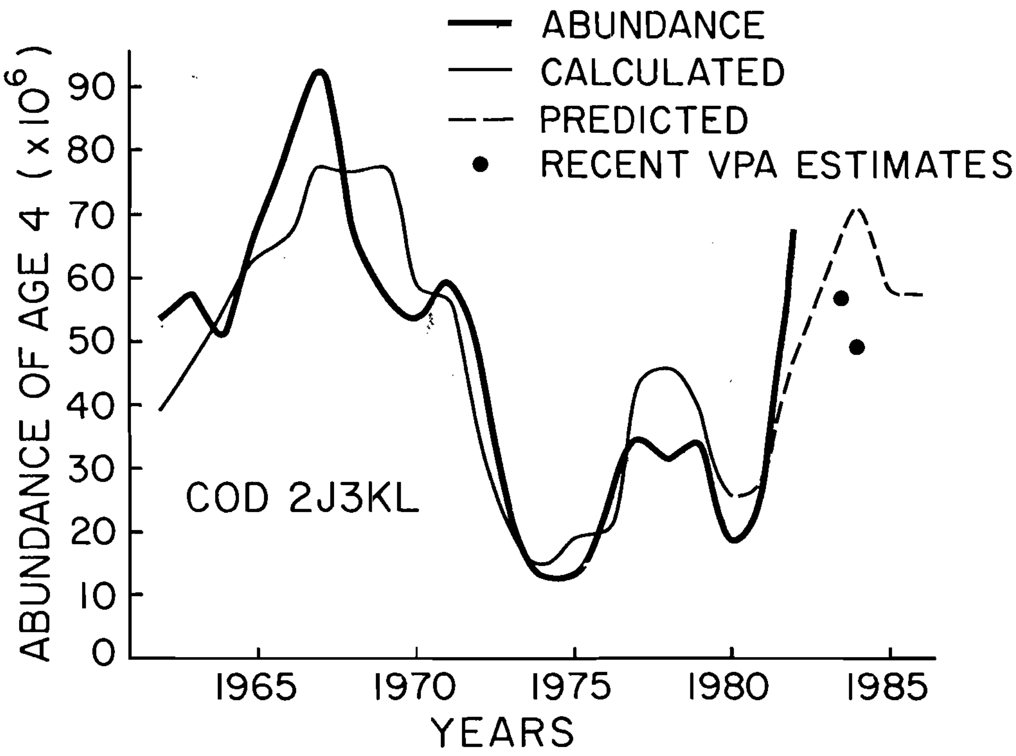

Fig. 5. Calculated and VPA estimates of cod and haddock abundances in several NAFO Subareas. The calculated abundance was determined from environmentally based regressions. Predicted values were also obtained from the regressions. Recent VPA estimates are plotted but are uncertain. The data were smoothed using a three year equally-weighted pumping mean.

APPENDIX

FISHERIES DATA

TABLE A1

Quebec landings in mt.

Year	Lobster	Halibut	Soft Shell Clams
1931			
32		110	
33		104	
34		54	
35		55	
36		71	
37		102	
38		136	
39	839	159	
40	871	109	
41	839	121	
42	807	45	
43	866	29	
44	1102	86	
45	1170	82	
46	1157	40	
47	848	27	
48	1084	34	
49	939	39	
50	1034	52	
51	1084	36	203
52	1048	54	290
53	1202	80	276
54	1275	70	187
55	1247	88	488
56	1656	93	603
57	1402	86	517
58	1220	111	567
59	1442	149	566
60	1610	127	429
61	1547	181	689
62	1919	154	732
63	1737	203	440
64	1438	194	496
65	1492	203	467
66	1774	172	556
67	1501	131	255
68	1275	129	284
69	1084	113	251
70	1198	146	172
71	1107	161	173
72	1012	152	651
73	980	119	329
74	1007	140	417
75	1202	114	459
76	1252	54	366
77	1416	40	338
78	1597	84	344
79	1873	76	488
80	1550	85	370
81	1760	71	155
82	1699	49	2
83	2092	97	0
84	1869	68	623

TABLE A2

New England landings in mt.

Year	Alewife	Butterfish	Hard-shell Clams	Herring	Menhaden	Scallops	Soft-shell Clams
1928	2067	703	1012	32004	2347	215	2481
29	1993	957	1564	48636	179	374	4062
30	1862	864	1734	37604	775	430	6032
31	2341	730	2182	28988	2	490	4885
32	1620	1026	1569	17270	24	713	4602
33	1278	705	1379	21812	467	979	4278
34	1638	873	1610	23228	1205	868	4362
35	1999	1041	1840	24644	1943	758	4446
36	1953	1171	1784	24352	1038	1678	5552
37	1908	1302	1728	24060	133	2599	6657
38	1954	853	2145	9547	149	2654	5777
39	1786	1437	2133	34105	55	3256	6779
40	1448	1123	2020	19982	40	2445	6978
41	1578	841	1926	32598	37	2620	6454
42	1708	558	1832	45213	34	2796	5929
43	3700	499	1610	27283	60	2196	3847
44	2357	240	1907	37857	32	1934	4141
45	1147	436	2744	42720	91	1812	3732
46	1222	367	2533	37378	93	4345	4984
47	1343	1360	2386	56289	101	5914	3996
48	1546	1319	2411	87132	552	5662	4609
49	2298	1227	2057	76392	5700	6341	4624
50	2584	1393	2155	88522	4220	6238	4040
51	2336	1877	2651	29445	5335	6552	3172
52	2690	2103	2520	69633	16370	6982	3063
53	3871	1588	3275	50141	18087	9066	2326
54	3314	1302	2742	58614	27073	7073	2151
55	3328	1784	2933	47304	36195	7642	1658
56	6189	2160	2684	66433	35729	7657	1383
57	10507	2381	2955	73032	18955	8519	1207
58	16780	2634	2626	80939	6284	7444	1080
59	6204	2059	2212	54765	23973	9189	1027
60	8699	2481	2288	70157	19337	10189	1275
61	10256	1887	2134	26243	11799	10784	1136
62	4582	2802	1688	71784	10774	9854	1141
63	6122	2726	1809	70087	160	8071	1261
64	3284	1301	1633	28668	3	6594	1208
65	4717	666	1471	34026	9	5595	1449
66	3943	538	1439	29712	6	5056	1885
67	3322	617	1315	31097	16	3187	1908
68	1199	489	1217	41672	10	3601	2038
69	967	578	1226	31118	21	2317	2418
70	1395	326	1192	30056	4766	2026	2964
71	1034	535	887	33937	11745	1971	2919
72	1907	178	1062	39737	13922	2006	3164
73	1559	657	1091	26004	30231	1791	3544
74	1629	882	931	32400	35581	2092	3308
75	2523	948	1070	35997	23073	3212	3487
76	1606	723	1191	50062	26768	5430	3857
77	1729	732	1083	50567	12142	8143	3816
78	1315	2869					
79	1181	1967					
80	1274	4444					
81	1093	4165					
82	743	8149					

TABLE A3

U.S. Landings from NAFO Subarea 5 in mt.

Year	Cod	Redfish	Year	Cod	Redfish
1893	48641		1938	37452	20640
94	57350		39	31903	25406
95	63687		40	28302	26763
96	49232		41	32263	59796
97	47106		42	29177	55893
98	45282		43	31232	48349
99	49528		44	33556	50439
1900	34870		45	33709	37912
01	46398		46	35166	42423
02	43033		47	27538	40160
03	40209		48	29379	43631
04	31176		49	28873	30743
05	37247		50	24256	34308
06	63276		51	18358	30077
07	57965		52	18465	21377
08	41433		53	11230	16791
09	40689		54	12237	12988
10	35688		55	12477	13914
11	27105		56	13246	14388
12	28678		57	13181	18490
13	24719		58	16316	16045
14	33661		59	16350	15521
15	18932		60	14430	11375
16	19268	53	61	17965	14076
17	21877	82	62	26558	14134
18	30563	41	63	29920	10046
19	30721	25	64	28416	8313
20	28046	31	65	42261	8057
21	32866	13	66	57255	8569
22	31638	14	67	42310	10857
23	31280	7	68	49176	6777
24	33475	35	69	45823	12380
25	35200	25	70	33368	15958
26	41130	30	71	35357	20034
27	42815	30	72	31547	19095
28	40756	55	73	34686	17360
29	43302	32	74	34456	10471
30	48390	47	75	33369	10571
31	39089	80	76	29676	10696
32	36161	28	77	39565	13223
33	37498	85	78	48029	14084
34	32410	519	79	50420	14755
35	36185	7549	80	61624	10183
36	36380	23162	81	55228	7915
37	46396	14823	82	71895	6903

TABLE A4

VPA (Virtual Population Analysis) estimates of abundance

	Cod (# of age 3)				Cod (# of age 4)	Haddock (# of age 1)	
Year	4T	$4V_sW$	$3P_s$	3NO	2J3KL	4VW	4X
1948						68737	
49						39536	
50	113987					72174	
51	109640					34546	
52	113532					26476	
53	108046					122270	
54	78707					42817	
55	70001					44458	
56	83924					64396	
57	106681					79935	
58	110471	68883				69600	
59	143344	75430	59386	53623		29692	
60	134847	70623	59260	52379		48545	
61	46119	63507	50943	81956		33497	
62	60134	71945	48671	107685	5418	58715	24933
63	41747	57005	42957	78128	5776	84522	91807
64	61261	71784	70839	111687	5058	91812	199270
65	52155	85028	80985	162347	6848	91519	16470
66	61216	82139	84419	210082	8167	15279	10107
67	106187	83088	98486	183210	9252	14779	17370
68	94971	105977	70186	100563	6702	10768	8063
69	57488	74812	54345	127855	5780	6701	14483
70	53455	51891	35514	80313	5359	8131	25306
71	86059	63903	60221	84468	5889	4439	6292
72	33293	48688	39399	62208	4752	8091	47423
73	44770	46253	31072	35192	2077	7795	44360
74	51594	36582	41773	36964	1237	4653	24044
75	39861	33839	55824	23428	1252	20061	49054
76	104560	40376	57645	26672	2376	27875	52098
77	163952	50052	70361	48189	3505	32785	30164
78	192774	46131	36572	38204	3194	42405	41818
79	112340	44113	20671	16511	3372	21032	33882
80	219468	74150	34161	20305	1861	39798	39844
81	120644	69027	79069	37192	2466	86306	58478
82	276388	80981	40822	23199	6719	71659	28652

Testing Predictions of Marine Invertebrates and Fish Stock Landings from Environmental Variables

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Drinkwater, K. F., and R. A. Myers. 1987. Testing predictions of marine invertebrates and fish stock landings from environmental variables, p. 62. In R. I. Perry and K. T. Frank [ed.] Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556.

Sutcliffe (1972, 1973) and Sutcliffe et al. (1977) found apparent correlations between environmental variables and lagged annual catch for several Gulf of St. Lawrence and Gulf of Maine stocks through exploratory analysis. The objectives of the present study were to test these predicted relationships using recent environmental catch data. Nine to fourteen years of new catch data were available for 13 stocks investigated. Correlations were calculated between the new catch data and the predicted catch based on the environmental variables. Individually, none were found to be statistically significant ($p \leq 0.05$); however, this was not unexpected because of the high autocorrelation in the catch and environmental data sets which reduced the effective number of degrees of freedom. Using a sign test we considered the hypothesis of an overall environmental effect on the landings. No significant effect was found as the correlation coefficients for five of 13 stocks reversed sign using the new data. The utility of environmentally based predictions was also tested. Overall, the predicted catches from the environmental regression were no better than predictions based on the long-term mean and significantly worse than predictions using catch data a few years previous. Changing effort for several of the Gulf of Maine stocks is felt to mask any possible detection of environmentally induced variability. In general, invertebrate stocks fared better than fish stocks and investigations of environmental effects on Quebec stocks of lobster and soft-shell clams are felt to be warranted.

Sutcliffe, W. H., Jr. 1972. Some relations of land drainage, nutrients, particulate material, and fish catch in two eastern Canadian bays. J. Fish. Res. Board Can. 29: 357-362.

Sutcliffe, W. H., Jr. 1973. Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence. J. Fish. Res. Board Can. 30: 856-859.

Sutcliffe, W. H., Jr., K. Drinkwater, and B. S. Muir. 1977. Correlations of fish catch and environmental factors in the Gulf of Maine. J. Fish. Res. Board Can. 34: 19-30.

Climate and Fish Recruitment in the Northwest Atlantic: Reconsideration of the Influence of River Runoff

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Koslow, J. A. 1987. Climate and fish recruitment in the northwest Atlantic: reconsideration of the influence of river runoff[1], p. 63-64. In R. I. Perry and K. T. Frank (ed.) Environmental effects on recruitment to Canadian Atlantic fish stocks. Can. Tech. Rep. Fish. Aquat. Sci. 1556.

Three hypotheses are re-examined that were proposed by Sutcliffe et al. (1976, 1977, 1983) related to the influence of freshwater outflows on physical oceanography and fishery recruitment in the northwest Atlantic.

1) Freshwater outflow through Hudson Strait, for which St. Lawrence River discharge can serve as proxy, regulates recruitment to Labrador shelf (2J3KL) cod due to its influence on water column stability and thereby nutrient dynamics and productivity downstream. As shown by Fortin et al. (1983), precipitation in the Hudson Bay watershed is not correlated with that along the St. Lawrence River. When other physical processes are considered, St. Lawrence discharge does not significantly enter a stepwise regression analysis with Labrador cod recruitment as dependent variable, and it entered only one of three other regression analyses of recruitment to Grand Banks (3NO, 3Ps) and Scotian Shelf (4VsW) cod.

2) Discharge from the St. Lawrence River significantly influences sea surface temperature (SST) from the Gulf of St. Lawrence to the Gulf of Maine through its influence on upper water column stability and mixing with deeper water. Lagged correlation analysis of spring discharge of the St. Lawrence with new time series of SST along the "oceanic pathway" (Loucks et al. 1985) indicates significant correlations generally only appear at 0-1 season lag as far downstream as Georges Bank rather than at the expected transit time for the spring outflow. Thus relationships between St. Lawrence discharge and SST beyond the upper Scotian Shelf appear to be due to mutual forcing by large- scale meteorological processes.

3) St. Lawrence discharge significantly influences fishery recruitment along the "oceanic pathway" through its influence upon physical processes (e.g. SST). Stepwise regression analyses were performed with recruitment to regional haddock stocks (4VW, 4X, 5Y, 5Z) with the variables entered stepwise forward and eliminated stepwise backward (as conducted previously with the cod stocks, where generally consistent results were achieved with the two methods). But with the haddock, 0-group mackerel appeared to be the most important factor affecting haddock recruitment when the regressions were performed stepwise forward, the negative relationship possibly being related to predation during the over-wintering period (Kulka and Stobo 1981). When variables were eliminated stepwise backward, several physical variables representing warm SST, low St. Lawrence discharge (but in the year of spawning rather than in the year preceding, despite the expected approximately 1-yr transit time), and large-scale atmospheric pressure patterns were generally associated with good haddock recruitment.

Due to intercorrelations among physical and biological processes in the northwest Atlantic, multiple regression analyses of recruitment data must be interpreted cautiously; results of univariate statistical analyses (e.g. with St. Lawrence River discharge) are very likely to be spurious. Regression analyses indicate that large-scale, coherent patterns of recruitment among shelf-spawning cod stocks appear related to large-scale atmospheric processes; patterns of recruitment among haddock stocks appear related to a complex of both predatory interactions, particularly by overwintering juvenile mackerel, and large-scale physical processes related to SST, meteorology and possibly runoff. Year-class success in cod and haddock stocks and environmental processes in the northwest Atlantic are also generally matched in terms of their spatial and frequency-domain scales of coherence. Changes in stock size, on the other hand, are generally not significantly associated with year-class success over the period in question. However, our present understanding of regional climatology (i.e. the interactions of large-scale atmospheric and oceanographic processes) is inadequate to interpret these results further.

[1]The full presentation of the material in this abstract can be found in:

Koslow, J. A., R. H. Loucks, K. R. Thompson, R. W. Trites. 1986. Relationships of St. Lawrence River outflow with sea-surface temperature and salinity in the northwest Atlantic, p. 271-282. In S. Skreslet (ed.) The Role of Freshwater Outflow in Coastal Marine Ecosystems. Springer-Verlag, N.Y.

Koslow, J. A., K. R. Thompson, and W. Silvert. 1987. Recruitment to northwest Atlantic cod (Gadus morhua) and haddock (Melanogrammus aeglefinus) stocks: influence of stock size and climate. Can. J. Fish. Aquat. Sci. 44: 26-39.

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DISCUSSION PERIOD

There was some discussion of the interpretation of the periodicity of results and the appropriateness of stepwise regressions for considering the environmental interrelations. Further discussion concerned mechanisms connecting periodicities in forcing functions to periodicities in the response of fish populations. Considering the large number of potential external forcings, each with their own periodicities, the possibility for resonant effects is likely. For example, it was suggested age-structured models often generate responses with periods of about 20 yr, and that the ability of a population to filter out certain periods and respond to others should be examined.

Projecting Year-Class Strength Without the Mediation of a Functional Relation[1]

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Although parent stock size, or an environmental variable like temperature, freshwater input or wind direction, may influence the size of a recruiting year-class of fish, there is usually no firm theoretical or observational support for any particular functional form. Moreover, the wide variability in year-class strength, and its importance for management, make knowing the expected value less important. We, therefore, examined methods for projecting recruitment using raw data rather than fitted curves.

We used stock size as the variable influencing recruitment because of the many traditional examples available, but the mathematical treatment is the same whatever the independent variable. Getz and Swartzmann (1981) introduced a transition matrix approach in which stock and recruitment axes are divided into intervals, and Overholtz et al. (1986) modified the method and applied it to Georges Bank haddock. A variant of this approach is now being used to make projections for the New England fishery (New England Fishery Management Council 1985; S. Murawski, pers. comm.). In this approach, the probability distribution for recruitment at a given stock size is a piecewise uniform function based on the boundaries of conveniently chosen recruitment intervals and the number of recruitments observed in each. We think it more in keeping with the use of raw data to assume that only previously observed recruitments are possible. We examined two ways to assign probabilities - one where all recruitments within a stock interval were equiprobable and another where probabilities decreased smoothly with increasing distance from the new stock size.

We compared different projection methods according to their prediction of the probability distribution of stocks in a simple fishery model (comparing the maximum deviations of their ogives from a simulated data set representing the true distribution). The methods compared were the Overholtz et al. transition matrix (which we call the New England method), estimating parameters of a Ricker function with multiplicative lognormal noise (the Ricker method), and our two methods. Where possible, we compared performances over a wide variety of data sets; the subjective choices of the New England method restricted us to fewer data sets.

We compared the methods on different underlying functional forms, and on different forms and amounts of noise. Results to date can be summarized as follows: Ricker and New England methods make assumptions about the form of the probability distribution for recruitment; when these assumptions are correct, they are a small help; when they are wrong, they are a large hindrance. The only time that the Ricker method was unambiguously the best is when that model is correct and the data are representative. For all other models, our methods work as well or almost as well as Ricker estimation or New England projection, and there are occasions when our methods work much better. In particular, if the distribution of recruitment probabilities is not unimodal, or if the data series contains a few extremely large recruitments, our methods are not misled as much as Ricker or New England methods. Real data sets are likely to contain these features.

[1]We will publish a more comprehensive report of this study elsewhere.

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DISCUSSION PERIOD

Silvert: If I understand your graphs, we've got some rather good news out of your talk. It seems that estimating the parameters of the Ricker curve would be a conservative policy to follow, that you would be less likely to overestimate recruitment than using any of the other techniques, even though it may be underestimated.

Evans: That's a correct interpretation within the class of models that we considered, and you may simply say that estimating Ricker parameters is likely to produce an underestimate if the truth is Beverton and Holt. I'm not sure that everyone would regard it as good news that you always come up with an underestimate.